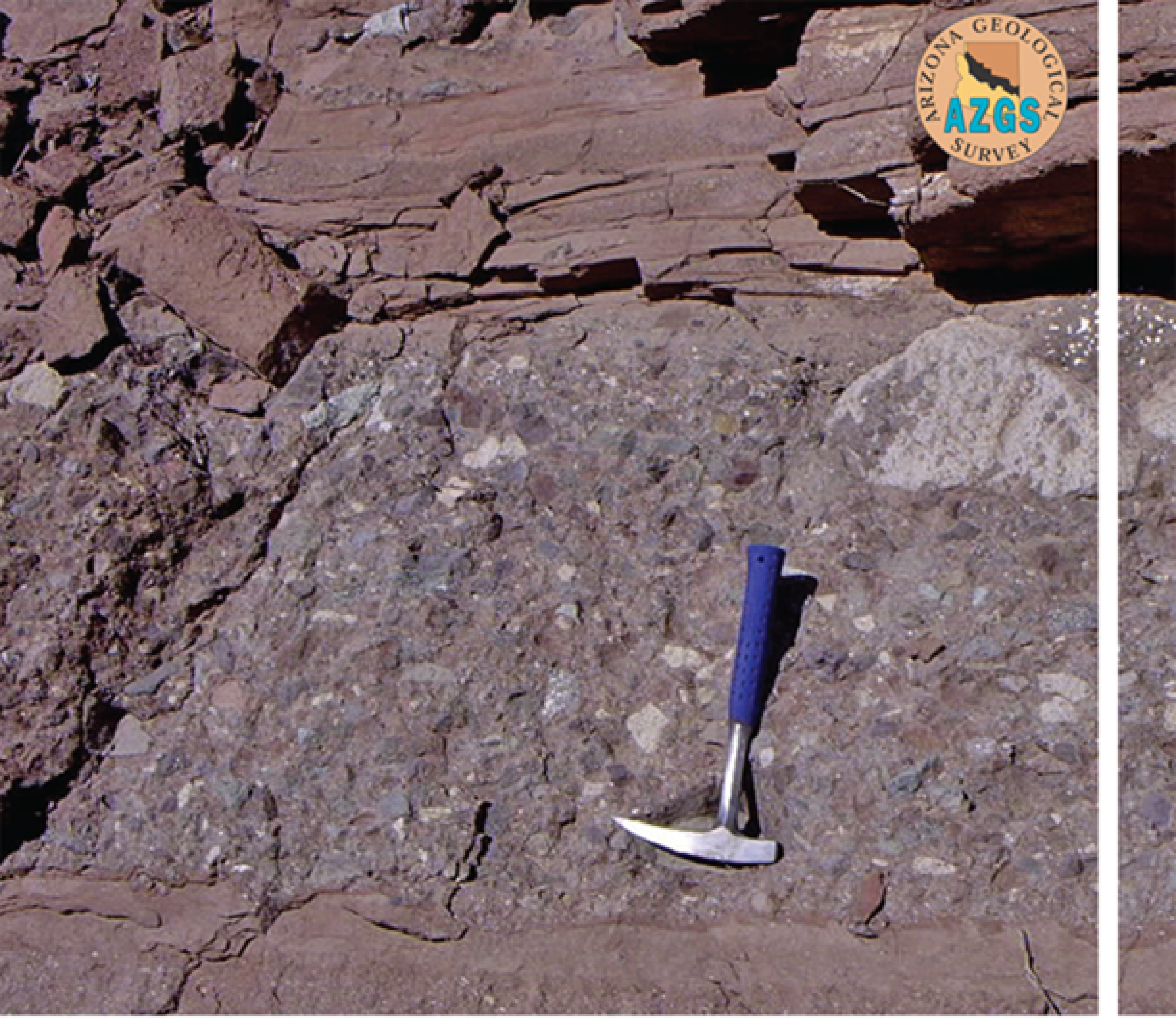

CONGLOMERATE CLAST COUNTS IN OLIGOCENE-MIOCENE STRATA NORTH FROM THE CATALINA CORE COMPLEX TO THE GILA RIVER, SOUTHEASTERN ARIZONA

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Conglomerate Clast Counts in Oligocene-Miocene Strata North from the Catalina Core Complex to the Gila River Valley, southeastern Arizona

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To provide insight into provenance relations for multiple mid-Oligocene to mid-Miocene sub-basins (typically half-grabens) dissected by erosion in uplands lying north of the Catalina core complex and west of the San Pedro trough, 136 outcrop counts were made of clast types in tilted conglomerates of the Cloudburst and San Manuel Formations and their lateral equivalents in exposures as far north as the Gila River near Kearny. Clast counts were not made for younger conglomerates of the post-mid-Miocene Quiburis Formation, which fills the San Pedro trough and onlaps flanking uplands (Dickinson, 1998), because Quiburis clast assemblages in all cases match bedrock sources exposed uphill on the modern landscape. By contrast, paleotopography during Cloudburst and San Manuel deposition can only be inferred from local paleocurrent indicators (clast imbrications; figure 39 of Dickinson, 1991, p. 70-71) and clast assemblages in tilted strata. Areas included in this study were the Guild Wash allochthon between the Tortolita and Suizo Mountains, the Star Flat allochthon on the east flank of the Black Mountains, the Black Hills (west of Mammoth), Camp Grant Wash (and Putnam Wash) between the Black Mountains and the Black Hills, multiple drainages of the Tortilla Mountains (Eagle Wash, Jim Thomas Wash, Hackberry Wash, Indian Camp Wash), and Ripsey Wash on the west flank of the Tortilla Mountains (Figs. 1-4).

Counting Procedure

Counts were made of 100-300+ clasts, typically cobbles but locally boulders or pebbles, at each outcrop station, for a total of 20,067 clasts. All clasts visible within selected exposed areas of specific conglomerate beds were tabulated at each outcrop station (mean count of 148 clasts per station with standard deviation of 36). The counts are frequency percentages (numbers of clasts regardless of mean diameter), rather than point counts (which would yield volumetric percent). Clasts were divided into the following ten groups for the counting of clast types:

pi (Pinal): schistose metamorphic rock derived predominantly from Precambrian Pinal Schist

gd (granodiorite-diorite): mafic granitoid rock derived dominantly from Precambrian basement (but perhaps in part from Cretaceous-Paleogene Laramide plutons)

or (Oracle): megacrystic granitic rock derived exclusively from Precambrian Oracle Granite

lc (leucocratic granitoid): alaskitic and aplitic granitic rock derived dominantly from dikes and apophyses within Oracle granite (but perhaps in part from the Eocene Wilderness Suite) – counted separately from Oracle (or) only in the Tortilla Mountains and along Ripsey Wash [change in counting procedure midway through project]

di (diabase): hypabyssal diabase derived from post-Apache Group Precambrian dikes and sills qt (quartzite): unmetamorphosed quartzite derived dominantly from Precambrian Apache Group including Troy Quartzite (but in part from Cambrian Bolsa Quartzite or Abrigo Formation)

ls (limestone): limestone derived predominantly from Paleozoic strata (but perhaps in part from Precambrian Mescal Limestone of the Apache Group)

wv (Williamson Canyon Volcanics): mafic volcanic rock derived from the Laramide Williamson Canyon Volcanics (Dripping Spring Mountains and Gila River gorge)

li (Laramide igneous): felsic to intermediate porphyry and altered volcanic rocks of inferred Laramide age (Late Cretaceous–Paleocene)

tv (Tertiary volcanic): unaltered intermediate to mafic or felsic volcanic rocks derived from the Galiuro Volcanics (or correlative volcanic units exposed in multiple tiltblocks farther west)

Clast Transects

Sequential clast counts were made at multiple outcrop stations along selected well exposed cross-strike transects to test for stratigraphic variations in clast assemblages. Transects are arbitrarily labeled A through Z (the latter composited from strike transects ZL and ZU), with sequential numbers denoting stations along each transect (A1, A2, etc., listed in order from downsection to upsection, or north to south for transect Z). Letters in parentheses denote the stratigraphy of each transect or station: b, Beehive Well Facies of San Manuel Formation (Camp Grant Wash); c, Cloudburst Formation and correlatives; h, Hackberry Wash Facies of Cloudburst Formation (Tortilla Mountains); k, Kannally Member of San Manuel Formation (Black Hills); s, San Manuel Formation (undivided) and correlatives; t, Tucson Wash Member of San Manuel Formation (Black Hills); and cs-hs, combined Cloudburst(–Hackberry) and San Manuel strata in continuous stratigraphic successions.

Data Presentation

Figure 1 is an overview of the study area showing the distribution of mid-Tertiary strata and the spans of Figures 2-4. Figure 2 shows the general geologic context of the Guild Wash and Star Flat allochthons and the locations of clast transects A-C. Figure 3 shows the Black Hills area (transects D-I) and the Camp Grant Wash area (transects J-P). Figure 4 shows the James Wash area (unsampled), the Tortilla Mountains (transects Q-Y) and Ripsey Wash (strike transects ZL-ZU). Figure 5 (same base as Figure 1) indicates key onlap-overlap relations of Cloudburst and San Manuel strata.

Table 1 lists the locations and stratigraphy of the clast transects, Table 2 is a compilation of frequency percentages of clast types at each station along the clast transects, Table 3 is a summary of notable areal and stratigraphic variations in clast type, and Table 4 tabulates available paleocurrent data for mid-Tertiary strata within the study area from Weibel (1981), Hansen (1983), Dickinson (1991), and this study.

Paleocurrent Trends

Clast imbrications were measured during a previous study (Dickinson, 1991) to delineate paleocurrent trends in many of the successions for which clast counts were made, and fresh paleocurrent data were collected for the Beehive Well Facies of the San Manuel Formation during this study. Mean clast orientations were estimated by eye at multiple outcrops and measured as present strike and dip of net imbrication planes at each outcrop. Strike and dip of bedding was measured at the same outcrops, and the imbrications were restored to original orientations by rotating bedding and imbrication attitudes jointly with a stereonet to bring bedding planes to horizontal. Initial dip of bedding was not inferred, but is unlikely to have exceeded 5˚, which is within the uncertainty limits within which imbrication attitudes can be estimated on outcrop. Net paleoflow is assumed to have been normal to restored imbrication in the initial updip direction.

The consistency of paleocurrent directions inferred from multiple outcrop stations for a given stratigraphic unit can be gauged from *R*, the relative magnitude of the net paleocurrent vector. *R* is given by the expression $(\Sigma \sin^2 + \Sigma \cos^2)^{1/2}/n$ where sin and cos are trigonometric functions for the paleocurrent vectors derived at *n* outcrop stations. The significance of *R* can be gauged from appreciation that *R* for 10-20 paleocurrent vectors distributed evenly through 90˚ of arc is ~0.9, whereas *R* for 10-20 paleocurrent vectors distributed evenly through 180˚ of arc is ~0.6.

Stratal Successions

Mid-Tertiary sedimentary strata of the study area can be divided into two principal stratal successions (Dickinson, 1991, p. 62-65), with stratigraphic names taken from the Black Hills near Mammoth where the earliest detailed stratigraphic mapping was undertaken (Heindl, 1963; Creasey, 1965, 1967): (1) the Cloudburst Formation, a lower succession of red to brown strata of redbed coloration resting concordantly on mid-Tertiary volcanic and volcaniclastic strata where the latter are present (mapped locally as a lower member of the Cloudburst Formation), but including the Hackberry Wash Facies (main part of the "Hackberry Formation" of Schmidt, 1971) where the formation rests unconformably on pre-Tertiary rocks without any intervening volcanic strata; (2) the overlying San Manuel Formation composed of buff to gray strata lacking redbed coloration.

Cloudburst and San Manuel Formations jointly form concordant and apparently conformable stratigraphic successions in depocenters of the deepest keels of the longest-lived evolving half-graben basins within the study area, but the San Manuel Formation overlaps the Cloudburst Formation with angular unconformity along the footwall flanks of some half-grabens, and oversteps the Cloudburst Formation to rest nonconformably with buttress unconformity on Precambrian basement forming the structural crests of tiltblocks and horsts outside the half-graben depocenters. As upward-fanning dips are characteristic within half-graben sedimentary accumulations, the mean dip of San Manuel strata is typically less than the mean dip of older Cloudburst strata. The contact between Cloudburst and San Manuel strata as mapped from the color contrast may not be everywhere synchronous, but limited geochronological information suggests no significant overlap in age.

Age Relations

As no age-diagnostic fossils have been recovered from mid-Tertiary strata of the study area, age brackets for the stratigraphic units are provided entirely by isotopic ages for lavas and tuffs at selected stratigraphic horizons.

Cloudburst Base – At the type locality within the Black Hills (Fig. 3), sedimentary strata of the Cloudburst Formation rest concordantly and with apparent conformity on mid-Tertiary volcanic rocks, mapped locally as a lower member of the Cloudburst Formation, which have yielded a K-Ar age (whole-rock) of 28.3 ± 0.6 Ma (Shafiqullah et al., 1978; table 2H of Dickinson and Shafiqullah, 1989). Mid-Tertiary volcanic rocks which underlie equivalents of the Cloudburst Formation to the west in the Guild Wash allochthon (Fig. 2) have yielded isotopic ages (table 2F of Dickinson and Shafiqullah, 1989; Spencer et al., 2002; Ferguson et al., 2003) of 26.7 ± 0.5 Ma (biotite K-Ar) and 26.4 ± 0.1 Ma (sanidine Ar/Ar). Younger K-Ar ages (hornblende, biotite, feldspar, whole-rock) of 25.1-23.5 Ma (table 2E and samples #1 and #18 of Dickinson and Shafiqullah, 1989) for sub-Cloudburst volcanic rocks in the Guild Wash allochthon are now regarded as spurious (Ferguson et al., 2003), and possibly related to a post-eruptive phase of metasomatic alteration. Conglomeratic strata of the basal Cloudburst Formation that directly overlie volcanic rocks in the Guild Wash and Star Flat allochthons, and in the Black Hills, are volcaniclastic (clasts ~100% volcanic rock), and were not counted during this study.

Intra-Cloudburst – Welded tuff interbedded with conglomerate of lower Cloudburst Formation in the Star Flat allochthon near the Willow Springs Ranch has yielded an Ar/Ar age (sanidine) of 26.3 ± 0.1 Ma (Orr et al., 2004), and andesitic lava intercalated within the Hackberry Wash Facies of the Cloudburst Formation near the head of Jim Thomas Wash in the Tortilla Mountains (Fig. 4) has yielded a K-Ar age (whole rock) of 25.4 ± 0.6 Ma (sample #5 of Dickinson and Shafiqullah, 1989). Tuffs interbedded with conglomerate of the Hackberry Wash Facies of the Cloudburst Formation where it onlaps pre-Tertiary rock in the northeastern Tortilla Mountains west of the Smith Wash fault (Fig. 4) have yielded somewhat younger Ar/Ar ages (sanidine) of 23.2 ± 0.2 Ma and 22.9 ± 0.2 Ma (Peters et al., 2003).

Uppermost Cloudburst – Reworked rhyolitic tuff-breccia of the uppermost Cloudburst Formation as exposed along Tucson Wash in the Black Hills has yielded a K-Ar age (feldspar) of 22.5 ± 0.5 Ma (sample #7 of Dickinson and Shafiqullah, 1989), and a rhyolite dike of similar petrology cutting Precambrian basement to the north near Putnam Wash has yielded a comparable K-Ar age (biotite) of 22.8 ± 0.7 Ma (table 2I of Dickinson and Shafiqullah, 1989). Rhyolitic domes or plugs associated with uppermost exposed strata of the Cloudburst Formation along Tar Wash in the Black Hills are presumably of similar age, but remain undated.

San Manuel Base – Basaltic lava ("basalt of Three Buttes") interbedded with conglomeratic strata equivalent in the Guild Wash allochthon (Fig. 2) to the lowermost San Manuel Formation of the Black Hills and Camp Grant Wash (Fig. 3) has yielded a K-Ar age (whole-rock) of 21.1 ± 0.4 Ma (Spencer et al., 2002). Petrologically similar olivine-bearing lava, underlying strata of the San Manuel Formation in a tributary to Camp Grant Wash from the west where San Manuel strata rest directly on Precambrian Oracle Granite, with no intervening Cloudburst Formation present, has yielded a K-Ar age (feldspar) of 22.1 ± 0.5 Ma (sample #6 of Dickinson and Shafiqullah, 1989).

Intra-San Manuel – Tuffs within the San Manuel Formation have yielded isotopic ages of 19.7 ± 0.3 Ma (sanidine Ar/Ar) and 17.7 ± 0.2 Ma (sanidine Ar/Ar) in the Guild Wash allochthon (Fig. 2); of 18.5 ± 3.6 Ma (apatite FT) from Smelter Wash between Mammoth and San Manuel (Fig. 1); of 20.1 ± 0.5 Ma (biotite K-Ar) from Jim Thomas Wash of the Tortilla Mountains (Fig. 4); of 19.6 ± 0.5 Ma (biotite K-Ar) from an outcrop just north of Kearny in a side canyon tributary to the Gila River (Fig. 4) north of the Tortilla Mountains; and of 20.3 ± 0.5 (biotite K-Ar) and 17.5 ± 1.0 Ma (biotite K-Ar) in the Ripsey Wash half-graben (Fig. 4) west of the Tortilla Mountains (table 2J and samples #2-#4 and #18 of Dickinson and Shafiqullah, 1989; Peters et al., 2003; Ferguson et al., 2003).

Net – Available isotopic ages thus indicate deposition of the Cloudburst Formation within the interval from 27-26 Ma to 23-22 Ma, or during ~4 myr of Late Oligocene time, and of the San Manuel Formation within the interval 22-21 to 18-17 Ma, or during ~4 myr of Early Miocene time. The thicknesses of the two formations (estimated from figs. 35-36 of Dickinson, 1991) imply mean sedimentation rates of 250-450 m/myr (as appropriate for synextensional basins). Isotopic control for the age of uppermost San Manuel Formation is unavailable, and deposition may have continued until ~16 Ma or even later.

Guild Wash Allochthon

Cloudburst and San Manuel equivalents in the Guild Wash allochthon (fig. 36F of Dickinson, 1991) have been subdivided into various local map units (Spencer et al., 2002; Ferguson et al., 2003) forming a homoclinal succession broken by minor normal faulting (Fig. 2). The homocline dips downward to the northeast into the subhorizontal but listric Guild Wash detachment fault inclined to the northwest off the flank of the Tortolita Mountains and to the southeast off the flank of the Suizo Mountains (Fig. 2). The dip of the listric floor of the detachment system during fault displacements is uncertain, but the present northeasterly dip of a low-angle normal fault, which offset mid-Tertiary volcanic rocks downward to the southwest during fault activity (Fig. 2), implies backtilting by rotation of the fault surface after fault slip (Ferguson et al., 2003). The rotation may have been achieved by domino-style rotation of multiple tiltblocks structurally overlying the detachment fault or by progressive bulk rotation of the entire detachment system, but in either case occurred during Cloudburst deposition but before San Manuel deposition.

Basal horizons of the Cloudburst equivalents rest depositionally on mid-Tertiary volcanic rocks, which form the floor of a half-graben sedimentary basin, with local interfingering of volcanic and sedimentary strata along the contact (Spencer et al., 2002). The highest exposed interval of the San Manuel equivalents is a mass of granite-clast megabreccia, of rock-avalanche origin, that was presumably derived from the headwall scarp for the half-graben along the southwest flank of the Black Mountains (Fig. 2). Dips decrease gradually or incrementally upward stratigraphically in the faulted homocline, from >60˚ at lower horizons to <15˚ at upper horizons (Ferguson et al., 2003), as typical for fanning dips in evolving half-graben basins. There is no stratal discordance between Cloudburst and San Manuel equivalents in the southern part of the homocline (Spencer et al., 2002), but San Manuel equivalents appear to overstep Cloudburst equivalents to rest directly on mid-Tertiary volcanic rocks in the northern part of the homocline (Fig. 2).

Well exposed transects of strata within the Guild Wash allochthon are rare owing to the low overall relief of weathered exposures and widespread alluviated terraces along Cadillac Wash and its tributaries. No systematic paleocurrent data is available from the Guild Wash allochthon, and the direction that provenance areas lay from present exposures is unknown, but suitable clast transects embracing both Cloudburst and San Manuel strata were located along Parker Wash to the south (transect A of Fig. 2) and Olsen Wash to the north (transect B of Fig. 2). Clasts were counted in streamcut outcrops beside alluviated wash floors, but volcaniclastic beds present at lower Cloudburst horizons were not counted.

Cloudburst counts (Table 2AB) record an inverted clast stratigraphy, with beds dominated by clasts derived largely from mid-Tertiary volcanic rocks succeeded upward stratigraphically by beds that are dominated by clasts derived from Precambrian Oracle Granite. This trend in clast composition apparently reflects unroofing of basement from beneath volcanic cover in the provenance area during Cloudburst sedimentation. On the south (Parker Wash), clasts in the overlying San Manuel succession (Table 2A) were derived predominantly from Precambrian basement (primarily Oracle Granite and secondarily Pinal Schist). On the north (Olsen Wash), however, San Manuel clasts were derived in subequal proportions from Oracle Granite and mid-Tertiary volcanic rocks (Table 2B). The areal variability of San Manuel clast counts within the Guild Wash allochthon suggests derivation from multiple local drainages tapping basement overlain variably by residual volcanic cover. The volcanic cover was at least locally removed by erosion before emplacement of the granite-clast megabreccia that forms the uppermost exposed horizon of the San Manuel succession.

Star Flat Allochthon

Cloudburst and San Manuel strata in the Star Flat allochthon (Fig. 3) form an east-dipping homocline that abuts downdip into a subhorizontal detachment fault (Dickinson, 1994) that is exposed along the north side of the allochthon, repeated on the east across a local normal fault, and upturned on the west to dips of 55˚-65˚ along the western edge of the exposed allochthon (inset map of Orr et al., 2004). San Manuel strata consistently dip more gently (5˚-15˚) than underlying Cloudburst strata (55˚-85˚), and unconformably overlap interfingering units of Cloudburst sedimentary strata and mid-Tertiary volcanic rocks. The San Manuel Formation is nowhere in contact with the Star Flat detachment fault (Fig. 2), and was probably deposited after displacement of the Cloudburst Formation along the detachment fault, which was inclined to the west during fault slip but has been backtilted by fault rotation to easterly dips.

No systematic paleocurrent data are available from the Star Flat allochthon, which is exposed for the most part in subdued upland topography, but clasts were counted in a contiguous section of Cloudburst and San Manuel strata exposed along Bloodsucker Wash (transect C of Fig. 2) just north of the Willow Springs Ranch. Clasts in exclusively volcaniclastic Cloudburst beds directly overlying or interfingering with mid-Tertiary volcanic rocks were not counted. Stratigraphically higher in the local section (Table 2C), clasts of mid-Tertiary volcanic rock and Precambrian Oracle Granite are jointly dominant in subequal proportions in both the Cloudburst and San

Manuel Formations, with subordinate clasts derived from Pinal Schist and quartzite of the Apache Group (the latter most notable in the San Manuel Formation), and minor clasts derived from diabase and limestone. San Manuel clasts may have been derived in significant proportion from reworking of Cloudburst clasts. The larger fraction of quartzite clasts in San Manuel beds as opposed to Cloudburst beds may reflect concentration of resistant quartzite clasts during reworking, and the higher ratio of volcanic clasts to granitic clasts in the SanManuel Formation may similarly reflect the greater persistence of durable volcanic clasts than granitic clasts, which can readily disintegrate to grus during weathering on outcrop.

Black Hills

Mid-Tertiary strata in the Black Hills west of Mammoth (Fig. 3) are well exposed along multiple deep ravines and gorges cutting structurally complex uplands rising west of the San Pedro River. Clast transects were chosen along wash floors where attractive outcrops are most closely spaced through the longest available stratigraphic successions exposed in the walls of various washes.

The Cloudburst Formation forms a steeply dipping (35˚-55˚) homocline that abuts downward, together with underlying mid-Tertiary volcanic rocks, against the Cloudburst detachment fault, a rotated normal fault that now dips gently (~4˚) to the east (Dickinson, 1991, p. 80) but dipped toward the west during fault slip. Outcrop relations imply a minimum of 5000 m of slip across the Cloudburst fault (Dickinson, 1991, p. 80). Southward, the Cloudburst allochthon above the detachment fault is truncated along the Turtle fault (Fig. 3), dipping ~65˚ NNW and interpreted as a sidewall ramp of the detachment system. Uppermost Cloudburst horizons overlap the offset Turtle fault to rest depositionally on Oracle Granite, intruded by bodies of Laramide porphyry, forming the Purcell tiltblock (Fig. 3), a basement inlier commonly termed the "Purcell window" by economic geologists. The Kalamazoo orebody, offset by the San Manuel fault from the San Manuel orebody, lies at depth beneath the Purcell window. Stratal relations around the Purcell window imply that Cloudburst strata progressively filled an evolving half-graben basin that formed during slip along the Cloudburst fault, and eventually overtopped the Turtle fault marking the southern flank or sidewall ramp of the fault system. Paleocurrent indicators (clast imbrications; n=72 stations) in Cloudburst strata of the Black Hills (Table 4A) document net paleoflow to the ENE (range NE to ESE), implying derivation of Cloudburst detritus from a backtilted block that formed the hanging wall of the Cloudburst fault system.

Cloudburst clast counts along four east-west transects (FGHI of Fig. 3), spaced 1-3 km apart from north to south, reveal somewhat different compositions suggesting derivation of detritus from multiple local drainages during evolution of the Cloudburst half-graben. For the two southern transects along Tucson Wash (Table 2F) and Cloudburst Wash (Table 2G), average clast compositions are misleading because both transects show a stratigraphic trend marked by an upward decrease in clasts derived form mid-Tertiary volcanic rocks and an accompanying upward increase in clasts derived from Precambrian Oracle Granite to form a consistent pattern that implies progressive unroofing of basement in the provenance. Essentially no other clast types are present along those transects. Farther north along Tar Wash (Table 2H), however, a more heterogeneous clast assemblage is present, with quartzite clasts subequal in abundance to volcanic and granitic clasts, and the net stratigraphic variability of clast types is more irregular. Minor contributions from Pinal Schist, diabase, granodiorite, limestone, and Laramide porphyry are also evident, reflecting a complex provenance in detail. Beds in the northernmost transect along North Side Wash (Table 2I) are all in the lower Cloudburst Formation where clasts of mid-Tertiary volcanic rocks are dominant, but the subordinate granitoid clasts include granodiorite subequal in abundance to Oracle Granite. The occurrence of granodiorite clasts in the northern transects (Table 2HI), but not in the southern transects (Table 2FG), is interpreted to reflect the presence of a large expanse of Precambrian granodiorite in basement lying west of the northern Black Hills but not west of the southern Black Hills (Figure 2). In Tar Wash, a half-dozen bodies of rock-avalanche megabreccia (each 2-4 m thick) composed of granodiorite, are also present within the Cloudburst succession, and may reflect exposure of granodiorite in the steep-faced footwall as well as in the backtilted hanging wall of the Cloudburst fault.

The Cloudburst detachment is offset by the low-angle San Manuel normal fault dipping 25˚-35˚ to the southwest (Fig. 3), and displacing bedrock of the Purcell tiltblock or window ~2500 m toward the S50-55W (Davis et al., 2001) or S40-45 W (Force and Cox, 1992; Force et al., 1995). The San Manuel Formation forms a gently dipping (15˚-35˚) homocline deposited within a half-graben basin developed adjacent to the San Manuel fault. Restoration of San Manuel bedding to horizontal implies that the San Manuel fault dipped 60˚-65˚ southwest during fault slip (Davis et al., 2001), and has subsequently been rotated along with the basin fill. Upward fanning dips in the San Manuel Formation of the hanging wall resulted from progressive tilting of the hanging wall as fault movements continued.

The San Manuel Formation of the Black Hills includes two members that display opposed paleocurrent indicators and different clast types indicative of contrasting provenance: (1) the lower or Kannally Member (Tsk of Fig. 3), resting nonconformably on Oracle Granite forming the northern end of the Santa Catalina Mountains or concordantly on thin uppermost Cloudburst Formation onlapping the Purcell window, was derived from the hanging wall of the San Manuel fault (fig. 39G of Dickinson, 1991), with paleocurrent indicators (clast imbrications; n=48 stations) documenting net paleoflow to N65E (Table 4C) off the flank of the Santa Catalina Mountains; (2) the upper or Tucson Wash Member (Tst of Fig. 3), resting conformably on the Kannally Member but locally overlapping the San Manuel fault trace (Fig. 3), was derived from the footwall of the San Manuel fault, with paleocurrent indicators (clast imbrications; n=60 stations) documenting net paleoflow to S48W (Table 4E).

Clast transects through the Kannally Member where exposed along upper Cottonwood Wash (transect D of Fig. 3) and Kalamazoo Wash (transect E of Fig. 3) in the southern Black Hills consistently show a dominance of Oracle Granite clasts (Table 2DE) with subordinate clasts of mid-Tertiary volcanic rocks, Pinal Schist, diabase, quartzite, limestone, and Laramide porphyry, and a single count at one station along Tucson Wash (transect F of Fig. 3) is similar (Table 2F). In detail, the variability in contents of Pinal Schist, quartzite and volcanic clasts suggests derivation of the detritus from multiple local drainages tapping Santa Catalina bedrock and its extensions to the north where now deeply eroded and covered by upland gravels south of Camp Grant Wash (Fig. 3). One anomalous count with an atypically high proportion of diabase clasts (Table 2E) is closely associated with an interbedded body of diabase megabreccia, and evidently had a restricted provenance. A transect through the entire Tucson Wash Member along lower Cottonwood Wash (transect D of Fig. 3), and a single count in Tucson Wash (transect F of Fig. 3), reveals a dominance of mid-Tertiary volcanic clasts over Oracle Granite clasts (Table 2DF), apparently reflecting derivation of detritus from the northeast in the footwall of the San Manuel fault where volcanic cover of the Galiuro Volcanics is extensively exposed above Precambrian basement in the Galiuro Mountains and their foothills.

Camp Grant Wash

Along Camp Grant Wash, and Putnam Wash above its confluence with Camp Grant Wash, mid-Tertiary strata form two east-dipping homoclines bounded by normal faults trending north-south (Fig. 3). The eastern homocline abuts downdip to the east into the low-angle Camp Grant fault, dipping <30˚ and interpreted as a northern extension of the San Manuel Fault (Hansen, 1983; Dickinson, 2000). The fault linkage is interrupted, however, for 6 km by displacement of the fault downward to the west across the steeper Cowhead Well fault trending NNW (Fig. 3). The two homoclines are separated by the Cowhead Well fault, and a buried basement tiltblock along the eastern upthrown side of the fault was detected gravimetrically in Putnam Wash by Hansen (1983). The western homocline is bounded on the west by the Cowhead Tank fault (Fig. 3) with underlying basement rock of the Antelope Peak tiltblock exposed on its upthrown eastern side (Figs. 3-4). Clast counts for conglomeratic strata forming northern continuations of the Camp Grant Wash–Putnam Wash homoclines along less dissected James Wash (Fig.4) and its Dodson Wash tributary were not made during this study.

Strata assigned from their redbed coloration to the Cloudburst Formation form a restricted enclave exposed within the eastern homocline in the walls of lower Camp Grant Wash and a major tributary from the east termed Big Red Canyon (Dickinson, 2000), and extend northward to Putnam Wash where they are truncated against the east-west Putnam Wash fault (Fig. 3), a transverse tear structure. The base of the Cloudburst Formation is unexposed, with lowermost exposed horizons forming the footwall of the Cowhead Well fault.

Cloudburst clast counts in Camp Grant Wash (transect O of Fig. 3) indicate a heterogeneous provenance including dominant sources in Oracle Granite, mid-Tertiary volcanic rock, and quartzite but including subordinate sources in Pinal Schist, granodiorite, diabase, and limestone (Table 2O). Paleocurrent indicators of net paleoflow to S80W (Table 4A) imply derivation of detritus from the footwall of the buried Cloudburst fault within the block now forming the footwall of the San Manuel fault where Pinal Schist and Precambrian granodiorite are part of a basement assemblage that is overlain by the Precambrian Apache Group and diverse Paleozoic strata (Fig. 3).

The San Manuel Formation is best exposed within the western homocline where dissected by tributaries to Camp Grant Wash and along Putnam Wash. Coarse facies in the lower and upper parts of the San Manuel succession bracket a finer grained middle interval termed the Beehive Well Facies (Dickinson, 2000), a basin-floor assemblage deposited by longitudinal paleoflow along the axis of a half-graben that developed adjacent to the San Manuel–Camp Grant fault. Underlying strata deposited as alluvial fans derived from the west were onlapped by the Beehive Well Facies as basin aggradation continued, and overlying strata were deposited as alluvial fans that prograded over the Beehive Well Facies from the east. Basal San Manuel strata overlie the Cloudburst Formation disconformably in the eastern homocline, but onlap Cloudburst Formation in the subsurface to rest nonconformably on Precambrian basement along the base of the western homocline (Fig. 3). This relationship suggests progressive erosional denudation of a tiltblock in the hanging wall of the San Manuel–Camp Grant fault as mid-Tertiary sedimentation proceeded. Displacements along the Cowhead Well and Cowhead Tank faults to split the half-graben basin into two homoclinal segments postdated San Manuel deposition.

Clasts in the coarse lower (Table 2LMP) and upper (Table 2JK) successions of the San Manuel Formation in both Camp Grant Wash and Putnam Wash are heterogeneous assemblages in which contributions from Precambrian basement are the most consistently abundant (Oracle Granite and Precambrian granodiorite), but mid-Tertiary volcanic rocks are locally prominent, and minor contributions from diabase, quartzite, limestone, and Laramide porphyries are typically present. The variability of clast proportions suggests derivation from local drainages tapping both the hanging wall (to the west) and the footwall (to the east) of the San Manuel fault. The basin-floor Beehive Well Facies, with a longitudinal S10E paleocurrent trend (Table 4D) along the axis of the disrupted half-graben basin, contains a wholly different clast assemblage in which the most abundant clasts are mafic volcanic rock (Table 2N) derived from the Cretaceous Williamson Canyon Volcanics of the Dripping Spring Mountains to the north. Subordinate clast types in the Beehive Well Facies include both Oracle Granite and quartzite, with minor clasts of Pinal Schist, granodiorite, limestone, and Laramide porphyry also present.

Tortilla Mountains

In the Tortilla Mountains just south of the Gila River, mid-Tertiary (sub-Cloudburst) volcanic rocks are absent, and the Hackberry Wash Facies (Dickinson, 1991, p. 71-73) of the Cloudburst Formation rests unconformably on varied pre-Tertiary rocks ranging in age from Precambrian to Cretaceous (Fig. 4). This stratigraphic relationship persists as far south as a local tiltblock along James Wash near Antelope Peak (Fig. 4). The Hackberry Wash Facies is thickest within a central half-graben of the Tortilla Mountains southwest of Kearny, and thins progressively eastward where it onlaps the northern end and eastern flank of the Crozier Peak tiltblock of the eastern Tortilla Mountains (Fig. 4). A heterogeneous lower member contains thick lenses of rock-avalanche megabreccia (Krieger, 1977; Dickinson, 2002), and a more homogeneous upper member is composed of sheetflood deposits forming an alluvial fan complex (Dickinson, 1991, 2002). Where Hackberry Wash Facies onlaps the northern end of the Crozier Peak tiltblock east of the central half-graben, only the upper member is present above a buttress unconformity.

In the Gila River valley near Kearny, the San Manuel Formation rests conformably on the Hackberry Wash Facies, with conglomerate of the basal San Manuel Formation gradationally overlying ~75 m of lacustrine mudstone forming the uppermost Hackberry Wash Facies. To the southeast, however, along the eastern flank of the Crozier Peak tiltblock (Fig. 4), a sharp contact between the two units suggests disconformity, and a modest discordance of 5˚-10˚ in dip may be present. Southwest of Kearny in the interior of the Tortilla Mountains, the formational contact passes into an angular unconformity well displayed in both limbs of the Jim Thomas syncline (Fig. 4) where basal San Manuel Formation overlaps previously tilted Hackberry Wash Facies. The angular discordance in bedding at the contact ranges from 10˚-15˚ in the east limb of the syncline to 30˚-50˚ in the west limb. At the western flank of the Tortilla Mountains near Ripsey Wash and along the southern fringe of the Tortilla Mountains near Lopez Ranch, the San Manuel Formation oversteps Hackberry Wash Facies to rest unconformably on pre-Tertiary rocks.

Strata within the central half-graben of the Tortilla Mountains dip homoclinally eastward off the steeply tilted Sultana tiltblock where bedding attitudes in pre-Tertiary strata reach the subvertical (Cornwall and Krieger, 1975a; Howard, 1991). Fanning dips in the Hackberry Wash Facies as exposed along Hackberry Wash, which obliquely dissects nearly the full width of the homocline, range upward from 65˚-85˚ at the unconformable basal contact with pre-Tertiary rocks to only 25˚-35˚ just below the concordant upper contact with overlying San Manuel Formation, which dips 25˚-30˚ into the Gila River valley where well exposed on a bold riverbank spur southeast of Kearny. Dips in the San Manuel Formation further decline to 10˚-15˚ across the Gila River to the northeast of Kearny. Progressive tilting of the accumulating half-graben basin fill accompanied displacements along a fault system delineating the steep southwest front of the Dripping Spring Mountains, but now buried beneath the segment of the San Pedro structural trough occupied by the Gila River valley. Along strike to the south, the homocline of the central half-graben merges across a broad monoclinal flexure with more gently dipping strata onlapping the Crozier Peak tiltblock. Displacements along the steep Indian Camp and Dubois Ranch faults, which dip 55˚-65˚ west and delineate the western flank of the Crozier Peak tiltblock, apparently postdated homoclinal tilt of the half-graben basin fill.

As homoclinal tilting of the half-graben basin fill proceeded, updip erosion of deeper horizons of the Hackberry Wash Facies allowed progressive stratal overlap to develop along the evolving unconformity at the base of the San Manuel Formation as the latter onlapped westward toward the crest of the tiltblock beneath the upturned half-graben fill. An updip segment of the half-graben was downfaulted to the southwest by the Hackberry fault (dip 55˚ WSW), which offsets the bedrock ridge capped by Ripsey Hill to the southwest with respect to the Sultana tiltblock (Fig. 4). The doubly plunging Jim Thomas syncline is restricted to the hanging wall of the Hackberry fault, and is thought to reflect the kinematic influence of complex subsurface fault geometry on the hanging wall block (Naruk et al., 1986; Howard and John, 1997). The north-plunging southern end of the Jim Thomas syncline is known as the Tecolote syncline (Howard and John, 1997) where it deforms pre-Tertiary strata.

The lower member of the Hackberry Wash Facies below the large megabreccia bodies exposed above the Sultana tiltblock west of Hackberry Wash (Table 2Y), and also in upper Jim Thomas Wash along the east flank of the Ripsey Hill ridge (Table 2T), was derived dominantly from underlying Precambrian rocks. The dominant clasts, subequal in abundance, are Oracle Granite and quartzite, with the latter probably derived from Apache Group overlying Oracle Granite of both the Sultana tiltblock and its offset counterpart forming the Ripsey Hill ridge beyond the Hackberry fault, along which displacements postdated deposition of the Hackberry Wash Facies. Subordinate clasts of Precambrian diabase, Laramide porphyry, and leucogranite could readily have been derived from the same provenance, with the leucogranite representing bodies of aplite and alaskite within Oracle Granite. Sparse limestone clasts were probably derived from Mescal Limestone of the Apache Group, and sparse clasts of Pinal Schist could have been derived from local enclaves of metamorphic rock within Oracle Granite. In Jim Thomas Wash east of the Ripsey Hill ridge, minor clasts of mafic volcanic rock are also present in the lower member of the Hackberry Wash Facies (Table 2T), and were apparently derived from the Upper Cretaceous Williamson Canyon Volcanics exposed along the flank of Ripsey Hill ridge stratigraphically beneath the unconformity at the base of the Hackberry Wash Facies (Fig. 4).

The two principal lenses of megabreccia that form prominent east-dipping flatirons on slopes west of Hackberry Wash each extend for 3.0-3.5 km along strike (north-south) and reach stratigraphic thicknesses of ~175 m in their cores (Dickinson, 2002). Monolithologic masses of Mississippian Escabrosa Limestone and Devonian Martin Formation are most characteristic of their interiors, although other associated stratigraphic units are also represented (Krieger, 1977). Dickinson (1991, p. 73) inferred erroneously that the megabreccia bodies were derived from the west, and generated by stratal sliding off the tilted backslope of the Sultana tiltblock. That interpretation fails for two reasons: (1) relations at the basal unconformity of the Hackberry Wash Facies and the clast assemblage of strata that stratigraphically underlie the megabreccia bodies within the lower member of the Hackberry Wash Facies show that Paleozoic strata had already been stripped from the Sultana tiltblock before emplacement of the megabreccia bodies; and (2) internal fabrics of crackle breccia and jigsaw breccia within the megabreccia bodies are now known to be characteristic of rock-avalanche deposits with a runout distance of 5-15 km from source (Yarnold and Lombard, 1989; Yarnold, 1993). These considerations imply that the megabreccia bodies were generated by rock avalanches off a fault scarp along the front of the Dripping Spring Mountains across the Gila River to the east where appropriate source rocks are widely exposed (Cornwall et al., 1971).

Paleocurrent indicators (clast imbrications) in the agradational alluvial fan complex of the upper member of Hackberry Wash Facies across the width of the Tortilla Mountains record paleoflow toward nearly due west (mean N80W), in approximately the same direction as that inferred for the travel path of the underlying rock-avalanche megabreccias (Table 4B). Clast assemblages are dominated by mafic volcanic rock from the Upper Cretaceous Williamson Canyon Volcanics, quartzite dominantly from the Precambrian Apache Group, limestone dominantly from varied Paleozoic units, and heterogeneous Laramide porphyries (Table 2UVW). All these source rocks are widespread in the Dripping Spring Mountains beyond the San Pedro trough (Cornwall et al., 1971; Cornwall and Krieger, 1975a; Banks and Krieger, 1977). Clasts derived from Oracle Granite, the dominant bedrock of the Tortilla Mountains, are notably absent except in trace amounts locally. Variations in the proportions of different clast types suggest derivation of different stratal components of the alluvial fan complex from different local paleodrainages within the provenance over time. Clasts derived from the Williams Canyon Volcanics are notably most prominent, to the near exclusion of other clast types, in exposures of the Hackberry Wash Facies farthest east, in Romero Wash along the flank of the Tortilla Mountains (Table 2Q). The greater relative abundance of mafic volcanic clasts eastward is expected from the known distribution of the volcanic source rocks, which are concentrated at the eastern end of the Dipping Spring Mountains flanking the Gila River gorge (Banks and Krieger, 1977).

Clast assemblages in the San Manuel Formation as exposed within the interior of the Tortilla Mountains (Table 2RST), and also within the San Pedro trough near Kearny (Table 2X), are dominated by clasts of Oracle Granite (Table 2RST), which forms the principal bedrock of all the major uplands jointly forming the Tortilla Mountains (Fig. 4). Subordinate clasts of Pinal Schist, leucogranite, diabase, quartzite, and Laramide porphyry present in varying proportions could derive from provenances in the same uplands, although higher proportions of diabase and limestone clasts near Kearny on the Gila River (Table 2X) may reflect a contribution of detritus from the Dripping Spring Mountains to the northeast. The prevalence of the same clast types in the San Manuel Formation throughout the Tortilla Mountains suggests that the structural crests of all the major tiltblocks in the Tortilla Mountains had been erosionally denuded to basement by the time that the San Manuel Formation accumulated in multiple local half-grabens (Fig. 4). Evidence for diverse local paleoflow (NE, ESE, WNW) from surrounding uplands into various basins or sub-basins (Table 4C) suggests that the nature of the San Manuel provenance did not vary significantly across the Tortilla Mountains from one tiltblock to another.

Ripsey Wash

The "Ripsey Wash sequence" (Schmidt, 1971) of the San Manuel Formation is exposed in a narrow outcrop belt, elongate along strike (Fig. 4), dissected longitudinally by Ripsey Wash and its tributaries. The Ripsey succession is composed of two stratigraphic components occupying superposed half-grabens controlled by displacements on different faults (Dickinson, 1996). The lower member was deposited against the Hackberry fault, which is displaced by the Ripsey fault against which the upper member was deposited. The upper member locally overlaps the offset Hackberry fault (Fig. 4), but no erosional unconformity or stratal discordance is clearly visible where the upper member overlaps the Hackberry fault to overlie the lower member. These relationships suggest that sedimentation was not interrupted during continued extensional deformation as faulting shifted from one locus to another. Local or intermittent rejuvenation of the Hackberry fault during displacements along the Ripsey fault is indicated by minor offsets of the upper member by the Hackberry fault (Fig. 4).

Progressive tilting of the compound half-graben basin fill during fault displacements is indicated by dips that fan upward stratigraphically by 10˚-20˚ within the Ripsey succession, although the changes in stratal dip are neither uniform nor consistent along strike. From place to place along strike, average dips for the lower member are 25˚-35˚ and average dips for the upper member are 15˚-25˚. The Hackberry and Ripsey faults both dip ~40˚ westward where well exposed, and restoration of bedding within the Ripsey succession to horizontal would imply initial dips of ~60˚ (50˚-70˚) before fault rotation. The Ripsey fault continues across the Gila River to the north as the Copper Butte fault with a comparable present dip of ~45˚ (Dickinson, 1995, 2001). Age control for the Ripsey succession is restricted to the lower member (intercalated tuffs of 20-18 Ma as noted above), and the time span required for deposition of the upper member is uncertain, but the Copper Butte fault offsets units as young as 18-16 Ma (Creasey et al., 1983; Dickinson, 1995, 2001; Richard and Spencer, 1998).

Transverse transects across the Ripsey succession are afforded only by steep and short tributary ravines dissecting uplands lying to the east and to the west of the main wash. Consequently, clast counts were made for this study along composite longitudinal transects that highlight areal rather than stratigraphic contrasts in clast type for each of the two members within the compound Ripsey half-graben (Table 2ZL-2ZU). Clast imbrications indicate that the lower member was deposited by paleoflow to the NE off the back flank of the Grayback tiltblock in the hanging wall of the half-graben, whereas the upper member was deposited by paleoflow to the SW off the frontal scarp of the Sultana tiltblock in the footwall (Table 4F; block terminology after Howard, 1991).

In the lower member, clasts were derived dominantly from Oracle Granite (60%-80%), with subordinate contributions from Laramide porphyry (≤10%) and minor contributions from Pinal Schist (≤5%). Toward the south, however, clasts of leucogranite are prominent (~25%), and may have been derived from the Laramide (Paleocene) Tea Cup Granodiorite (61-63 Ma) exposed to the west of Ripsey Wash (Cornwall and Krieger, 1975b; fig. 7 of Barton et al., 2007). Present exposures of Tea Cup Granodiorite are more extensive to the north than to the south, but areas of exposure may have been somewhat different in Miocene time. One anomalous clast count with subequal proportions of Oracle Granite and Pinal Schist clasts (Table 4ZL) suggests that various paleodrainages feeding the lower member of the Ripsey succession were restricted in areal extent and locally tapped a restricted provenance.

Clast assemblages in the upper member are considerably more heterogeneous, although clasts of Oracle Granite remain dominant (55%-75%), or at least prominent (30%-35%), throughout the member (Table 4ZU), as expected from the bedrock geology of the Sultana block (Cornwall and Krieger, 1975a). Subordinate contributions from Precambrian diabase (5%-20%) apparently reflect the widespread distribution of multiple diabase dikes and sills within the Sultana block (Howard, 1991). Clasts of varied Laramide porphyries increase in abundance toward the south (from <5% to ~15%), as expected from the progressively greater abundance of porphyry dikes southward in the Sultana block (Schmidt, 1971; Cornwall and Kreiger, 1975a). Clasts of mafic granitoid rock that are significant within the upper member only on the south (nearly nil on the north but 5%-10% on the south) probably reflect sources in the Laramide (Cretaceous) Tortilla Quartz Diorite (70-75 Ma) exposed at the southernmost end of the Sultana block (Cornwall and Krieger, 1975a). Subordinate clasts of Pinal Schist (only 10%-15% on the south but 25%-35% on the north) are somewhat unexpected, for no large exposures of Pinal Schist are known within the Sultana block immediately adjacent to the Ripsey Wash half-graben (Cornwall and Kreiger, 1975a, 1975b). Exposures of Pinal Schist are prominent, however, in the continuation of the Sultana block north of the Gila River (Cornwall et al., 1971; Creasey et al., 1983), and the appearance of Pinal Schist clasts in the upper member of the Ripsey succession may reflect a longitudinal component of paleoflow from the north in upper reaches of paleodrainages entering the Ripsey Wash half-graben from the northeast. The increase in the abundance of Pinal Schist clasts toward the north (Table 2ZU) is compatible with that inference.

Summary Clast Compositions

In southwestern (Guild Wash and Star Flat allochthons) and southeastern (southern Black Hills) parts of the study area, the Cloudburst Formation includes mainly clasts of Tertiary volcanic rocks and Oracle Granite (Table 3A), with inverse clast stratigraphy reflecting the progressive unroofing of Precambrian basement in source areas during Cloudburst sedimentation. Somewhat farther north (northern Black Hills and Camp Grant Wash), subequal proportions of Tertiary volcanic and Oracle Granite clasts (~30% each) are joined in the Cloudburst Formation by a significant proportion of quartzite clasts (~20%) derived from the Precambrian Apache Group overlying basement, and by minor contributions from Precambrian granodiorite, Pinal Schist, diabase, and Laramide porphyry (Table 3A). The paucity of quartzite clasts farther south can be attributed to a general lack of local exposures of the Apache Group southward (Fig. 3). In the Tortilla Mountains on the north, the lower member of the Hackberry Wash Facies of Cloudburst Formation contains mainly Oracle Granite and quartzite (Apache Group) clasts (one-third each) derived from the subjacent Sultana tiltblock, as were accompanying diabase clasts (~10%) and diverse minor clast types derived also from rock units exposed within the Sultana tiltblock (Table 3B). The general lack of Tertiary volcanic clasts in the Hackberry Wash Facies can be attributed to the lack of Tertiary volcanic rocks in the Tortilla Mountains (Figs. 4-5). The upper member of the Hackberry Wash Facies overlying rock-avalanche megabreccias derived from the Dripping Spring Mountains to the east contains clasts derived also from bedrock of the Dripping Spring Mountains, with clasts from Cretaceous Wiliamson Canyon Volcanics dominant (especially toward the east) but accompanied by clasts of Precambrian quartzite and Paleozoic limestone.

In most parts of the study area, Oracle Granite clasts are dominant or at least most abundant in the San Manuel Formation (Table 3CDEF), reflecting exposure of Precambrian basement along the crests of multiple tiltblocks flanking local half-graben basins. Notable exceptions include the upper or Tucson Wash Member of the Black Hills in which Tertiary volcanic clasts derived from the Galiuro Volcanics to the east are more abundant (Table 3B), and the medial or Beehive Well Facies of Camp Grant Wash in which clasts of Upper Cretaceous Williamson Canyon Volcanics transported longitudinally southward along the floor of a half-graben basin are dominant (Table 3C). Subordinate clast types that are also present in significant proportions from place to place include Pinal Schist (Table 3CF), Precambrian granodiorite (Table 3D) and diabase (Table 3EF), Precambrian quartzite (Table CDE), and Laramide porphyry (Table 3DE). In southwestern parts of the study area (3CD), Tertiary volcanic clasts in the San Manuel Formation may be reworked from the underlying Cloudburst Formation, but elsewhere reworking from older Tertiary strata is not evident.

References Cited

Banks, N.G., and Krieger, M.H., 1977, Geologic map of the Hayden quadrangle, Pinal and Gila Counties, Arizona: U.S. Geological Survey Geologic Quadrangle Map GQ-1391, scale 1:24,000 with 15 pp. text.

Barton, M.D., Seedorff, E., Maher, D.J., Stavast, W.J.A., Kamilli, R.J., Hayes, T.S., Long, K.R., and Haxel, G.B., 2007, Laramide porphyry copper systems and superimposed Tertiary extension: A life cycle approach to the Globe-Superior-Ray area, Arizona: Arizona Geological Society Ores and Orogenesis Symposium Field Trip No. 4, 61 p.

Cornwall, H.R., and Krieger, M.H., 1975a, Geologic map of the Kearny quadrangle, Pinal County, Arizona: U.S. Geological Survey Geologic Quadrangle Map GQ-1188, scale 1:24,000 with 9 pp. text.

Conrwall, H.R., and Krieger, M.H., 1975b, Geologic map of the Grayback quadrangle, Pinal County, Arizona: U.S. Geological Survey Geologic Quadrangle Map GQ-1206, scale 1:24,000 with 2 pp. text.

Cornwall, H.R., Banks, N.G., and Phillips, C.H., 1971, Geologic map of the Sonora quadrangle. Pinal and Gila Counties, Arizona: U.S. Geological Survey Geologic Quadrangle Map GQ-1021, scale 1:24,000.

Creasey, S.C., 1965, Geology of the San Manuel area, Pinal County, Arizona: U.S. Geological Survey Professional Paper 471, 64 p.

Creasey, S.C., 1967, General geology of the Mammoth quadrangle, Pinal County, Arizona: U.S. Geological Survey Bulletin 1218, 94 p.

Creasey, S.C., Peterson, D.W., and Gambell, N.A., 1983, Geologic map of the Teapot Mountain quadrangle, Pinal County, Arizona: U.S. Geological Survey Geologic Quadrangle Map GQ-1559, scale 1:24,000.

Davis, G.H., Constenius, K.N., Dickinson, W.R., Rodriguez, E.P., and Cox, L.J., 2001, Fault and fault-rock characteristics associated with Cenozoic extension and core-complex evolution in the Catalina-Rincon region, southeastern Arizona: Geological Society of America Bulletin, v. 116, p. 128-141.

Dickinson, W.R., 1991, Tectonic setting of faulted Tertiary strata associated with the Catalina core complex in southern Arizona: Geological Society of America Special Paper 264, 106 p.

Dickinson, W.R., 1993, Summary geologic map of Black Hills near Mammoth, Pinal County, Arizona: Arizona Geological Survey Contributed Map CM-93-B, scale 1:24,000.

Dickinson, W.R., 1994, Geologic map of the Star Flat–Willow Springs area, Pinal County, Arizona: Arizona Geological Survey Contributed Map CM-94-B, scale 1:24,000 with 3 pp text.

Dickinson, W.R., 1995, Tertiary stratigraphic and structural relationships in the Copper Butte area, Teapot Mountain quadrangle, Pinal County, Arizona: Arizona Geological Survey Contributed Report CR-95-H, 16 p.

Dickinson, W.R., 1996, Geologic map of Ripsey Wash area, Pinal County, Arizona: Arizona Geological Survey Contributed Map CM-96-B, scale 1:24,000 with 7 pp text.

Dickinson, W.R., 1998, Facies map of post-mid-Miocene Quiburis Formation, San Pedro trough, Pinal, Pima, Graham, and Cochise Counties, Arizona: Arizona Geological Survey Contributed Map CM-98-A, scale 1:24,000 (10 map sheets with 6 pp text).

Dickinson, W.R., 2000, Summary of Tertiary stratigraphic and structural relationships, Camp Grant Wash–Antelope Peak area, Pinal County, Arizona: Arizona Geological Survey Contributed Map CM-00-B, scale 1:24,000 with 10 pp text

Dickinson, W.R., 2001, The wonders of Copper Butte: Arizona Geological Society Fall Field Trip, 15 p.

Dickinson, W.R., 2002, Structural and stratigraphic relationships of mid-Tertiary strata in the Hackberry Wash–Indian Camp Wash intramontane depression, Tortilla Mountains, Pinal County, Arizona: Arizona Geological Survey Contributed Map CM-02-B, scale 1:24,000 with 13 pp text.

Dickinson, W.R., and Shafiqullah, M., 1989, K-Ar and F-T ages for syntectonic mid-Tertiary volcanosedimentary sequences associated with the Catalina core complex and San Pedro trough in southern Arizona: Isochron/West No. 52, p. 15-27.

Ferguson, C.A., Johnson, B.J., Skotnicki, S.J., Maher, D.J., Spencer, J.E., Gilbert, W.G., Richard, S.M., Youberg, A., Demsey, K.A., and House, P.K., 2003, Geologic map of the Tortolita Mountains, Pinal and Pima Counties, Arizona: Arizona Geological Survey Digital Geologic Map 26 (DGM-26), 1 CD-ROM (46 pp, 2 sheets, scale 1:24,000).

Force, E.R., and Cox, L.J., 1992, Structural context of mid-Tertiary mineralization in the Mammoth and San Manuel districts, southeastern Arizona: U.S. Geological Survey Bulletin 2042-C, 28 p.

Force, E.R., Dickinson, W.R., and Hagstrum, J.T., 1995, Tilting history of the San Manuel–Kalamazoo porphyry system, southeastern Arizona: Economic Geology, v. 90, p. 67-80.

Hansen, J.B., 1983, Style of deformation of the upper plate rocks of the San Manuel-Camp Grant Wash low-angle normal fault system, Black Hills, Pinal County, Arizona [MS thesis]: Tucson, University of Arizona, 164 p.

Heindl, L.A., 1963, Cenozoic geology in the Mammoth area, Pinal County, Arizona: U.S. Geological Survey Bulletin 1141–E, p. E1-E41.

Howard, K.A., 1991, Intrusion of horizontal dikes: Tectonic significance of Middle Proterozoic diabase dike sheets widespread in the upper crust of the southwestern United States: Journal of Geophysical Research, v. 96, p. 12461-12478.

Howard, K.A., and John, B.E., 1997, Fault-related folding during extension: Plunging basement-cored folds in the Basin and Range: Geology, v. 25, p. 223-226.

Krieger, M.H., 1968, Geologic Map of the Lookout Mountain quadrangle, Pinal County, Arizona: U.S. Geological Survey Geologic Quadrangle Map GQ-670, scale 1:24,000 with 2 pp. text.

Krieger, M.H., 1974a, Geologic map of the Winkelman quadrangle, Pinal County, Arizona: U.S. Geological Survey Geologic Quadrangle Map GQ-1106, scale 1:24,000 with 8 pp. text.

Krieger, M.H., 1974b, Geologic map of the Crozier Peak quadrangle, Pinal County, Arizona: U.S. Geological Survey Geologic Quadrangle Map GQ-1107, scale 1:24,000 with 11 pp. text.

Krieger, M.H., 1974c, Geologic map of the Putnam Wash quadrangle, Pinal County, Arizona: U.S. Geological Survey Geologic Quadrangle Map GQ-1109, scale 1:24,000 with 7 pp. text.

Krieger, M.H., 1977, Large landslides, composed of megabreccia, interbedded in Miocene basin deposits, southeastern Arizona: U.S. Geological Survey Professional Paper 1008, 25 p.

Naruk, S.J., Bykerk-Kauffman, A., Currier-Lewis, D., Davis, G.H., Faulds, J.E., and Lweis, S.W., 1986, Kink folding in an extended terrane: Tortilla Mountains, southeastern Arizona: Geology, v. 14, p. 1012-1015.

Orr, T.R., Shipman, T.C., and Spencer, J.E., 2002, Geologic map of the North of Oracle 7.5’ quadrangle, southeastern Pinal County, Arizona: Arizona Geological Survey Digital Geologic Map 23 (DGM-23), 1 CD-ROM with 1 Adobe PDF file (1 sheet, layout scale 1:24,000).

Orr, T.R., DeLong, S.B., Spencer, J.E., and Richard, S.M., 2004, Geologic map of the Fortified Peak 7.5’ quadrangle, southeastern Pinal County, Arizona: Arizona Geological Survey Digital Geologic Map 18, version 2.0 (DGM-18, v. 2.0), scale 1:24,000.

Peters, L., Ferguson, C.A., Spencer, J.E., Orr, T.R., and Dickinson, W.R., 2003, Sixteen $^{40}Ar/^{39}Ar$ geochronology analyses from southeastern Arizona: Arizona Geological Survey Open-File Report 03-02, 37 p.

Richard, S.M., and Spencer, J.E., 1998, Compilation geologic map of the Ray-Superior area, central Arizona: Arizona Geological Survey Open-File Report 98-13, scale 1:24,000 with 47 pp. text.

Richard, S.M., Youberg, A., Spencer, J.E., and Ferguson, C.A., 2002, Geologic map of the Durham Hills 7.5’ quadrangle, Pinal County, Arizona: Arizona Geological Survey Digital Geologic Map 19 (DGM-19), 1 CD-ROM with 1 Adobe PDF file (1 sheet, layout scale 1:24,000).

Schmidt, E.A., 1971, A structural investigation of the northern Tortilla Mountains, Pinal /County, Arizona [PhD thesis]: Tucson, University of Arizona, 248 p.

Shafiqullah, M., Damon, P.E., Lynch, E.J., and Kuck, P.H., 1978, Mid-Tertiary magmatism in southeastern Arizona, in Callender, J.F., Wilt, J.C., and Clemons, R.E., eds., Land of Cochise: New Mexico Geological Society 19th Annual Field Conference, p. 231-241.

Spencer, J.E., Richard, S.M., Youberg, A., Ferguson, C.A., and Orr, T.R., 2002, Geologic map of the Chief Butte 7.5’ quadrangle, southeastern Pinal County, Arizona: Arizona Geological Survey Digital Geologic Map 22 (DGM-22), 1 CD-ROM with 1 Adobe PDF file (1 sheet, layout scale 1:24,000).

Weibel, W.L., 1981, Depositional history and geology of the Cloudburst Formation near Mammoth, Arizona [MS thesis]: Tucson, University of Arizona, 81 p.

Yarnold, J.C., 1993, Rock-avalanche characteristics in dry climates and the effect of flow into lakes: Insights from mid-Tertiary sedimentary breccias near Artillery Peak, Arizona: Geological Society of America Bulletin, v. 105, p. 345-360.

Yarnold, J.C., and Lombard, J.P., 1989, Facies model for large rock avalanche deposits formed in dry climates, in Colburn, I.P., Abbott, P.L., and Minch, J., eds., Conglomerates in basin analysis: Pacific Section, SEPM (Society for Sedimentary Geology), Book 82, p. 9-31.

Youberg, A., Ferguson, C.A., Richard, S.R., Johnson, B.J., Maher, D.J., and Gilbert, W.G., 2002, Geologic map of the Desert Peak 7.5' quadrangle, southeastern Pinal County, Arizona: Arizona Geological Survey Digital Geologic Map 20 (DGM-20), 1 CD-ROM with 1 Adobe PDF file (1 sheet, layout scale 1:24,000.

Figure Captions

Fig. 1. Location map for Figures 2-4 adapted after figures 1-2 of Dickinson (1991) as modified by references for Figures 2-4 of this report. Thin veneers of Quaternary alluvium and local patches of post-mid-Miocene surficial cover omitted for reasons of scale. Geologic contacts simplified after Figures Figs. 2-4. Towns (black dots): D, Dudleyville; H, Hayden; K, Kearny; M, Mammoth; O, Oracle; S, San Manuel.

Fig. 2. Sampled transects A-C (bracketed lines) in the Guild Wash and Star Flat allochthons structurally above Guild Wash and Star Flat detachment faults (double ticks) in southwestern part of study area (see Fig. 1 for location). Geologic relations (simplified for reasons of scale) after Dickinson (1994), Richard et al. (2002), Spencer et al. (2002), Youberg et al. (2002), Ferguson et al. (2003), and Orr et al. (2004). Cloudburst Formation and volcanic rocks locally interbedded in Guild Wash and Star Flat allochthons (see map relations for latter).

Fig. 3. Sampled transects D-P (bracketed lines) in Black Hills and Camp Grant Wash (including Putnam Wash) in southeastern part of study area (see Fig. 1 for location). Geologic relations (simplified for reasons of scale) after Dickinson (1993, 1998, 2000), Krieger (1968, 1974c), and Orr et al. (2002). Detachment fault (double ticks) backdipping to the east: Cloudburst (Black Hills). Low-angle normal faults (offset segments of same fault surface marked with single ticks): San Manuel (Black Hills), Camp Grant (Camp Grant Wash). Key steep faults (no ticks): BCf, Black Canyon; Chf, Cholla; CTf, Cowhead Tank; CWf, Cowhead Well; PWf, Putnam Wash; RRf, Red Rock; Tf, Turtle (CWf and RRf probably same fault surface with connecting trace masked by basin fill onlapping paleofault scarp). P denotes Purcell tiltblock (inlier or "window") of Oracle granite bounded on northwest by offset Turtle fault. Basin fill (post-mid-Miocene) includes Quiburris Formation of San Pedro trough (to east) and correlative upland gravels (to west). Intra–San Manuel stratigraphy: Tbw, limit (double-headed arrow) of Beehive Well Facies (half-graben basin-floor facies with atypical longitudinal paleocurrents) in Camp Grant Wash; Tsk-Tst, contact between lower (Kannally) and upper (Tucson Wash) Members in Black Hills. Mid-Tertiary volcanic rocks (locally treated as lower member of Cloudburst Formation) include volcaniclastic strata, especially near base on west overlying inlier of Oracle Granite. Apache Group and Oracle Granite include multiple dikes and sills of Precambrian diabase.

Fig. 4. Sampled transects Q-Z (bracketed lines) in Tortilla Mountains and Ripsey Wash (northern part of study area including James Wash; see Fig. 1 for location). Geologic relations (simplified for reasons of scale) after Dickinson (1996, 1998, 2002) and Krieger (1974a). Major mountain

peaks (triangles): AP, Antelope Peak; CP, Crozier Peak; RH, Ripsey Hill. Key faults: CHf, Cactus Hill; CTf, Cowhead Tank; CWf, Cowhead Well; DRf, Dubois Ranch; Hf, Hackberry; ICf, Indian Camp; LRf, Lopez Ranch; Rf, Ripsey; SWf, Smith Wash. Legend: basin fill (post-mid-Miocene) equals Quiburis Formation of San Pedro trough (extending northwest along Gila River where modern floodplain alluvium not shown) and upland correlatives on southwest; San Manuel Formation of Ripsey Wash occupies compound half-graben (lower succession beside offset Hackberry fault and upper succession beside younger Ripsey fault with u/l line denoting contact); Hackberry Wash Facies of Cloudburst Formation includes intercalated volcanic interval on southwest; Apache Group and Oracle Granite include multiple dikes and sills of Precambrian diabase; Oracle Granite includes multiple intrusions of Cretaceous diorite near Crozier Peak (Krieger, 1974b) and of Cretaceous porphyry dikes in northwest part of area.

Fig. 5. Key paleogeologic relations within study area (Fig. 1). Shaded areas show mid-Tertiary volcanic and sedimentary exposures providing outcrop control for inferred onlaps and overlaps. Towns (black dots): D, Dudleyville; H, Hayden; K, Kearny; M, Mammoth; O, Oracle; S, San Manuel.

Table 1. Designations and Locations of Clast-Count Transects

Transect[1]	Figure	Area	Stratigraphy	Geography	Stations[1]
A(cs)	2	Guild Wash allochthon	Cloudburst-San Manuel	Parker Wash	3 (1c + 2s)
B(cs)	2	Guild Wash allochthon	Cloudburst-San Manuel	Olsen Wash	5 (2c + 3s)
C(cs)	2	Star Flat allochthon	Cloudburst-San Manuel	Bloodsucker Wash	4 (2c + 2s)
D(kt)	3	Black Hills	San Manuel (Tsk-Tst)	Cottonwood Wash	7 (3k + 4t)
E (k)	3	Black Hills	San Manuel (Tsk)	Kalamazoo Wash	8 (k)
F (ck)	3	Black Hills	Cloudburst-San Manuel	Tucson Wash	8 (6c + 2s)
G (c)	3	Black Hills	Cloudburst	Cloudburst Wash	6 (c)
H (c)	3	Black Hills	Cloudburst	Tar Wash	8 (c)
I (c)	3	Black Hills	Cloudburst	North Side Wash	3 (c)
J (s)	3	Camp Grant Wash	San Manuel	Tunnel Ranch Cyn	3 (s)
K (s)	3	Camp Grant Wash	San Manuel	North Fork Cyn	8 (s)
L (s)	3	Camp Grant Wash	San Manuel	Palmer Draws	4 (s)
M (s)	3	Camp Grant Wash	San Manuel	Bloodsucker Wash	5 (s)
N (b)	3	Camp Grant Wash	Beehive Well	Cowhead Well	2 (b)
O (c)	3	Camp Grant Wash	Cloudburst	Camp Grant Wash	6 (c)
P (s)	3	Camp Grant Wash	San Manuel	Putnam Wash	2 (s)
Q (hs)	4	Tortilla Mountains	Hackberry-San Manuel	Romero Wash	6 (3h+3s)
R (s)	4	Tortilla Mountains	San Manuel	Eagle Wash	2 (s)
S (s)	4	Tortilla Mountains	San Manuel	Hackberry Wash	3 (s)
T (hs)	4	Tortilla Mountains	Hackberry-San Manuel	Jim Thomas Wash	6 (2h +4s)
U (h)	4	Tortilla Mountains	Hackberrry	Hackberry Wash	3 (h)
V (h)	4	Tortilla Mountains	Hackberry	Indian Camp Wash	4 (h)
W (h)	4	Tortilla Mountains	Hackberry	Hackberry Wash	4 (h)
X (s)	4	Gila River Valley	San Manuel	Gila River	5 (s)
Y	(h)	Tortilla Mountains	Hackberry	Flatiron Canyon	3 (h)
Z (s)	4	Ripsey Wash	San Manuel	Ripsey Wash	18 (s)

[1]Abbreviations: b, Beehive Well Facies of San Manuel Formation (Tbw); c, undifferentiated Cloudburst Formation and correlatives (Tc, Tcs); h, Hackberry Wash Facies of Cloudburst Formation (Tch); k, Kannally Member of San Manuel Formation (Tsk); s, undifferentiated San Manuel Formation and correlatives (Tsm, Tcg, Txg); t, Tucson Wash Member of San Manuel Formation (Tst)

Table 2. Frequency percentages (where n=number of clasts counted at each station) of conglomerate clast types (see text for abbreviations of clast types) at 134 stations in transects A-Z (Table 1) with submeans (averages of N stations in italics where asterisks denote anomalous clast counts ignored for calculations of submeans) for various stratigraphic units in selected transects (Table 1 footnote above gives stratigraphic abbreviations for stations and submeans)

Station	n	pi	gd	or	lc	di	qt	ls	wv	li	tv
Parker Wash (A) – [traverse upstream past streamcuts along floor of Parker Wash south of Hiway 79]											
A1 (c)	274	-	-	9	-	-	-	-	-	-	91
A2 (s)	188	30	1	60	-	6	1	-	-	-	2
A3 (s)	156	25	2	71	-	1	1	-	-	-	-
s (N=2)	*(344)*	*28*	*2*	*65*	-	*4*	*1*	-	-	-	-
Olsen Wash (B) – [traverse upstream past streamcuts along floor of Olsen Wash north of Hiway 79]											
B1 (c)	148	3	-	23	-	1	14	-	-	1	58
B2 (c)	200	3	-	62	-	-	15	-	-	2	18
s (N=2)	*(348)*	*3*		*43*	-	-	*14*	-	-	*2*	*38*
B3 (s)	167	7	-	44	-	2	2	-	-	1	44
B4 (s)	158	3	-	44	-	1	4	-	-	-	48
B5 (s)	168	5	3	52	-	1	2	-	-	-	37
s (N=3)	*(493)*	*5*	*1*	*47*	-	*1*	*3*	-	-	*tr*	*43*
Bloodsucker Wash (C) – [the Bloodsucker Wash that exits east into Camp Grant Wash near Willow Springs Ranch]											
C1 (c)	158	1	-	62	-	-	2	1	-	-	34
C2 (c)	155	15	-	34	-	6	3	6	-	-	36
c (N=2)	*(313)*	*8*	-	*48*	-	*3*	*2*	*4*	-	-	*35*
C3 (s)	133	12	-	25	-	2	22	-	-	-	39
C4 (s)	136	10	-	29	-	3	17	1	-	-	40
s (N=2)	*(269)*	*11*	-	*27*	-	*2*	*20*	*Tr*	-	-	*40*
Cottonwood Wash (D) – [traverse downstream along Cottonwood Wash subparallel to Hiway 77]											
D1 (k)	169	6	-	89	-	2	1	-	-	2	-
D2 (k)	139	1	-	65	-	2	5	1	-	2	24
D3 (k)	112	-	-	80	-	-	4	-	-	2	14
k (N=3)	*(420)*	*2*	-	*78*	-	*1*	*3*	*tr*	-	*2*	*12*
D4 (t)	217	-	-	21	-	-	-	-	-	-	79
D5 (t)	192	-	-	46	-	-	-	-	-	-	54
D6 (t)	202	-	-	47	-	-	-	-	-	-	53
D7 (t)	138	-	-	59	-	-	-	-	-	-	41
t (N=4)	*(749)*	-	-	*43*	-	-	-	-	-	-	*57*

Station	N	pi	gd	or	lc	di	qt	ls	wv	li	tv
Kalamazoo Wash (E) – [traverse down unnamed canyon leading north to edge of Kalamazoo window]											
E1 (k)	112	12	-	69	-	4	-	-	-	12	3
E2 (k)	130	13	-	69	-	5	9	-	-	2	2
E3 (k)	141	20	-	55	-	12	6	1	-	5	1
E4 (k)	135	26	-	48	-	10	10	2	-	4	-
E5 (k)	123	21	-	39	-	15	15	3	-	6	1
*E6 (k)	146	8	-	17	-	45	21	8	-	1	-
E7 (k)	125	28	-	37	-	9	17	4	-	4	1
E8 (k)	155	11	-	45	-	20	20	1	-	2	1
k (N=7)	*(921)*	*19*	-	*52*	-	*11*	*11*	*1*	-	*5*	*1*
Tucson Wash (F) – (traverse downstream along Tucson Wash which exits Black Hills at Mammoth]											
F1 (c)	214	-	-	14	-	-	-	-	-	-	86
F2 (c)	163	-	-	24	-	-	-	-	-	-	76
F3 (c)	302	-	-	32	-	-	-	-	-	-	68
F4 (c)	168	-	-	65	-	-	-	-	-	-	35
F5 (c)	160	-	-	82	-	-	-	-	-	-	18
F6 (c)	300	-	-	87	-	-	-	-	-	-	13
c (N=6)	*(1307)*	-	-	*51*	-	-	-	-	-	-	*49*
F7 (k)	157	10	-	78	-	3	2	-	-	7	-
F8 (t)	167	2	-	36	-	-	2	-	-	2	58
Cloudburst Wash (G) – [traverse down Cloudburst Wash which enters Tucson Wash just below San Manuel Mine]											
G1 (c)	118	-	-	11	-	-	3	-	-	-	86
G2 (c)	139	-	-	30	-	-	-	-	-	-	70
G3 (c)	230	-	-	23	-	-	-	-	-	-	77
G4 (c)	239	-	-	81	-	-	-	-	-	-	19
G5 (c)	175	-	-	90	-	-	-	-	-	-	10
G6 (c)	185	-	-	97	-	-	-	-	-	-	7
c (N=6)	*(1086)*	-	-	*55*	-	-	*tr*	-	-	-	*45*
Tar Wash (H) – [traverse downstream along Tar Wash which exits Black Hills north of Mammoth]											
H1 (c)	140	1	1	37	-	1	2	-	-	-	58
H2 (c)	100	-	-	38	-	-	11	-	-	-	47
*H3 (c)	143	1	1	74	-	2	5	-	-	2	15
H4 (c)	135	2	8	28	-	10	46	2	-	1	3
H5 (c)	111	2	4	33	-	7	38	2	-	4	10
H6 (c)	144	-	1	47	-	1	29	1	-	-	21
H7 (c)	125	7	10	29	-	3	40	2	-	4	5
H8 (c)	112	4	10	24	-	8	34	2	-	4	14
c (N=7)	*(867)*	*2*	*5*	*34*	-	*4*	*29*	*1*	-	*2*	*23*

Station	n	pi	gd	or	lc	di	qt	ls	wv	li	tv
North Side Wash (I) – [traverse down unnamed canyon along north side of Cloudburst allochthon]											
I1 (c)	225	-	7	12	-	-	-	-	-	-	81
I2 (c)	140	-	8	6	-	-	-	-	-	-	86
I3 (c)	167	-	3	12	-	-	-	-	-	-	85
c (N=3)	*(532)*	-	*6*	*10*	-	-	-	-	-	-	*84*
Tunnel Ranch Canyon (J) – [traverse up unnamed canyon exiting west into Camp Grant Wash at Tunnel Ranch]											
J1 (s)	167	4	13	33	-	2	11	-	-	2	35
J2 (s)	105	-	26	26	-	2	5	-	-	5	36
J3 (s)	171	1	31	26	-	3	7	-	-	-	32
s (N=3)	*(443)*	*2*	*23*	*28*	-	*2*	*8*			*2*	*35*
North Fork Canyon (K) – [traverse up north fork of Tunnel Ranch Canyon from forks of canyon]											
K1 (s)	115	-	28	51	-	3	9	-	-	3	6
K2 (s)	130	1	35	46	-	2	11	1	-	2	2
K3 (s)	139	-	28	52	-	4	9	2	-	1	4
K4 (s)	128	-	25	59	-	4	8	2	-	1	1
K5 (s)	130	-	32	49	-	5	10	3	-	-	1
K6 (s)	161	-	22	56	-	3	9	1	-	-	9
s (N=6)	*(803)*	*tr*	*28*	*52*	-	*4*	*9*	*2*	-	*1*	*4*
K7 (s)	120	4	25	21	-	4	25	4	-	4	13
K8 (s)	107	3	17	20	-	2	31	4	-	2	21
s (N=2)	*(227)*	*4*	*21*	*20*	-	*3*	*28*	*4*		*3*	*17*
Palmer Draws (L) – [two steep draws on west side of Camp Grant Wash just north of Palmer Wash]											
L1 (s)	144	11	21	39	-	2	11	2	-	3	11
L2 (s)	140	15	23	37	-	3	11	2	-	2	7
L3 (s)	152	9	9	18	-	2	20	4	-	8	30
L4 (s)	151	12	14	23	-	1	20	3	-	1	26
s (N=4)	*(587)*	*12*	*17*	*29*	-	*2*	*15*	*3*	-	*4*	*18*
Bloodsucker Wash (M) – [the Bloodsucker Wash exiting east into Camp Grant Wash at Cowhead Well]											
M1 (s)	196	5	21	70	-	4	-	-	-	-	-
M2 (s)	144	6	38	54	-	2	-	-	-	-	-
M3 (s)	132	2	22	72	-	2	-	-	-	-	2
M4 (s)	188	8	17	69	-	2	1	1	-	-	2
M5 (s)	160	4	25	64	-	1	-	-	-	-	6
S (N=5)	*(820)*	*5*	*25*	*66*	-	*2*	*tr*	*tr*	-	-	*2*
Cowhead Well (N) – [cliff face above Cowhead Well on north near mouth of Bloodsucker Wash]											
N1 (b)	134	5	4	21	-	-	9	3	56	2	-
N2 (b)	104	1	3	15	-	-	14	10	56	1	-
b (N=2)	*(238)*	*3*	*3*	*18*	-	-	*12*	*6*	*56*	*2*	-

Station	n	pi	gd	or	lc	di	qt	ls	wv	li	tv
Camp Grant Wash (O) – [base of cliffs forming west wall of Camp Grant Wash below Cowhead Well]											
O1 (c)	100	13	9	11	-	9	28	10	-	6	14
O2 (c)	122	10	1	38	-	13	20	8	-	5	5
O3 (c)	160	5	-	11	-	8	16	1	-	2	57
O4 (c)	142	5	-	1	-	1	18	6	-	1	68
O5 (c)	136	2	18	62	-	10	5	1	-	-	2
O6 (c)	136	7	2	57	-	5	24	2	-	1	2
C (N=6)	*(796)*	*7*	*5*	*30*	-	*8*	*18*	*5*	-	*2*	*25*
Putnam Wash (P) – [traverse downstream along Putnam Wash upstream from Beehive Well]											
P1 (s)	196	7	32	47	-	4	3	1	-	2	4
P2 (s)	167	5	23	59	-	1	5	-	-	3	4
s (N=2)	*(363)*	*6*	*28*	*53*	-	*3*	*4*	*tr*	-	*2*	*4*
Romero Wash (Q) – [traverse downstream beside Romero Wash at east face of Tortilla Mountains]											
Q1 (h)	178	-	-	-	3	-	7	5	84	-	-
Q2 (h)	187	-	-	-	-	-	-	4	95	1	-
Q3 (h)	152	-	-	-	-	-	-	-	100	-	-
h (N=3)	*(517)*	-	-	-	*1*	-	*2*	*3*	*93*	*1*	-
Q4 (s)	119	-	-	93	-	-	1	-	-	3	3
Q5 (s)	165	1	-	80	6	2	6	1	-	4	-
Q6 (s)	131	2	-	84	7	-	4	-	-	3	-
s (N=3)	*(415)*	*1*	-	*86*	*4*	*1*	*4*	*tr*	-	*3*	*1*
Eagle Wash (R) – [traverse downstream along Eagle Wash of Tortilla Mountains north of Lopez Ranch]											
R1 (s)	141	3	-	82	-	4	4	-	-	7	-
R2 (s)	133	4	-	72	2	4	10	-	-	8	-
s (N=2)	*(274)*	*4*		*77*	*1*	*4*	*7*	-	-	*7*	-
Hackberry Wash (S) – [traverse upstream in upper Hackberry Wash above junction with Eagle Creek]											
S1 (s)	127	5	-	64	5	3	5	1	-	17	-
S2 (s)	114	5	1	69	11	-	4	-	-	10	
S3 (s)	176	5	-	72	5	1	11	-	-	6	-
s (N=3)	*(417)*	*5*	*tr*	*68*	*7*	*1*	*7*	*tr*		*11*	-
Jim Thomas Wash (T) – [traverse downstream in west limb of Jim Thomas syncline]											
T1 (h)	152	3	-	52	3	7	13	-	9	10	3
T2 (h)	162	2	-	22	4	6	49	1	10	3	3
h (N=2)	*(314)*	*2*		*37*	*4*	*6*	*31*	*1*	*10*	*6*	*3*
T3 (s)	131	5	2	56	11	1	12	-	-	13	-
T4 (s)	138	1	1	45	10	1	23	1	-	18	-
T5 (s)	109	3	1	60	14	1	13	-	-	8	-
T6 (s)	106	1	-	67	5	-	7	-	-	20	-
s (N=4)	*(484)*	*2*	*1*	*57*	*10*	*1*	*14*	*tr*	-	*15*	

Station	n	pi	gd	or	lc	di	qt	ls	wv	li	tv
Hackberry Wash (U) – [traverse up middle Hackberry Wash between Hackberry Spring and Eagle Wash junction]											
U1 (h)	195	8	-	-	1	6	24	27	30	2	2
U2 (h)	146	6	-	-	-	2	41	15	36	-	-
U3 (h)	119	13	2	-	2	1	30	9	38	5	-
h (N=3)	*(460)*	*9*	*1*	-	*1*	*3*	*32*	*17*	*35*	*2*	-
Indian Camp Wash (V) – [traverse downstream from just above power line crossing of Indian Camp Wash]											
V1 (h)	113	1	-	-	6	2	4	25	40	22	-
V2 (h)	158	2	1	-	4	5	28	16	28	16	-
V3 (h)	157	1	-	1	1	4	27	27	25	14	-
V4 (h)	138	-	-	-	3	2	35	19	29	12	-
h (N=4)	*(566)*	*1*	*tr*	*tr*	*4*	*3*	*24*	*22*	*30*	*16*	-
Hackberry Wash (W) – [traverse downstream along walls of Hackberry Wash below Hackberry Spring]											
W1 (h)	105	4	-	-	2	7	5	9	59	14	-
W2 (h)	169	2	-	-	-	2	5	4	60	27	-
W3 (h)	127	-	-	-	-	-	2	2	54	42	-
W4 (h)	106	-	-	-	-	1	6	20	50	23	-
h (N=4)	*(507)*	*2*	-	-	*tr*	*2*	*4*	*9*	*56*	*27*	-
Gila River Valley (X) – [traverse across Gila River east of Kearny from point south of river to ravine west of farm)											
X1 (s)	104	2	-	70	11	5	2	-	-	10	-
X2 (s)	103	-	-	77	11	3	3	-	-	6	-
X3 (s)	104	2	1	57	8	8	16	1	-	7	-
X4 (s)	124	2	2	44	6	16	12	11	-	6	1
X5 (s)	101	1	1	45	2	16	27	5	-	2	-
s (N=5)	*(536)*	*1*	*1*	*59*	*8*	*10*	*12*	*3*	-	*6*	-
Flatiron Canyon (Y) – [across upper reach of unnamed canyon cutting past south end of megabreccia flatiron]											
Y1 (h)	134	2	-	34	7	24	23	-	-	11	-
Y2 (h)	134	2	1	35	10	12	31	-	-	9	-
Y3 (h)	125	-	-	42	7	4	33	8	-	6	-
h (N=3)	*(393)*	*1*	*tr*	*37*	*8*	*13*	*29*	*3*	-	*9*	-

Lower Ripsey Succession (ZL) – [strike traverse from north to south along lower San Manuel Formation as exposed in compound Ripsey half-graben, with submeans for northern and southern segments of half-graben]

Station	n	pi	gd	or	lc	di	qt	ls	wv	li	tv
ZL1 (s)	128	2	-	85	3	-	1	-	-	8	1
ZL2 (s)	104	2	-	89	-	-	-	-	-	9	-
S (N=2)	*232*	*2*	-	*87*	*2*	-	*1*	-	-	*8*	-
*ZL3 (s)	119	44	2	49	-	3	-	-	-	2	-
ZL4 (s)	121	7	-	59	21	-	-	-	-	13	-
ZL5 (s)	113	-	-	66	24	-	-	-	-	10	-
ZL6 (s)	123	-	-	56	35	-	-	-	-	9	-
s (N=3)	*(357)*	*2*	-	*60*	*27*	-	-	-	-	*11*	-

Upper Ripsey Succession (ZU) – [strike traverse from north to south along upper San Manuel Formation as exposed in compound Ripsey half-graben, with submeans for northern, central and southern segments of half-graben]

Station	n	pi	gd	or	lc	di	qt	ls	wv	li	tv
ZU1 (s)	128	36	-	59	-	4	-	-	-	1	-
ZU2 (s)	150	27	-	68	-	5	-	-	-	-	-
ZU3 (s)	183	18	-	64	-	18	-	-	-	-	-
ZU4 (s)	147	26	1	52	-	21	-	-	-	-	-
ZU5 (s)	111	26	-	56	2	15	-	-	-	1	-
ZU6 (s)	139	27	1	52	3	14	-	-	-	3	-
s (N=6)	*(858)*	*27*	*tr*	*58*	*1*	*13*	-	-	-	*1*	-
ZU7 (s)	127	18	1	57	1	15	-	-	-	8	-
ZU8 (s)	173	6	-	78	1	4	-	-	-	11	-
ZU9 (s)	143	17	-	68	1	6	-	-	-	8	-
s (N=3)	*(443)*	*14*	*tr*	*68*	*1*	*8*	-	-	-	*9*	-
ZU10 (s)	129	7	6	31	4	17	3	8	-	24	-
ZU11 (s)	130	15	8	29	2	22	4	8	-	12	-
ZU12 (s)	103	9	6	35	4	16	13	5	-	12	-
s (N=3)	*(362)*	*10*	*7*	*32*	*3*	*18*	*7*	*7*	-	*16*	-

Table 3. Averages (means) or ranges to nearest 5% (arrows=downsection to upsection) for clast counts (frequency percentages) in Cloudburst and San Manuel Formations of various subareas (Figs. 2-4); data extracted from Table 2 (T=lettered clast transects; N=number of total stations)

Subarea	T	N	pi	gd	or	lc[1]	di	qt	ls	wv	li	tv
Cloudburst Formation undifferentiated in southern subareas (A)												
Guild Wash – Star Flat	ABC	5	4	-	10→60	-	1	7	-	-	1	90→20
southern Black Hills	FG	12	-	-	15→85	-	-	-	-	-	-	85→15
northern Black Hills	HI	11	2	5	31	-	3	19	-	-	1	39
Camp Grant Wash	O	6	7	5	30	-	8	18	5	-	2	25
Hackberry Wash Facies of Cloudburst Formation in Tortilla Mountains subarea (B)												
lower member	TY	5	2	-	36	6	11	30	2	4	8	1
upper member (west)	UVW	11	3	-	-	2	3	19	16	41	16	-
upper member (east)	Q	3	-	-	-	1	-	2	3	93	-	-
San Manuel Formation in southern subareas (C)												
Guild Wash – Star Flat	ABC	7	13	1	47	-	2	7	-	-	-	30
Kannally Member	DEF	11	14	-	61	-	8	8	3	-	5	2
Tucson Wash Member	DF	5	tr	-	42	-	-	tr	-	-	-	57
San Manuel Formation in Camp Grant – Putnam Wash subarea (D)												
lower member	JK	11	1	26	40	-	3	12	2	-	2	14
Beehive Well Facies	N	2	3	3	18	-	-	12	6	56	2	-
upper member	LMP	11	8	22	50	-	2	7	1	-	2	8
San Manuel Formation in Tortilla Mountains subarea (E)												
interior Tortilla Mtns	QRST	12	3	tr	71	6	2	8	tr	-	10	tr
Gila River valley	X	5	1	1	59	8	10	12	3	-	10	-
Ripsey Wash sequence (Schmidt, 1971) of San Manuel Formation (F)												
lower member (north)	ZL	2	2	-	87	2	-	1	-	-	8	-
lower member (south)	ZL	3	2	-	60	27	-	-	-	-	11	-
upper member (north)	ZU	6	27	tr	58	1	13	-	-	-	1	-
upper member (center)	ZU	3	14	tr	68	1	8	-	-	-	9	-
upper member (south)	ZU	3	10	7	32	3	18	7	7	-	16	-

[1] counted separately from Oracle Granite only in Tortilla Mountains and Ripsey Wash subareas

Table 4. Net paleoflow directions derived from paleocurrent indicators (clast imbrications) at *n* outcrop stations within various stratigraphic units as exposed in different locales and areas (listed south to north within each group) where *R* is relative magnitude of net paleocurrent vector (see text for discussion of *R*)

Location (and area)	Stations (*n*)	Paleoflow Direction	Resultant *R*
Cloudburst Formation undifferentiated (A)			
upper Tucson Wash (Black Hills south of Black Cyn fault)	6	N46E	0.96
lower Tucson Wash (Black Hills north of Black Cyn fault)	6	N25E	0.90
Cloudburst Wash (Black Hills)	12	N25E	0.81
Tucson and Cloudburst Washes (Black Hills) – this study	*24*	*N30E*	*0.86*
Tucson and Cloudburst Washes (Black Hills) - Weibel (1981)	48	S77E	0.76
Tucson and Cloudburst Washes (Black Hills) – overall mean	*72*	*N74E*	*0.66*
Camp Grant Wash	12	S80W	0.91
Hackberry Wash Facies of Cloudburst Formation (B)			
Smith Wash and northward (northeastern Tortilla Mountains)	8	N84W	0.65
Indian Camp Wash (central Tortilla Mountains)	12	N88W	0.83
lower Hackberry Wash (above megabreccia lenses)	26	N76W	0.80
net Hackberry Wash Facies (Tortilla Mountains)	*46*	*N81W*	*0.78*
Kannally (lower) Member of San Manuel Formation and San Manuel Formation undifferentiated (C)			
Kannally Member of Black Hills (multiple ravines)	20	N60E	0.92
Kannally Member of Black Hills – Hansen (1983)	28	N69E	-
lower San Manuel Formation in Putnam Wash	0	S68E	0.88
Eagle Wash (southeastern Tortilla Mountains)	3	S74E	0.96
Corkscrew Canyon (southwestern Tortilla Mountains)	15	S87W	0.80
Jim Thomas Wash (western Tortilla Mountains)	4	N39E	0.94
Beehive Well Facies of San Manuel Formation (D)			
Cowhead Well, Bloodsucker Wash near Camp Grant Wash	16	S10E	0.95
Tucson Wash Member of San Manuel Formation (E)			
Cottonwood and Smelter Washes nr San Manuel (Black Hills)	15	S32W	0.89
Mammoth Wash near Mammoth (Black Hills)	15	S87W	0.80
net Tucson Wash Member (Black Hills) - this study	*30*	*S60W*	*0.77*
Highway 77 roadcuts (Black Hills) – Hansen (1983)	30	S37W	-
Overall Black Hills mean (multiple operators)	*60*	*S48W*	-
Ripsey Wash sequence (Schmidt, 1971) of San Manuel Formation (F)			
lower succession (deposited in Hackberry fault half-graben)	6	N47E	0.94
upper succession (deposited in Ripsey fault half-graben)	18	S37W	0.69

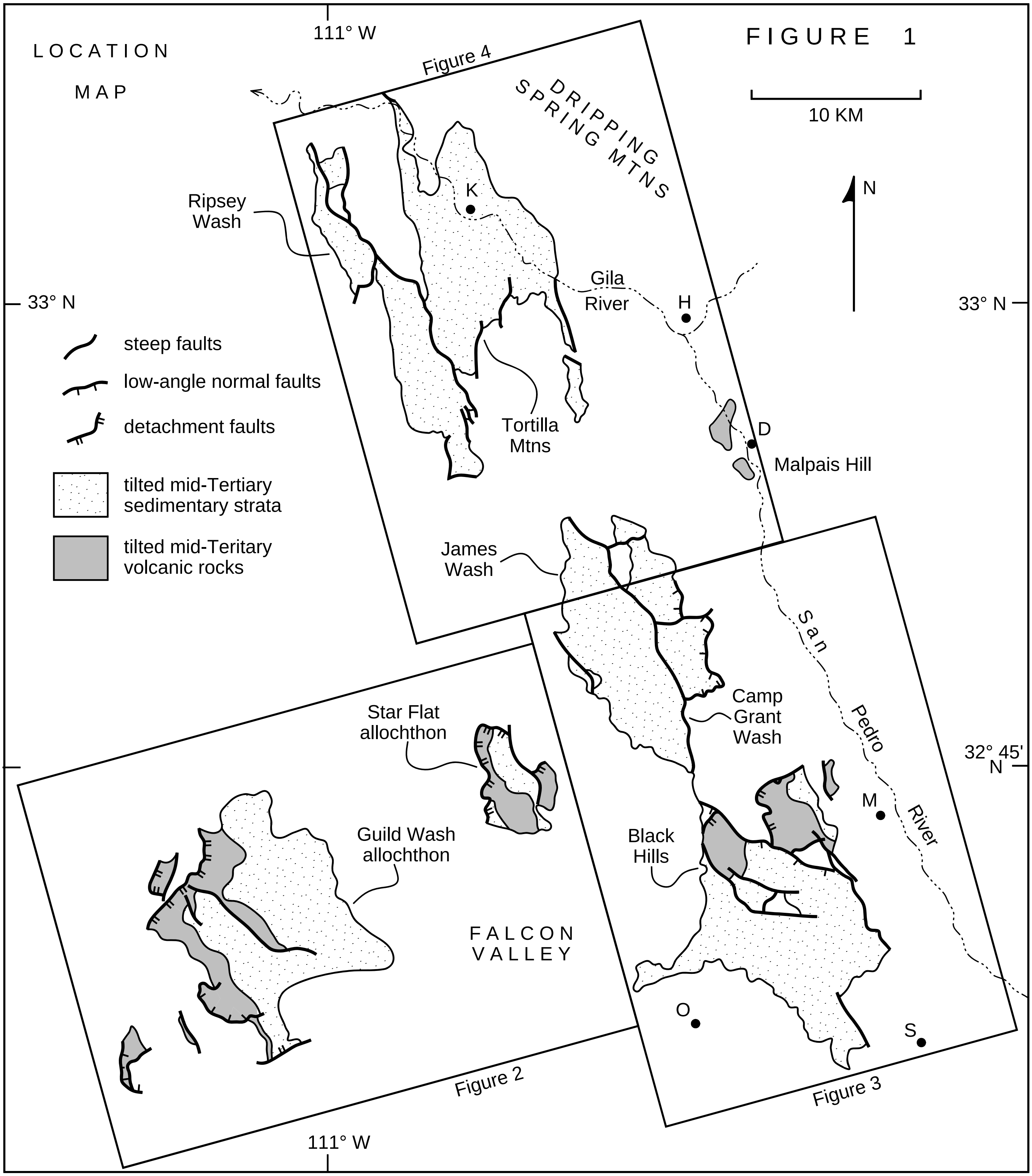


FIGURE 1
LOCATION
MAP
111° W
Figure 4
DRIPPING
SPRING MTNS
10 KM
N
Ripsey
Wash
K
Gila
River
H
33° N
33° N
steep faults
low-angle normal faults
detachment faults
tilted mid-Tertiary
sedimentary strata
tilted mid-Teritary
volcanic rocks
Tortilla
Mtns
D
Malpais Hill
James
Wash
San
Pedro
River
Camp
Grant
Wash
Star Flat
allochthon
32° 45'
N
Guild Wash
allochthon
M
Black
Hills
FALCON
VALLEY
O
S
Figure 2
Figure 3
111° W

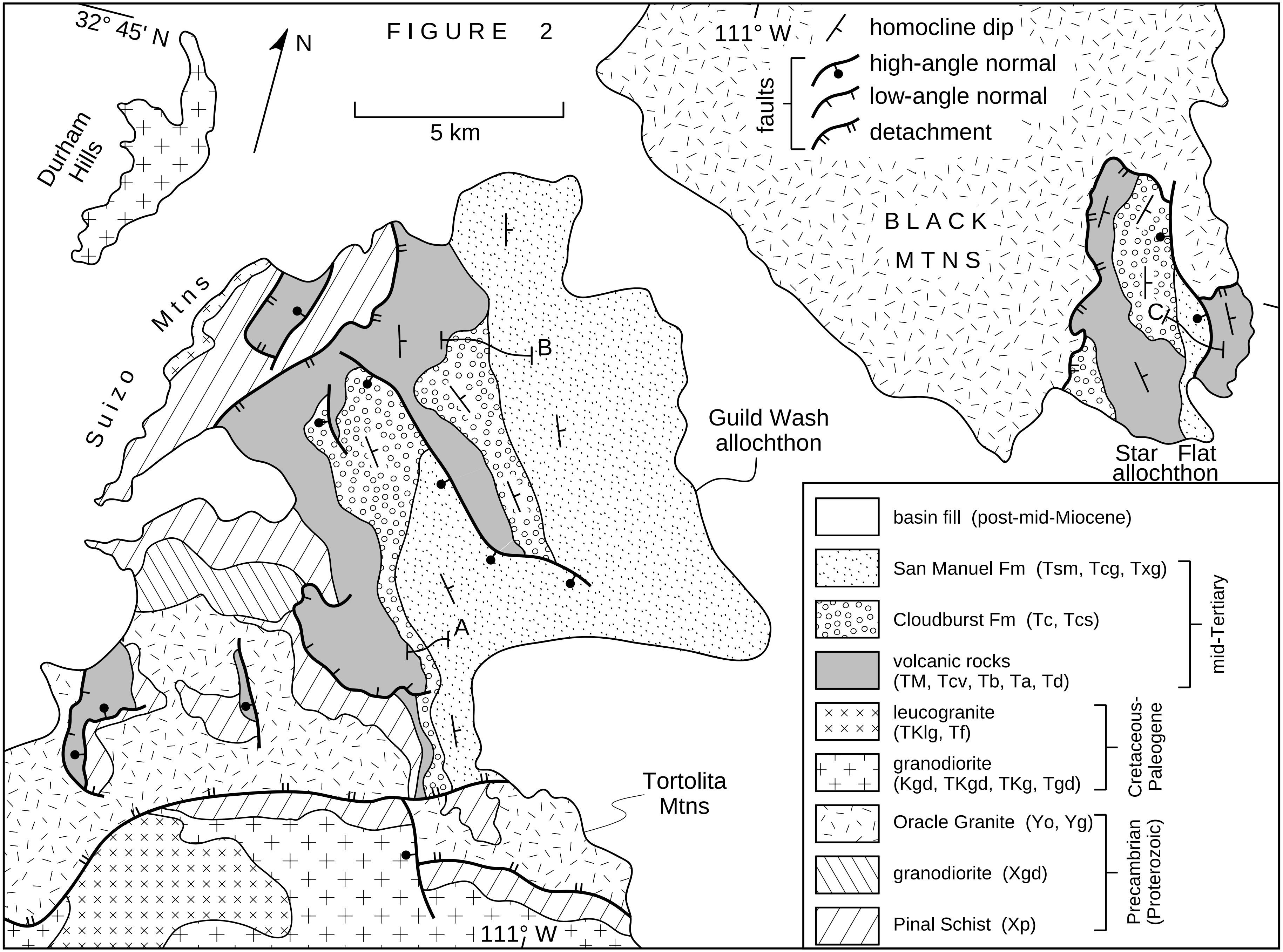


FIGURE 2
32° 45' N
N
5 km
Durham Hills
Suizo Mtns
111° W
homocline dip
faults
high-angle normal
low-angle normal
detachment
BLACK MTNS
B
A
C
Guild Wash allochthon
Star Flat allochthon
Tortolita Mtns
111° W
basin fill (post-mid-Miocene)
San Manuel Fm (Tsm, Tcg, Txg)
Cloudburst Fm (Tc, Tcs)
volcanic rocks (TM, Tcv, Tb, Ta, Td)
mid-Tertiary
leucogranite (TKlg, Tf)
granodiorite (Kgd, TKgd, TKg, Tgd)
Cretaceous-Paleogene
Oracle Granite (Yo, Yg)
granodiorite (Xgd)
Pinal Schist (Xp)
Precambrian (Proterozoic)

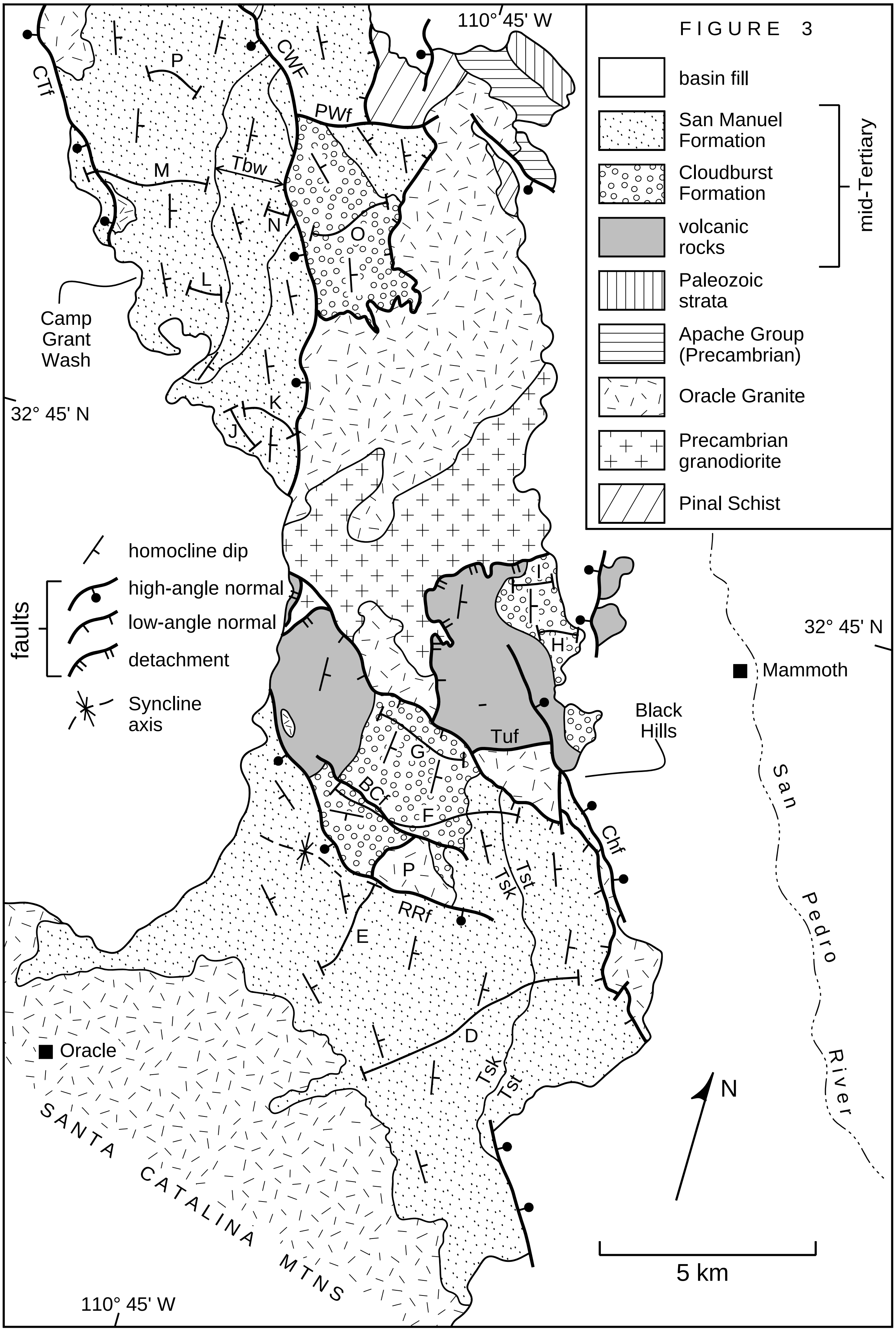
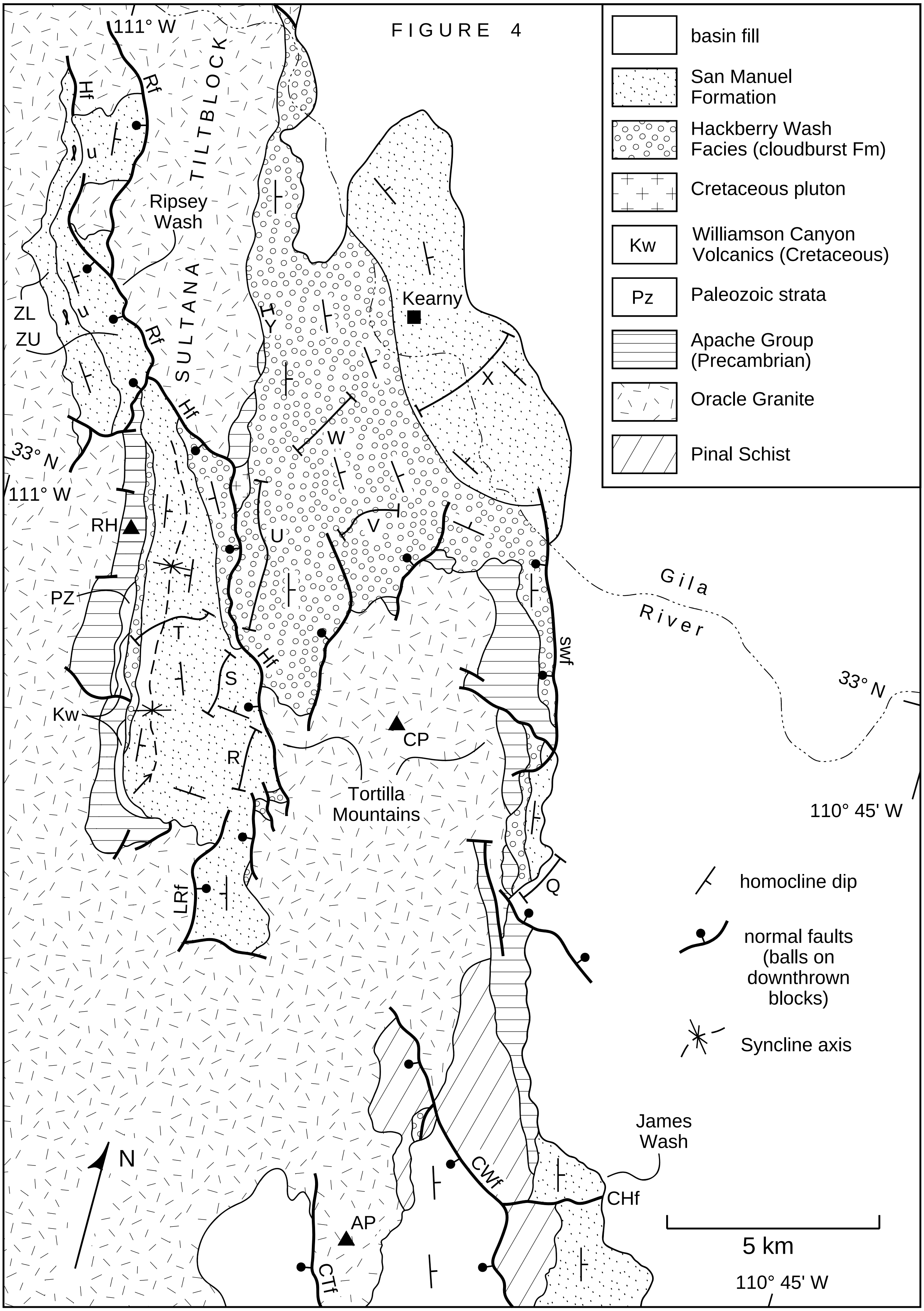


FIGURE 3
basin fill
San Manuel Formation
Cloudburst Formation
volcanic rocks
mid-Tertiary
Paleozoic strata
Apache Group (Precambrian)
Oracle Granite
Precambrian granodiorite
Pinal Schist
homocline dip
faults
high-angle normal
low-angle normal
detachment
Syncline axis
110° 45' W
32° 45' N
CTf
CWF
PWf
Tbw
P
M
N
O
L
K
J
I
H
G
F
E
D
Tuf
BCf
RRf
Tsk
Tst
Chf
Camp Grant Wash
Black Hills
Mammoth
San Pedro River
Oracle
SANTA CATALINA MTNS
N
5 km


basin fill
San Manuel Formation
Hackberry Wash Facies (cloudburst Fm)
Cretaceous pluton
Kw
Williamson Canyon Volcanics (Cretaceous)
Pz
Paleozoic strata
Apache Group (Precambrian)
Oracle Granite
Pinal Schist
homocline dip
normal faults (balls on downthrown blocks)
Syncline axis
111° W
33° N
110° 45' W
SULTANA TILTBLOCK
Ripsey Wash
Kearny
Gila River
Tortilla Mountains
James Wash
RH
CP
AP
PZ
Kw
ZL
ZU
Hf
Rf
LRf
swf
CWf
CHf
CTf
u
T
S
R
U
V
W
X
Y
Q
N
5 km
FIGURE 4

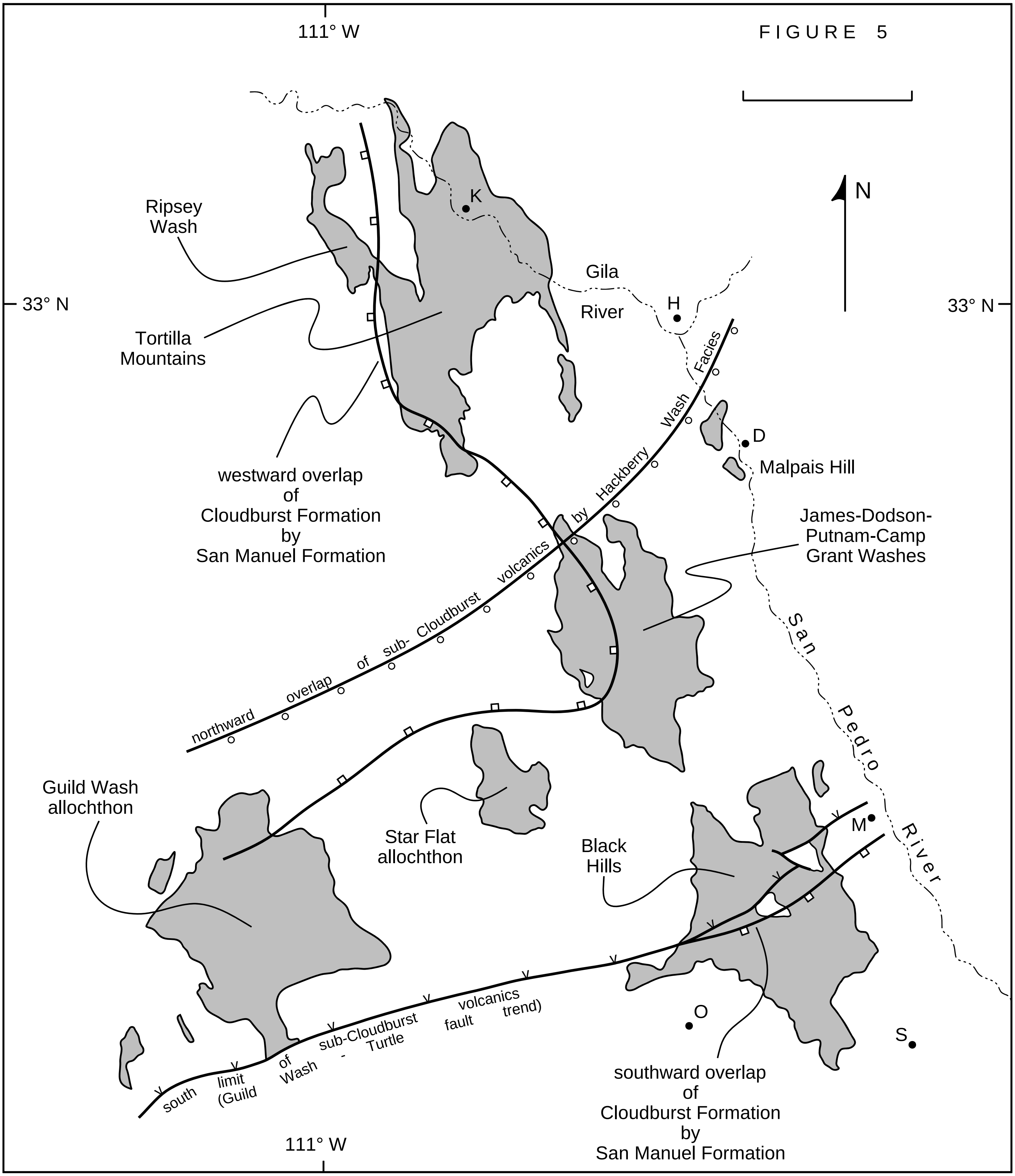

111° W
N
Ripsey
Wash
K
Gila
River
H
33° N
33° N
Tortilla
Mountains
northward overlap of sub-Cloudburst volcanics by Hackberry Wash Facies
D
Malpais Hill
westward overlap
of
Cloudburst Formation
by
San Manuel Formation
James-Dodson-
Putnam-Camp
Grant Washes
San Pedro River
Guild Wash
allochthon
Star Flat
allochthon
Black
Hills
M
south limit (Guild of Wash sub-Cloudburst - Turtle volcanics fault trend)
O
S
southward overlap
of
Cloudburst Formation
by
San Manuel Formation
111° W

FIGURE 5