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## *Stratigraphy and structure of the Laramide Carthage - La Joya Basin, central New Mexico*

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2009, pp. 227-234. <https://doi.org/10.56577/FFC-60.227>

in:

*Geology of the Chupadera Mesa*, Lueth, Virgil; Lucas, Spencer G.; Chamberlin, Richard M.; [eds.], New Mexico Geological Society 60<sup>th</sup> Annual Fall Field Conference Guidebook, 438 p. <https://doi.org/10.56577/FFC-60>

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# STRATIGRAPHY AND STRUCTURE OF THE LARAMIDE CARTHAGE-LA JOYA BASIN, CENTRAL NEW MEXICO

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**ABSTRACT**—The elongate, north-northwest trending Carthage–La Joya basin of central New Mexico developed in the middle Eocene, late in the Laramide orogeny. Sedimentary strata in the basin consist of a fluvialite red-bed succession of sandstone, conglomerate, and minor mudstone as much as ~300 m thick. Sediments were derived mostly from the nearby Sierra uplift to the west, and were deposited on an east-facing, braided-alluvial piedmont system. In the northern part of the Carthage–La Joya basin, however, scattered deposits of a southwest-facing piedmont system are preserved. These deposits may provide a depositional record of the Montosa uplift to the northeast. An axial-river facies stratigraphically intervenes between deposits of the opposing piedmont facies in parts of the northern basin and overlies Mesozoic strata on the east flank of the basin, where it shows evidence for southeasterly paleoflow. These axial-river deposits are dominated by well-rounded, varicolored quartzite clasts that appear to have been derived from the Mogollon Highland far to the west in central Arizona, and record an extrabasinal river that at times spilled over the Sierra uplift from the Baca basin.

The Carthage–La Joya basin region is extraordinarily complex structurally, but relatively few structures can be definitively shown to be Laramide. These include (1) the reverse faults and folds of the Amado–Cañas structural zone in the west-central part of the basin, (2) the Stapleton thrust fault in the northern part of the basin, (3) two northeast-striking systems of high-angle Laramide faults in the northern part of the basin (the Parida and Milagro structural zones) that may be related to the dextral-oblique Montosa fault system to the east, and (4) widespread, low-angle, top-east normal faults in Permian evaporite strata.

## INTRODUCTION

Late Laramide deposits in central New Mexico consist of red beds of sandstone, conglomerate, and minor mudstone that crop out west and east of Socorro (Wilpolt et al., 1946; Wilpolt and Wanek, 1951; Potter, 1970; Snyder, 1971; Johnson, 1978; Cather, 1980; Cather and Johnson, 1984, 1986; Lucas and Williamson, 1993; Cather, 2004). Most workers have assigned these deposits to the Baca Formation (cf. Lucas and Williamson, 1994). The Baca Formation was deposited in two basins: the Baca basin to the west of Socorro and the Carthage–La Joya basin to the east (Cather and Johnson, 1984, 1986). The basins were separated by a Laramide positive area, the Sierra uplift, parts of which are now subsided to form the Socorro and La Jencia basins of the Rio Grande rift (Cather, 1983).

The Carthage–La Joya basin is one of a series of en echelon, north-northwest trending Laramide basins of probable strike-slip origin that formed along the eastern margin of the Colorado Plateau (Chapin and Cather, 1981, 1983). Exposed in scattered outcrops along the east flank of the Socorro Basin (Fig. 1), the fill of Carthage–La Joya basin is as much as ~300 m thick. The fill unconformably overlies strata of Pennsylvanian to Late Cretaceous age, including the Crevasse Canyon Formation, Mancos Shale, Tres Hermanos Formation, Dakota Sandstone, the Chinle Group, and the Madera Group. The Baca Formation contains Bridgerian fossils in its lower part near Carthage (Gardner, 1910; Lucas and Williamson, 1994), and grades upwards into middle Eocene volcanoclastic rocks of the Spears Group throughout the basin (Cather et al., 1987; Cather, 2004). The Baca Formation in the Carthage–La Joya basin thus appears to be entirely of middle Eocene age. Apatite fission-track cooling ages of Proterozoic and Paleozoic clasts in the Baca Formation indicate that, during uplift and erosion of the Sierra uplift, the sources of these clasts cooled below ~110° C (~3–5 km paleodepth) in the late Paleocene through early middle Eocene (~57–45 Ma ago; Kelley et al., 1997; 2009).

Previous reconnaissance studies interpreted a relatively simple, east-facing braided alluvial plain system as the dominant ancient depositional system within the Carthage–La Joya basin (Cather and Johnson, 1984, 1986). Recent geologic mapping (Cather, 2002; Cather et al., 2004; Cather and Colpitts, 2005; Cather and Osburn, 2007) and reconnaissance by the writer, however, has revealed significant facies complexity in the basin.

## SEDIMENTARY ARCHITECTURE

The Eocene clastic rocks of the Carthage–La Joya basin can be divided into several mappable units, based on depositional facies and provenance (petrofacies). Recent maps (Cather, 2002; Cather et al., 2004; Cather and Colpitts, 2005; Cather and Osburn, 2007) distinguish braided-alluvial piedmont deposits (both east- and southwest-facing; see Cather and Johnson, 1984, 1986, for detailed facies description and interpretation), and extrabasinal braided axial-river deposits derived from far to the west. Piedmont deposits are further divided into three petrofacies based on clast composition. These facies include: (1) basement-derived deposits (map unit Tbp<sub>g</sub>) that consist of a dominance (>50%) of Proterozoic granite, gneiss, and schist clasts with subordinate limestone, sandstone, and siltstone clasts mostly from Paleozoic source terranes; (2) sedimentary-derived deposits (Tbp<sub>s</sub>) with a dominance of Paleozoic limestone, sandstone, and siltstone clasts and subordinate Proterozoic clasts; and (3) volcanic-bearing deposits in the upper Baca Formation (Tbp<sub>v</sub>) that contain 10–50% andesite clasts. The Baca Formation is transitional with the overlying Spears Group, the base of which is defined by the first up-section occurrence of >50% volcanic detritus (Cather et al., 1994).

### Piedmont Deposits

As noted by Cather and Johnson (1984, 1986), braided-stream deposits of east-facing piedmonts volumetrically dominate the

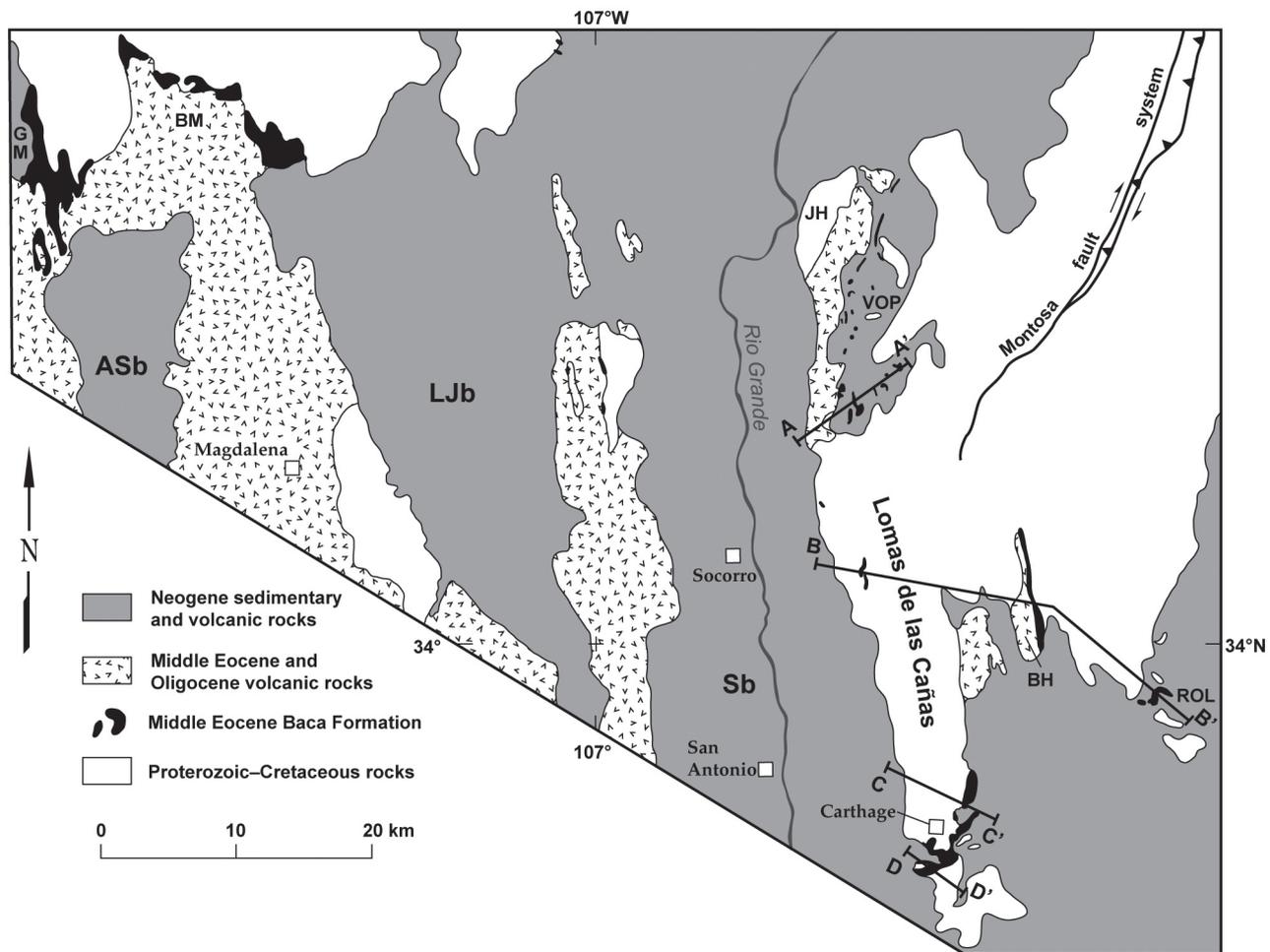


FIGURE 1. Simplified geologic map of central New Mexico showing outcrops of Eocene Baca Formation and modern basins of the Rio Grande rift. Abbreviations are: GM, Gallinas Mountains; ASb, Abbe Springs Basin; LJb, La Jencia Basin; BM, Bear Mountains; Sb, Socorro Basin; JH, Joyita Hills; VOP, Valle del Ojo de la Parida; BH, Blackington Hills; ROL, Rancho Ojo del Llano.

fill of the Carthage–La Joya basin (Fig. 2). These deposits consist mostly of Proterozoic and Paleozoic detritus (units Tbp<sub>g</sub> and Tbp<sub>s</sub>, respectively) derived from the nearby Sierra uplift to the west. These units alternate haphazardly along depositional strike in the western part of the Carthage–La Joya basin. No simple unroofing successions were observed. Indeed, in the southern part of the basin near the ghost town of Carthage, Proterozoic detritus constitutes most of the lower part of the Baca Formation and Paleozoic clasts become predominant up-section (Cather and Osburn, 2007). The reason for this inverted unroofing history is unknown; possibilities are discussed below. Maximum clast size in the east-facing piedmont deposits generally decreases eastward. This size progression is poorly developed, however, and boulders of granite and sandstone as large as two meters are occasionally seen even in the eastern basin-fill exposures near the Blackington Hills (Fig. 3), ~15 km from the Sierra uplift.

Braided-alluvial piedmont deposits consisting of Proterozoic and Paleozoic detritus derived from the east and northeast are present in the southern and eastern parts of the Mesa del Yeso quadrangle (Cather et al., 2004). Presumably part of a southwest-facing piedmont system that drained the Laramide Montosa uplift (Cather, 1992), these deposits are indistinguishable from

the nearby east-facing piedmont deposits except by paleocurrent analysis. Axial-river gravels stratigraphically intervene between the deposits of opposing piedmont systems in east-central part of the Mesa del Yeso quadrangle (Cather et al., 2004), forming a Waltherian facies succession that suggests the east-facing piedmont prograded eastward over axial and southwest-facing piedmont deposits (Fig. 4).

#### Axial River Deposits

Texturally and compositionally mature pebble and cobble gravels interfinger with Eocene piedmont deposits in the southern Mesa del Yeso quadrangle (Cather et al., 2004) and unconformably overlie Mesozoic strata in the northern Prairie Spring quadrangle near Rancho Ojo del Llano. These gravels are dominated by well-rounded, multicolored quartzite clasts (Fig. 5), with subordinate clasts of felsic metavolcanic rocks, chert, quartz, and petrified wood. Several clasts of gray porphyry were noted, but these are too altered for radiometric dating. Less than ~10% of the clasts are subangular to subrounded pebbles of locally derived Upper Paleozoic lithotypes similar to those in associated piedmont deposits. No granite clasts were observed.

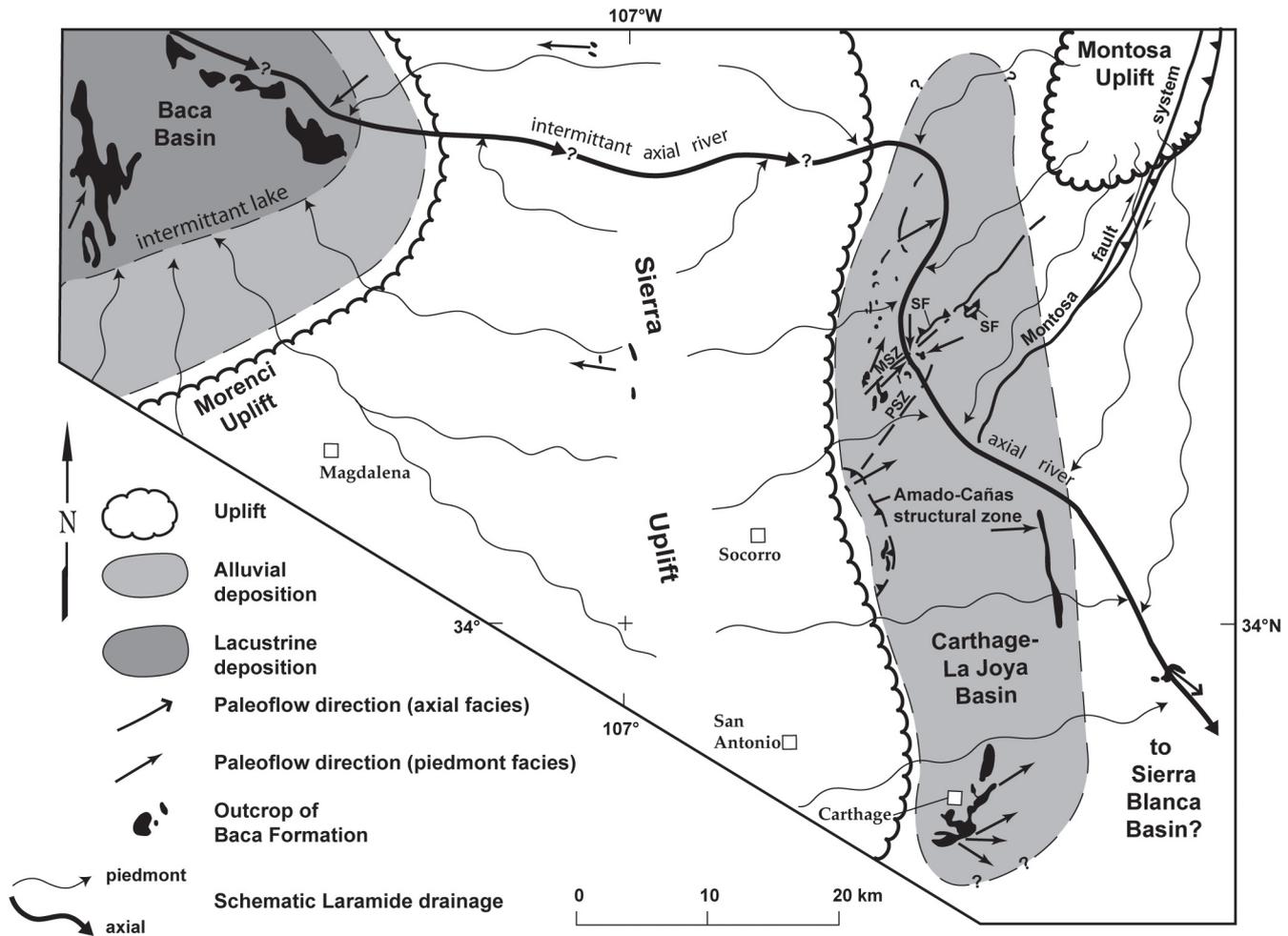


FIGURE 2. Late Laramide (middle Eocene) paleogeographic map of central New Mexico, showing distribution of uplifts, basins, measured paleocurrents, and schematic Laramide paleodrainage relative to modern outcrops of the Eocene Baca Formation. Map area is the same as Figure 1 (no palinspastic restoration of subsequent Neogene extension). Paleocurrent data are from Cather and Johnson (1984), Cather (2002), Cather et al. (2004), Cather and Colpitts (2005), Cather and Osburn (2007), and Read et al., (2007). Abbreviations are: SF, Stapleton fault; MSZ, Milagro structural zone; PSZ, Parida structural zone.

Poorly exposed due to weak induration, these gravels have yielded paleocurrent information only in a road-metal quarry



FIGURE 3. Large granite boulder in piedmont facies of Baca Formation near Blackington Hills (348269E, 3763649N, NAD 1927).

near Rancho Ojo del Llano. There, pebble imbrication indicates generally southeasterly paleoflow (Fig. 6). In the southern Valle del Ojo de la Parida (Cather et al., 2004), these gravels are stratigraphically juxtaposed between deposits of opposing, northeast- and southwest-facing piedmonts, thus suggesting the intervening axial system flowed either northwest or southeast. The latter direction is more likely given the paleogeography of the Carthage-La Joya basin (Fig. 2).

The clast types present in these gravels, with the exception of the Pennsylvanian-Permian types, are not well-matched to any known local source terrane. The clasts in these deposits are too coarse to have been recycled from local Mesozoic or Paleozoic strata. In central New Mexico, basement terranes are dominated by granitic gneiss, and quartzite is generally gray in color and not areally extensive. The lack of granite, preponderance of varicolored quartzite, and the notable roundness of the quartzite clasts suggest these deposits were derived from afar. The Eocene conglomerates of the western Baca basin exhibit clast populations that are quite similar to those of the axial-river facies of

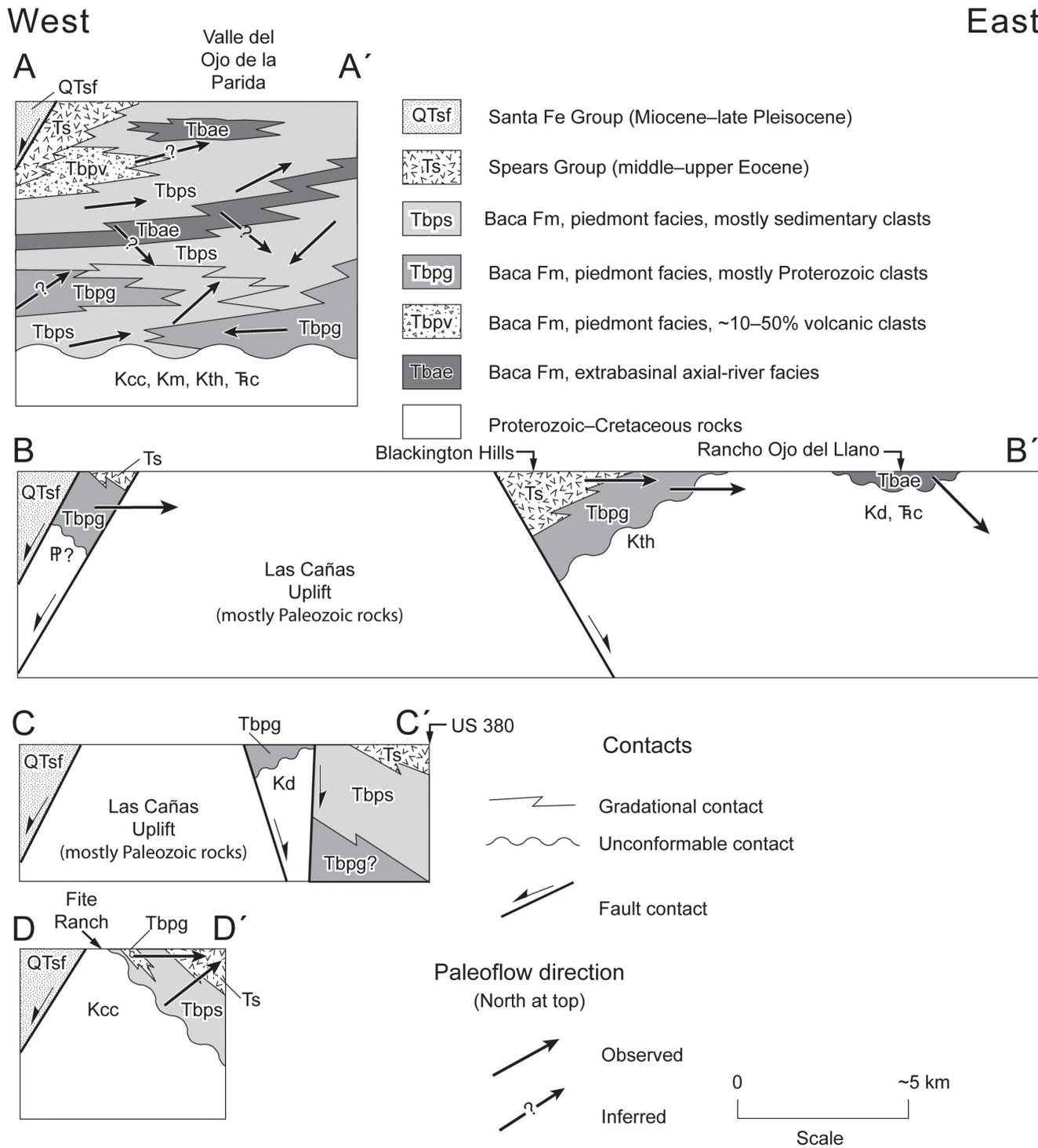


FIGURE 4. Schematic cross sections showing distribution of facies and paleocurrents of the Baca Formation in the Carthage–La Joya basin. Lines of section are shown on Figure 1. Vertical scale is arbitrary. Subcrop strata are: Kcc, Crevasse Canyon Formation; Km, Mancos Shale; Kth, Tres Hermanos Formation; Kd, Dakota Sandstone; Trc, Chinle Group; IP, Pennsylvanian undivided.

the Carthage–La Joya basin. The Baca basin conglomerates were derived from the Mogollon Highland of central Arizona (Cather and Johnson, 1984, 1986), which contained significant exposures of the varicolored Proterozoic Mazatzal Quartzite.

**STRUCTURAL GEOLOGY**

The Carthage–La Joya basin encompasses what is probably the most structurally complex area of central New Mexico. Much of



FIGURE 5. Gravel of the axial-river facies at Rancho Ojo del Llano (356148E, 3759575N). Note dominance of well-rounded quartzite clasts.

this area is a complex uplift (the Las Cañas uplift) that forms part of the east shoulder of the Socorro Basin of the Rio Grande rift. The Las Cañas uplift plunges to the south near Carthage (Cather and Osburn, 2007), and is truncated to the north by Laramide northeast-striking fault systems near Valle del Ojo de la Parida (Cather and Colpitts, 2005; Cather et al., 2004). It is bounded on the west and on the east by rift-age normal faults (Cather and Osburn, 2007). Because Cenozoic deposits have been eroded from the Las Cañas uplift, the sedimentary record of the Carthage–La Joya basin is fragmentary and is reasonably complete only in its northern, eastern, and southern parts.

A great diversity of structures exists in the Carthage–La Joya basin area (Smith, 1983), including high-angle faults of diverse orientations and ages, low-angle faults of at least two types, and folds that range from broad and open to tight and overturned. Most of these structures are attributable to either Laramide or Rio Grande rift deformation. It is quite possible, however, that some faults have reactivated older structures inherited from Late Paleozoic or Precambrian orogenies.

High-angle ( $>60^\circ$  dip; most are  $70\text{--}80^\circ$  dip) faults can be broadly divided into two age groups. The oldest set (Rejas, 1965) forms northeast-striking structural zones as much as one kilometer wide in the northern Las Cañas uplift and in the Valle del Ojo de la Parida (Fig. 2). In the southeastern Mesa del Yeso quadrangle, one of these zones (the Parida structural zone of Cather et al., 2004) may have acted at times as an intrabasin source of Paleozoic detritus to the Eocene Baca Formation in the northern Carthage–La Joya basin, and another (the Milagro structural zone) is buried by late Eocene–Oligocene volcanic and volcanoclastic rocks (Cather et al., 2004). These northeast-striking zones thus appear to be of Laramide age, and may be related to dextral-reverse faulting in the similarly-oriented Laramide Montosa fault system to the east (e.g., Behr, 1999).

The younger set of high-angle faults strikes generally north or northwest. These faults are the most numerous in the study area; most exhibit normal separation. They cut Oligocene and Miocene strata on the east and west flanks of the Las Cañas uplift and

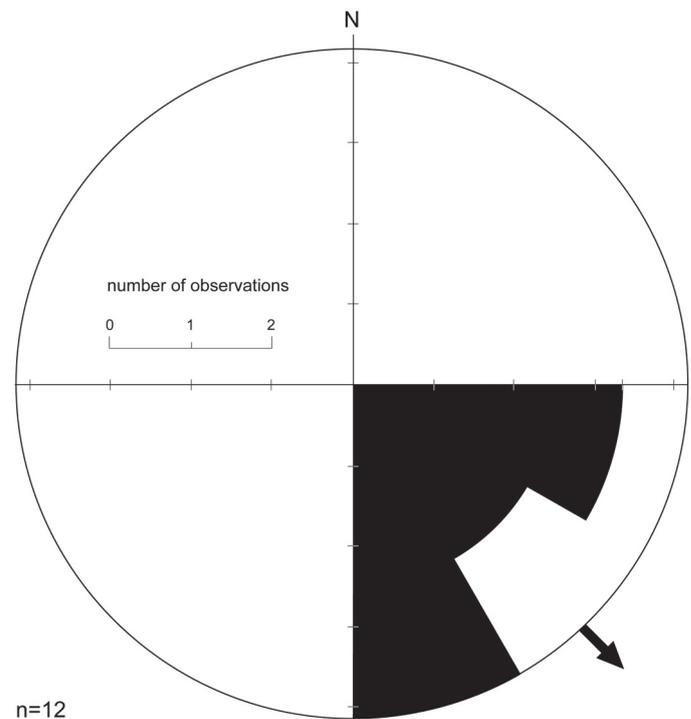


FIGURE 6. Paleocurrent directions from pebble imbrications in axial-river facies at Rancho Ojo del Llano.

thus are, at least locally, rift-age. The north-striking, high-angle Ranchitos fault on the east side of the uplift exhibits evidence for post-Laramide sinistral-normal oblique slip (Cather and Osburn, 2007). It is possible that other north-striking faults in the region also had rift-age components of sinistral slip.

Low-angle faults in the Carthage–La Joya basin area are of two types. Most juxtapose younger strata over older, and thus in that sense are normal faults. Faults of this type are only known to occur within the evaporite-bearing parts of the Permian stratigraphic interval, mostly in the upper Yeso Formation and the San Andres Formation (Maulsby, 1981; Bausch, 1982; Fagrellius, 1982; Colpitts, 1986; Craig, 1992; Linden, 1990). Locally these detachment faults excise more than 200 m of the Permian section (Smith, 1983). They are most commonly manifested by modest amounts (10s of meters) of missing section in the upper Yeso Formation. Locally, detachment faulting has produced major stratigraphic excision causing the San Andres Formation to overlie the upper part of the Yeso Formation. In most places the detachment faults are within gypsum beds and are marked by little or no angular discordance between upper- and lower-plate strata. However, pronounced angular discordance and down-dip truncation of tilted upper-plate strata are common locally (Fig. 7). Such truncation is probably the result of a ramp-flat fault geometry (Fig. 8), where a fault steps stratigraphically down-section in the direction of upper-plate transport. Shear indicators and the angular truncation of upper plate strata by detachment faults indicate mostly top-east slip on these faults.

Throughout most of the Las Cañas uplift, the age of low-angle normal faulting is only broadly constrained to be post-Permian



FIGURE 7. View to southeast of low-angle normal fault (dashed line) that divides upper Yeso Formation in footwall from tilted and faulted strata of Glorieta Sandstone and San Andres Formation in hanging wall. Note down-dip truncation of upper-plate beds. Image was taken from 338178E, 3764245N of an exposure in southwestern corner of Bustos Well quadrangle.

and to predate the modern landscape. It is possible that detachment faulting in the Carthage–La Joya basin area began in the Laramide, as shown by detachment-related structures that are cross-cut by a dike to the east near Chupadera Mesa (Cather, 2009, this guidebook). Recent mapping near the Blackington Hills (Cather and Osburn, 2007) suggests the faulting continued, at least locally, into the Neogene. There, the north-striking Bustos fault cuts upper Eocene–Oligocene volcanic rocks and causes ~1000 m of normal stratigraphic separation of the 35.5 Ma-old Datil Well Tuff. The strata in the hanging wall are tilted about 30° west relative to footwall strata. The association of such a large rotation with only modest stratigraphic separation indicates a strongly listric fault geometry, and may be the result of roll-over above a listric normal fault that flattens into a decollement within the Permian section (Cather and Osburn, 2007). Strongly listric normal faults that cut the Paleogene volcanic section have also been described in the Joyita Hills (Stop 2 of Smith et al., 1983).

The second type of moderate- to low-angle (<60°) faults place older rocks over younger and thus are thrust or reverse faults. In the Carthage–La Joya basin area, thrust faults have been documented in two areas. East of Valle del Ojo de la Parida, a low-angle thrust fault (herein termed the Stapleton fault; Fig. 2) of probable Laramide age placed an allochthon of the middle Yeso Formation (Torres Member) over Triassic and Upper Cretaceous strata (Stop 1 of Smith et al., 1983; Linden, 1990; Cather et al., 2004). The structural context of the Stapleton fault is unclear due to incomplete mapping in the Sierra de la Cruz quadrangle, but it lies near the trend of the Milagro structural zone and may be related to it. The influence of the Stapleton fault on sedimentation in the Carthage–La Joya basin is unknown.

An arcuate zone of discontinuous folds and reverse faults deforms Proterozoic, Pennsylvanian and Permian strata along the west flank of the Las Cañas uplift between Cerros de Amado and Arroyo de las Cañas (Smith, 1983; Cather and Colpitts, 2005).

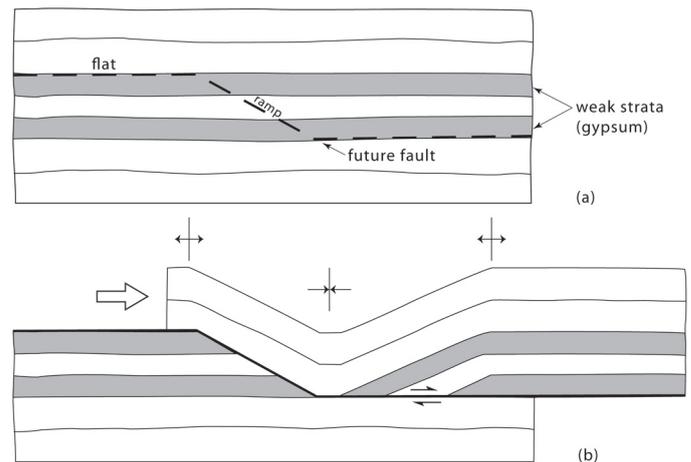


FIGURE 8. Schematic balanced cross sections showing bedding configuration and fault-bend folds resulting from ramp-flat geometry on a low-angle normal fault. Note that the slip surface steps downsection between weak beds, resulting in excision of section and angular relationships between strata across the fault surface. (a) Pre-deformation cross section. (b) Cross section following deformation. Note that the acute angular truncation of upper-plate strata points opposite to the direction of upper-plate slip.

These structures (herein termed the Amado–Cañas structural zone; Fig. 2) generally verge to the east (ranging from southeast to northeast) and are well exposed near Arroyo del Tajo. These contractile structures are responsible for the structural relief that allows the exposure of Proterozoic rocks east of Socorro (the only other exposures of Proterozoic rocks on the east flank of the Socorro Basin are in the Joyita Hills). The structures of the Amado–Cañas zone are probably Laramide, as this is the only post-Permian contractile deformation known in the region. The Amado–Cañas structural zone may be a remnant of the eastern frontal margin of the Sierra uplift, the principal source of detritus to the Carthage–La Joya basin. Scattered, fault-bounded exposures of west-derived piedmont deposits of the Baca Formation occur within the Amado–Cañas structural zone (Cather and Colpitts, 2005), however, and imply that the zone developed intrabasally and was itself not a major source of sediment to the Carthage–La Joya basin. The Baca Formation within the Amado–Cañas structural zone overlies Pennsylvanian strata; elsewhere in the basin it overlies Mesozoic beds (Fig. 4).

Folds are widely distributed in the Carthage–La Joya basin area. Large-scale, east-vergent, locally overturned folds are related to thrust faults in the Amado–Cañas structural zone (Fig. 9). Tight, small-scale folds of diverse orientation are developed locally in gypsiferous parts of the Permian section, where they may be related to low-angle normal faults. Broad open folds are widely developed in the area. Most have northerly trends and may be related to the pervasive, high-angle, north-striking faults in the region.

## DISCUSSION

The significant structural and facies complexity in the Carthage–La Joya basin demonstrated by recent mapping has impli-



FIGURE 9. Folded Abo and Yeso formations in a large overturned syncline in footwall of a thrust fault in the Amado–Cañas structural zone. Thrust fault (unseen in photo) places upright strata of the Pennsylvanian Atrasado Formation over overturned beds of the Permian Abo Formation (Cather and Colpitts, 2005). View to northeast across Arroyo de las Cañas from 334265E, 3765709N.

cations for the Laramide and younger tectonic development of central New Mexico. The deposits of a southwest-facing piedmont system provide sedimentologic evidence for the Laramide Montosa uplift. Evidence for this uplift was previously limited to the contractile structural style of the Montosa fault system (Cather, 1992; Behr, 1999) and to Paleocene–Eocene apatite fission-track cooling ages in the Los Pinos and Manzano Mountains (Kelley et al., 1992).

The presence in the axial-river facies of exotic quartzite clasts that appear to have been derived from the Mogollon Highland of central Arizona implies that middle Eocene drainage in the Baca basin at times spilled eastward across the Sierra uplift. The Baca basin was hydrologically closed during much of the middle Eocene, as shown by the dominance of closed-lake deposits in the Bear and Gallinas mountains area (Cather and Johnson, 1984, 1986). The middle part of the formation (middle sandstone member of Potter, 1970) in these areas, however, is fluvial and may represent a time of through-going drainage to the Carthage–La Joya basin. The speculative course of this paleoriver is depicted in Figure 2. Axial-river deposits on the east flank of the Carthage–La Joya basin near Rancho Ojo del Llano show evidence of southeasterly paleoflow, toward the Sierra Blanca basin. Similar conglomeratic deposits are present in the lower part of the Eocene Cub Mountain Formation of the western Sierra Blanca basin (Cather, 1991). These deposits, however, were derived from the southwest, not the northwest as would be required for derivation from the Carthage–La Joya basin.

Three types of structures in the Carthage–La Joya basin region are of probable Laramide age. (1) Contractile Laramide structures that include the thrust faults and related folds of the Amado–Cañas structural zone and the Stapleton thrust fault. (2) Northeast-striking zones of Laramide high-angle faults (the Parida and Milagro structural zones) are present in the northern part of the basin and are possibly related to the dextral-oblique Montosa thrust system to the east. (3) Widespread, low-angle, top-east normal faults in the Permian section.

The regional pattern of Laramide faults is compatible with regional northeast-southwest shortening, with contractile deformation being localized in the Sierra and Montosa uplifts. Northeast-striking shear zones may have linked these uplifts with dextral slip (Fig. 2). The Sierra uplift occupies a sinistral step in the regional dextral fault system, and may be related to contraction in a restraining bend (Cather, 2009, this guidebook). Top-east detachment faults are polygenetic but may have been initiated during Laramide deformation by either tectonic end-loading or gravitational gliding on the east flank of the Sierra uplift (Cather, 2009, this guidebook). It is possible that stratal excision by these normal faults contributed to the subsidence of the Carthage–La Joya basin.

Eocene deposits of the Carthage–La Joya basin indicate that erosional denudation of the Sierra uplift was complex. The haphazard lateral alternation of Proterozoic- and Paleozoic-dominated detritus in piedmont deposits along depositional strike in the western part of the basin may reflect the vagaries of drainage evolution on the uplift. Such a mechanism is less plausible to explain the lack of unroofing successions in the basin. Indeed, in the southern part of the basin, detritus derived primarily from Proterozoic terranes is overlain by clastics derived from Paleozoic sources (Fig. 4, section C-C'). The anomalous unroofing successions of the Carthage–La Joya basin may record structural rather than paleodrainage complexity in the uplift. For example, diachronous uplift of fault blocks within the Sierra uplift may have caused burial of older source terranes by detritus shed from adjacent younger blocks. Alternatively, the anomalous evolution of source terranes in the uplift may be the result of evolving strike-slip juxtaposition of fault blocks within the uplift. The Sierra uplift hosts the southern extension of the Nacimiento fault, which exhibits evidence for ~25 km dextral separation, some or most of which is Laramide (see summaries in Cather, 2004; Cather et al., 2006).

The distribution of sedimentary facies and sediment-dispersal patterns in the Carthage–La Joya basin suggest the Las Cañas uplift did not exist in the Eocene. Piedmont deposits consisting largely of Proterozoic detritus derived from the west dominate the exposures in the Blackington Hills area (Fig. 2). This indicates no substantial uplift existed between these outcrops and the Sierra uplift to the west. The Las Cañas uplift is a rift-flank uplift that probably resulted largely from the Neogene west-down reactivation of Laramide reverse faults as normal faults. As portions of the Laramide Sierra uplift collapsed extensionally to produce the Socorro Basin (Cather, 1983), isostatic footwall uplift associated with this collapse inverted of part of the Carthage–La Joya basin to form the Las Cañas uplift.

#### ACKNOWLEDGMENTS

Mapping was funded by the New Mexico Bureau of Geology and Mineral Resources (P.A. Scholle, Director) and by the STATEMAP Program of the National Cooperative Geologic Mapping Act. I benefitted from discussions with C.E. Chapin, R.M. Chamberlin, S.A. Kelley, G.A. Axen, C.T. Smith, and R.M. Colpitts, Jr. The manuscript was improved by reviews from G.A. Axen, C.E. Chapin and S.A. Kelley. Leo Gabaldon drafted the figures. My equine friends Vicki, Sasquatch and Lucy did most of the legwork.

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