New Mexico Geological Society

Downloaded from: https://nmgs.nmt.edu/publications/guidebooks/65

Redefinition of the base of the Cub Mountain Formation and preliminary depostional and tectonic interpretations of the Early-Middle Eocene strata in the Sierra Blanca Basin, New Mexico

Daniel J. Koning and Logan Roberts

2014, pp. 273-286. https://doi.org/10.56577/FFC-65.273
Supplemental data: https://nmgs.nmt.edu/repository/index.cfml?rid=2014007

in:

Geology of the Sacramento Mountains Region, Rawling, Geoffrey; McLemore, Virginia T.; Timmons, Stacy; Dunbar, Nelia; [eds.], New Mexico Geological Society 65 th Annual Fall Field Conference Guidebook, 318 p.
https://doi.org/10.56577/FFC-65

This is one of many related papers that were included in the 2014 NMGS Fall Field Conference Guidebook.

Annual NMGS Fall Field Conference Guidebooks

Every fall since 1950, the New Mexico Geological Society (NMGS) has held an annual Fall Field Conference that explores some region of New Mexico (or surrounding states). Always well attended, these conferences provide a guidebook to participants. Besides detailed road logs, the guidebooks contain many well written, edited, and peer-reviewed geoscience papers. These books have set the national standard for geologic guidebooks and are an essential geologic reference for anyone working in or around New Mexico.

Free Downloads

NMGS has decided to make peer-reviewed papers from our Fall Field Conference guidebooks available for free download. This is in keeping with our mission of promoting interest, research, and cooperation regarding geology in New Mexico. However, guidebook sales represent a significant proportion of our operating budget. Therefore, only *research papers* are available for download. *Road logs*, *mini-papers*, and other selected content are available only in print for recent guidebooks.

Copyright Information

Publications of the New Mexico Geological Society, printed and electronic, are protected by the copyright laws of the United States. No material from the NMGS website, or printed and electronic publications, may be reprinted or redistributed without NMGS permission. Contact us for permission to reprint portions of any of our publications.

One printed copy of any materials from the NMGS website or our print and electronic publications may be made for individual use without our permission. Teachers and students may make unlimited copies for educational use. Any other use of these materials requires explicit permission.

This page is intentionally left blank to maintain order of facing pages.

REDEFINITION OF THE BASE OF THE CUB MOUNTAIN FORMATION AND PRELIMINARY DEPOSITIONAL AND TECTONIC INTERPRETATIONS OF EARLY-MIDDLE EOCENE STRATA IN THE SIERRA BLANCA BASIN, NEW MEXICO

DANIEL J. KONING[1] AND LOGAN ROBERTS[2]
[1] New Mexico Bureau of Geology and Mineral Resources, New Mexico Institute of Mining and Technology, Socorro, NM, dkoning@nmbg.nmt.edu
[2] Department of Earth and Planetary Sciences, New Mexico Institute of Mining and Technology, Socorro, NM

ABSTRACT—The Sierra Blanca Sierra Blanca Basin preserves a 140–800 m-thick sequence of lower to middle Eocene fluvial strata with distinctive reddish floodplain deposits. These strata have been assigned to the Cub Mountain and the overlying Sanders Canyon Formations. We propose redefining the base of the Cub Mountain Formation to the top of an extensive paleosol that very likely coincides with the regional Cenozoic-Cretaceous unconformity. The paleosol is 3 to 8 m thick, light gray to light grayish green, and contains dark purplish black, manganese or iron oxide concretions that are 3–10 cm in diameter. The paleosol underlies reddish floodplain deposits and Eocene fossil localities. Where the paleosol is absent, the lowest occurrence of reddish floodplain deposits, or coarse channel-fills clearly associated with the reddish floodplain deposits, should serve as the base of the formation.

Near the type area of the Cub Mountain Formation, past studies have included in the basal Cub Mountain Formation a 30–60 m-thick conglomeratic sandstone interval that underlies this paleosol, but our redefinition results in this interval correlating with the Ash Canyon Member of the Crevasse Canyon Formation (Upper Cretaceous). Because imbricated gravels are relatively sparse above the paleosol near the Cub Mountain Formation type area, we suspect that much of the imbrication measurements used to support a northeast paleoflow direction for the Cub Mountain Formation actually came from the upper Crevasse Canyon Formation. Collection of new paleoflow data from strata clearly overlying the paleosol indicate southerly paleocurrents ranging from west to southwest to southeast. Stratigraphic interpretations for the 1160 m-thick Lewelling unit, designated for volcaniclastic strata overlying the Crevasse Canyon Formation in the Lewelling No. 2 well, suggest major structures (likely reverse faults) on the southwest side of the Laramide-age Sierra Blanca Basin.

INTRODUCTION AND PREVIOUS WORK

Located between the towns of Carrizozo and Ruidoso in south-central New Mexico, the Sierra Blanca Basin preserves 140–800 m of lower to middle Eocene sedimentary rocks belonging to the Cub Mountain and Sanders Canyon Formations (Fig. 1). Both of these fluvial units are recognizable by their reddish to reddish brown mudstone to fine sandstone beds and their stratigraphic position below pyroxene- and plagioclase-phyric flows and volcaniclastic strata of the Sierra Blanca volcanic field. The two units were initially grouped into the original Cub Mountain Formation, which was proposed in the 1950s by Robert Weber. Bodine (1956) introduced the name "Cub Mountain Formation." As related in Weber (1964) and Lucas et al. (1989), Bodine (1956) mistakenly omitted a footnote saying that the Cub Mountain Formation concept was developed by Weber, who was to present a proper definition of the unit. Weber (1964) did designate and describe a type area of the Cub Mountain Formation in Chaves Canyon, located between Cub and Chaves Mountains (Fig. 2; SW1/4 SW1/4 sec. 16 to the SW1/4 SW1/4 of sec. 24, T9S, R10E). The basal contact of the Cub Mountain Formation was assigned to "…the base of the lowest impure arkosic sandstone, or the base of the lowest red or variegated clayey to silty bed, whichever feature provided the most useful datum locally" (Weber, 1964, p. 105). He noted that the lower half of the formation is arkosic and contains clasts of quartzite, volcanic rocks (silicified rhyolite and latite(?)), chert,

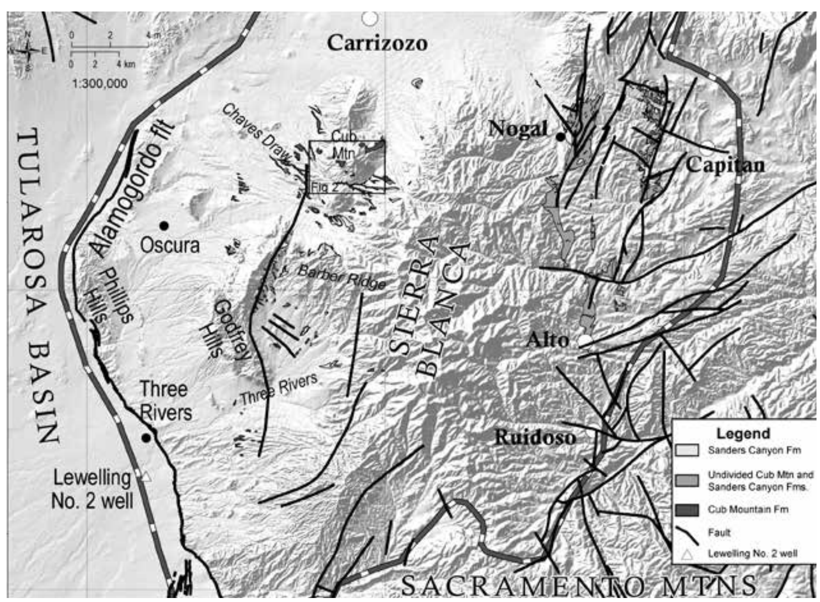

FIGURE 1. Shaded-relief map showing the approximate boundary of the Sierra Blanca Basin, mapped outcrops of Cub Mountain and Sanders Canyon Formations (from Koning et al., 2014, and Rawling, 2012a, 2012b), major faults, and location of the geologic map of Fig. 2. Faults south and east of Sierra Blanca are from the New Mexico Bureau of Geology (2003). The thick, gray-and-white dashed line provides an approximation of the boundary of the Sierra Blanca Basin.

__Appendix data for this paper can be accessed at:__
http://nmgs.nmt.edu/repository/index.cfm?rid=2014007

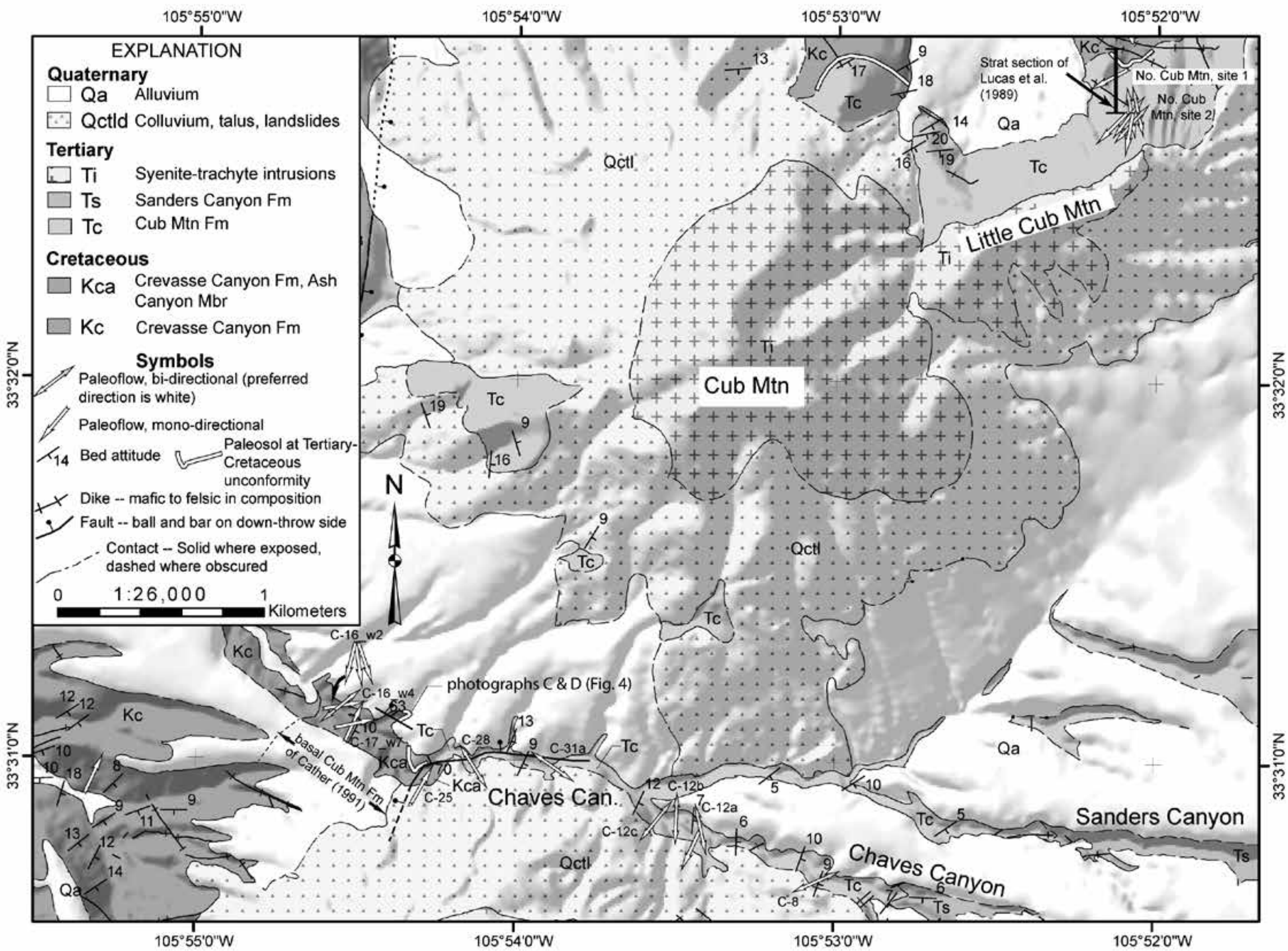

FIGURE 2. Geologic map of the Cub Mountain Formation type area, including exposures on the north side of Cub Mountain. Modified from Koning et al. (2011), with new paleocurrent data added. Note that all Crevasse Canyon Formation outcrops depicted on this map were included in the Cub Mountain Formation by Arkell (1983).

granite, and petrified wood. Weber (1964) described an upward change in sand lithology from arkosic to graywacke, with the latter containing abundant mafic minerals and fragments of andesite and mud pellets.

Arkell (1983, 1986) noted that the basal contact of the Cub Mountain Formation, as defined by Weber (1964), proved very difficult to map because of its gradual character and lack of lithologic contrast across it. Arkell (1983) consequently extended the Cub Mountain Formation down-section to include what later workers considered as the upper half of the Crevasse Canyon Formation (e.g., compare Koning et al. (2011) with plate 1 of Arkell (1983)).

Lucas et al. (1989) studied the lower, arkosic part of Weber's Cub Mountain Formation and established an early-middle Eocene age based on fossils. These workers and Cather (1991) also interpreted a general northeast paleoflow direction for the unit, based largely on clast imbrication measurements on conglomerates that are relatively common in the lower part of Weber's Cub Mountain Formation. Cather (1991) formalized the upper, volcaniclastic part of the Cub Mountain Formation as the Sanders Canyon Formation. He stated that the basal contact of the Cub Mountain Formation is marked by conspicuously coarse conglomerate and pebbly sandstone that overlie sparsely pebbly sandstone and mudstone of the Ash Canyon Member in SE1/4 SW1/4 sec. 16, T9S, R10E (note this is slightly east of the contact proposed by Weber, 1964). The location of Cather's basal contact is shown in Figure 2. At the type area, Cather (1991) noted that abundance of pebbles in the Cub Mountain Formation decreases markedly up-section and that they are generally absent in the upper half of the unit. Cather (2004) summarizes the Cub Mountain Formation and discusses Laramide basins in central and northern New Mexico.

This paper presents new data and interpretations from recent mapping efforts that relate to the Cub Mountain and Sanders Canyon Formations (Rawling, 2012a, 2012b; Koning et al., 2014; Kelley et al., 2014). First, we argue an extensive and distinctive paleosol should define the base of the Cub Mountain Formation and that underlying, conglomerate-

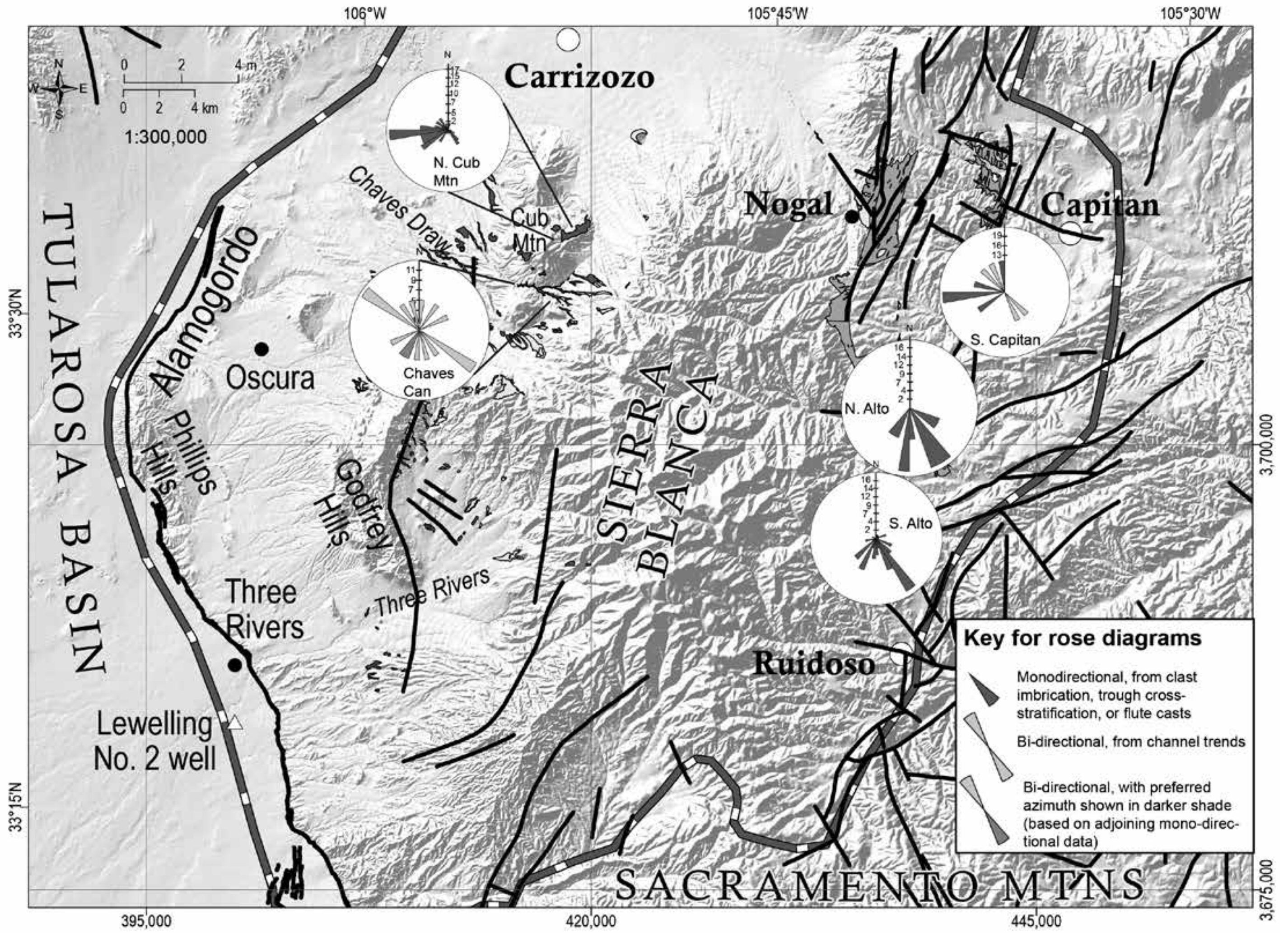

FIGURE 3. Rose diagrams of our paleocurrent measurements plotted on the base map depicted in Figure 1. Paleocurrents were measured at four sites in the Cub Mountain Formation (North Cub Mountain, Chaves Canyon, South Capitan, and South Alto) and one site in the Sanders Canyon Formation (North Alto). Note that the North Cub Mountain, North Alto, and South Alto sites only plot imbrication data. The complete paleocurrent dataset is found in Appendix 1.

rich strata in fact correlate to the Ash Canyon Member of the Crevasse Canyon Formation. This redefinition of the Cub Mountain base means much of the clast imbrication data in Lucas et al. (1989) and Cather (1991) were probably taken from the Ash Canyon Member. Second, we present updated descriptions of the Crevasse Canyon, Cub Mountain and Sanders Canyon Formations and discuss their related paleocurrent data. Third, investigation of cuttings and geophysical logs of the Lewelling #2 well, located 3 km south of Three Rivers, suggest Laramide structures along the southwestern margin of the Laramide-age Sierra Blanca Basin. These data are incorporated into a new hypothesis concerning the structural configuration of the Sierra Blanca Basin in the early to middle Eocene.

METHODS

Data collection involved geologic mapping, measuring paleocurrent azimuths, and describing well data. Trends of channel-fills, trough cross-stratification, and clast imbrication were measured using a Brunton compass at five sites. Four sites are in the Cub Mountain Formation and one is in the Sanders Canyon Formation (Fig. 3, Table 1, Appendices 1 and 2). Because strata dip less than 17 degrees, dip correction was not applied. Cuttings and down-hole geophysical data from the Lewelling No. 2 well are housed at the New Mexico Bureau of Geology and Mineral Resources. Cuttings were inspected using a binocular microscope.

PROPOSAL TO USE A PALEOSOL TO DEFINE THE BASE OF THE CUB MOUNTAIN FORMATION

Recent mapping in the western Sierra Blanca Basin identified an extensive and distinctive paleosol at the base of strata containing fine-grained red beds (Fig. 4). At the Cub Mountain Formation type area, the paleosol lies above a conglomerate-rich interval previously assigned to the lower Cub Mountain Formation (Cather, 1991) (Fig. 2). West of the Sierra Blanca massif, the paleosol has been found everywhere that the Cretaceous-Eocene transition is exposed (Fig 2; Table 2). We are

TABLE 1. Summary of paleocurrent data from clast imbrications

		Imbrication	
Study Site	**Sub-Sites**	**Average Azimuth (°)**	**Error (+/- °)**
North Cub Mountain	Exp 1, 1b	243 n=32	20
	Exp 2	225 n=38	20
So. Capitan	Exp 1	255 n=5	22
N. Alto	Exp 1	120 n=16	20
	Exp 2	179 n=25	20
	Exp 3	201 n=12	20
S. Alto	Exp 1	163 n=12	20

See Appendix 1 for complete listing of measurements, including bi-directional data and location information. Exp= Exposure; n=number of measurements

not aware that it exists in the Capitan area (Rawling, 2012a, 2012b) and further investigation there is warranted. This paleosol occupies a similar stratigraphic position as the pre-Eocene, lateritic weathering profile described by Chamberlin (1989) for west-central New Mexico. However, the paleosol near Cub Mountain is less red, contains larger concretions of iron or manganese oxides, and lacks bedding. This paleosol appears to have been recognized by Lucas et al. (1989; units 2 and 4 of Fig. 5).

Paleosol Description

West of the Sierra Blanca massif, the paleosol is 3 to 8 m thick and light gray to light grayish green to light purple to yellow (Fig. 4; Table 2). It has developed in massive, bioturbated, siltstone to coarse-grained sandstone. The paleosol exhibits dark purplish black concretions 3–20 cm in diameter that are inferred to be cemented by manganese or iron oxides (Fig. 4). Locally, two paleosols are present separated by ~4 m of sandstone (e.g., Fig. 5; Lucas et al., 1989). In many places, sandstones underlying the paleosol, over a stratigraphic distance of 20–30 m, are also massive and fine- to coarse-grained. These massive sedimentary rocks capped by a paleosol indicate a slowing of sedimentation rates at the end of Crevasse Canyon deposition followed by relative landscape stability. The paleosol is stratigraphically concordant and nowhere has it been observed to be completely scoured by overlying Cub Mountain streams, except perhaps in the Capitan-Ruidoso area. Its continuity west of Sierra Blanca indicates that fluvial action associated with overlying red beds did not produce widespread paleovalleys or deep scours.

Redefinition of the base of the Cub Mountain Formation

We argue that the top of this paleosol should be used to define the base of the Cub Mountain Formation (Figs. 5, 6). It marks a major unconformity that very likely corresponds to the regional unconformity between Cretaceous and Paleogene strata. Red to reddish-brown floodplain deposits that characterize the Cub Mountain Formation have not been found below the paleosol. Although gray mudstones, similar to those in the Crevasse Canyon Formation, are locally found a short distance above the paleosol (e.g., site 5, Table 2), such instances are uncommon. Where the paleosol may not be present, such as in the Capitan-Ruidoso area, we propose using the lowest occurrence of the red to reddish-brown floodplain deposits, or channel-fills that are clearly associated with the red floodplain deposits, to map the base of the Cub Mountain Formation (cf., Weber, 1964). This criteria was in fact used in the Capitan-Ruidoso area (Rawling, 2012a, 2012b) and also appears to have been used by Lucas et al. (1989) north of Cub Mountain (Fig. 5). They did not directly interpret a paleosol but did map the Cub Mountain contact similar to Koning et al. (2011).

STRATIGRAPHIC UNITS ABOVE AND BELOW PALEOSOL

Previous work on the Cub Mountain Formation focused on exposures only adjacent to Cub Mountain (Weber, 1964; Arkell, 1983, 1986; Lucas et al., 1989; Cather, 1991). We incorporate observations gathered across a much wider area to present detailed descriptions of strata and their associated paleocurrents (Fig. 1) The Capitan-Ruidoso area was excluded because the Cub Mountain and Sanders Canyon were lumped together there (Rawling, 2012a, 2012b). A schematic stratigraphic section for Cretaceous and Eocene strata is presented in Figure 6. Sandstone petrographic data for these units are presented in Cather (1991).

Crevasse Canyon Formation (Upper Cretaceous)

The Crevasse Canyon Formation consists of interbedded sandstone and mudstone deposited in a fluvial environment (Fig. 7). The sandstone is generally yellow and associated with channel-fills that may be amalgamated to form thick (1–10? m-thick) sandstone packages, especially in the upper part of the formation. Floodplain facies includes mudstone in addition to horizontal, thinly bedded to laminated, very fine- to fine-grained sandstone. The Crevasse Canyon Formation differs from the overlying Cub Mountain Formation by its yellowish green to gray floodplain deposits and its slightly finer (in a gross sense) sand sizes in channel-fills. The proportion of sandstone channel-fills to floodplain deposits increases up-section in the Crevasse Canyon Formation, so that in the upper half floodplain deposits are subequal or subordinate to the sandstone channel-fills (Fig. 6). This upper half approximately coincides with what Arkell (1983) called his basal Cub Mountain unit. Coal beds are found in lower Crevasse Canyon strata. The sandstone in the upper part of the Crevasse Canyon Formation ranges from fine- to medium-grained (locally coarse-grained). Pebble-conglomerate beds appear in the uppermost 30–60 m of the unit, which we assign to the Ash Canyon Member of the Crevasse Canyon Formation (per Bushnell, 1953, and Lozinsky, 1985, in the Truth or Consequences region). Ash Canyon Member gravel are

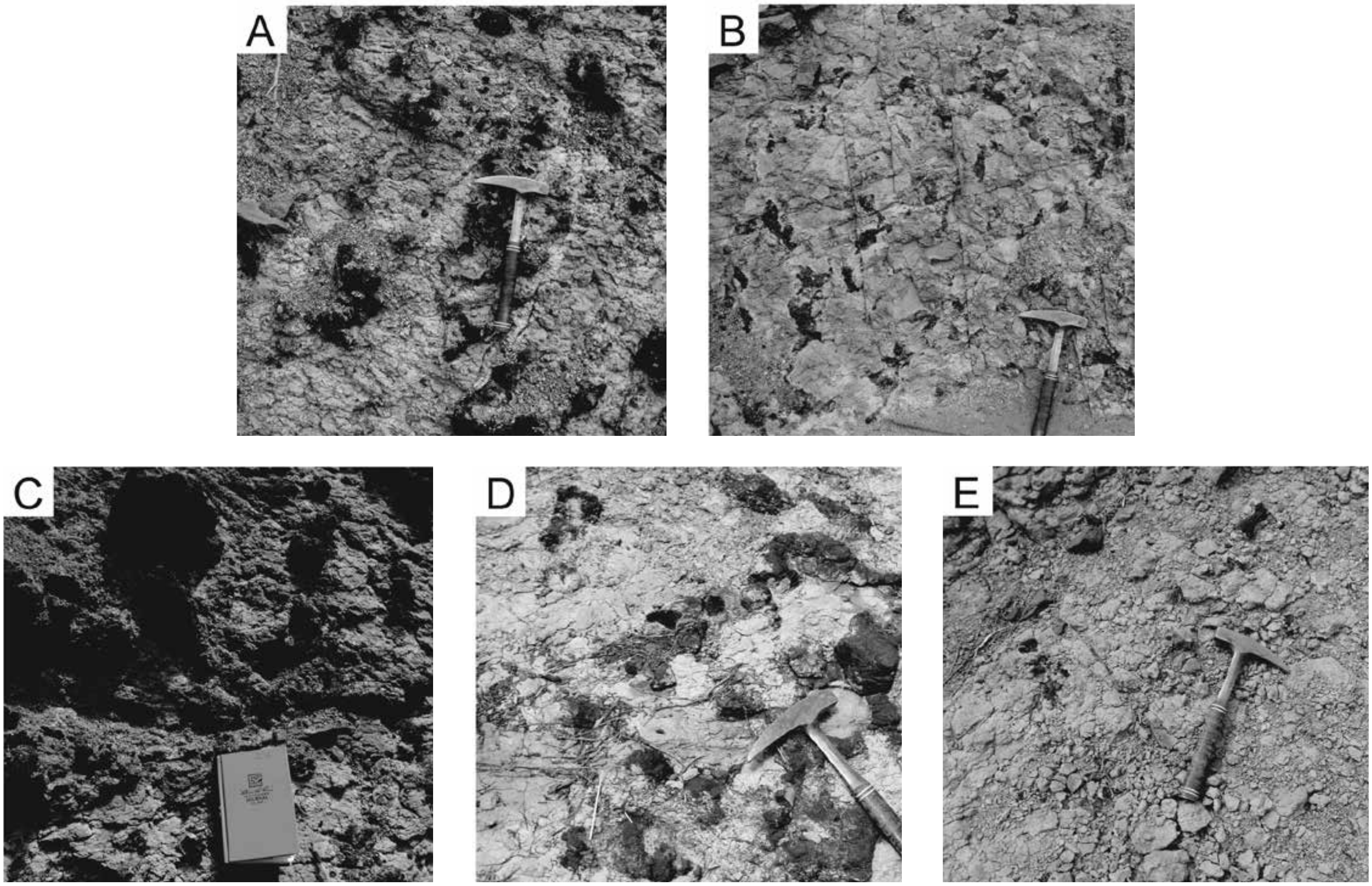

FIGURE 4. Photographs of the paleosol whose top we propose should define the base of the Cub Mountain Formation. These photographs were taken at three different sites. Photos A and B were taken northeast of Cub Mountain (UTM coordinates 419705 m E, 3712510 m N, NAD83, zone 13). Photos C and D are from exposures in the Cub Mountain type area (415863 m E, 3709150 m N; Fig. 2). Photo E was taken 8 km northeast of Three Rivers (404810 m E, 3693660 m N, NAD83, zone 13). These photographs are referenced in Table 2, which provides detailed descriptions of the respective sites.

TABLE 2. Descriptions of marker paleosol and adjoining strata

Study Site	Description
NE of Cub Mtn (*A, B)	Bioturbated to massive and mottled zone. Light purple to light grayish green and composed of siltstone and fine-grained sandstone. 10–15% irregular concretions inferred to be composed of Mn). Underlying sandstone is similar except not mottled, but it contains 0.5% coarse sand grains of chert. Overlying sandstone is grussy, fL-cU, subangular, moderately to poorly sorted, and arkosic; it contains 5–10% intraformational chips of green mudstone; horizontal planar-laminated; above the sandstone lies soft red mudstone (unclear if the mudstone is in place). No red beds seen below the soil. 6–10 m thick.
Cub Mtn type area (*C,D)	Light gray (N7/) fL-mL sandstone that is subangular to subrounded, well sorted, and composed of quartz, ~10%(?) feldspar, and 3–10% lithic grains. ~15% dark purple MnO(?) concretions that are ~3–20 cm long. Massive and probably bioturbated. No red beds seen below the soil. >6 m thick.
NE of Three Rivers (*E)	Yellow fU-cL sandstone that is internally massive and likely bioturbated. 10% purple FeO or MnO concretions. Strata below consists of mL-cL, light yellowish gray sandstone with siltstone rip-ups. Red beds are confined to above the soil. Thickness not measured.
N of Cub Mtn, Site 1	Purplish MnO(?) concretions are found at the top of a gray mudstone. 40 ft above lies a ledge-forming interval of orangish tan sandstone. The lower 6 m of this interval is a clast-supported conglomerate (medium to thick, tabular and lenticular beds). Gravel is well-rounded and comprised of medium and very coarse pebbles. Clast composition: chert, quartzite, and 5–10% metarhyolite or metagranite; trace deep red cherts. No consistent clast imbrication. Above the conglomerate is medium to coarse-grained sandstone that is extensively cross-laminated; yellow at base but redder near the top.
N of Cub Mtn, Site 2	Massive and well-cemented paleosol that forms a 2 m-thick bed, with 10–15% purplish black MnO(?) concretions that are cobble to boulder in size. Purplish and mottled sediment extends for 1.5 m above the concretion zone. Parent material was a clayey-silty, very fine- to fine-grained sand but the paleosol is now cemented and altered. At top of purplish-mottled, non-concretion-bearing sediment is 30–60 cm of an internally massive, medium-grained sandstone that appears to have paleoburrows. Total paleosol thickness: 4 m. The paleosol is overlain by 6 m or more of a slightly purplish, dark gray mudstone that is bioturbated.

* Letters correspond with photo labels in Figure 4.

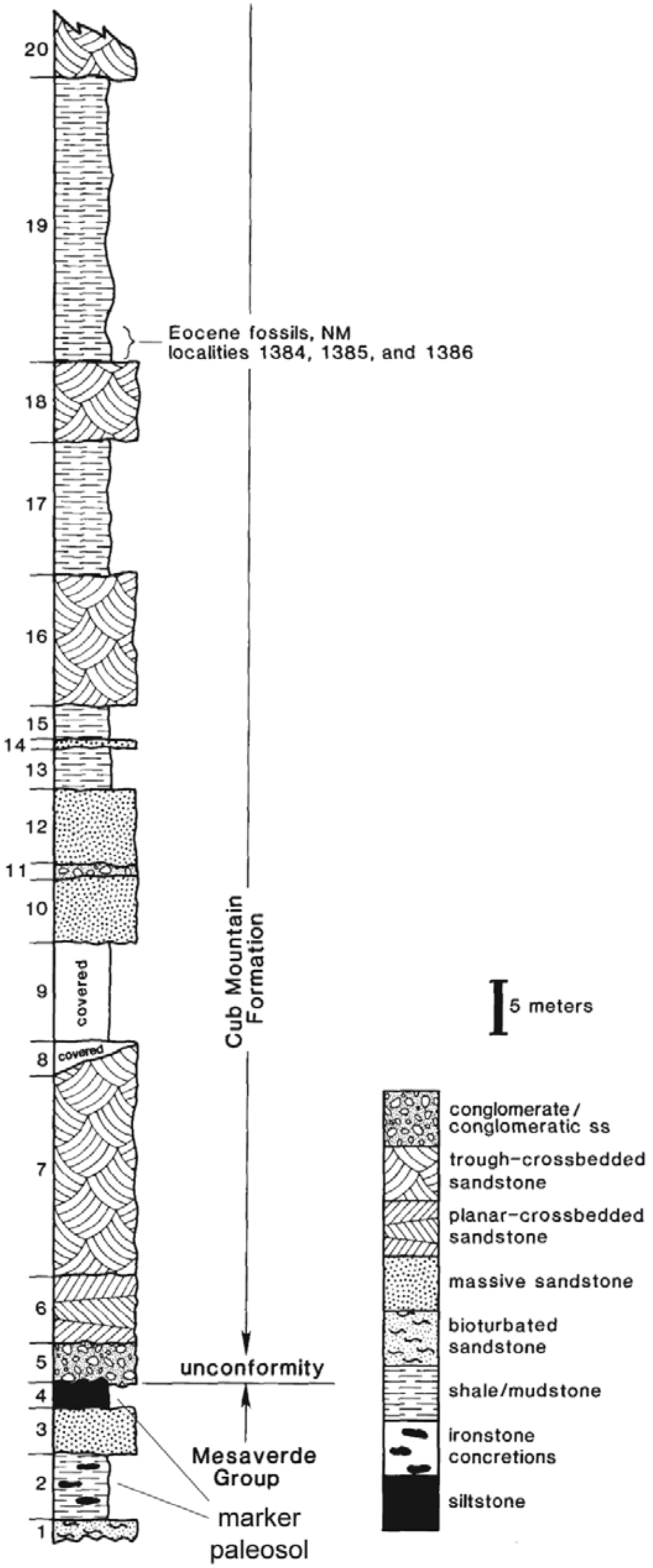

FIGURE 5. Stratigraphic section of the Cub Mountain Formation on the north side of Little Cub Mountain, slightly modified from Lucas et al. (1989). Legend is also from Lucas et al. (1989). See Figure 2 for location of the section. We annotate two paleosols at the top of the Crevasse Canyon Formation; the corresponding units were noted by Lucas et al. (1989) but they did not interpret them as paleosols.

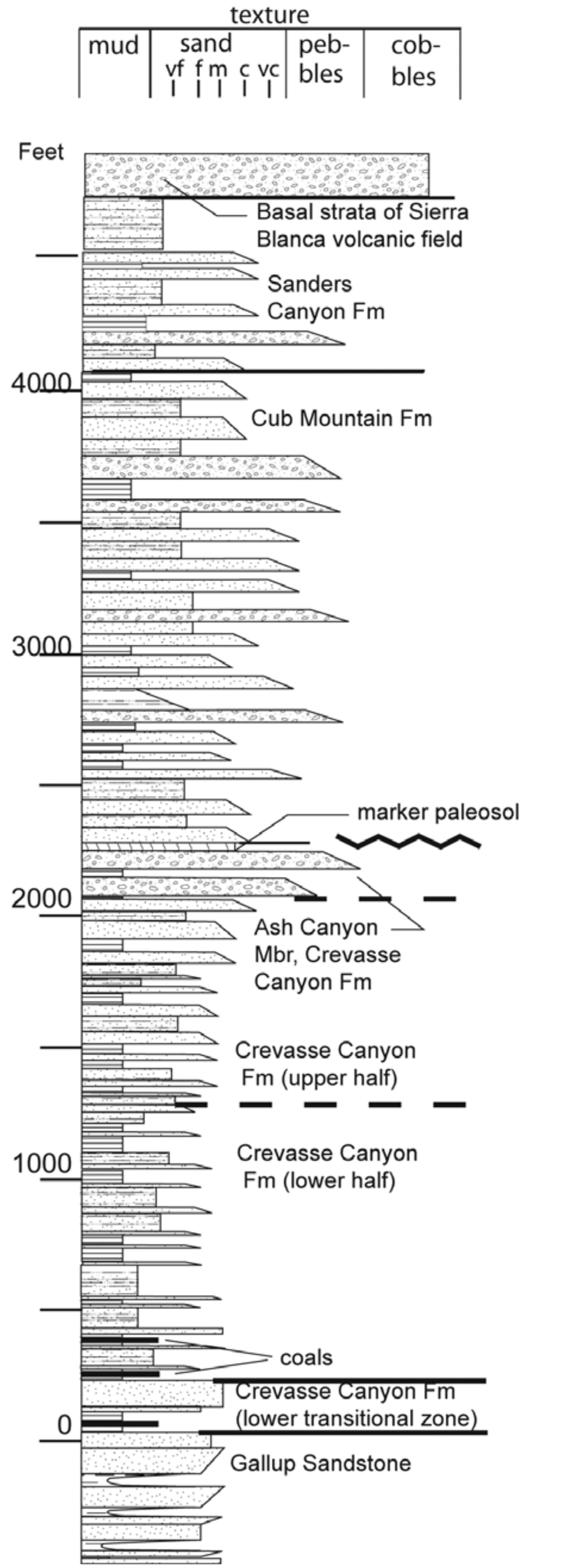

FIGURE 6. Schematic stratigraphic column for the Crevasse Canyon, Cub Mountain, and Sanders Canyon Formations in the Cub Mountain area. Thicknesses were obtained from map measurements from Koning et al. (2014).

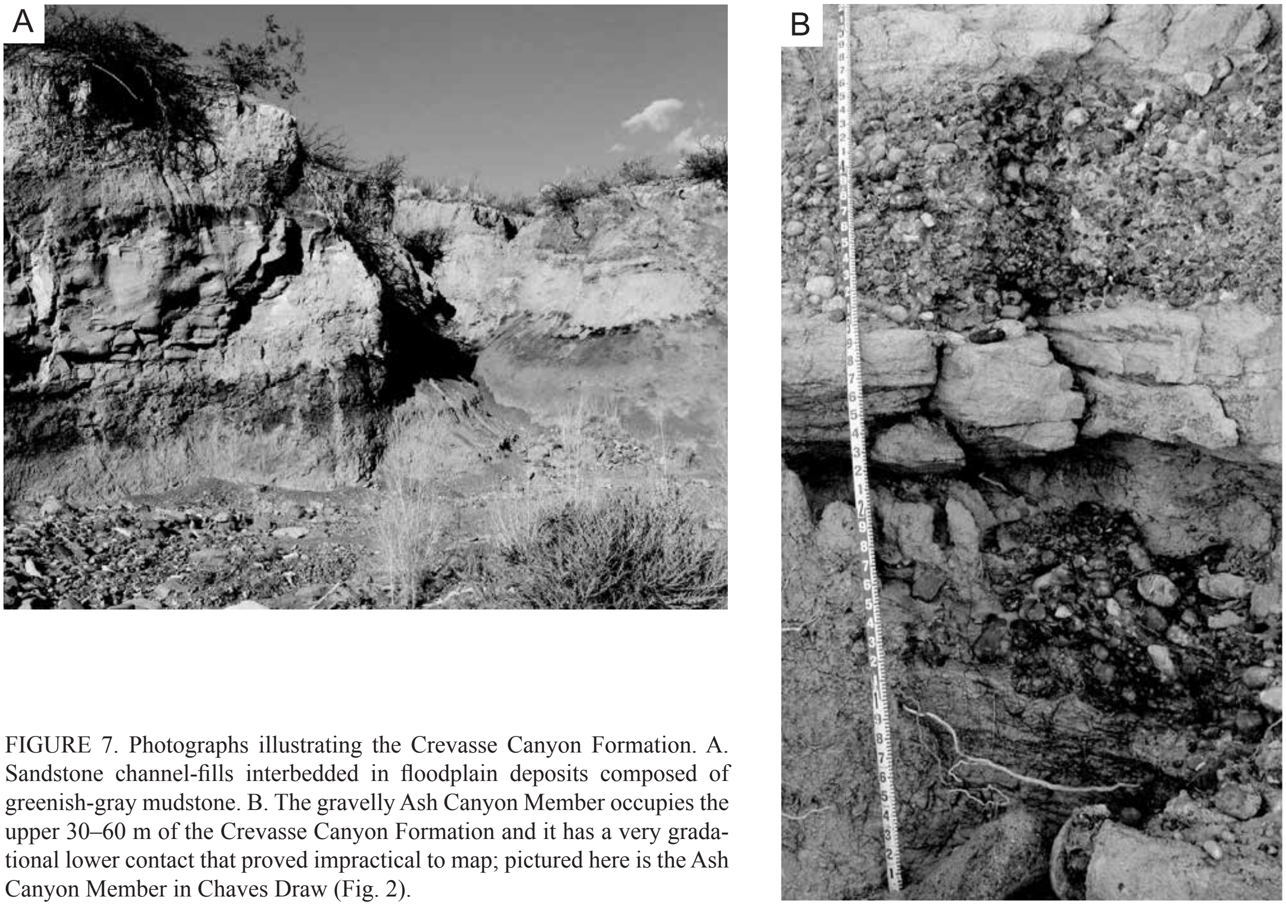

FIGURE 7. Photographs illustrating the Crevasse Canyon Formation. A. Sandstone channel-fills interbedded in floodplain deposits composed of greenish-gray mudstone. B. The gravelly Ash Canyon Member occupies the upper 30–60 m of the Crevasse Canyon Formation and it has a very gradational lower contact that proved impractical to map; pictured here is the Ash Canyon Member in Chaves Draw (Fig. 2).

composed of rhyolite, felsic intrusive clasts, quartzite, and chert. Imbrication-derived paleocurrents were measured in the uppermost 30–60 m of the Crevasse Canyon Formation in Chaves Draw and indicate northeast and southeast paleoflow directions (Fig. 2; Koning et al., 2011). The Crevasse Canyon Formation is weakly to well-cemented by calcium carbonate. Except for its transitional base, no fossils have been discovered in the Crevasse Canyon Formation in the Sierra Blanca Basin. The Ash Canyon Member unconformably underlies late Maastrichtian strata (i.e., the Tyrannosaurus rex-bearing McRae Formation) near Truth or Consequences and it is likely older than Maastrichtian in the Sierra Blanca Basin.

Cub Mountain Formation (lower to middle Eocene)

Description

Overlying the aforementioned paleosol, the Cub Mountain Formation is a fluvial deposit composed of interbedded sandstone-pebbly sandstone channel-fills and floodplain deposits (Fig. 8). It differs from the underlying Crevasse Canyon Formation by the reddish to reddish-brown color of its floodplain deposits, whereas those of the Crevasse Canyon Formation are gray to yellowish-green. No reddish to reddish-brown floodplain sediment was observed below the paleosol in the course of recent geologic mapping. Another distinctive feature of the Cub Mountain Formation is the abundance of medium-size sand grains in its channel-fills (overall, slightly coarser than most Crevasse Canyon channel-fills) and the tendency of cemented sandstone to exhibit a "pockety" outcrop appearance, as is shown for the lower conglomerate in the stratigraphic section of Lucas et al. (1989, Fig. 3B).

Sandstone channel-fills are arkosic and range in color from white to pale yellow to light reddish-gray; the reddish floodplain deposits are composed of mudstone and very fine- to fine-grained sandstone (Fig. 8). Locally, very coarse sand and pebbles (2–11 mm long) are present in the sandy channel-fills; these subrounded clasts are composed of quartz, quartzite, rhyolite or metarhyolite, and chert. Near Cub Mountain, limestone-bearing pebble conglomerate beds are increasingly observed to the north. Channel-fill sandstones are cross-stratified (foresets up to 50 cm-thick) or horizontal-planar-bedded. Locally, beds of light gray, fine- to medium-grained, sandstone are present in the upper half of the Cub Mountain Formation. These sandstone intervals contain ~20% lithic fragments and mafic grains (including abundant biotite). The Cub Mountain Formation differs from the overlying Sanders Canyon Formation by its general lack of light gray channel-fills and lesser amounts of volcanic detritus in its sand fraction (less than 20%). The thickness of the Cub Mountain Formation ranges from 470 m at its type area to possibly 640 m. Mammalian fossils in the Cub Mountain Formation indicate an Eocene age of ~53–45 Ma (Lucas et al., 1989; Paleobiology Database, 2013).

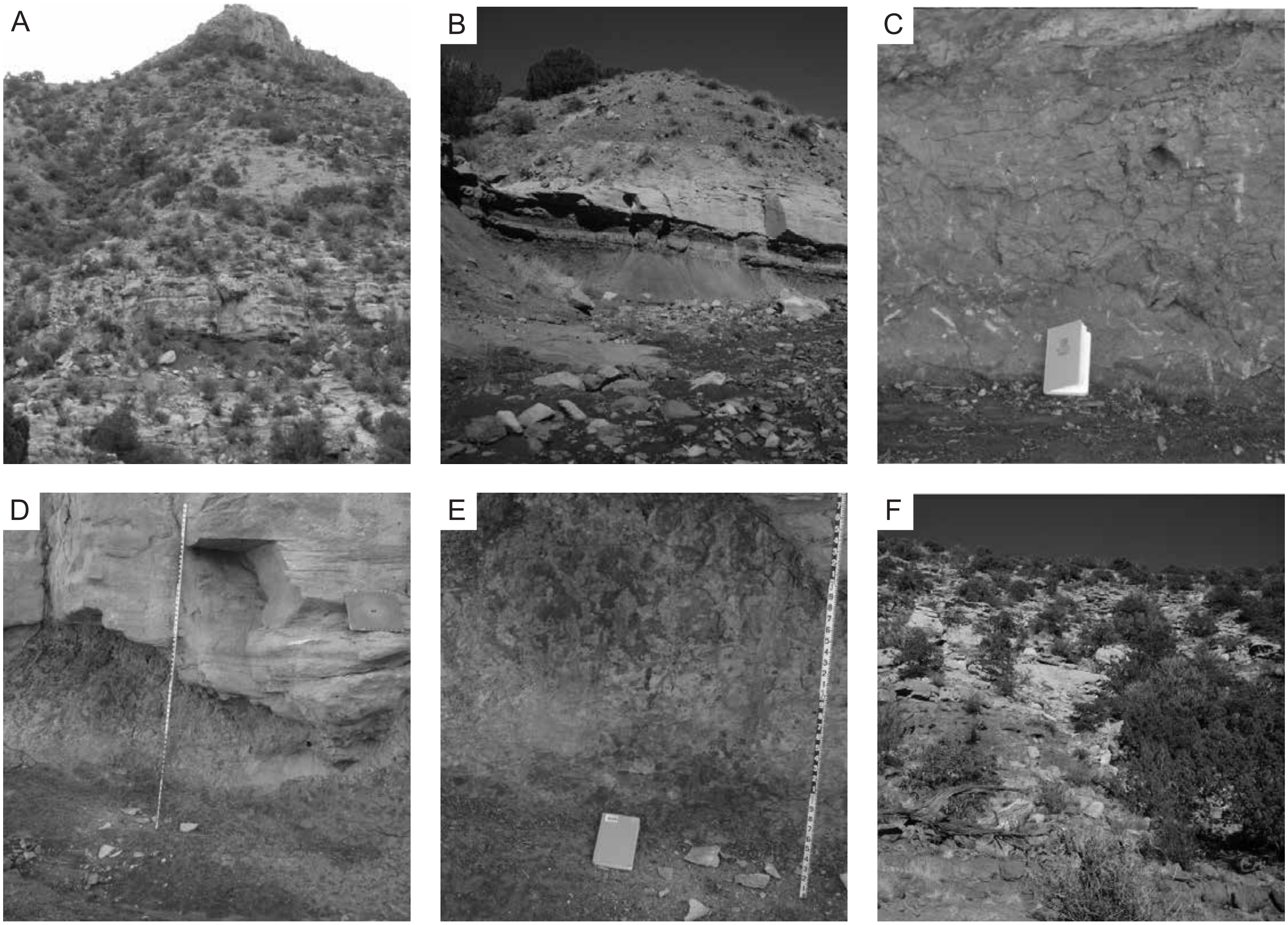

FIGURE 8. Photographs showing the Cub Mountain Formation. A. Cub Mountain exposure on the north side of Little Cub Mountain, looking southwest. Fossils collected from here indicated an age of ~53–45 Ma for the Cub Mountain (Lucas et al., 1989). Photos B through E are from Chaves Canyon south of Cub Mountain. B. Sandstone channel-fill overlying reddish floodplain deposits. C. Burrows in fine sandstone floodplain deposits. D. About 1 m of scour relief at the base of another sandstone channel-fill sequence. Measuring tape is 2 m tall. E. Mottling and bioturbation in very fine- to fine-grained sandstone beneath the channel-fill seen in photo D. F. Outcrops of Cub Mountain Formation on the western slopes of Cub Mountain.

Paleoflow

It is likely that that much of the data supporting previous interpretations of a northeastward paleoflow direction (Lucas et al., 1989; Cather, 1991) came from the Ash Canyon Member of the Crevasse Canyon Formation. To test this hypothesis, we collected more paleoflow data above the paleosol whose top we define as the base of the Cub Mountain Formation (Figs 2 and 3; Appendices 1 and 2). Measurements generally consist of clast imbrications. Because of the dearth of gravel above the paleosol in Chaves Draw, paleoflow measurements there are generally from channel trends or trough cross-stratification. The resulting data indicate an overall southwest paleoflow direction (Figs. 2, 3).

Paleocurrents in two outcrops of Cub Mountain Formation were measured in the Capitan-Ruidoso areas. The northern outcrop, which we call the South Capitan site, is a road-cut exposure in the lower Cub Mountain Formation. Here, the best mono-directional paleocurrent data come from imbricated intraformational shale rip-ups, which gave a general westward paleoflow (Appendix 1; Fig. 3). The southern outcrop, the South Alto site, exhibits upward fining sequences of fluvial deposits. Imbrications were measured from three conglomerate bed locations at this site. Clast imbrications at both the North and South Alto sites indicate a southwest to southeast paleoflow direction.

Sanders Canyon Formation

Description

The Sanders Canyon Formation is a fluvial deposit similar to the underlying Cub Mountain Formation, but it contains a higher proportion of volcanic detritus in its sand and gravel fraction. This unit is composed of interbedded, reddish gray to reddish brown floodplain deposits and light gray, sandy channel-fills (Fig. 9). The average sandstone to mudstone ratio of this fluvial unit is about 30:70 and decreases up-section (Cather, 1991). The unit appears to be finer-grained west of Cub Mountain than to the southeast. Because of weak cementation, this unit typically forms poor outcrops or is a slope-former. Its thickness is highly variable and ranges from 90–300 m.

Channel-fills are commonly <35 cm-thick and contain horizontal-planar (locally slightly wavy), laminated to very thin beds. Locally, planar- to tangential cross-lamination is present (foresets up to 25 cm-thick). Sandstone locally contains mudstone rip-up clasts (Fig. 9A) and is mostly fine- to medium-grained. There are 1% very fine to very coarse pebbles and lesser cobbles-boulders (maximum boulder size of 32 x 15 cm); the clasts are mainly composed of plagioclase-phyric andesite. Floodplain deposits consist of reddish to maroon mudstone, siltstone, and very fine- to fine-grained sandstone.

The Sanders Canyon Formation lies conformably above the Cub Mountain Formation. Its upper contact appears to be conformable within 15 km of the type area (Fig. 9B), as demonstrated by interfingering relations with overlying volcanclastic rocks of the Sierra Blanca field (S.A. Kelley, personal commun. 2014) and observations by Cather (1991). Near the Barber Ridge region, this contact exhibits signs of large-scale soft-sediment deformation, such as clastic dikes. These features are probably due to rapid loading by the overlying Sierra Blanca volcanic flows and volcaniclastic sediment. Although no fossils or other age control has been found in this unit, the ages of the sub and superjacent units indicate an approximate age of 45–38 Ma (Cather, 1991).

Paleoflow

Cather (1991) used imbricated clasts at two sites to infer a northeast paleocurrent direction for the Sanders Canyon Formation in its type area. So far, we have measured only one outcrop of Sanders Canyon Formation, corresponding to the North Alto site (Fig. 3, Appendix 1). This outcrop consists of a road cut exhibiting gray, volcanic-bearing sandstone and pebbly sandstone. Paleocurrent measurements from clast imbrications gave a south- to southeast-trending paleo-flow direction.

CENOZOIC STRATIGRAPHY AT THE LEWELLING NO. 2 WELL

The subsurface stratigraphy at the Lewelling No. 2 well has noteworthy implications for the structure of the Laramide basin in which the Cub Mountain Formation was deposited. Located 3 km south of Three Rivers (Fig. 1), the Lewelling No. 2 well was spudded in Quaternary basin fill. The cuttings and geophysical logs associated with this well (for strata below the surface casing depth of 335 ft) were inspected in order to make an east-west cross-section at that latitude (Koning, 2009; Koning et al., 2014). The resulting formation picks are shown in Figure 10. Cuttings descriptions of select samples are presented in Appendix 3 and the resistivity, conductivity, and gamma curves depicted in Figure 11. We interpret that sedimentary strata between 4150 ft and 5130 ft belong to the Crevasse Canyon Formation because this interval contains light gray to gray mudstone and quartz-rich sandstone, local coal, and no evidence for red beds. Consistent with the regional stratigraphy, below the Crevasse Canyon Formation are 290 ft (88 m) of interbedded sandstone and shale of the Gallup Sandstone underlain by 735 ft (224 m) of low-resistivity Mancos Shale with a 73 ft- (22 m-) thick sandstone tongue in its middle (the Tres Hermanos Formation).

We define the informal Lewelling unit as the strata in the well above the Crevasse Canyon Formation and below the bottom of

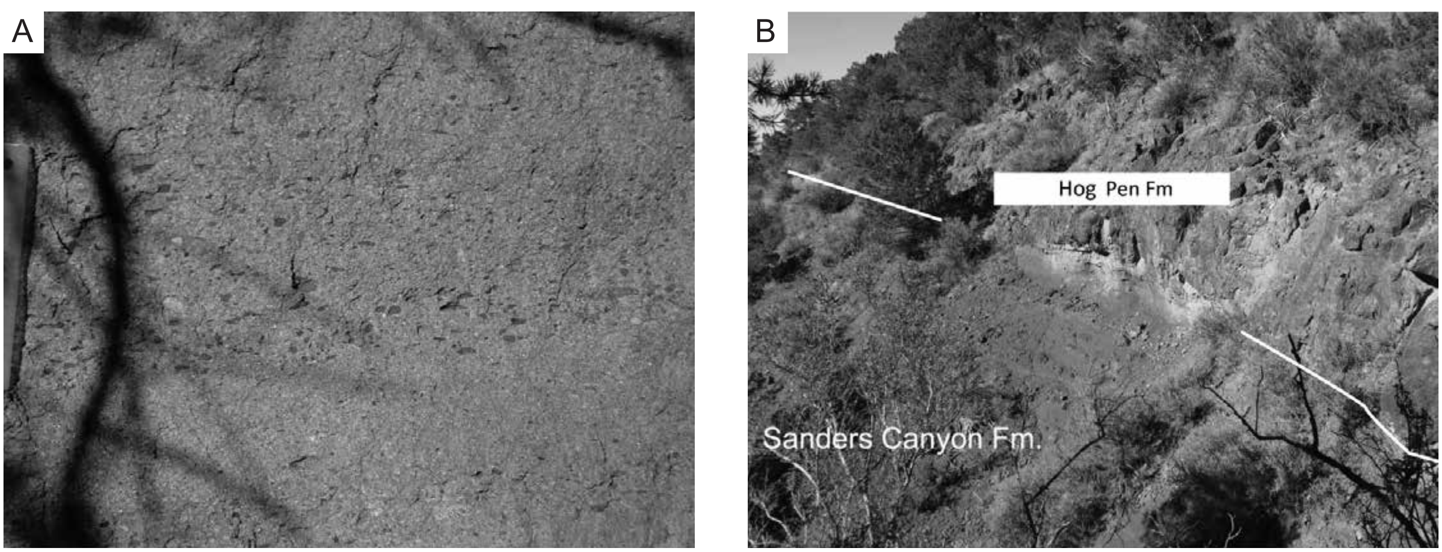

FIGURE 9. Photographs of the Sanders Canyon Formation. A. Clay rip-ups in medium- to very coarse-grained sandstone of a channel-fill. Sanders Canyon Formation sandstone exhibits a light gray color and generally has 15–30% volcanic lithic grains. B.Photograph illustrating the contact between the Hog Pen Formation (lower formation of the Sierra Blanca volcanic package, per Kelley et al., this volume) and the underlying Sanders Canyon Formation. Photo taken in upper Chaves Canyon and the contact is shown by the white line. To the south, field observations noted local interfingering relations of this contact (Shari Kelley, personal commun., 2014). Note the cobbles and pebbles interbedded in the uppermost Sanders Canyon Formation. In this area, Cather (1991) observed outsized, pyroxene-bearing volcanic pebbles and cobbles in the dominantly fine-grained, uppermost Sanders Canyon Formation.

the surface casing (between 335 and 4150 ft depth). Five subunits are differentiated within the Lewelling unit (Figs. 10–12). In Subunits 2 through 5, the gamma ray curve mimics the resistivity whereas both mirroring and parallel tracking occur in Subunit 1. Below, we describe these units.

Description

Subunit 5 (335–460 ft)

Light gray, cemented, fissile siltstone and very fine-grained sandstone dominate the cuttings above 460 ft. The light gray siltstone-very fine sandstone contains ~15% very fine mafic minerals. ~5% of the cuttings fragments contain outsized pyroxene or amphibole grains (up to 2 mm long), some of which are clearly embedded in the light gray siltstone-very fine-grained sandstone. The light gray siltstone-very fine sandstone is homogenous between 330 and 460 ft, but locally in this interval there are minor amounts of arkosic sand. This arkosic sand is creamy-orange colored, subangular to subrounded, semi-equant, and composed largely of quartz and feldspar. The geophysical signature of Subunit 5 is similar to that of Subunit 4 (see below).

Subunit 4 (460–620 ft)

Subunit 4 is characterized by relatively broad lows and peaks in the resistivity and gamma ray curves, interpreted as alternating fine-grained and coarse-grained intervals. The cuttings show a mix of arkosic and volcaniclastic sand along with minor light gray, cemented, fissile siltstone-very fine-grained sandstone (Fig. 11). The latter is less abundant than in Subunit 5 and possibly could be slough from higher in the borehole. Large pyroxene grains are less abundant than above.

Subunit 3 (620–1185 ft)

This unit is transitional between Subunit 4 above and Subunit 2 below. It is composed mainly of sand with lesser mudstone-siltstone (the troughs of the resistivity curves). In the cuttings, the cemented, light gray, fissile siltstone-very fine-grained sandstone chips seen in Subunit 4 are lacking. Like Subunit 4, both the gamma ray and resistivity curves display high amplitudes, but the thicknesses of the peaks and troughs (i.e., thicknesses of amalgamated channel-fills and fine-grained intervals) are less than in Subunit 4. Gamma ray intensity progressively decreases with depth. The sand is more angular than in Subunit 4 (being mostly subangular) and consists of gray-brown, arkosic lithic fragments mixed with porphyritic volcanic grains similar to the volcanic grains in Subunit 4. The arkosic grains may be related to nearby Eocene-Oligocene intrusions or a Proterozoic basement source.

Subunit 2 (1185–3650 ft)

The gamma ray and resistivity curves of this thick unit are characterized by low amplitudes and relatively narrow troughs and peaks. It is composed mainly of angular-subangular, moderately sorted sand and pebbly sand that is a mix between the aforementioned arkosic grains and feldspar-phyric volcanic grains (similar to that described higher in the well). Except at its base, there is less than 10% quartz in the sand fraction and the quartz is angular. There is minor fine-grained, gray to brown, non-porphyritic lithic grains. Some of these grains might have garnet and sillimanite or kyanite, which would suggest metamorphism and a Proterozoic age. Some intervals are marked by a decrease in drilling rate and notations of "granite" in the mud log. These are probably granitic conglomerate layers rather than granite sills because they do not correspond with spikes in resistivity. Between 3180 and 3650 ft, drilling rate slowed down and notes of "granite" are frequent in the mud log. We interpret that the strata in Subunit 2 generally consist of amalgamated channel-fill sandstones and lesser conglomerates. Mudstone are sparse and thin. An overall decrease in resistivity with depth is attributed to more saline water below 2300 ft. A 30 ft-thick interval at the base of Subunit 2 contains 25–30% quartz grains, reflecting a transition into the underlying Subunit 1.

Subunit 1 (3650–4150 ft)

On the down-hole geophysical logs, features that distinguish this unit include an overall lower gamma ray signal but higher amplitudes of gamma ray, resistivity, and conductivity curves whose peaks are relatively broad. In the cuttings, this interval is distinguished by the presence of relatively abundant quartz grains (20–60% of sand) that tend to be subrounded-rounded, fragments of quartz-rich and cemented sandstone, persistence of feldspar-phyric volcanic sand, and gray to red mudstone in the cuttings. Overall, there is less angular arkosic detritus in this interval.

Lithofacies interpretations

We interpret that: (1) Subunits 1, 4, and 5 represent a relatively large fluvial system, perhaps on a basin floor (particularly for Subunits 4 and 5); (2) Subunit 2 represents smaller, steeper streams on a piedmont slope or alluvial fan; and (3) Subunit 3 represents a transitional zone extending across the toe of a piedmont onto the outer flanks of a fluvial basin-floor environment. Features supporting a piedmont or alluvial fan interpretation for Subunit 2 include: (a) consistently coarse texture, (b) relatively thin channel-fill complexes (i.e., thin peaks in gamma and resistivity curve), (c) sparse, thin mudstone beds, and (d) relatively angular, quartz-poor sand.

We interpret that Subunits 1, 4, and 5 were deposited by a larger fluvial system, with a floodplain, on a basin floor or in a valley. A floodplain is indicated by mudstone, siltstone, and very fine-grained sandstone in the cuttings. The broad peaks and troughs on the resistivity-gamma curves indicate relatively thick channel-fill and floodplain intervals, respectively. Subrounded-rounded quartz sand grains are more common in Subunits 1, 4, and 5, compared to Subunits 2 and 3, and possibly were derived from erosion of Mesozoic strata.

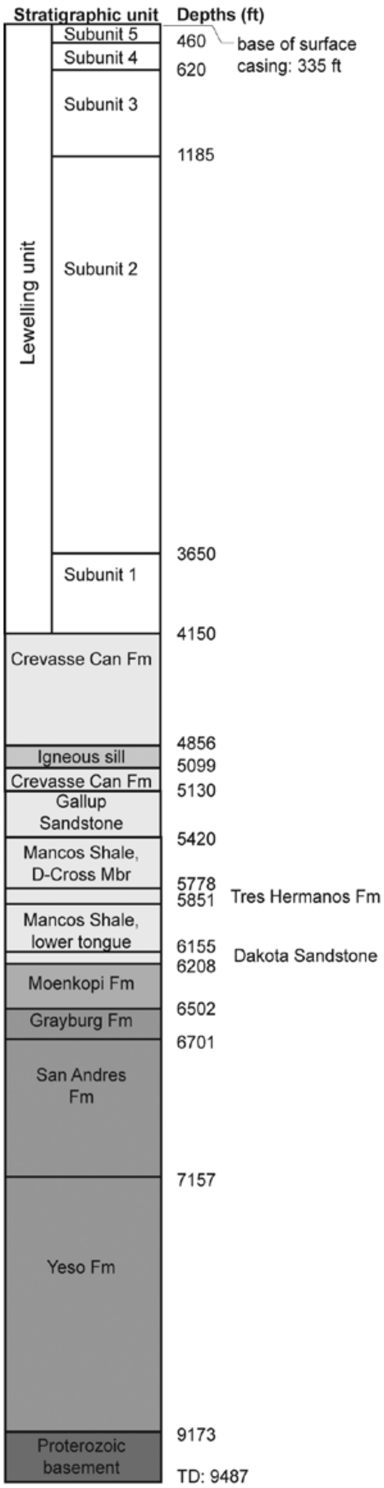

FIGURE 10. Stratigraphic picks of the Lewelling No. 2 well.

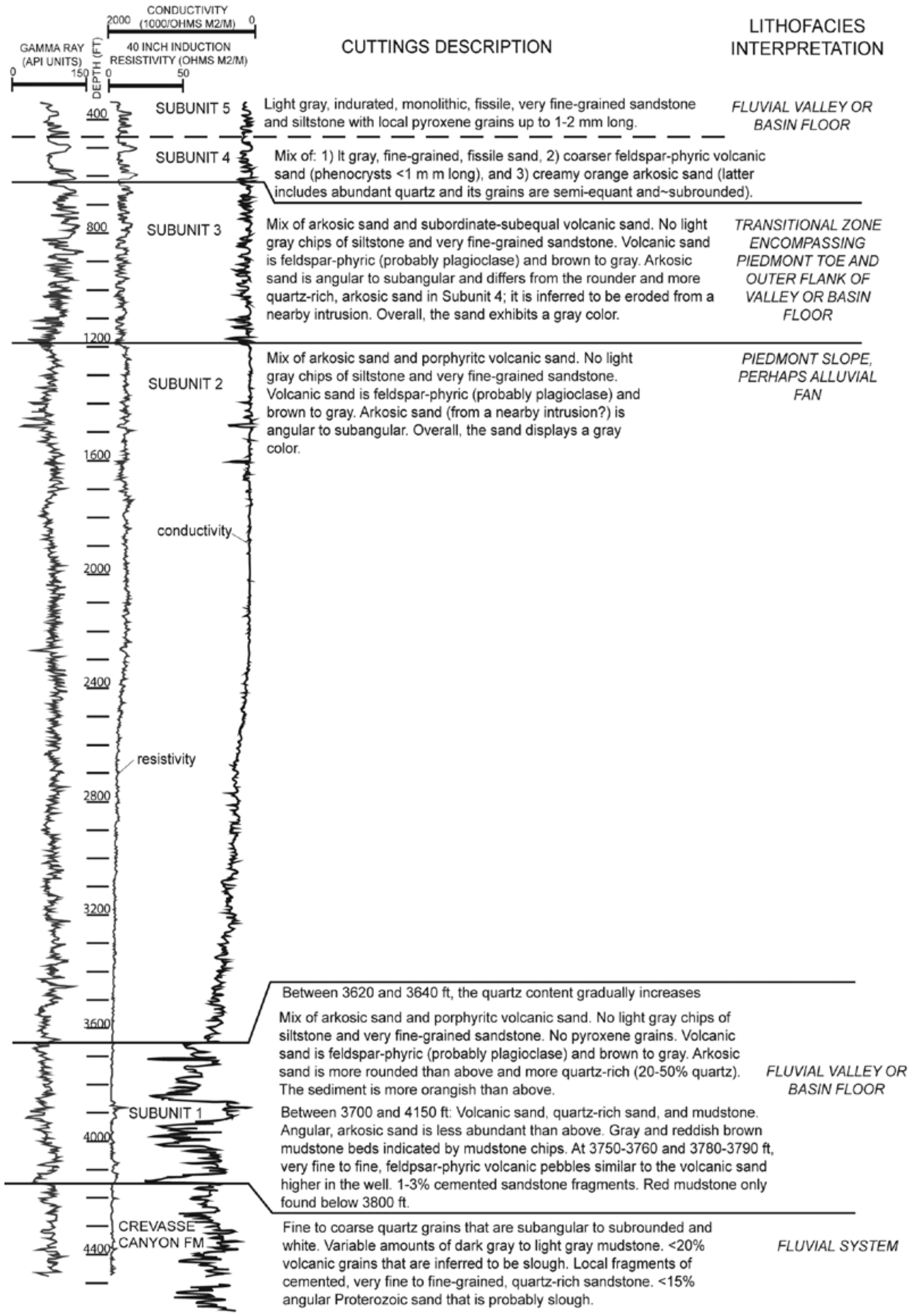

FIGURE 11. Gamma ray, resistivity, and conductivity curves for the upper 4500 ft of the Lewelling No. well. Our five subdivisions of the Lewelling unit are shown, along with descriptive notes and lithofacies interpretations.

DISCUSSION

Provenenance and stratigraphic correlations of Lewelling unit

No direct age control is available for the Lewelling unit, but we know it postdates the underlying Upper Cretaceous Crevasse Canyon Formation. Four possible stratigraphic and provenenace correlations are: (1) Neogene sediment shed from an eroding Sierra Blanca volcanic highland to the east; (2) Neogene sediment shed from highlands to the west; (3) Eocene sediment shed from highlands to the west; or (4) Subunit 1 is correlative to the Cub Mountain-Sanders Canyon Formation and higher units are Neogene. A high diversity of volcanic rock types and minimal Proterozoic detritus would be consistent with the first and second options.

The potential presence of Proterozoic detritus is important because it would support the existence of a Laramide uplift to the west of the well, as was previously suggested by Herrick (1904), Kottlowski et al. (1956), Lucas et al. (1989), and Cather (2002, 2004). Such an uplift is consistent with east-vergent thrust faults and associated folds locally found at the base of the Sacramento Mountains (Pray, 1961; Cather, 2004). There may be some crystalline basement (Proterozoic) detritus in Subunit 2, as indicated by grains with interpreted sillimanite and garnet. But the exact amount of Proterozoic detritus and the variety of volcanic grains is difficult to discern with a binocular microscope, especially given the abundance of intrusions in the Sierra Blanca massif whose detritus might be mistaken as Proterozoic. Future thin section inspection and quantitative geochemical analyses will allow better quantification of the abundance of Proterozoic grains versus volcanic and Oligocene-Eocene intrusive grains.

Laramide structures and basin configuration

Any of the four stratigraphic and age correlations of the Lewelling unit are consistent with an interpretation that Laramide structures bounded the southwest side of the basin in which the Cub Mountain was deposited. Correlation of the entire Lewelling unit to Neogene strata implies that the Cub Mountain-Sanders Canyon Formations were eroded from what is now the western side of the Alamogordo fault prior to Neogene sedimentation, or were never deposited there. If the Cub Mountain-Sanders Canyon Formations only correlates to Subunit 1, then lower-middle Eocene strata would be anomalously thin here compared to the Cub Mountain type area (150 m, located 600–800 m to the east). Unless Subunit 1 has been significantly offset by a normal fault, this thickness contrast is best explained by a west-side-up Laramide structure between the Lewelling No. 2 well and Cub Mountain Formation outcrops to the east. The Alamogordo fault may be such a structure.

The Crevasse Canyon Formation is thinner at the Lewelling No. 2 well than to the east. It is at most 460 m thick in the Lewelling No. 2 well (if we include Unit 1 with the Crevasse Canyon Formation) but more likely 300 m thick (excluding Unit 1 from the Crevasse Canyon Formation). In the Cub Mountain area, the Crevasse Canyon is 550 m (1800 ft) thick and in the Capitan area it is 240–280 m (800–900 ft) thick (Koning et al., 2011; Rawling, 2012a; Koning et al., this volume). So the Crevasse Canyon Formation is thinnest on the east, thickens to the center of the Sierra Blanca Basin, and appears to be thin again at the Lewelling No. 2 well. The thin Crevasse Canyon Formation at the Lewelling No. 2 well could be due to normal faulting cutting out section. Another alternative is Laramide activity along the Alamogordo fault, in which the west side moved up and erosion thinned the Crevasse Canyon Formation west of the fault.

Assigning Subunits 1–4 to the lower(?) and middle Eocene (i.e., pre-Sierra Blanca volcanic field), results in the Eocene section being slightly thicker than Cub Mountain-Sanders Canyon strata in the type area (1160 m at the well vs. 600–800 m to the east). This is consistent with a Laramide basin tilting westward towards a reverse fault bounding an uplift to the west of the well (Fig. 12), similar to reverse fault-bounded uplifts in the Las Cruces area (Seager, 2004).

To test the hypothesis that Laramide structures bounded the southwest side of the basin and that the basin was tilted to the southwest (Fig 12; cf., Chapin and Cather, 1981), we propose: (1) assessing the amount of Proterozoic detritus in the Lewelling No. 2 unit using the electron microprobe at New Mexico Tech for quantitative geochemical analyses; (2) collecting more paleocurrent data; (3) assessing thickness trends of the Cub Mountain and Sanders Canyon Formation; (4) conducting outcrop descriptions that include facies classification and measurement of clast sizes; and (5) doing petrographic comparisons of sediment between the Lewelling No. 2 well and outcrops of Cub Mountain Formation. The hypothesis predicts that a preferred southwest-south paleoflow orientation in the central and eastern part of the basin is consistent with high tectonic subsidence rates near the western margin of the basin (Fig. 12), whereas a preferred southeast orientation, such as that seen in our North and South Alto sites, would suggest that structures in the Capitan-Ruidoso area were inducing Laramide subsidence on the east side of the basin.

CONCLUSIONS

We propose a redefinition for the base of the Cub Mountain Formation, present new paleocurrent data suggesting west- to southeast-flowing (but generally southerly) paleodrainages, and present evidence for Laramide structures along the southwestern margin of the Laramide-age Sierra Blanca Basin. A laterally extensive paleosol is observed beneath Cub Mountain red beds and very likely represents the Cenozoic-Cretaceous unconformity. We propose that the top of this paleosol should coincide with the Cub Mountain basal contact. Where the paleosol is not present, the lowest occurrence of reddish floodplain deposits, or channel-fills that are clearly associated with the red floodplain deposits, should be used to map the lower Cub Mountain contact .

Previous workers have interpreted northeast paleoflow directions for the Cub Mountain Formation, based largely on clast imbrication measurements that likely came from gravelly channel-fills below the paleosol demarcating the base of our redefined

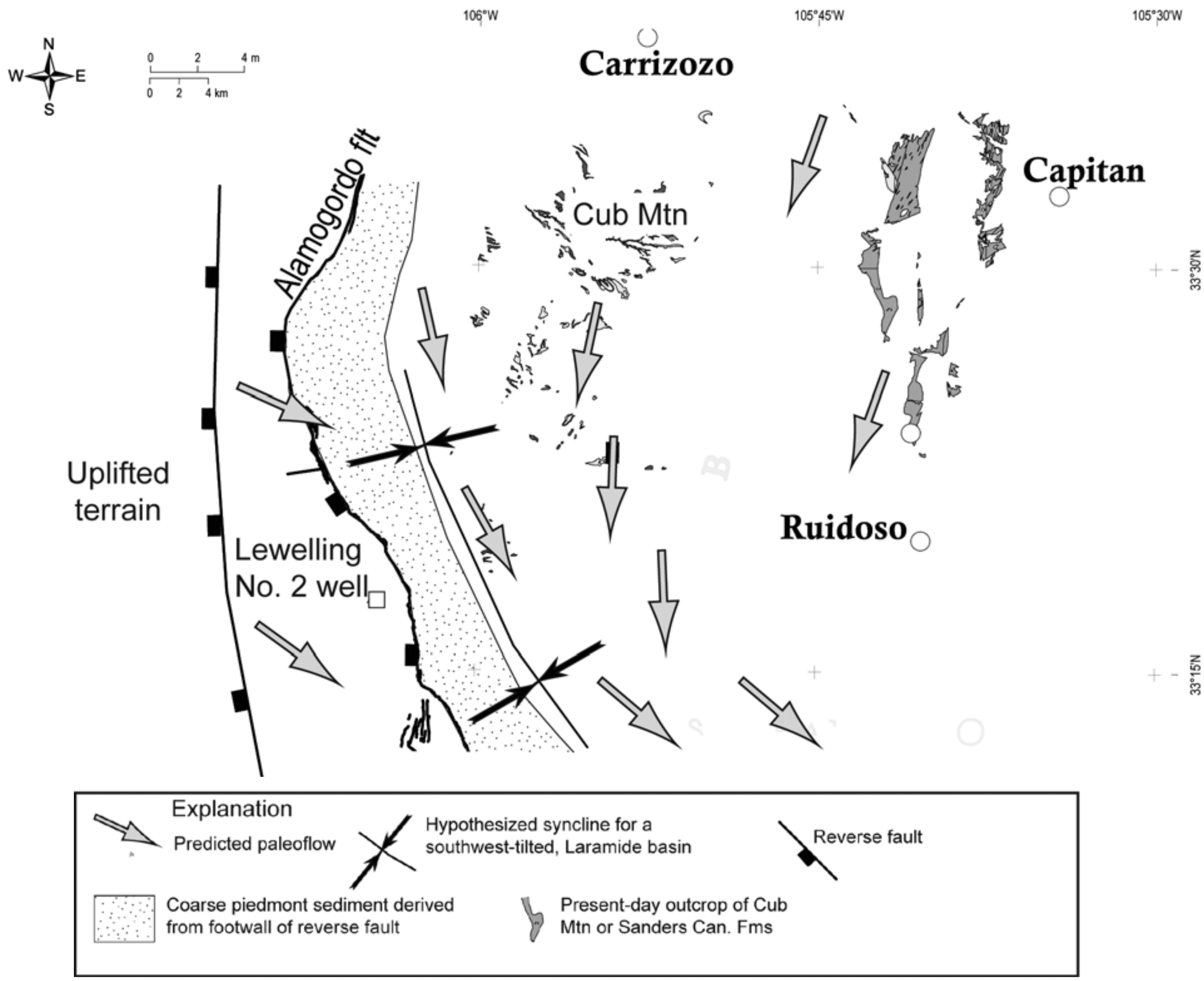

FIGURE 12. Paleogeographic map illustrating our hypothesis regarding the structural and depositional setting of the Cub Mountain Formation. In this scenario, a Laramide uplift exists a close distance west of the Lewelling No. 2 well, bounded by reverse faults. The fault shown bounding the east side of the uplift could possibly correlate with the Jarilla fault of Cather and Harrison (2002), or it could correspond with the Alamogordo fault. For reference, the modern cities of Carrizozo, Capitan, and Ruidoso are shown.

Cub Mountain Formation. Consequently, most of these measurements reflect paleoflow of the Ash Canyon Member of the Crevasse Canyon Formation. New paleocurrent measurements from above the paleosol show southerly paleoflow directions ranging from west to southeast for the Cub Mountain Formation.

Although there is uncertainty on the age and stratigraphic correlations of the 330–4150 ft depth interval of the Lewelling No. 2 well, reasonable tectonic scenarios resulting from these correlations imply that a reverse fault bounded the southwestern side of the Laramide-age Sierra Blanca Basin. Ongoing work will test this hypothesis.

ACKNOWLEDGMENTS

We wish to thank our reviewers, John Hawley and Steve Cather. We also appreciate Shari Kelley's inspection and comments on the Lewelling No. 2 well cuttings. This work was largely supported by the STATEMAP component of the National Cooperative Geologic Mapping Program.

REFERENCES

Arkell, B.W., 1983, Geology and coal resources of the Cub Mountain area, Sierra Blanca coal field, New Mexico [Masters Thesis]: Socorro, NM, New Mexico Institute of Mining and Technology, 104 p.

Arkell, B.W., 1986, Stratigraphy of western part of Sierra Blanca Basin, *in* Ahlen, J.L., and Hanson, M.E., eds., Southwest Section of AAPG, Transactions and Guidebook of 1986 Convention, Ruidoso, New Mexico: New Mexico Bureau of Mines and Mineral Resources, p. 73–76.

Bodine, M.W., Jr., 1956, Geology of Capitan coal field, Lincoln County, New Mexico: New Mexico Bureau of Mines and Mineral Resources, Circular 35, 27 p.

Bushnell, H.P., 1953, Geology of the McRae Canyon area, Sierra County, New Mexico [M.S. thesis]: Albuquerque, University of New Mexico, 106 p.

Cather, S.M., 1991, Stratigraphy and provenance of Upper Cretaceous and Paleogene strata of the western Sierra Blanca Basin, New Mexico: New Mexico Geological Society, Guidebook 42, p. 265–275.

Cather, S.M., 2002, The Sierra Blanca Basin: New Mexico Geological Society, Guidebook 53, p. 21.

Cather, S.M., 2004, Laramide orogeny in central and northern New Mexico and southern Colorado, *in* Mack, G.H., and Giles, K.J., eds., The Geology of New Mexico: A Geologic History: New Mexico Geological Society, Special Publication 11, p. 203–248.

Cather, S.M. and Harrison, R.W., 2002, Lower Paleozoic isopach maps of southern New Mexico and their implications for Laramide and Ancestral Rocky Mountain tectonism: New Mexico Geological Society, Guidebook 53, p. 85–101.

Cather, S.M., 1990, Stress and volcanism in the northern Mogollon-Datil volcanic field, New Mexico: Effects of the post-Laramide tectonic transition: Geological Society of America Bulletin, v. 102, p. 1447–1458.

Chamberlin, R.M, 1989, Criteria for the recognition of a pre-Eocene lateritic weathering profile, west-central New Mexico: New Mexico Geological Society, Guidebook 40, p. 34–35.

Chapin, C.E., and Cather, S.M., 1981, Eocene tectonics and sedimentation in the Colorado Plateau-Rocky Mountain area: Arizona Geological Society, Digest, v. 14, p. 173–198.

Herrick, C.L., 1904, Lake Otero, an ancient salt lake basin in southeastern New Mexico: American Geologist, v. 34, p. 174–189.

Kelley, S.A., Koning, D.J., and Allen, B., 2014, Preliminary Geologic Map of the Tularosa and Bent Region, northeastern Tularosa Basin, Otero County, New Mexico: New Mexico Bureau of Geology and Mineral Resources, Open-file Report 563.

Koning, D.J., 2009, Preliminary geologic map of the Three Rivers 7.5-minute quadrangle, Otero County, New Mexico: New Mexico Bureau of Geology and Mineral Resources, Open-file Geologic Map OF-GM-187, scale 1:24,000.

Koning, D.J., Kempter, K.A., Zeigler, K.E., and Cikoski, C.T., 2011, Preliminary geologic map of the Cub Mountain 7.5-minute quadrangle, Lincoln County, New Mexico: New Mexico Bureau of Geology and Mineral Resources, Open-file Geologic Map OF-GM-138, scale 1:24,000.

Koning, D.J., Kelley, S.A., and Goff, F., 2014, Preliminary Geologic Map of the Northeastern Tularosa Basin and Western Sierra Blanca Basin, Lincoln and Otero Counties, New Mexico: New Mexico Bureau of Geology and Mineral Resources, Open-file Report 564.

Kottlowski, F.E., Flower, R.H., Thompson, M.L., and Foster, R.W., 1956, Stratigraphic studies of the San Andres Mountains, New Mexico: New Mexico Bureau of Mines and Mineral Resources, Memoir 1, 132 p.

Lozinsky, R.P., 1985, Geology and late Cenozoic history of the Elephant Butte area, Sierra County, New Mexico: New Mexico Bureau of Mines and Mineral Resources, Circular 187, 40 p.

Lucas, S.G., Cather, S.M., Sealey, P., and Hutchison, J.H., 1989, Stratigraphy, paleontology, and depositional systems of the Eocene Cub Mountain Formation, Lincoln County, New Mexico – a preliminary report: New Mexico Geology, v. 11, p. 11–17.

New Mexico Bureau of Geology and Mineral Resources, 2003, Geologic Map of New Mexico: New Mexico Bureau of Geology and Mineral Resources, published in cooperation with the U.S. Geological Survey, scale 1:500,000.

Paleobiology Database, 2013, Bridgerian age/stage and Wasatchian age/stage: fossilworks, <http://fossilworks.org/bridge.pl?action=displayInterval&interval_no=231> <http://fossilworks.org/bridge.pl?action=displayInterval&interval_no=232>, accessed Nov. 14, 2013.

Pray, L.C., 1961, Geology of the Sacramento Mountains escarpment, Otero County, New Mexico: State Bureau of Mines and Mineral Resources, Bulletin 35, 144 p.

Rawling, G.C., 2012a, Geology of the Capitan and Nogal Quadrangles, Lincoln County, New Mexico: New Mexico Bureau of Geology, Open-file Report 538, scale 1:24,000.

Rawling, G.C., 2012b, Geology of the Ruidoso area, Lincoln and Otero Counties, New Mexico: New Mexico Bureau of Geology, Open-file Report 507, scale 1:24,000.

Seager, W. R., 2004, Laramide (late Cretaceous to Eocene) tectonics of southwestern New Mexico, *in* Mack, G.H., and Giles, K.J., eds., The Geology of New Mexico: A Geologic History: New Mexico Geological Society, Special Publication 11, p. 183–202.

Weber, R.H., 1964, Geology of the Carrizozo quadrangle, New Mexico: New Mexico Geological Society, Guidebook 15, p. 100–109.

View of Cub Mountain from Nogal Peak, looking west-northwest. Weber (1964) designated the type locality of the Cub Mountain Formation in the west-flowing canyon to the left (south) of the mountain. The dark shade right of Cub Mountain corresponds to the Carrizozo lava flow. The Oscura Mountains occupy the skyline. *Photo courtesy of Dan Koning.*