Research Paper

GEOSPHERE

GEOSPHERE, v. 14, no. 5

https://doi.org/10.1130/GES01641.1

26 figures; 1 supplemental file

CORRESPONDENCE: tom.lehman@ttu.edu

CITATION: Lehman, T.M., Wick, S.L., Beatty, H.L., Straight, W.H., and Wagner, J.R., 2018, Stratigraphy and depositional history of the Tornillo Group (Upper Cretaceous–Eocene) of West Texas: Geosphere, v. 14, no. 5, p. 2206–2244, https://doi.org/10.1130/GES01641.1.

Science Editor: Raymond M. Russo
Associate Editor: Todd LaMaskin

Received 27 November 2017
Revision received 30 March 2018
Accepted 22 June 2018
Published online 14 August 2018

GOLD OPEN ACCESS

THE GEOLOGICAL SOCIETY OF AMERICA®

Stratigraphy and depositional history of the Tornillo Group (Upper Cretaceous–Eocene) of West Texas

Thomas M. Lehman[1], **Steven L. Wick**[2], **Heather L. Beatty**[3], **William H. Straight**[4], **and Jonathan R. Wagner**[5]

[1]Department of Geosciences, Texas Tech University, Lubbock, Texas 79409-1053, USA
[2]Texas Vertebrate Paleontology Collections, 10100 Burnet Road, Austin, Texas 78758, USA
[3]Texas Department of Transportation Austin District, P.O. Box 15426, Austin, Texas 78761, USA
[4]Division of Natural Science, Northern Virginia Community College, Sterling, Virginia 20164, USA
[5]603 Prickly Pear Pass, Buda, Texas 78610, USA

ABSTRACT

Fluvial strata of the Tornillo Group preserve a succession of Late Cretaceous, Paleocene, and early Eocene continental faunas and floras and provide a record of the Laramide orogeny in the southern part of the North American Cordillera. Contacts between units in the Tornillo Group (Javelina, Black Peaks, and Hannold Hill formations) have proven difficult to identify, but minor adjustments to the stratigraphy allow each to be readily mapped and provide a means to assess intraformational thickness variation and syndepositional deformation within the Tornillo Basin. The Javelina Formation is thin in the southwestern part of the basin, and the Black Peaks Formation thins toward both southwestern and northeastern sides, suggesting that development of the monoclines that bound the basin began in latest Cretaceous through Paleocene time. An obscure structure extending southeastward from Grapevine anticline divides the basin into northeastern and southwestern segments. The Javelina Formation thins southwest of this structure and lacks lacustrine facies found to the northeast. The upper half of the Black Peaks Formation is absent southwest of this line, and northeast-facing monoclinal folds that affect the Hannold Hill Formation in the same vicinity are truncated at the base of the overlying Canoe Formation. Depositional limits of the Hannold Hill Formation probably did not extend to the southwest. The middle Eocene Canoe Formation is largely unaffected by contractive deformation that affects the Tornillo Group. Although incipient Laramide-age deformation broadly defined the Tornillo Basin during latest Cretaceous through Paleocene time, deformation here occurred mostly during the early Eocene.

INTRODUCTION

The "Tornillo Clay" of Udden (1907) comprises continental strata of Late Cretaceous through early Eocene age exposed in and around Big Bend National Park (hereafter "the Park") in Brewster County, Texas (Fig. 1). These largely fluvial strata are composed of recessively weathering multicolored mudstones interbedded with conglomeratic sandstone lenses that support cuestas, hogback ridges, and low-lying badlands terrain.

These strata are of broad interest because they preserve the southernmost succession of Late Cretaceous, Paleocene, and early Eocene continental faunas and floras known in North America, and the strata reflect a different biome than is preserved at well-studied sites in more northerly latitudes (Schiebout, 1974; Rapp et al., 1983; Standhardt, 1986; Lehman, 1987; Runkel, 1988; Wheeler and Lehman, 2000). The Tornillo beds also record the progression of the Laramide orogeny in the southern Cordillera and development of an intermontane basin at that time, the Tornillo Basin (Wilson, 1970; Lehman, 1991).

The Tornillo Clay was studied in detail and mapped for the first time by Maxwell et al. (1967), who revised the name to Tornillo Group and subdivided the strata into three formations: in ascending order, these are the Javelina Formation, Black Peaks Formation, and Hannold Hill Formation. Although Udden (1907) originally believed these beds were entirely Late Cretaceous in age, Maxwell et al. (1967) showed that the Tornillo Group also included Paleocene and Eocene strata. They attempted to place the contacts between the three formations so that they coincided approximately with the Cretaceous/Paleocene and Paleocene/Eocene boundaries. Their geologic map of Big Bend National Park remained the most detailed depiction of the distribution of these strata available for more than 40 years. Subsequently, the Tornillo Group stratigraphy proposed by Maxwell et al. (1967) was adopted for the Geologic Atlas of Texas (1979, Emory Peak–Presidio Sheet).

Maxwell et al. (1967, p. 97) remarked that correlation of formations within the Tornillo Group "would be difficult without the aid of vertebrate fossils." And, referring to its subdivisions, he stated that (p. 103) "it is doubtful if either can be accurately identified without fossils." Owing to such practical difficulties in recognizing the formations, and following Lawson's (1972) suggestion, Schiebout et al. (1987) offered a revision of the Tornillo Group demoting the unit in rank to formation, with the Javelina, Black Peaks, and Hannold Hill recognized instead as members, and including the Big Yellow Sandstone (formerly the basal unit of the overlying Big Bend Park Group) as the uppermost member of the formation. Lehman (1988) and Runkel (1988) objected to these suggested revisions, and they advocated continued use of the nomenclature of Maxwell

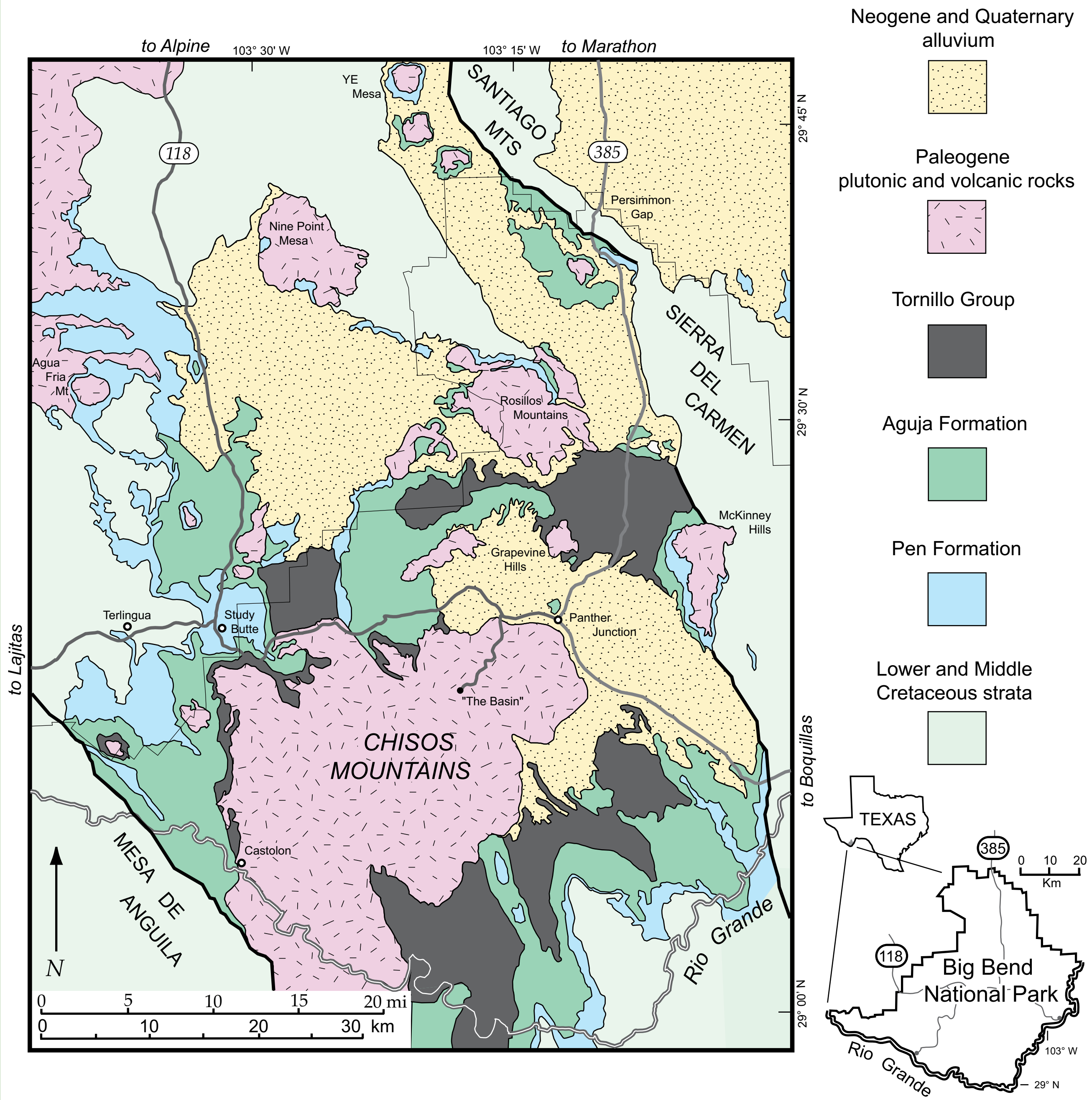


Figure 1. Generalized geologic map of the Big Bend region in Texas showing the regional extent of the Tornillo Group and its relationship to surrounding geologic features (modified from Geologic Atlas of Texas, 1979, Emory Peak–Presidio Sheet).

et al. (1967). On a subsequent geologic map of Texas (Hartmann and Scranton, 1992), these strata were identified as the Tornillo Formation. However, at the scale of this map (1:500,000), internal subdivisions were not shown.

During the 1990s, detailed studies of the Tornillo Group and mapping of key areas further elucidated the stratigraphic and nomenclatural problems (Beatty, 1992; Straight, 1996; Vines, 2000; Wheeler and Lehman, 2000, 2005, 2009; Wagner, 2001; Schmidt, 2009). From this work, it became clear that the distribution of each unit, and the positions of contacts between them, were not shown accurately or consistently on the existing geologic maps. Because these strata occur in multiple fault-bounded exposures with intervening areas interrupted by late Paleogene intrusive rocks or covered by Neogene and Quaternary alluvium, there are many isolated outcrops. Using the existing stratigraphic definitions, it was difficult to correlate accurately between separate exposures, and it became necessary to address these problems in order to provide a consistent framework for future work. Regardless of whether the Tornillo Group subdivisions are recognized as members or formations (as advocated here), the boundaries need to be clarified and more conveniently defined so that they could be shown consistently in mapping, and the relative stratigraphic positions of significant paleontological sites could be properly determined. A consistent stratigraphic framework is also needed for more derived studies of paleoclimatology (e.g., Nordt et al., 2003; Bataille et al., 2016) and fluvial sequence stratigraphy (e.g., Atchley et al., 2004).

Beginning in 2002, a joint U.S. Geological Survey and U.S. National Park Service effort was undertaken to produce a new geologic map of Big Bend National Park (Turner et al., 2011). As part of that effort, all exposures of the Tornillo Group were investigated and mapped (Lehman, 2002, 2004, 2007). These investigations indicated that simple changes in the positions of the formation boundaries allow for consistent recognition and mapping of the three formations. The Cretaceous–Paleocene and Paleocene–Eocene boundaries do not occur at readily identifiable lithologic contacts. The original type sections of all three formations needed to be revisited, because each was discovered to include strata equivalent to the other units as mapped elsewhere in the Park. The changes implemented did not require redefinition of the stratigraphic nomenclature, only revision of the formation contacts.

The present paper reviews the recent studies of Tornillo Group stratigraphy, reevaluates the type sections, and provides explanation for the emended formation contacts utilized in the new map of the Park (Turner et al., 2011). The emendations described herein are based primarily on study of the belt of exposures north of the Chisos Mountains. Mapping of the more remote regions south of the Chisos Mountains indicates that criteria described here are also applicable there. The maps and sections shown here are based on unpublished maps of Lehman (2007) cited by Collins et al. (2006) and Turner et al. (2011), some of which were also presented by Cooper (2011) and can be compared with maps of the same areas originally given by Maxwell et al. (1967). Detailed descriptions for 32 measured stratigraphic sections, location data for each section, and corresponding graphic stratigraphic columns showing the position of significant fossil localities are provided as Supplemental Material[1].

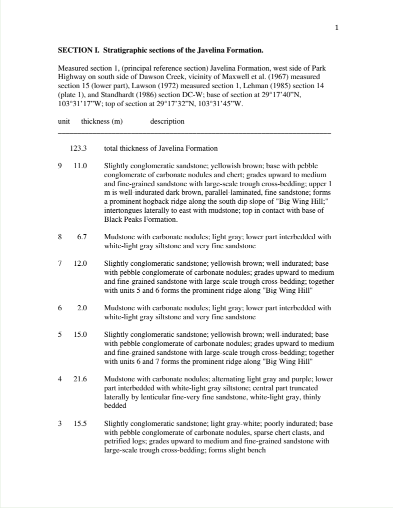
General Distribution

The best exposed and most accessible outcrops of the Tornillo Group extend in a belt north of the Chisos Mountains from Tornillo Flat (a broad expansion of the central part of the Tornillo Creek drainage basin) up the headwaters of Tornillo Creek, and from there into the tributaries of Terlingua Creek on the western side of the Park (Fig. 2). Much of the research on the Tornillo Group has been conducted in this region. A second major outcrop belt extends south of the Chisos Mountains around Chilicotal Mountain into Juniper Draw, westward along the flanks of Cow Heaven Mountain to the region south of Punta de la Sierra, and southward into Coahuila, Mexico (Shiller, 2017). This outcrop belt was mapped as part of the present study (Lehman, 2007), and several sections were measured in the Glenn Springs area; but these exposures are much less accessible, and alluvial cover is more extensive.

The only complete sections of the entire Tornillo Group are exposed on Tornillo Flat, where these strata were first recognized. Here a series of northwest-trending normal faults disrupt the Tornillo Group exposure into three southwest-tilted fault blocks, such that the section there is repeated three times (Lehman and Busbey, 2007). The Canoe fault, which passes along the southwestern flank of the Canoe syncline, was recognized by Maxwell et al. (1967); but a second fault, herein termed the Exhibit Ridge fault, passes along the southwestern side of Exhibit Ridge, and also partially repeats the Tornillo Group section. All three formations are exposed on Tornillo Flat, and the Hannold Hill Formation has not been recognized elsewhere. Farther west, in the headwaters of Tornillo Creek, and in the drainages of Rough Run, Dawson, and Alamo creeks, only the Javelina Formation and lower part of the Black Peaks Formation are present. Similarly, south of the Chisos Mountains, the upper parts of the Black Peaks Formation and Hannold Hill Formation are absent, and younger strata there rest directly on the lower part of the Black Peaks Formation.

JAVELINA FORMATION

The Javelina Formation consists of strata dominated by well-indurated sandstone beds, unlike the uppermost part of the underlying Aguja Formation and lowermost part of the overlying Black Peaks Formation, which both include a greater proportion of mudstone (Fig. 3). As a result, exposures of the Javelina Formation typically form a parallel series of resistant and relatively continuous cuestas or hogback ridges, whereas immediately overlying and underlying strata typically form recessive slopes or low badlands and are covered by alluvium in many areas. This distinctive physiographic expression aids in recognition of Javelina Formation exposures on topographic maps and aerial photographs.


1

SECTION I. Stratigraphic sections of the Javelina Formation.

Measured section 1, (principal reference section) Javelina Formation, west side of Park Highway on south side of Dawson Creek, vicinity of Maxwell et al. (1967) measured section 15 (lower part), Lawson (1972) measured section 1, Lehman (1985) section 14 (plate 1), and Standhardt (1986) section DC-W; base of section at 29°17’40”N, 103°31’17”W; top of section at 29°17’32”N, 103°31’45”W.

unit	thickness (m)	description
	123.3	total thickness of Javelina Formation
9	11.0	Slightly conglomeratic sandstone; yellowish brown; base with pebble conglomerate of carbonate nodules and chert; grades upward to medium and fine-grained sandstone with large-scale trough cross-bedding; upper 1 m is well-indurated dark brown, parallel-laminated, fine sandstone; forms a prominent hogback ridge along the south dip slope of "Big Wing Hill;" intertongues laterally to east with mudstone; top in contact with base of Black Peaks Formation.
8	6.7	Mudstone with carbonate nodules; light gray; lower part interbedded with white-light gray siltstone and very fine sandstone
7	12.0	Slightly conglomeratic sandstone; yellowish brown; well-indurated; base with pebble conglomerate of carbonate nodules; grades upward to medium and fine-grained sandstone with large-scale trough cross-bedding; together with units 5 and 6 forms the prominent ridge along "Big Wing Hill"
6	2.0	Mudstone with carbonate nodules; light gray; lower part interbedded with white-light gray siltstone and very fine sandstone
5	15.0	Slightly conglomeratic sandstone; yellowish brown; well-indurated; base with pebble conglomerate of carbonate nodules; grades upward to medium and fine-grained sandstone with large-scale trough cross-bedding; together with units 6 and 7 forms the prominent ridge along "Big Wing Hill"
4	21.6	Mudstone with carbonate nodules; alternating light gray and purple; lower part interbedded with white-light gray siltstone; central part truncated laterally by lenticular fine-very fine sandstone, white-light gray, thinly bedded
3	15.5	Slightly conglomeratic sandstone; light gray-white; poorly indurated; base with pebble conglomerate of carbonate nodules, sparse chert clasts, and petrified logs; grades upward to medium and fine-grained sandstone with large-scale trough cross-bedding; forms slight bench

[1]Supplemental Material. Descriptions and locations of measured stratigraphic sections. Please visit https://doi.org/10.1130/GES01641.S1 or access the full-text article on www.gsapubs.org to view the Supplemental Material.

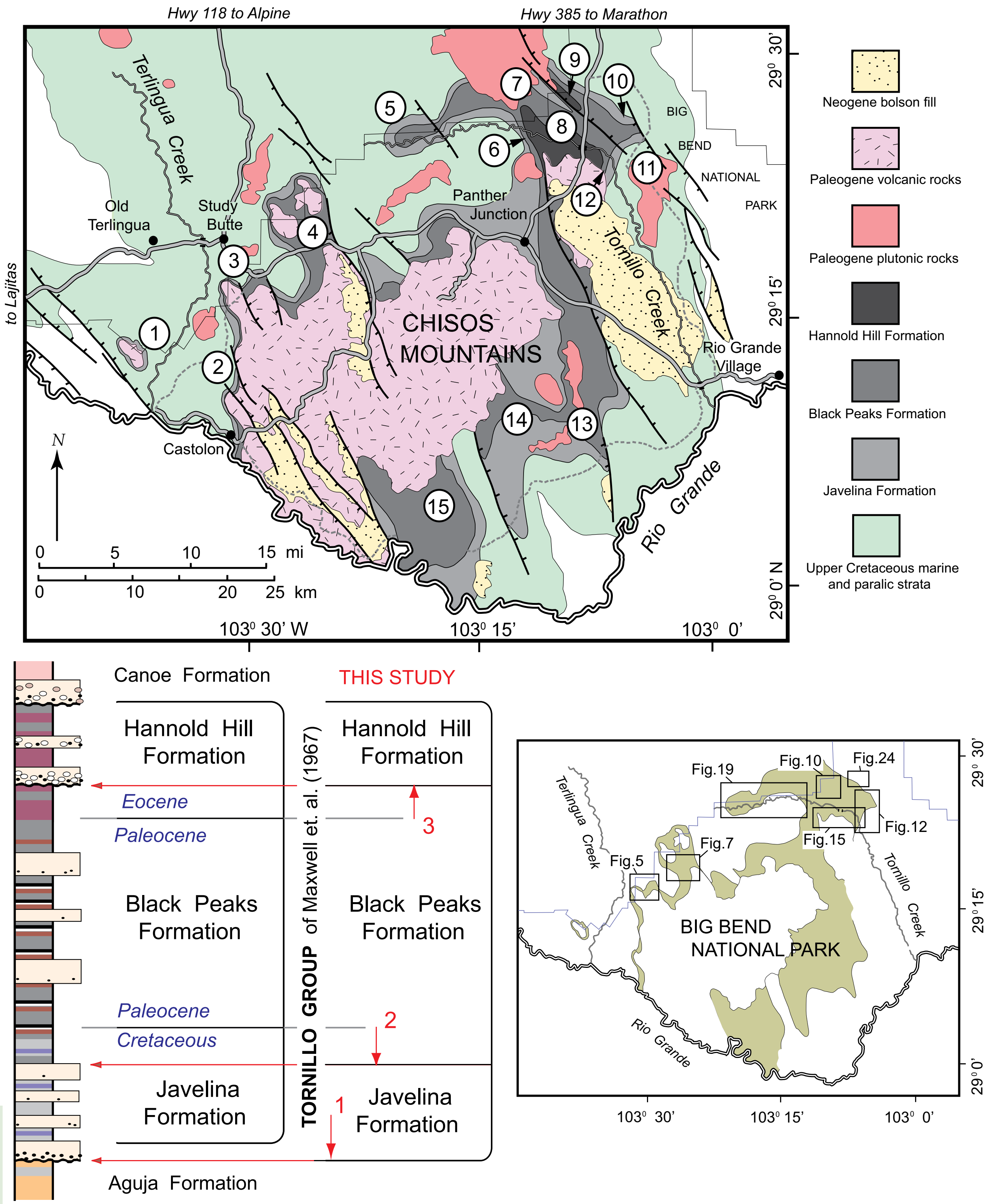


Figure 2. Generalized geologic map of Big Bend National Park and vicinity (modified from Turner et al., 2011) showing the basic distribution of formations in the Tornillo Group, its relationship to major geologic features, and the location of significant exposures discussed in the text: (1) Sierra Aguja; (2) valley south of Pena Mountain; (3) Dawson Creek; (4) Rough Run Creek; (5) north of Paint Gap Hills; (6) north of Grapevine Hills; (7) south of Rosillos Mountains; (8) Tornillo Flat; (9) Canoe Valley; (10) south of Dagger Flat; (11) northwest of McKinney Hills; (12) divide between Hannold Draw and Big Yellow arroyo; (13) Glenn Spring; (14) north of Talley Mountain; (15) south of Punta de la Sierra. Shown below (right) is an index map with locations for the geologic maps shown in Figures 5 through 19 in relation to the outcrop belt of the Tornillo Group and a generalized stratigraphic section of the Tornillo Group (left) showing positions of contacts between its constituent formations as described by Maxwell et al. (1967) and the emended formation contacts shown by Turner et al. (2011) as described in the present study.

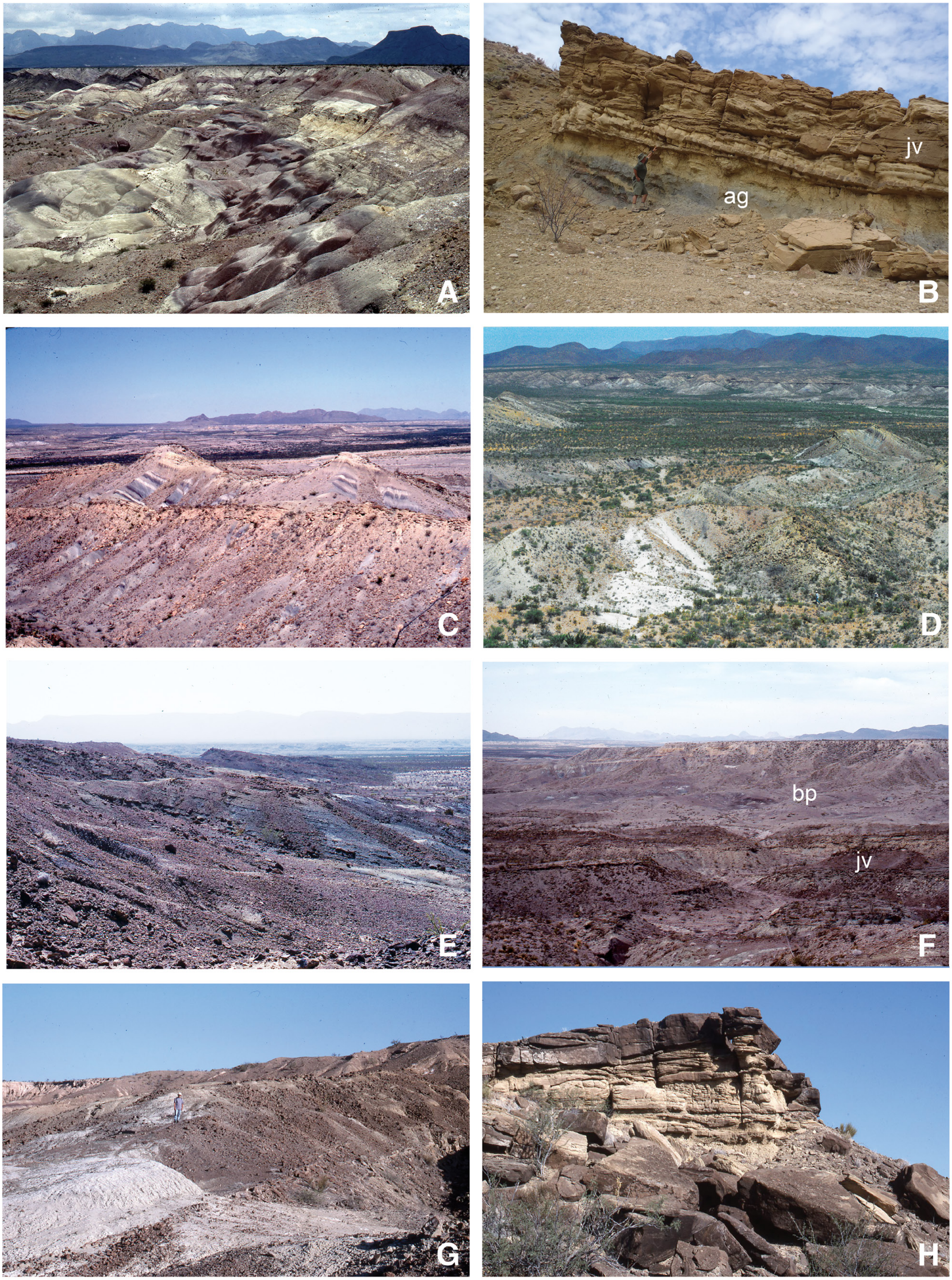


Figure 3. Outcrop features of the Javelina Formation. (A) Lower part of type section of the Javelina Formation on the south side of Dawson Creek (units 1–5, section 1), showing friable tan white-weathering conglomeratic sandstone interbedded with light-gray and purple mudstone typical of the western facies of the formation; (B) basal sandstone of the Javelina Formation (jv) and contact with underlying Aguja Formation (ag) exposed east of Paint Gap Hills (unit 1, section 9); (C) lower part of Javelina Formation northwest of McKinney Spring showing prominent hogback ridges held up by well-indurated sandstone (units 5–9, section 5) alternating with variegated mudstone typical of eastern facies of the formation; (D) upper part of Javelina Formation north of Grapevine Hills (units 3–7, section 8) showing lenticular white-weathering tuff bed (in left foreground) dated at ca. 69 Ma; (E) lacustrine facies in upper part of Javelina Formation at Pterosaur Ridge (units 14–16, section 7) showing rhythmically bedded green siltstone and bioturbated dark-brown sandstone; (F) Javelina/Black Peaks formational contact northeast of McKinney Springs (units 11–17, section 5) showing prominent physiographic break between dark-brown ridge-forming sandstone beds in Javelina Formation (jv) and slope-forming variegated mudstone of the Black Peaks (bp); (G) typical lacustrine mudstone beds in upper Javelina Formation at Pterosaur Ridge (unit 15, section 7); (H) typical fluvial channel sandstone in upper Javelina Formation at Pterosaur Ridge (unit 3, section 7).

Type Section

Maxwell et al. (1967; their plate 7, section no. 14) designated a type section for the Javelina Formation on Dawson Creek (Figs. 4 and 5). However, elsewhere in the text (p. 94), they indicated a section measured near Tule Mountain as the type. The formation name is derived from Javelina Creek (shown as "Javalina Creek" [sic] on the McKinney Spring 7.5′ topographic quadrangle; U.S. Geological Survey, 1971), but no section was measured in that vicinity, and recent mapping indicates that a complete section may not be present there; the Javelina is in fault contact with the underlying Aguja Formation (Turner et al., 2011). Similarly, there is not a complete section of the Javelina Formation near Tule Mountain (Maxwell et al., 1967; their plate 7, section no. 15); instead, the Aguja and Black Peaks formations are juxtaposed there by faulting (Turner et al., 2011).

In the Dawson Creek area, the Javelina Formation is in depositional contact with underlying and overlying strata, and the section there is best retained as the type for the formation (Figs. 4 and 5). However, the upper part of the section measured there by Maxwell et al. (1967) is now known to include strata equivalent to the Black Peaks Formation and Canoe Formation (see below; Lehman, 1989; Lehman and Busbey, 2007). Therefore, only the lower 126 m of the section measured there (Maxwell et al., 1967; to top of their unit 21, p. 95) are retained as the type of the Javelina Formation. Only this part of the section is equivalent to the Javelina Formation as originally mapped farther east by Maxwell et al. (1967) in the type area for the overlying Black Peaks Formation (see below). The part of the section at Dawson Creek delimited here as Javelina Formation was also measured by Lawson (1972; 134 m, section 1, Lawson figure 4), Standhardt (1986; 130 m, section DC-W, Standhardt's figure 8), and Lehman (1990; 122 m), and all recognized the same basic lithologic units. More recently, Atchley et al. (2004) and Leslie et al. (2018) measured the same section; the Javelina Formation as recognized here extends from their 42 m mark up to their 175 m mark, and so the total thickness they determined (133 m) is also comparable. A thickness of 123 m was obtained for the type section of the Javelina Formation in the present study (Fig. 6).

Lower Contact

The base of the Javelina Formation coincides with a transition from recessively weathering mudstone, covered by alluvium in many areas, to ridge-forming conglomeratic sandstone (Figs. 3 and 6). Furthermore, mudstones in the upper part of the Aguja Formation (the upper shale member of Lehman, 1985) tend to be drab yellow or olive gray with a few discontinuous

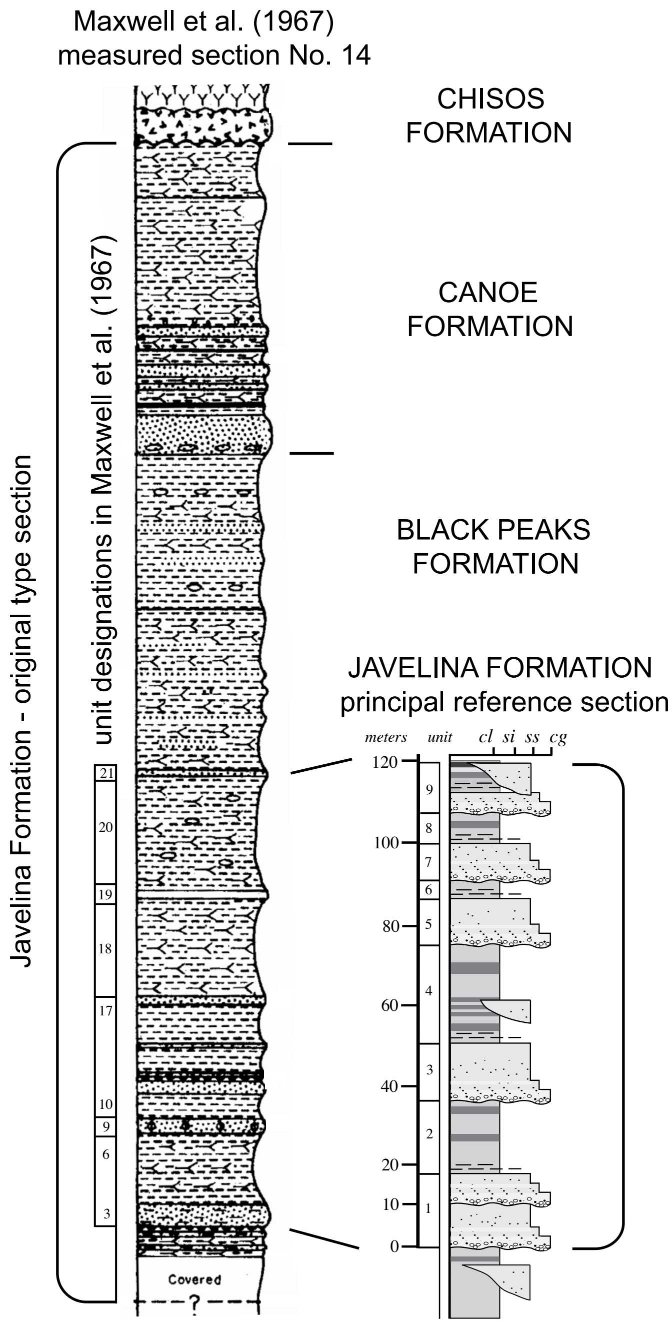
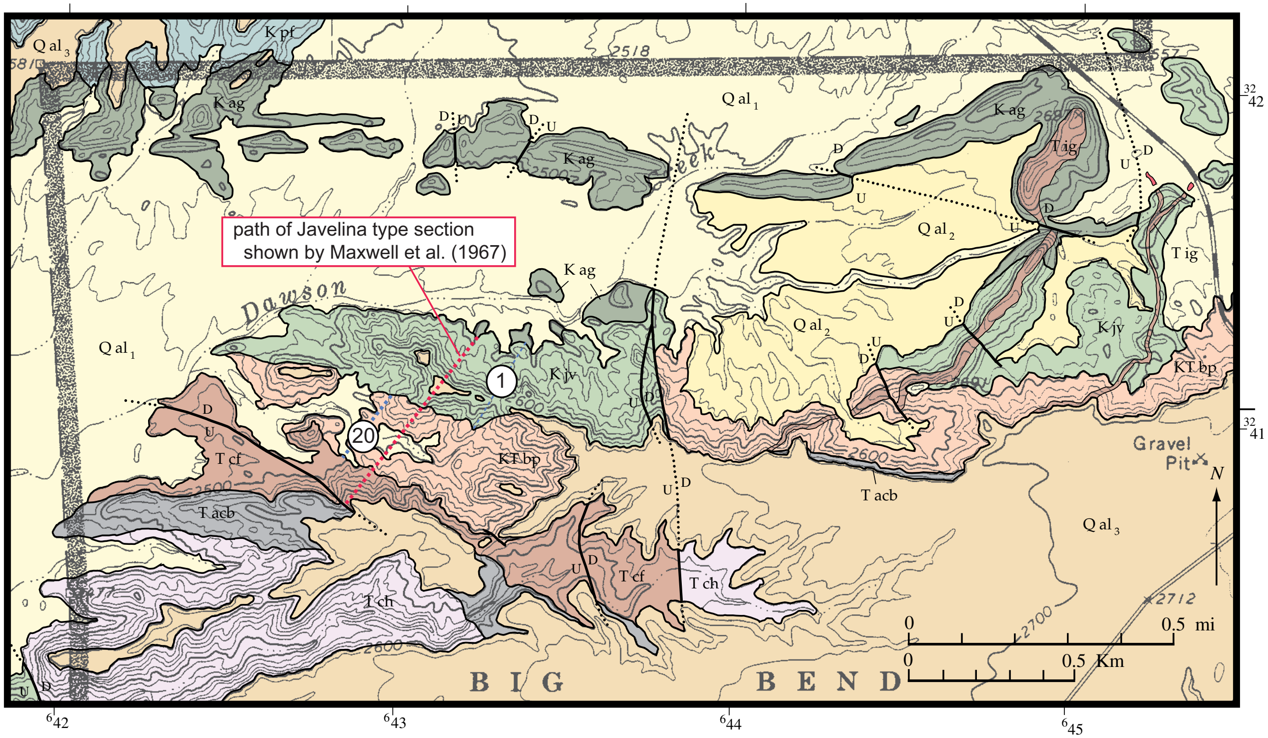


Figure 4. Original type section of the Javelina Formation (left, modified from Maxwell et al., 1967) showing unit numbers corresponding to the original description and correspondence with stratigraphic units recognized in the present study; on right is shown the principal reference section for the Javelina Formation measured for the present study (Dawson Creek, section 1). cl—claystone; si—siltstone; ss—sandstone; cg—conglomerate.



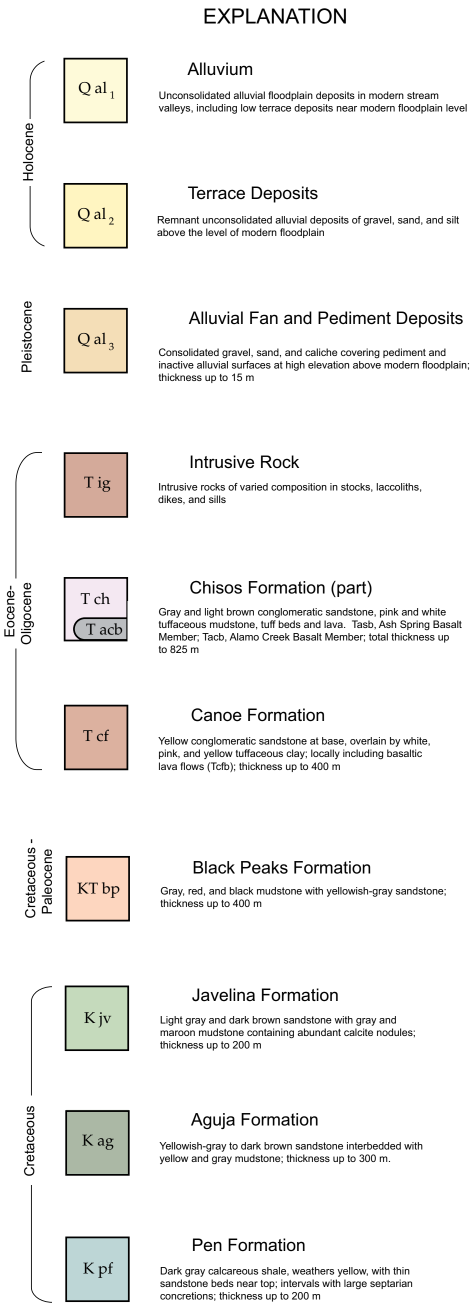


Figure 5. Geologic map of the type area of the Javelina Formation on the south side of Dawson Creek, near the west entrance to Big Bend National Park, showing path of original type section measured by Maxwell et al. (1967) and that part of the section identified as Javelina Formation in the present study (section 1).

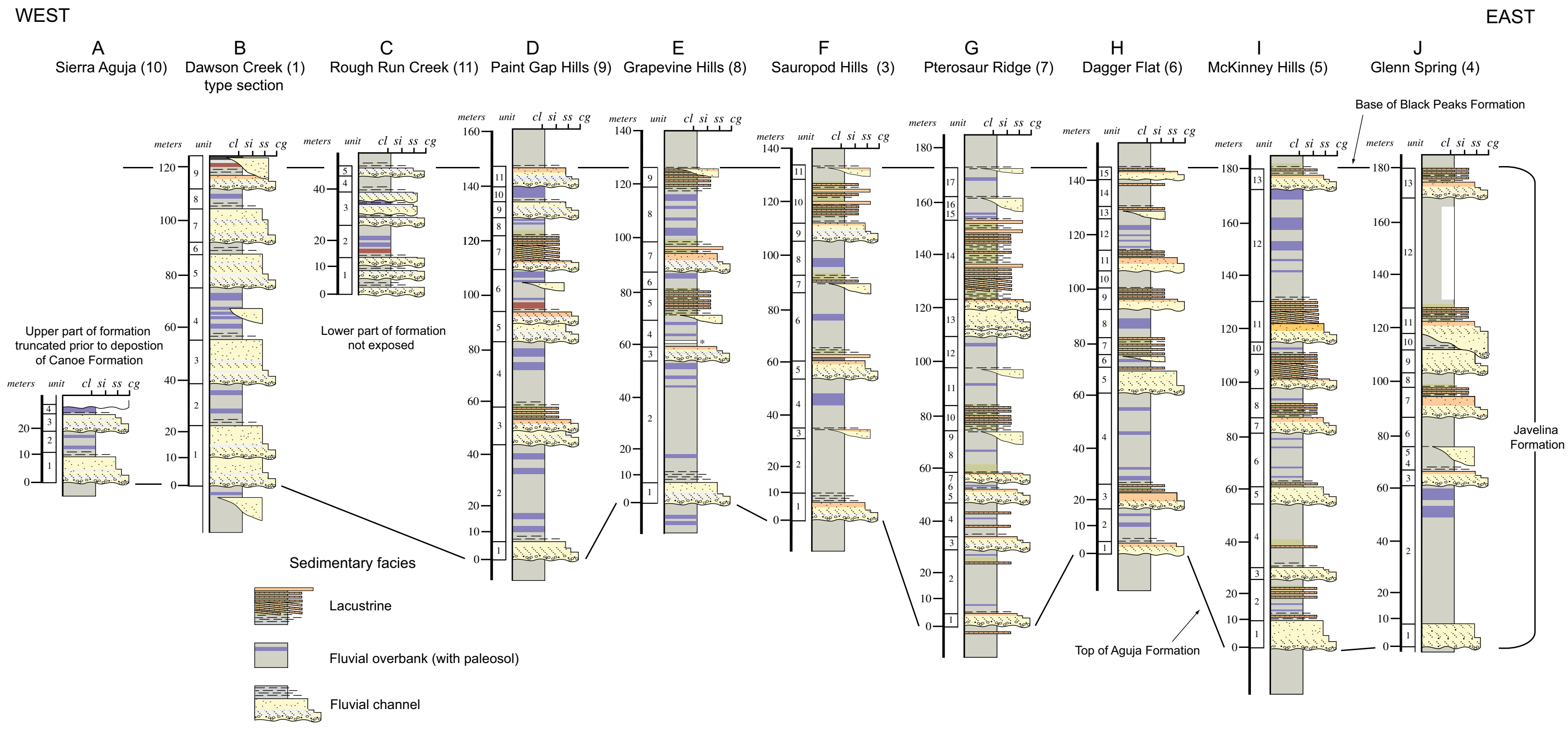


Figure 6. Correlation of key stratigraphic sections of the Javelina Formation in Big Bend National Park, Texas (see Supplemental Material, section I [text footnote 1] for detailed descriptions of sections). cl—claystone; si—siltstone; ss—sandstone; cg—conglomerate.

red or purple beds, but these brightly colored beds are more numerous and laterally extensive in the Javelina Formation. The contact between the Javelina Formation and the underlying Aguja Formation was therefore placed by Maxwell et al. (1967, p. 81) "at the top of a sandstone above which the beds are predominantly varicolored bentonitic clay." This color change appears to be gradational, and so the contact defined in this way is somewhat arbitrary.

However, Lehman (1985, 1989) found that in many areas the sandstone bed mapped as the contact by Maxwell et al. (1967), or one immediately above or below it stratigraphically, also contains lenses of chert-pebble conglomerate at its base. In contrast, conglomerate beds in the underlying Aguja Formation are composed of clasts exclusively of intrabasinal origin (carbonate concretions, wood, and bone). The lowermost sandstone with chert-pebble conglomerate also records a shift in paleocurrent orientation and sandstone petrology, likely corresponding to the onset of initial subsidence in the Tornillo Basin (Lehman, 1991), and so this stratigraphic horizon is of tectonic significance. Although the mudstone color contrast appears to be gradational, the lowermost sandstone with chert-pebble conglomerate occurs at a progressively lower stratigraphic level from west to east across the Park, suggesting that part of the upper shale member of the underlying Aguja Formation may have been truncated by erosion prior to deposition of the Javelina Formation; and the contact may be disconformal (a depositional sequence boundary; Lehman, 2009, Lehman's figure 45). The base of this sandstone, rather than its top (as originally placed by Maxwell et al., 1967), is therefore a more appropriate formational contact because this corresponds more closely with this stratigraphic discontinuity (Wagner, 2001).

Recently, it has also been discovered that the uppermost Aguja Formation includes a series of rhythmically bedded mafic pyroclastic deposits that are lacking in the overlying Javelina Formation (Breyer et al., 2007; Befus et al., 2008). Although these pyroclastic deposits occur only in a few areas, they grade laterally into more extensive mudstone beds that typically have an unusual blue or olive-green coloration (Munsell 5 GY 3/2–7/2) due to high chlorite content—probably an alteration product of the mafic pyroclastic material. Distinctive, white, and thoroughly agatized wood is also abundant in these green beds (e.g., Lehman and Wheeler, 2001). These unique aspects of the uppermost Aguja beds therefore also aid in identifying the base of the overlying Javelina Formation.

The lower contact of the Javelina Formation is herein recognized as the base of the lowermost sandstone unit containing chert-pebble conglomerate above which the intercalated mudstone deposits are brightly colored. This minor adjustment allows for more consistent determination of relative stratigraphic positions of fossil collection sites within the formation. In most areas, the contact thus defined is very close to its position as originally mapped by Maxwell et al. (1967), and so the recent mapping does not differ much in this respect. Exceptions exist northwest of McKinney Hills, and in the region around Talley Mountain in the headwaters of Juniper Draw, where Maxwell et al. (1967) placed the contact much higher in the section than elsewhere; a substantial part of the section shown in those areas as Aguja Formation is included here instead within the Javelina Formation. This error in mapping led to mistaken early reports that remains of sauropod dinosaurs occurred within the Aguja Formation (e.g., Davies, 1983); these sites are instead within the Javelina Formation.

Upper Contact

The upper contact of the Javelina Formation was placed by Maxwell et al. (1967, p. 98) at the base of a sandstone bed that "overlies the Javelina with an irregular base and lies between the highest known dinosaurs and the lowest recognized Paleocene mammals." However, this sandstone bed is discontinuous and otherwise not distinctive, and the scarcity of vertebrate fossils makes it impractical to utilize fossil content to locate the formational contact. As a result, the Javelina/Black Peaks formational contact was only mapped by Maxwell et al. (1967) in two areas: western Tornillo Flat and west of Glenn Springs. Later it became clear that extensive exposures of Black Peaks Formation had been incorrectly mapped as Javelina Formation simply because at that time Paleocene fossils had not yet been discovered in most areas (reviewed by Lehman and Busbey, 2007).

Lawson (1972), Schiebout et al. (1987), and Lehman (1985, 1989) recognized this problem and offered various possible solutions. Lehman (1985, p. 71) noted that in many of the areas mapped by Maxwell et al. (1967), the Javelina Formation consisted of a lower "sandstone-dominated" interval, entirely Cretaceous in age, and an upper "mudstone-dominated" interval, mostly Paleocene in age. The Cretaceous–Paleogene boundary is within the lower part of the "mudstone-dominated" interval. Straight (1996) observed that at the type section of the Black Peaks Formation on western Tornillo Flat, the mapped position for the upper boundary of the Javelina Formation had been placed by Maxwell et al. (1967) near the top of Lehman's (1985) "sandstone-dominated" interval of the Javelina Formation; and so, in the Black Peaks type area, the "mudstone-dominated" interval was actually included in the lower part of the Black Peaks Formation. The same is true at the only other exposure of Black Peaks Formation mapped by Maxwell et al. (1967) in the unnamed syncline west of Glenn Springs. Hence, for consistency, the Javelina/Black Peaks formational contact is everywhere placed at that level in recent mapping (Turner et al., 2011).

This revised upper contact is: (1) compatible or nearly so with the position shown by Maxwell et al. (1967) in the two areas where they mapped the overlying Black Peaks Formation; (2) consistent with their general concept that the Javelina Formation was Late Cretaceous, and the Black Peaks Formation was Paleocene in age, because the K/Pg boundary is within the lowermost part of the "mudstone-dominated" interval just above the formational contact; (3) recognizable because it coincides with a prominent physiographic break in the stratigraphic succession and so is readily mapped; and (4) practicable because fossils are generally uncommon in this interval, and the K/Pg boundary does not occur at a marked lithologic break, making it impossible to place the formation contact at the system boundary for mapping purposes.

Therefore, herein the limits of the Javelina Formation are clarified to conform with the original definition of the unit. Only the lower "sandstone-dominated" part of the original type section on Dawson Creek is recognized as the Javelina Formation. This part of the type section corresponds closely with the limits of the unit as it has been mapped previously elsewhere in the region. In this way, the upper boundary also corresponds approximately with the position shown at the base of the type section of the overlying Black Peaks Formation on Tornillo Flat. The revised contact also corresponds with a distinctive physiographic break; the Javelina Formation is a persistent ridge-forming unit, whereas the lower part of the Black Peaks Formation is a slope-forming unit (Fig. 6). The contact between the two units is, however, entirely gradational and intertonguing. The top of the highest persistent ridge-forming sandstone unit varies as these units thin and pinch out where traced along strike. So, for example, in the measured section taken at "Sauropod Hills" (Fig. 6, section 3) the upper contact of the Javelina Formation is placed at the top of a thin lenticular sandstone bed (unit 11 of section 3); however, this bed thickens and holds up a prominent cuesta ~1 km northwest of the path taken for the section. Similarly, at Grapevine Hills (Fig. 6, section 8), the upper contact is placed at the top of a series of inconspicuous thin sandstone beds (unit 9 of section 8), but that unit also thickens south of the line of section and is a conspicuous cliff-former. As a result of this intertonguing pattern, the mapped position of the uppermost ridge-forming sandstone varies locally over a stratigraphic interval of 20–30 m, and the contact must be chosen arbitrarily within this zone of gradation.

Key Beds

Thus far, no means of confidently correlating individual units within the Javelina Formation has been discovered (Fig. 6). A tuff bed is present within the middle part of the formation northwest of Grapevine Hills (Lehman et al., 2006), but this bed has not been identified in other exposures. The formation comprises alternating sandstone and mudstone intervals, and in most areas, there appear to be four major sandstone intervals that can be traced laterally several kilometers within a given exposure. But, whether any of these is correlative regionally is unknown. Several of the sandstone intervals are "compound" sand bodies composed of multiple-channel aggradational sequences, and, in some exposures, as few as three to as many as five distinct sandstone intervals are present (Fig. 6). Distinctive paleosols identified at some exposures (e.g., Rough Run Creek) have not been confidently recognized elsewhere.

Nordt et al. (2003) theorized on the basis of stable isotope excursions detected in the Dawson Creek section that two disconformities are present within the Javelina Formation. Atchley et al. (2004) also identified a stratigraphic sequence boundary, and based on magnetic polarity zonation, Leslie et al. (2018) interpreted an unconformity within the same section. However, it has not been possible to identify the purported isotopic excursions in other sections of the Javelina Formation (e.g., Schmidt, 2009), and the positions of unconformities hypothesized by Nordt et al. (2003), Atchley et al. (2004), and Leslie et al. (2018) do not correspond with one another or with any prominent stratigraphic or petrologic characteristics that would allow for their identification or correlation in other sections of the Javelina Formation.

Distribution

In most areas, the distribution of the Javelina Formation documented by recent mapping is much reduced compared to that shown by Maxwell et al. (1967). Although the major outcrop areas are the same, significant parts of these areas are now mapped as Black Peaks Formation (e.g., compare Fig. 7 with Maxwell et al., 1967). Some strata included in the Javelina Formation by Maxwell et al. (1967) along the south flank of Dawson Creek and in the Rough Run Creek drainage between Dogie Mountain and Little Christmas Mountain are mapped here as Canoe Formation. Runkel (1988, 1990) also recognized that the strata in this area do not pertain to the Javelina Formation, but instead identified them with the Devil's Graveyard Formation. The correlative Canoe Formation nomenclature is preferred here for mapping purposes simply for sake of uniformity of use within the Park (Turner et al., 2011).

In a few areas, the Javelina Formation exposures are more extensive than shown previously. For example, around Talley Mountain, and in the headwaters of Juniper Draw, much of the area shown as Aguja Formation by Maxwell et al. (1967) is actually Javelina Formation. Similarly, extensive areas mapped as Hannold Hill Formation by Maxwell et al. (1967) on Tornillo Creek north of Grapevine Hills are shown here to be Javelina Formation. Exposures of Chisos Formation in the lower reaches of Blue Creek were inadvertently mapped as Javelina Formation by Maxwell et al. (1967) because the overlying Ash Spring Basalt Member was mistakenly identified as the Alamo Creek Basalt Member of the Chisos Formation (Lehman, 2004).

Thickness Variation

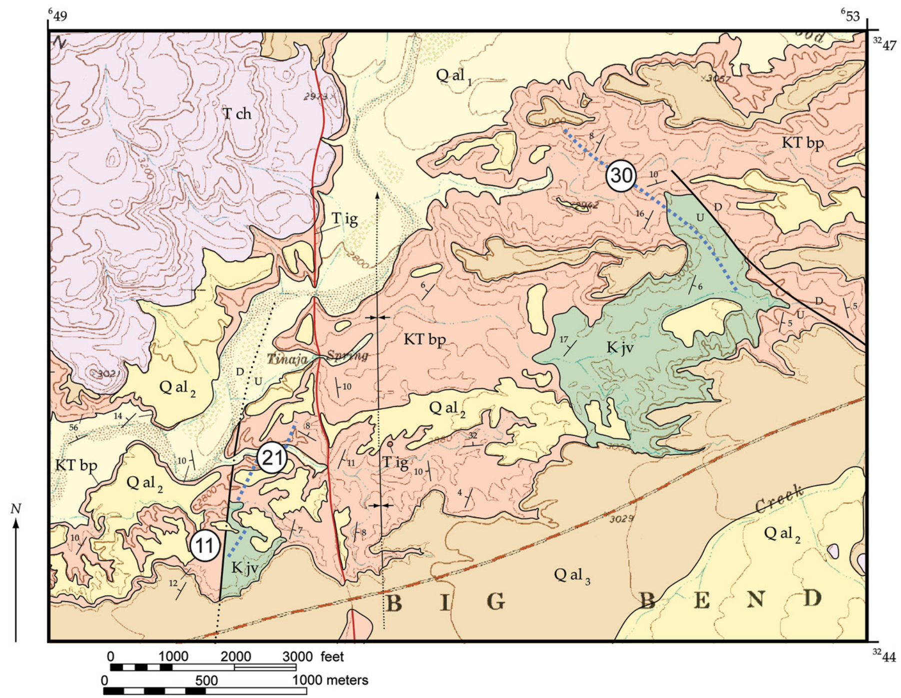
As presently recognized and mapped (Turner et al., 2011), the Javelina Formation has a relatively consistent thickness typically ranging between 123 m (Dawson Creek) and 183 m (northern Tornillo Flat; Fig. 6). The more extreme thickness variations reported by Maxwell et al. (1967) are a result of previously unrecognized faults that cut out part or all of the Javelina Formation in those areas. The thinnest section observed in the present study (114–122 m) is northwest of Grapevine Hills; however, here it is possible that a fault obscured in a covered interval has cut out part of the section (Straight, 1996) or that one or more of the mudstone intervals has been tectonically thinned along the steeply dipping limb of the fold (Grapevine anticline) where the section was taken. The thickest sections measured (185–190 m) on eastern Tornillo Flat and at Glenn Springs may result from the presence here of an additional sandstone unit at the top of the formation (thus including strata that would otherwise be regarded as part of the overlying Black Peaks Formation), but it may instead reflect a greater rate of subsidence along the eastern margin of the Tornillo Basin during deposition of the Javelina Formation (an interpretation advocated by Lehman, 1991).

Facies Variation

Although the basic ratio of sandstone to mudstone does not differ dramatically over the region, there is a subtle change in facies from west to east (Fig. 6). Western exposures of the Javelina Formation (in the Rough Run Creek, Dawson Creek, and Alamo Creek drainages, south of Punta de la Sierra, and west of Cow Heaven Mountain) have fine-grained sandstone beds that are clayey and friable and weather to pale gray or yellow. Paleosols are very pronounced, such that the mudstone intervals exhibit vivid red and purple beds. In contrast, in eastern exposures of the formation (in the Tornillo Creek drainage, Juniper Draw, and around Chilicotal Mountain), the sandstone beds are coarser grained, weather to olive green, and have highly indurated dark reddish-brown tops with pervasive bioturbation. There is also clear evidence for lacustrine deposition in the eastern exposures (rhythmically bedded strata and thin limestone beds with aquatic invertebrates and charophytes). If the western and eastern exposures of the Javelina Formation are mostly or entirely equivalent in age, this facies change suggests that stream channels in the eastern part of the outcrop belt experienced more extended periods of stagnant water conditions (meander cutoffs that produced oxbow lakes; Lehman and Langston, 1996) or episodic impounding of flow that resulted in shallow submergence of the eastern part of the drainage basin.

Biostratigraphy

The Javelina Formation has a fossil vertebrate fauna of middle to late Maastrichtian age (Edmontonian to Lancian North American Land Mammal Ages



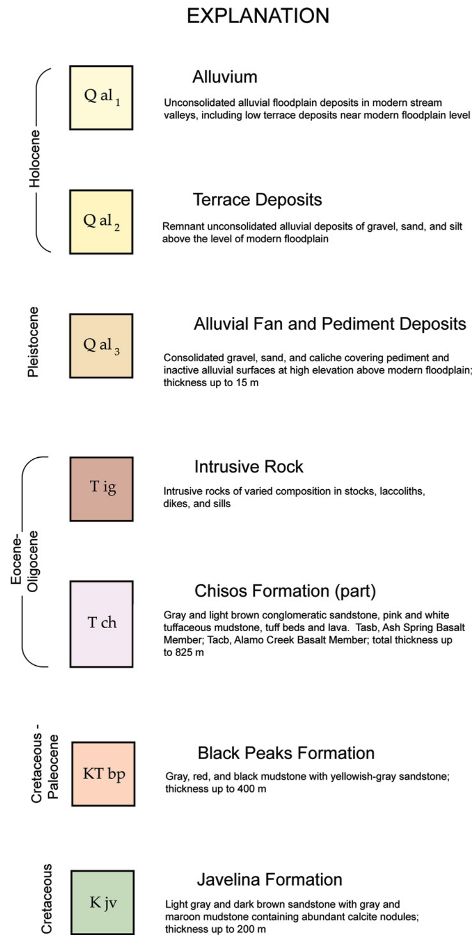


Figure 7. Geologic map of the region along Rough Run Creek showing distribution of formations in the Tornillo Group and location of stratigraphic sections.

chronology [NALMA]). The tuff bed in the middle of the formation (see above) provides a U/Pb isotopic age of 69.0 ± 0.9 Ma, which lies near the lower and upper Maastrichtian boundary (Lehman et al., 2006). Most of the significant vertebrate fossil sites are found in the upper half of the formation, generally above the level of the tuff bed (Supplemental Material, section I [footnote 1]). The lowermost part of the formation may be of Edmontonian age and has yielded remains of several dinosaurs not known from the upper part of the formation—the ceratopsian *Bravoceratops polyphemus* (Wick and Lehman, 2013) and hadrosaur *Kritosaurus* sp. (Lehman et al., 2016). Although remains of both ceratopsian and hadrosaurian dinosaurs are rare throughout the formation, those documented in the upper part—*Torosaurus* cf. *utahensis* (Hunt and Lehman, 2008) and ?*Gryposaurus alsatei* (Lehman et al., 2016)—differ from those found near the base. The occurrence of *Tyrannosaurus* (Lawson, 1976; Wick, 2014) and *Torosaurus* is compatible with a Lancian age assignment for the upper part of the formation.

Remains of sauropod dinosaurs are very common throughout the formation, and most or all of the specimens collected in the upper part of the formation are attributable to *Alamosaurus sanjuanensis* (e.g., TMM 41541 and 45891; Lawson, 1972; Lehman and Coulson, 2002; Woodward and Lehman, 2009; Fronimos and Lehman, 2014; Tykoski and Fiorillo, 2016). Sauropod specimens from the lower part of the formation (e.g., TMM 40597) are less diagnostic but may represent a different species (Wick and Lehman, 2014).

Pterosaurs are also abundant locally in the upper part of the Javelina Formation (e.g., at "Pterodactyl Ridge"; Lehman and Busbey, 2007) and appear to exhibit a stratigraphic succession of species, with an unnamed species occurring in the middle of the formation (TMM 42489; section 7)—*Quetzalcoatlus* sp., occurring abundantly throughout much of the upper part of the formation (e.g., TMM 41544; section 7), and *Q. northropi,* collected only in the uppermost Javelina and lower part of the overlying Black Peaks Formation (e.g., TMM 41450; section 1). Specimens of other dinosaurs (e.g., ankylosaurs and theropods; Lawson, 1976) and smaller vertebrates such as fishes, turtles, and crocodylians (Standhardt, 1986; Tomlinson, 1997) are less abundantly preserved and appear to have limited biostratigraphic significance.

Petrified wood is abundant throughout the Javelina Formation (Wheeler and Lehman, 2000, 2005, 2009), and the wood types represented also vary between the lower and upper parts of the formation. Wood types from the lowermost part of the formation, particularly the basal sandstone, represent primarily podocarpacean conifers and some dicot wood types (e.g., *Metcalfeoxylon*, *Baasoxylon*, and *Gassonoxylon*) that also occur in the uppermost part of the underlying Aguja Formation. These wood types are all absent higher in the formation, where instead trunks of the malvalean tree *Javelinoxylon multiporosum* (Wheeler et al., 1994) are common, and auraucariacean conifer woods occur rarely. Both vertebrate fauna and woody flora of the Javelina Formation suggest a biostratigraphic separation between the lower (Edmontonian) and upper (Lancian) parts of the formation. These observations may support the presence of an intraformational unconformity within the Javelina Formation hypothesized by Leslie et al. (2018). They correlated the lower part of the formation with magnetic polarity chron C31 (ca. 70–69 Ma) and the upper part of the formation with chron C 29r (ca. 66 Ma).

BLACK PEAKS FORMATION

The Black Peaks Formation, like the underlying Javelina, consists of an alternating series of mudstone and sandstone beds; however, the Black Peaks is dominated by mudstone and is primarily a recessive, slope-forming unit (Fig. 8). As a result, it is covered by Quaternary alluvium in many areas. The most extensive exposures form badlands along the flanks of major drainages where overlying Quaternary pediment gravel forms a capping bed that slows erosion. There are several thick, erosionally resistant ridge- or cliff-forming sandstone units within the middle of the formation; the lower of these contains abundant fossil logs and is a regionally extensive marker bed (the "log jam sandstone" of Lehman and Busbey, 2007).

Color bands in the mudstone intervals of the Black Peaks Formation are more distinct, generally thinner, and more laterally continuous than those in either the underlying Javelina Formation or overlying Hannold Hill Formation. Moreover, there are distinctive, laterally extensive black mudstone beds that are key marker horizons (Schiebout, 1970, 1974), and these are unlike any mudstone layers observed in underlying or overlying strata. The black mudstone beds occur as part of characteristic black-white-red color-banded "triplets" that are distinctive compared to others in the Tornillo Group (Fig. 8). These "candy-striped" intervals are a key feature of use in recognizing isolated exposures of the Black Peaks Formation (Lehman and Busbey, 2007).

Type Section

The name Black Peaks Formation is derived from three small mafic intrusions on eastern Tornillo Flat (McKinney Springs 7.5′ topographic quadrangle; U.S. Geological Survey, 1971). However, much of the upper part of the formation is covered in that area (McKinney Hills section 18 of the present study and sections 34 and 35 of Maxwell et al., 1967). The type section of the Black Peaks Formation was designated at western Tornillo Flat by Maxwell et al. (1967), and this is the only area in the region where a complete and well-exposed section of the entire formation exists (Figs. 9 and 10).

Maxwell et al. (1967) measured 264 m of Black Peaks Formation at the type section. Schiebout (1970) measured the same section but determined a thickness of only 170 m (Fig. 9). She hypothesized that the discrepancy may have been due to use of different dip values and different methods for measurement (alidade versus Jacob's staff). Schiebout (1970) reported a dip of 4°, whereas the map given by Maxwell et al. (1967) shows 5° nearby. Measurements taken for the present study yielded dips up to 6° and locally as much as 14° near the top of the exposure. However, several additional factors probably contributed to confusion regarding the limits and thickness of the formation (see below).

Lower Contact

The mapped position of the Javelina/Black Peaks contact in the type area was shown much lower than the point where the base of the type section was indicated by Maxwell et al. (1967; section 33 on their plate II). The base of their section is shown on the southwest flank of the headwaters of Star Creek, but the mapped position of the basal contact is more than 1 km northwest of there, in the headwaters of the next drainage (Fig. 10). The upper part of the section measured by Maxwell et al. (1967; their units 14–33) is comparable in character and thickness (153 m) to the entire section measured by Schiebout (1970; 170 m), and also comparable to the measurement of that part of the section made for the present study (187 m). The lower 111 m of the section measured by Maxwell et al. (1967; their units 2–13) includes several very thick mudstone intervals (e.g., 59 m; units 11–13) that are lacking in Schiebout's (1970) section. Hence, it appears certain that Schiebout (1970) did not include the lowermost 111 m of strata in the section shown by Maxwell et al. (1967). This discrepancy likely accounts for the difference in total thickness.

The sandstone bed mapped as the base of the formation by Maxwell et al. (1967; unit 2 of their type section) corresponds quite closely with the position of the K/Pg boundary, as is now better known and recognized in exposures

Figure 8. Outcrop features of the Black Peaks Formation: (A) upper part of type section of Black Peaks Formation on western Tornillo Flat showing one of the few major ridge-forming sandstone beds in the section (unit 16, section 12), dark-gray and variegated mudstone typical of the upper part of the formation; (B) oblique low-altitude aerial photo of the type section of the Black Peaks Formation on western Tornillo Flat (units 10–19, section 12); (C) lower part of the Black Peaks Formation north of McKinney Springs showing the "Black Peaks" (small intrusions on left) and distinctive regularly alternating red and dark-gray mudstone beds (units 3–9, section 18); (D) typical "candy-striped" beds in lower Black Peaks Formation on Willow Creek, with thin but laterally extensive regularly alternating dark-gray, red, and white color bands (units 3–5, section 20); (E) typical black mudstone marker bed on Tornillo Flat (bed "G" of Schiebout, 1974; unit 17, section 12) showing sequence from red mudstone with carbonate nodules at base, overlain by white and/or light-gray mudstone, capped by black mudstone (staff is 1.5 m long); (F) lower part of Black Peaks Formation on the south side of Dawson Creek (units 1–5, section 20) showing contacts with underlying Javelina Formation and overlying Canoe Formation; (G) lowermost part of Black Peaks Formation north of McKinney Springs (unit 1, section 18); (H) "log jam sandstone" bed in middle of Black Peaks Formation south of Dogie Mountain (unit 11, section 21) showing typical unconsolidated tan-yellow sandstone with resistant petrified logs capping hoodoo (person is indicating root buttress of log).

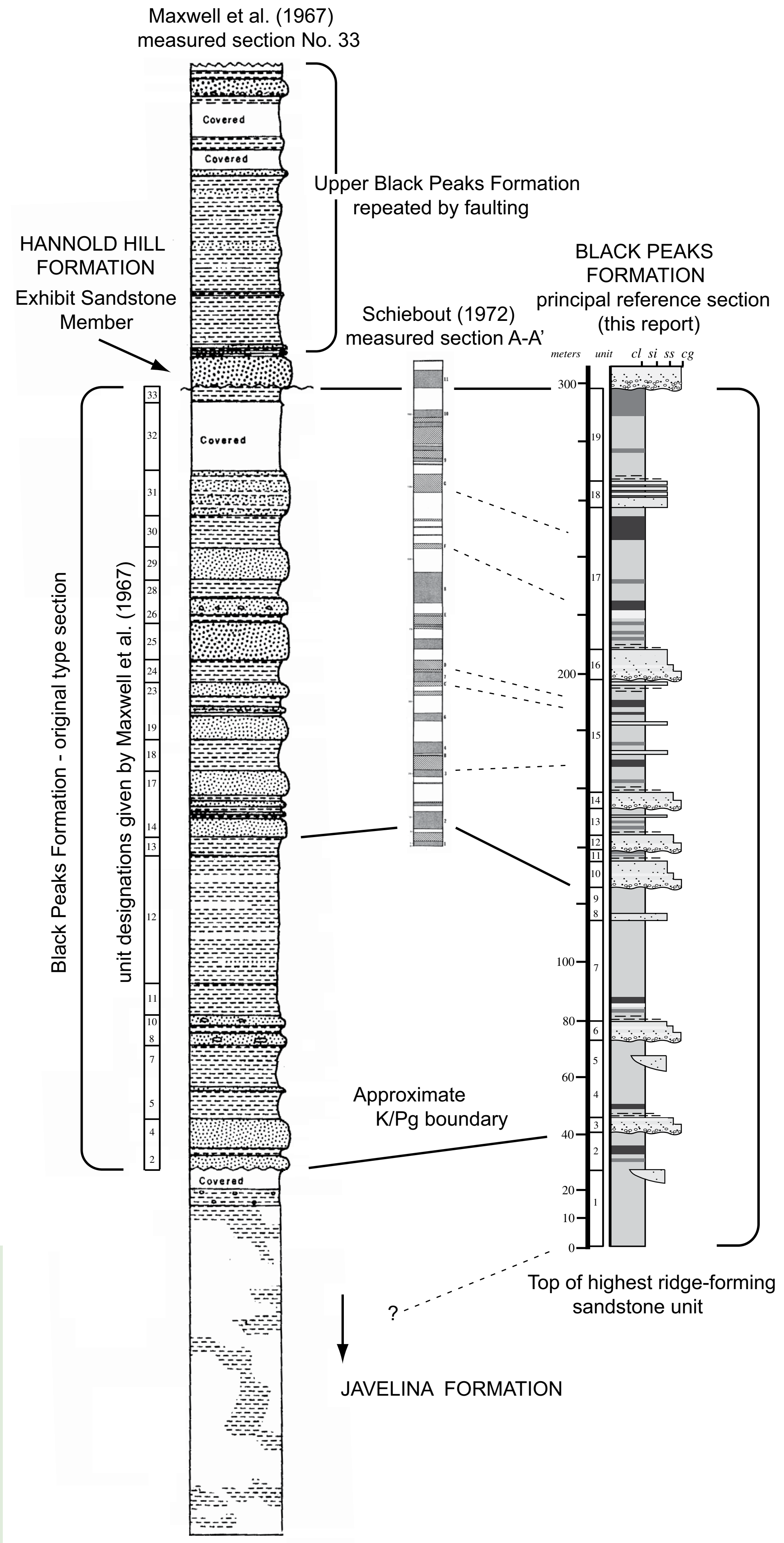


Figure 9. Original type section of the Black Peaks Formation (left, modified from Maxwell et al., 1967) showing unit numbers corresponding to the original description and correspondence with stratigraphic units recognized in the present study; section measured in the same area by Schiebout (1974); and (right) the principal reference section for the Black Peaks Formation measured in the same area for the present study (section 12); approximate level of the Cretaceous/Paleogene (K/Pg) boundary recognized as original base of formation versus top of highest ridge-forming sandstone of Javelina Formation recognized in the present study. cl—claystone; si—siltstone; ss—sandstone; cg—conglomerate.

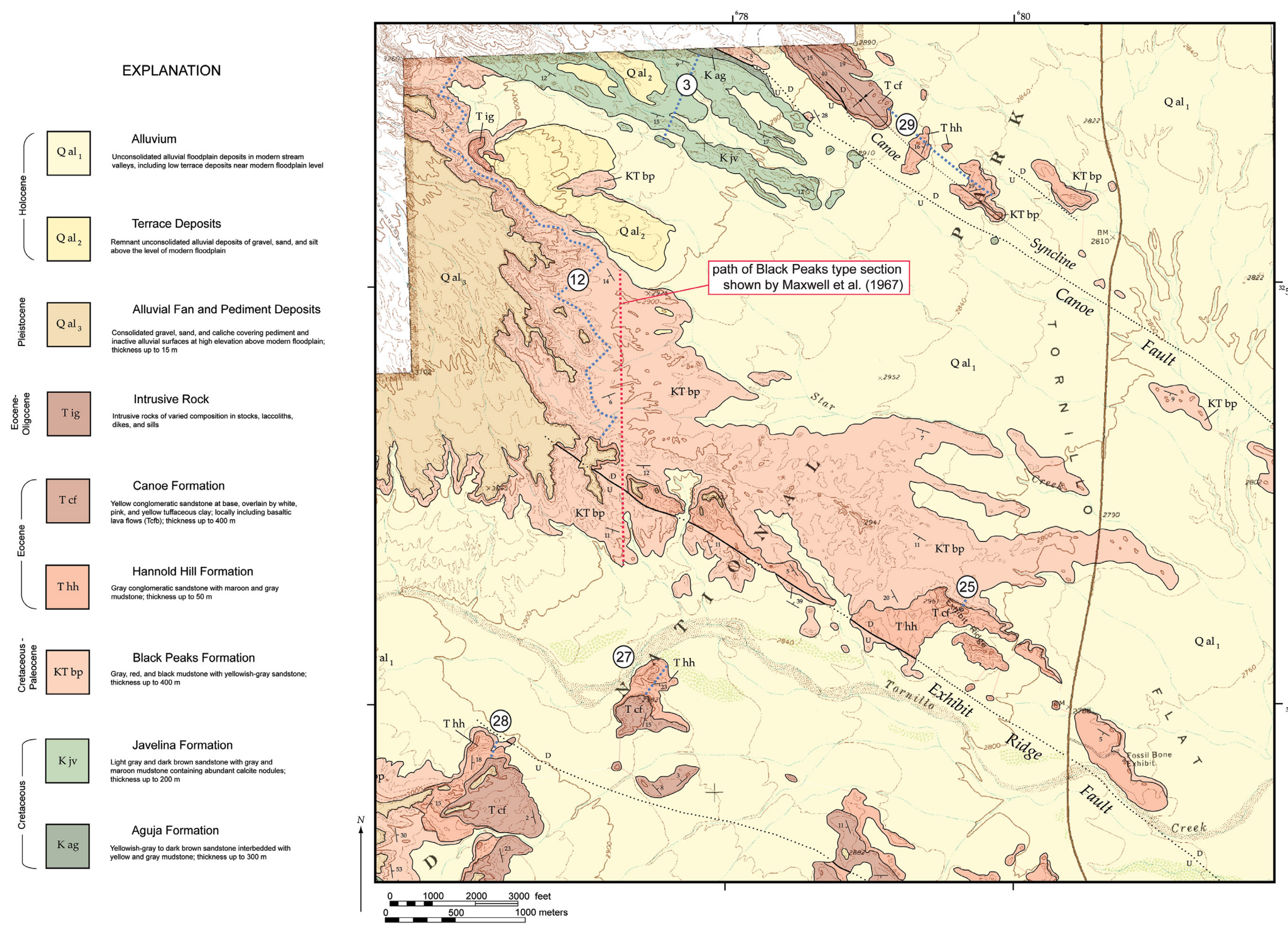


Figure 10. Geologic map of the type area of the Black Peaks Formation on western Tornillo Flat in Big Bend National Park, showing path of original type section measured by Maxwell et al. (1967) and that part of the section identified as Black Peaks Formation in the present study.

elsewhere on Tornillo Flat; but no useful fossils have ever been collected from the boundary interval in this vicinity. As noted above, however, fossils are generally scarce in these deposits, and it is impossible to precisely locate the K/Pg boundary in most exposures, including at the Black Peaks type area. Moreover, this basal sandstone bed indicated by Maxwell et al. (1967) is not a prominent ridge-forming unit; it is lenticular and difficult to recognize, and even absent in some exposures, and thus impractical to recognize as the base of the Black Peaks Formation. The base of this sandstone bed (Fig. 9; unit 3 of the present Tornillo Flat section 12) is 43 m above the top of the Javelina Formation as recognized here and depicted in recent mapping (Turner et al., 2011). If all of the strata mentioned above (i.e., the entire "mudstone-dominated" interval of Lehman, 1985) are included within the Black Peaks Formation, then the complete thickness of the formation measured here is 302 m. Subtracting the 43 m below the basal K/Pg sandstone bed identified by Maxwell et al. (1967), the remaining thickness (259 m) determined here is remarkably close to the 264 m they originally measured. A total thickness of 285 m for the Black Peaks Formation type section was measured by Bataille et al. (2016), using the formation contacts advocated here and mapped by Turner et al. (2011), a value that is also comparable to that determined in the present study.

The only other outcrop of Black Peaks Formation mapped by Maxwell et al. (1967) is in the unnamed syncline west of Glenn Springs; and in this area, they definitely included the entire "mudstone-dominated" interval within the formation because the top of the section there is marked by the "log jam sandstone" marker bed (Fig. 11, section 16; see below). As described above in relation to the underlying Javelina Formation, and as shown in recent mapping (Turner et al., 2011), the lower boundary of the Black Peaks Formation is emended such that it includes not only the 111 m of predominantly mudstone originally included by Maxwell et al. (1967) but the entire "mudstone-dominated" interval of Lehman (1985) down to the top of the prominent ridge-forming sandstone that marks the top of the Javelina Formation. These strata are mostly Paleocene in age, as is the remainder of the Black Peaks Formation, and as adjusted, the Cretaceous–Paleogene boundary resides within the lowermost part of the Black Peaks Formation, near the contact with the underlying Javelina Formation.

Upper Contact

The top of the Black Peaks Formation was placed by Maxwell et al. (1967, p. 98) at "the base of a sandstone below Lower Eocene (Wasatchian) mammalian remains." This somewhat obscure contact reflected an attempt by Maxwell et al. (1967) to locate the formation boundary coincident with or close to the Paleocene/Eocene series boundary. However, vertebrate fossils are extremely scarce in this part of the stratigraphic section, and it has since proven impractical, if not impossible, to recognize this sandstone bed in any exposures outside of Tornillo Flat, including at the type area (where even here it is shown as a dashed contact on the map given by Maxwell et al., 1967). The Paleocene/Eocene series boundary cannot be confidently identified in the section (see below). Furthermore, neither Maxwell et al. (1967) nor Schiebout (1970) recognized a fault, herein termed the "Exhibit Ridge fault" that interrupts and repeats the upper part of the Black Peaks type section, including the contact with the overlying Hannold Hill Formation (Fig. 10; Beatty, 1992; Lehman, 2004). For example, in the measured section given by Maxwell et al. (1967; their plate IX, section 33) the lower part of the overlying Hannold Hill Formation includes a "black clay" that is almost certainly one of the distinctive black marker beds recognized by Schiebout (1970; her marker bed "G") in the uppermost Black Peaks (Fig. 9). These structural complications probably led to errors in recognition and mapping of the upper contact of the formation.

Fortunately, the overlying Hannold Hill Formation has a lithologically distinctive and laterally continuous ridge-forming sandstone unit—the Exhibit Sandstone Member (named by Maxwell et al., 1967), which can be recognized in all exposures. The base of this conglomeratic sandstone is readily identified, easily located, and corresponds with a sharp break in the physiographic expression of the strata. This contact may also mark an erosional disconformity recording a hiatus of uncertain duration (see below). Beatty (1992) suggested that the upper boundary of the Black Peaks Formation be raised slightly to correspond with the base of the Exhibit Sandstone Member of the Hannold Hill Formation. This slight change allows for consistent recognition of the formation contact throughout the region. This position also coincides with an obvious lithologic change, a marked physiographic break, and may correspond to a depositional sequence boundary. The base of this unit is therefore mapped as the Black Peaks/Hannold Hill contact (see below). The mapped position of the contact shown by Maxwell et al. (1967) on Exhibit Ridge is actually quite close to that shown here, and it is possible that the lower exposure of the Exhibit Sandstone Member, repeated by faulting, was actually the contact they originally selected.

Key Beds

The middle part of the Black Peaks Formation has a laterally extensive fluvial channel sandstone interval with abundant petrified logs (Figs. 8 and 11). Wherever this sandstone interval is exposed, numerous fossil logs are observable. Close inspection reveals that the logs occur in two distinct sandstone layers, a few meters apart, separated by a mudstone bed. This sandstone interval has been referred to informally as the "log-jam sandstone" (Lehman and Busbey, 2007). In the foothills of Exhibit Ridge, the "log-jam sandstone" can be traced for more than five kilometers, with many hundreds of logs exposed, one every several meters or so. The "log-jam sandstone" is exposed all around Tornillo Flat, repeated in each fault block, as well as on the south side of the Chisos Mountains over 30 km to the south, and as far as 40 km to the west at Dogie Mountain and farther southwest in the valley east of Pena Mountain. Most or all of the logs lie prone in the sandstone; some are up to 8 or 9 m long with root masses 1–2 m across. Of the many logs examined microscopically,

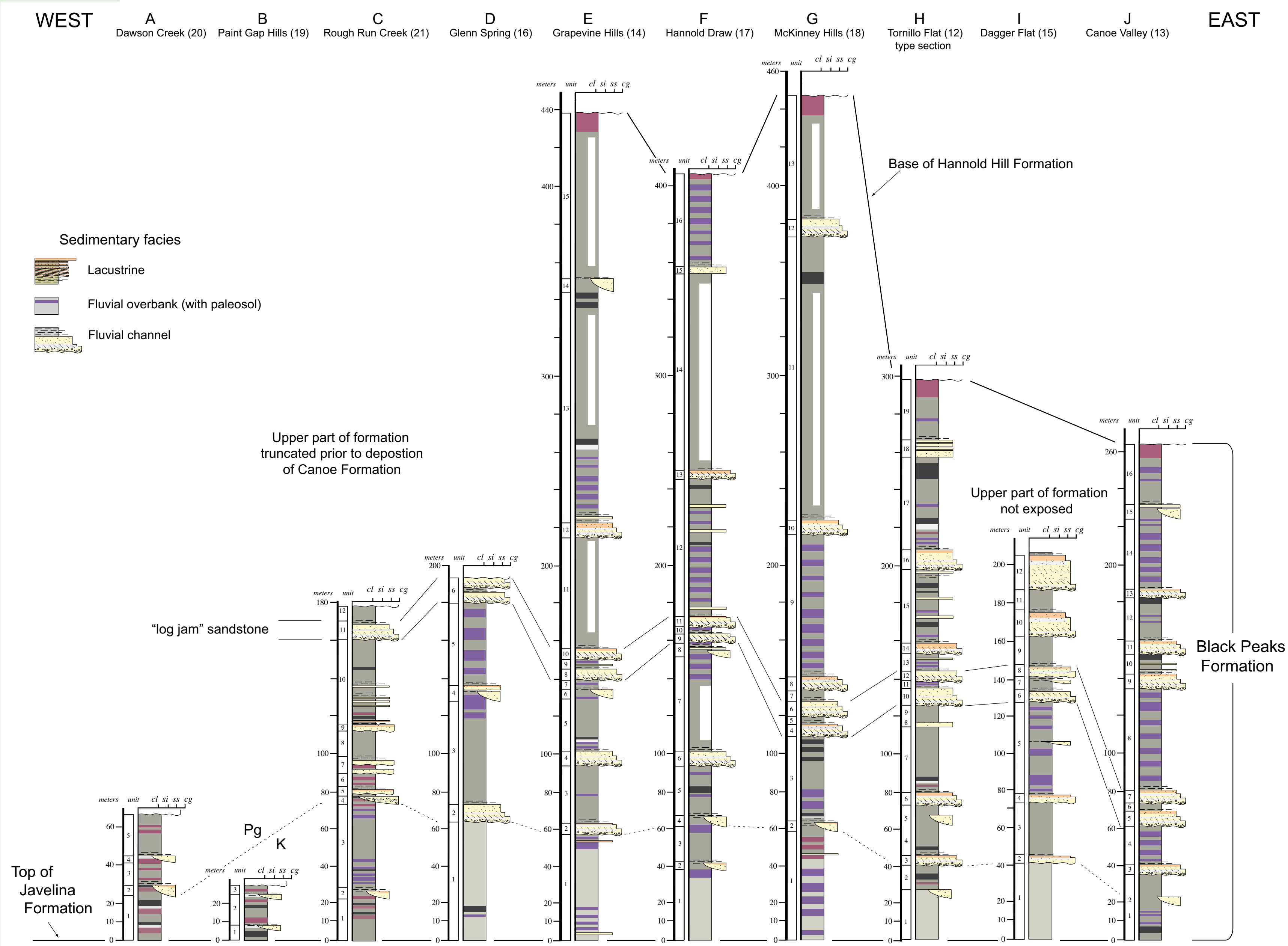


Figure 11. Correlation of key stratigraphic sections of the Black Peaks Formation in Big Bend National Park, Texas (see Supplemental Material, section II [text footnote 1] for detailed descriptions of sections). cl—claystone; si—siltstone; ss—sandstone; cg—conglomerate.

all but two belong to the same species—*Paraphyllanthoxylon abbotti* (Wheeler, 1991; Wheeler and Lehman, 2009). There are undoubtedly many thousands of specimens exposed in the Park. Very few petrified logs are found immediately below or above this zone; so it can be used with some confidence for correlation of isolated exposures (Fig. 11).

The distinctive black mudstone beds recognized by Schiebout (1970; her marker beds "B–G") can be traced several kilometers along the foothills of Exhibit Ridge, and some of these may also be identified in exposures northwest and west of McKinney Hills (see section 18). However, there are additional similar black mudstone beds stratigraphically lower than those identified by Schiebout (1970), and it is difficult to distinguish among these beds in distant exposures for correlation purposes. Nevertheless, their presence alone is a key feature of use in recognizing isolated exposures of Black Peaks Formation (Fig. 11).

In all areas, the Black Peaks Formation is divisible roughly into three parts—a lower "mudstone-dominated" interval that spans the K/Pg boundary, a central "sandstone-dominated" interval that includes the "log-jam sandstone" near its base, and an upper "mudstone-dominated" interval; each of these is typically ~100 m in thickness (Fig. 11).

Distribution

The Black Peaks Formation is much more extensive in the western part of the Park than was shown by Maxwell et al. (1967), although it is thinner over much of this region (less than 200 m), and only the lower part of the formation is present in this region due to erosional truncation prior to deposition of the overlying Canoe Formation or Chisos Formation (Fig. 11). Only the lower "mudstone-dominated" interval up to the "log-jam sandstone" remains over much of that region. The Black Peaks Formation is also more extensive in the region south of the Chisos Mountains than previously shown, and here also only the lower part of the formation is present.

Thickness Variation

The principal reference section on western Tornillo Flat is 302 m in thickness (section 12), and southwest of "Pterodactyl Ridge" on northern Tornillo Flat, the thickness is 267 m (Fig. 11; section 13). In both of these areas, the formation is fairly well exposed, and structural complications are minimal. However, both areas straddle the boundary between the Park and adjacent Rosillos Mountain Ranch, and some of the best exposures for parts of the formation exist outside the Park on the adjacent private property.

On eastern Tornillo Flat, northwest of McKinney Hills (section 18) and near the mouth of Hannold Draw (section 17; the "Crusher 2" section of Maxwell et al., 1967; plate IX, section 26), the formation is significantly thicker, 408–449 m, but large parts of the lower and upper mudstone intervals are covered by alluvium in these areas. Nevertheless, these thickness determinations are likely to be reasonably accurate; there appears to be little structural complexity in those areas. The thickest section of the Black Peaks Formation was measured north of Grapevine Hills (section 14 of the present study), where as much as 540 m may be present (Fig. 11). However, the uppermost 150 m of this section are mostly covered, and its thickness was estimated from the dip. It is possible that a fault obscured in the covered interval has exaggerated the true thickness here. At least the lower 410 m of the section are relatively clear of cover, and its measured thickness is probably accurate. Nearby on the east side of the Grapevine Hills laccolith, the "log-jam sandstone" is exposed along the flank of the intrusion, and the interval above that to the base of the Hannold Hill Formation is also fairly well exposed. Here, that interval alone is 221 m in thickness, compared to 299 m measured north of the intrusion. Hence, the total thickness of Black Peaks Formation measured north of Grapevine Hills may be as much as 78 m excessive (462 m instead of 540 m) and, if so, closer to the value determined for eastern Tornillo Flat. In all of these areas, the upper contact of the Black Peaks with the Hannold Hill Formation is present. The total thickness appears to diminish northward to Canoe Valley. Elsewhere in the Park, the Black Peaks Formation is unconformably overlain by strata younger than the Hannold Hill Formation, and so its remaining thickness is typically 200 m or less.

During recent mapping, a previously unrecognized exposure of the base of the Hannold Hill Formation (Exhibit Sandstone Member) was found on the northern bank of Tornillo Creek northwest of McKinney Hills (Fig. 12). This outcrop makes it possible to measure the complete section of Black Peaks Formation there also, and to place the vertebrate fossil localities (TMM 40147; locality T2 of Maxwell et al., 1967) near the Black Peaks intrusions in their proper stratigraphic position, which was previously uncertain. Maxwell et al. (1967; plate IX, sections 34 and 35) measured several partial sections in that area, including the central 87 m of Black Peaks Formation, equivalent to units 3 through 9 of the present section (Fig. 11; McKinney Hills section 18). The significant vertebrate fossil collections made at TMM 40147 were taken from the interval between unit 4 and unit 6 of the present section. This zone is just above the "log-jam sandstone" and slightly higher stratigraphically than TMM 41377 (the "Schiebout-Reeves Quarry" of Schiebout, 1974) that is just below the "log-jam sandstone" on western Tornillo Flat.

The lower part of the Black Peaks Formation, below the "log-jam sandstone," varies substantially in thickness across the Park. In most areas, this interval ranges from 100 m to 180 m in thickness; however, at Pena Mountain near the southwestern corner of the Park, it is only 74 m; at the northernmost complete section near Canoe Valley, it is only 60 m, and near Grapevine Hills, it is only 45 m (on Rosillos Mountain Ranch; Adams, 2014). Similarly, the interval between the top of the Javelina Formation and the K/Pg boundary (where it can be identified) also varies substantially—from in excess of 80 m on Rough Run Creek to less than 30 m on Dawson Creek. These dramatic thickness changes indicate that there were significant local variations in sediment accumulation across the region during latest Cretaceous through early to middle Paleocene time (see below).

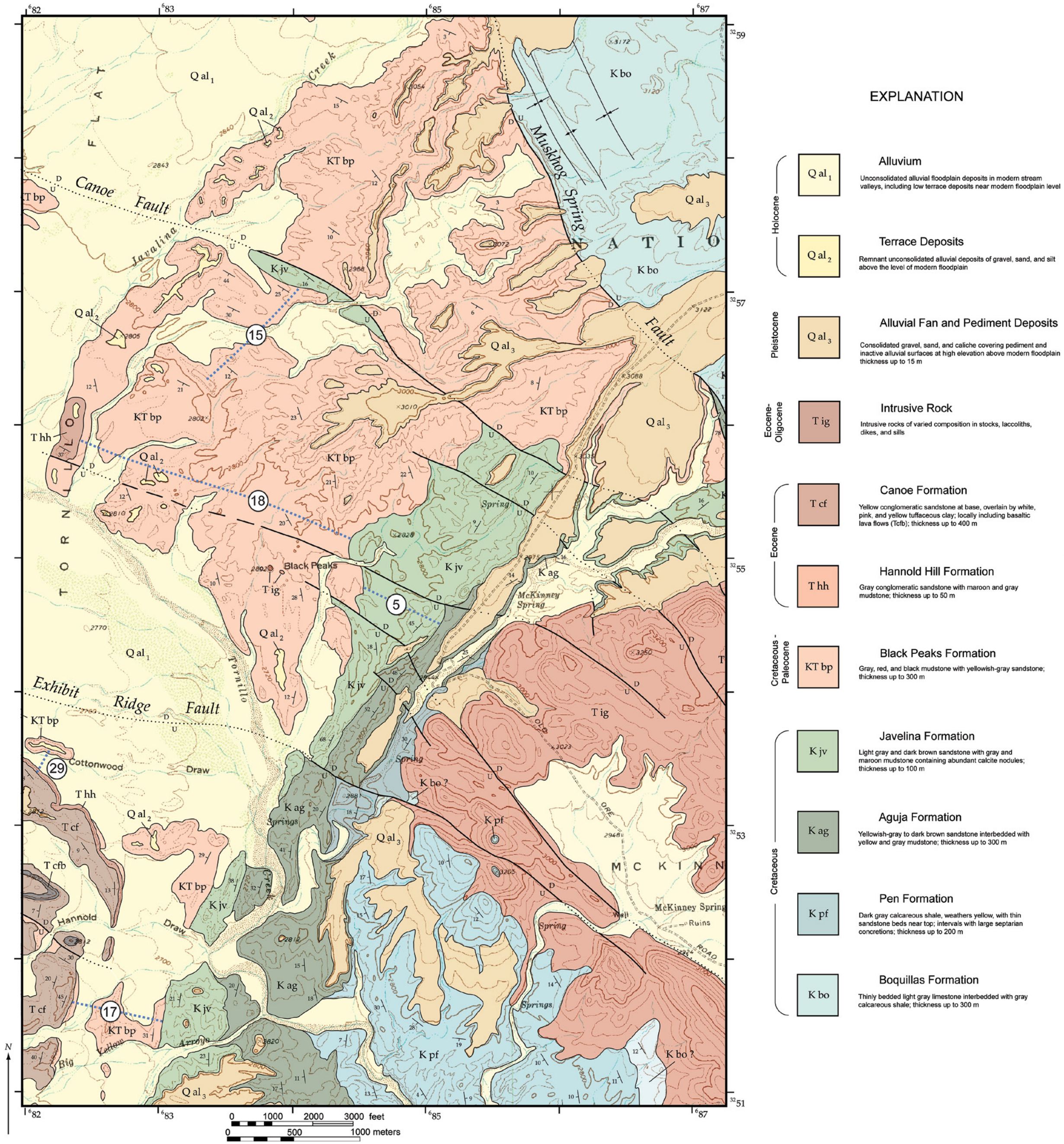


Figure 12. Geologic map of region north and west of McKinney Hills showing distribution of formations in the Tornillo Group and location of stratigraphic sections.

The "log-jam sandstone" in the middle of the Black Peaks Formation is consistently ~20 m thick, wherever it can be recognized. The upper part of the formation is absent over most of the western and southern parts of the Park, but also appears to vary significantly in thickness where its upper contact with the Hannold Hill Formation is exposed. In part, this may be due to extensive cover in those areas and resulting incorrect estimations of total thickness (see above); but where its full thickness can be measured on southern Tornillo Flat, this upper interval is between 200 and 300 m thick, while it is only 160–180 m on northern Tornillo Flat (Fig. 11).

Facies Variation

The sedimentary facies of the Black Peaks Formation are generally uniform in character stratigraphically and regionally across the Park. There are significant lacustrine deposits, however, in the lowermost part of the formation (organic-rich shale and thin limestone beds with charophyte algae and aquatic gastropods); these facies are poorly developed or entirely absent in the upper part of the formation. Although overbank flood-plain deposits comprise the dominant facies in the formation, the distinct color bands that reflect well-differentiated paleosol horizons within these facies vary both stratigraphically and regionally (Fig. 11). In some stratigraphic intervals, the paleosol horizons are very pronounced; in others, they are absent or muted. Some intervals with numerous prominent paleosol horizons grade laterally into correlative intervals having fewer, less pronounced horizons. Variations in alluvial paleosol successions are thought to correspond with global or regional climate changes, but also with local differences in the original soil-forming processes and changes in the intensity or duration of soil development (e.g., Retallack, 1990). If the marked thickness changes within each interval of the Black Peaks Formation reflect significant local variations in sedimentation rate (see above), this would be expected to result in differing paleosol maturity. Although detailed studies of the Black Peaks paleosol succession have been conducted at a single stratigraphic section on Tornillo Flat (e.g., White and Schiebout, 2003, 2008; Bataille et al., 2016), it has not been possible to discern a consistent stratigraphic or regional pattern to their occurrence that would allow for correlation across the Park.

Nature of the K/Pg Boundary

An attempt was made during the original mapping of the Tornillo Group by Maxwell et al. (1967) to place the Javelina–Black Peaks formational contact at the K/Pg boundary (see historical account given by Wilson and Runkel, 1989). Later workers, using the geologic map of Maxwell et al. (1967) for guidance, therefore believed that strata shown as Javelina Formation were entirely Cretaceous in age, and those shown as Black Peaks Formation were assumed to be entirely Paleocene in age. Because the lowermost Paleocene faunas recovered from the Black Peaks Formation by Wilson (in Maxwell et al., 1967) and Schiebout (1974) were ascertained to represent a Torrejonian (middle Paleocene) assemblage, it was reported at that time that the earliest Paleocene (Puercan) interval was absent in the Tornillo Group, and that the K/Pg boundary here is unconformable. So, in the early 1970s, it was generally believed that strata of earliest Paleocene age were either not deposited in Big Bend or were eroded away prior to deposition of the Black Peaks Formation.

It was subsequently discovered, however, that the K/Pg boundary does not everywhere coincide with the position of the Javelina/Black Peaks formational contact as it had been mapped by Maxwell et al. (1967). Lawson (1972) collected a Paleocene mammalian assemblage at a site (TMM 41400, LSUMG 111; aka "Tom's Top") in strata mapped as the Javelina Formation on Dawson Creek. Another Paleocene site (TMM 42327, LSUMG 108; aka "Dogie") was found in strata mapped as Javelina Formation on Rough Run Creek. As described above, this was a result of inadvertently mapping much of the lowermost "mudstone-dominated" interval of the Black Peaks Formation as the upper part of the Javelina Formation over broad areas of the western part of the Park.

Standhardt (1986, 1995) conducted a screen-washing effort at the "Tom's Top" and "Dogie" sites, as well as others, to better document the vertebrate faunas within the K/Pg boundary interval. The "Tom's Top" and "Dogie" sites did not yield definitively Puercan taxa, and so have been a subject of varied interpretation (e.g., Standhardt, 1995; Williamson, 1996; Lofgren et al., 2004; Lehman and Busbey, 2007). Recently, Leslie et al. (2018) conducted a thorough review of the fauna known from both sites and determined that they are middle Torrejonian (To2) in age. These sites are, however, ~20 m ("Tom's Top") to 80 m ("Dogie") above the highest occurrence of dinosaur bones in those areas, leaving open the possibility that early Paleocene (Puercan) sites might be present but remain undiscovered. Despite repeated prospecting of the 20–80 m stratigraphic interval between the highest in situ dinosaur bones and lowest Paleocene mammal sites in the "Tom's Top" and "Dogie" site areas, no significant additional fossiliferous sites have been identified there. Lehman and Coulson (2002; see also Straight, 1996; Coulson, 1998) reported a Paleocene vertebrate fossil site (TMM 43621-2, aka "Hoplochelys Ridge") only 2 m above an in situ *Alamosaurus* skeleton (TMM 43621-1) north of Grapevine Hills. However, the only diagnostic mammalian fossil recovered thus far at this site is a single lower molar of *Periptychus* sp. A definitive Torrejonian fauna (with the condylarth *Periptychus carinidens*) was collected 20 m above the "Hoplochelys Ridge" site (TMM 43380).

Lehman (1990) and Lehman and Busbey (2007) reported little success in identifying any possible physical or geochemical evidence for the K/Pg boundary iridium abundance anomaly or impact horizon. Recently Cobb (2016), however, documented what may be the K/Pg boundary tsunami deposit on Rough Run Creek (a bed informally referred to previously as the "odd conglomerate" by Lehman and Busbey, 2007). Exposures in this area indicate that strata within the K/Pg boundary interval may be preserved at least locally within the lower Black Peaks Formation. The bioturbated interval that Wiest et al. (2018)

and Leslie et al. (2018) hypothesized may represent the K/Pg boundary in the Dawson Creek section is at a stratigraphic level at least 60 m below the position of the boundary established on the basis of in situ dinosaur specimens nearby on Rough Run Creek. The Dawson Creek section may be unlikely to preserve a conformable K/Pg boundary because it lies along the south flank of the Terlingua monocline, a Laramide structure that was active during deposition of the Javelina and Black Peaks formations (see below).

Biostratigraphy

The Black Peaks Formation preserves a succession of middle Torrejonian (TMM 42327, 41400, and 40147, To2 interval zone) through Tiffanian (TMM 40536, probably Ti3; TMM 41365, probably Ti5) vertebrate fossil sites (Supplemental Material, section II [footnote 1]). Wilson (in Maxwell et al., 1967), Schiebout (1974), Schiebout et al. (1987), Standhardt (1986, 1995), and Leslie et al. (2018) have documented the vertebrate fauna from these sites. Although Schiebout (1974) reported that possible Clarkforkian or Wasatchian sites may occur in the uppermost part of the Black Peaks Formation, the supposed Clarkforkian site (TMM 41364) yielded the taeniodont *Psittacotherium*, which otherwise has its last appearance in Tiffanian (Ti5?) strata in North America (Lofgren et al., 2004). The purported Wasatchian site (TMM 41221) yielded a mandible fragment of *Hyracotherium* and an incisor of *Coryphodon* "both from float on a sandstone" (Schiebout, 1995); however, the previously unrecognized Exhibit Ridge fault (Fig. 9; see above) makes stratigraphic placement of the site uncertain, and so the specimens might have been derived from the overlying Exhibit Sandstone Member of the Hannold Hill Formation, which bears definitive in situ Wasatchian vertebrates (see below). It has not been possible to unequivocally identify the geochemical isotopic excursion associated with the Paleocene/Eocene boundary (Paleocene/Eocene Thermal Maximum [PETM]; White and Schiebout, 2003, 2008; Bataille et al., 2016). The fluvial sandstone interval in the uppermost part of the Black Peaks Formation (Fig. 11; unit 18 of section 12), which Schiebout (1974) reported as the site of TMM 41221, may also record a significant change in stream regimen that Bataille et al. (2016) interpreted to coincide with the Paleocene/Eocene boundary. Nevertheless, it remains uncertain if the Paleocene/Eocene series boundary occurs within the uppermost part of the Black Peaks Formation, and, if so, at what stratigraphic level, or, if instead, it lies at the base of the overlying Hannold Hill Formation.

HANNOLD HILL FORMATION

The Hannold Hill Formation consists predominantly of well-indurated coarse conglomeratic sandstone beds with intervening mudstone beds; therefore, this formation is a prominent ridge-forming unit (Fig. 13). There are two laterally extensive sandstone units; the lower one was formally named the Exhibit Sandstone Member (Maxwell et al., 1967). Both sandstone units hold up distinct cuestas and include thick lenses of conglomerate that are immediately recognizable and distinct from any other conglomerate beds in the Tornillo Group (Fig. 13). The conglomerates are composed of well-rounded pebbles and cobbles of limestone, sandstone, and chert, along with abraded petrified wood and reworked marine bivalve shells derived from all of the underlying Cretaceous and Paleocene units. These conglomeratic sandstone beds allow for ready recognition of Hannold Hill Formation outcrops. The mudstone intervals have color bands like those in the Black Peaks and Javelina formations, but color bands are thick and alternate only between wine-red and gray. Hannold Hill mudstones lack the distinctive black beds evident in the underlying Black Peaks Formation.

Type Section

The type section of the Hannold Hill Formation was measured at the abandoned "Rock Crusher" locality on Big Yellow Arroyo (Figs. 14 and 15; Maxwell et al., 1967; plate IX, section 26). However, the distinctive conglomeratic sandstone beds of the formation and all of the diagnostic early Eocene vertebrate fossil localities exist instead to the north and west on Tornillo Flat. Tracing of the Hannold Hill strata southward from Tornillo Flat, where their relationship with the underlying Black Peaks Formation is easily observed, reveals that the Hannold Hill Formation was thinned by erosion prior to deposition of the overlying Canoe Formation and is progressively thinner to the south and east in the vicinity of the original type section (Figs. 14 and 15). In the "Rock Crusher" area, much or all of the Hannold Hill Formation is absent, and the type section was actually measured almost entirely within the underlying Black Peaks Formation. Only the uppermost part of the section in that vicinity may be correlative with the Hannold Hill Formation, as recognized on Tornillo Flat (Fig. 14).

Fortunately, Maxwell et al. (1967) measured two complete sections of the Hannold Hill Formation, one just east of the Park highway on the south side of Tornillo Creek (their section 30) and one on the north side of Tornillo Creek at Exhibit Ridge near the fossil bone exhibit (their section 31). These two sections show each of the four major subdivisions of the formation, as well as positions of several of the key vertebrate fossil sites and are comparable in thickness (39–44 m). The complete section on the south side of Tornillo Creek is herein designated a principal reference section of the Hannold Hill Formation (Fig. 16). Maxwell et al. (1967; plate IX, section 30) obtained a thickness of 42 m for this section. This same section was measured for the present study, and a total thickness of 50 m was determined (Fig. 16).

Lower Contact

An attempt was made during the original mapping of the Tornillo Group in Big Bend to place the Black Peaks/Hannold Hill formational contact at the Paleocene–Eocene series boundary (see above). However, a recognizable lithologic

Figure 13. Outcrop features of Hannold Hill Formation: (A) base of Hannold Hill Formation on Tornillo Flat (unit 1, section 25) showing Exhibit Sandstone Member resting on thick purple mudstone interval typical of the uppermost Black Peaks Formation; (B) Hannold Hill Formation on western Tornillo Flat (section 27) showing entire section from Exhibit Sandstone Member to lower mudstone, upper sandstone, and upper mudstone overlain by Canoe Formation; (C) Hannold Hill Formation north of Grapevine Spring (section #28) showing typical dark yellowish-brown sandstone and weakly banded purple and gray mudstone (Exhibit Sandstone, lower mudstone, and upper sandstone); (D) upper sandstone and upper mudstone intervals of Hannold Hill Formation overlain by Canoe Formation northwest of Grapevine Spring; (E) upper sandstone interval north of Grapevine Spring showing thick basal conglomerate overlain by sandstone (unit 4, section 28); (F) detailed view of upper sandstone outcrop visible in E showing interbedded sandstone and pebble and/or cobble conglomerate beds (divisions of scale on staff are 10 cm); (G) conglomerate in base of Exhibit Sandstone Member on Tornillo Flat (unit 1, section 23) composed of limestone and chert pebbles.

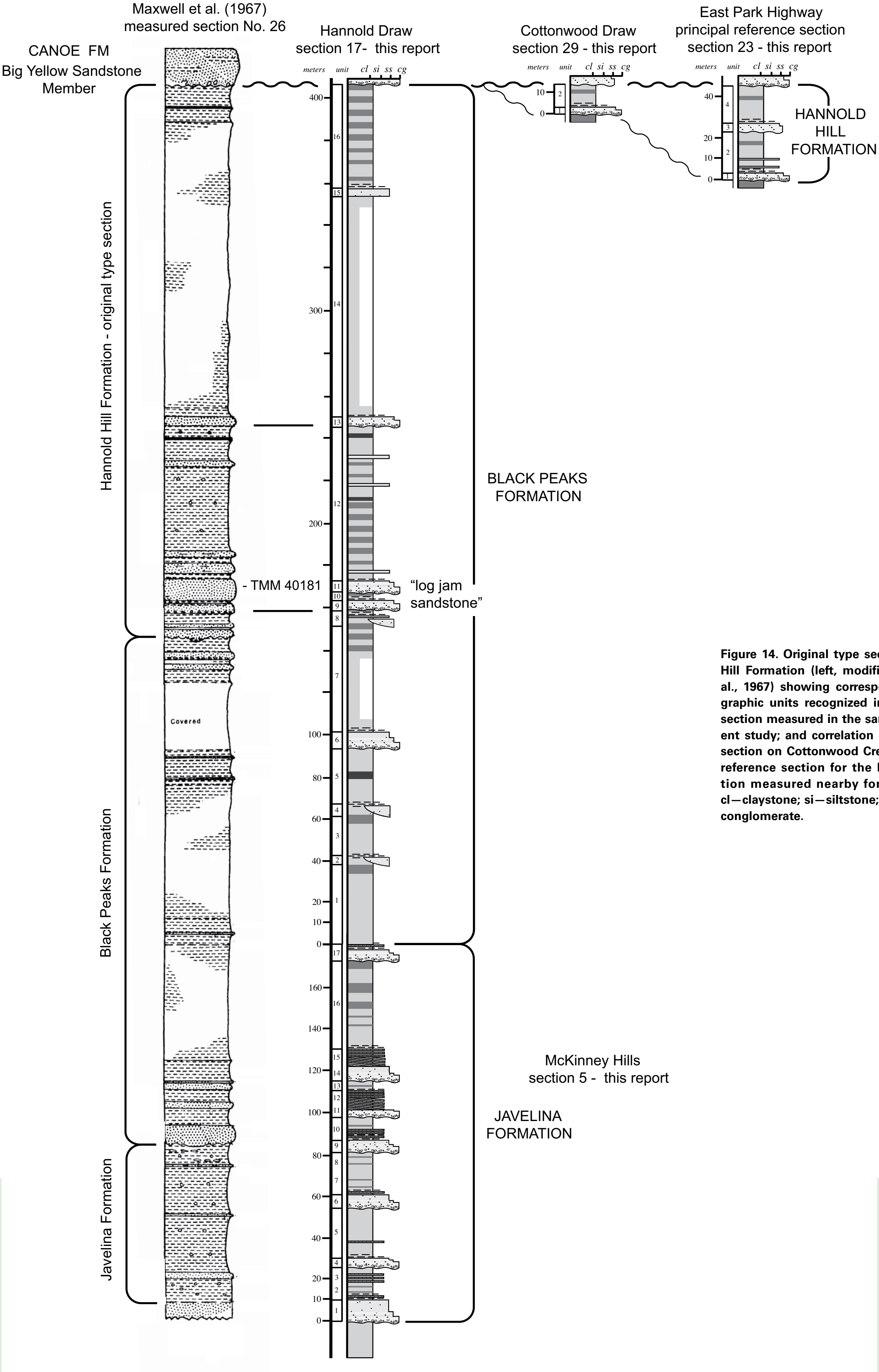


Figure 14. Original type section of the Hannold Hill Formation (left, modified from Maxwell et al., 1967) showing correspondence with stratigraphic units recognized in the present study; section measured in the same area for the present study; and correlation (right) with adjacent section on Cottonwood Creek and the principal reference section for the Hannold Hill Formation measured nearby for the present study. cl—claystone; si—siltstone; ss—sandstone; cg—conglomerate.

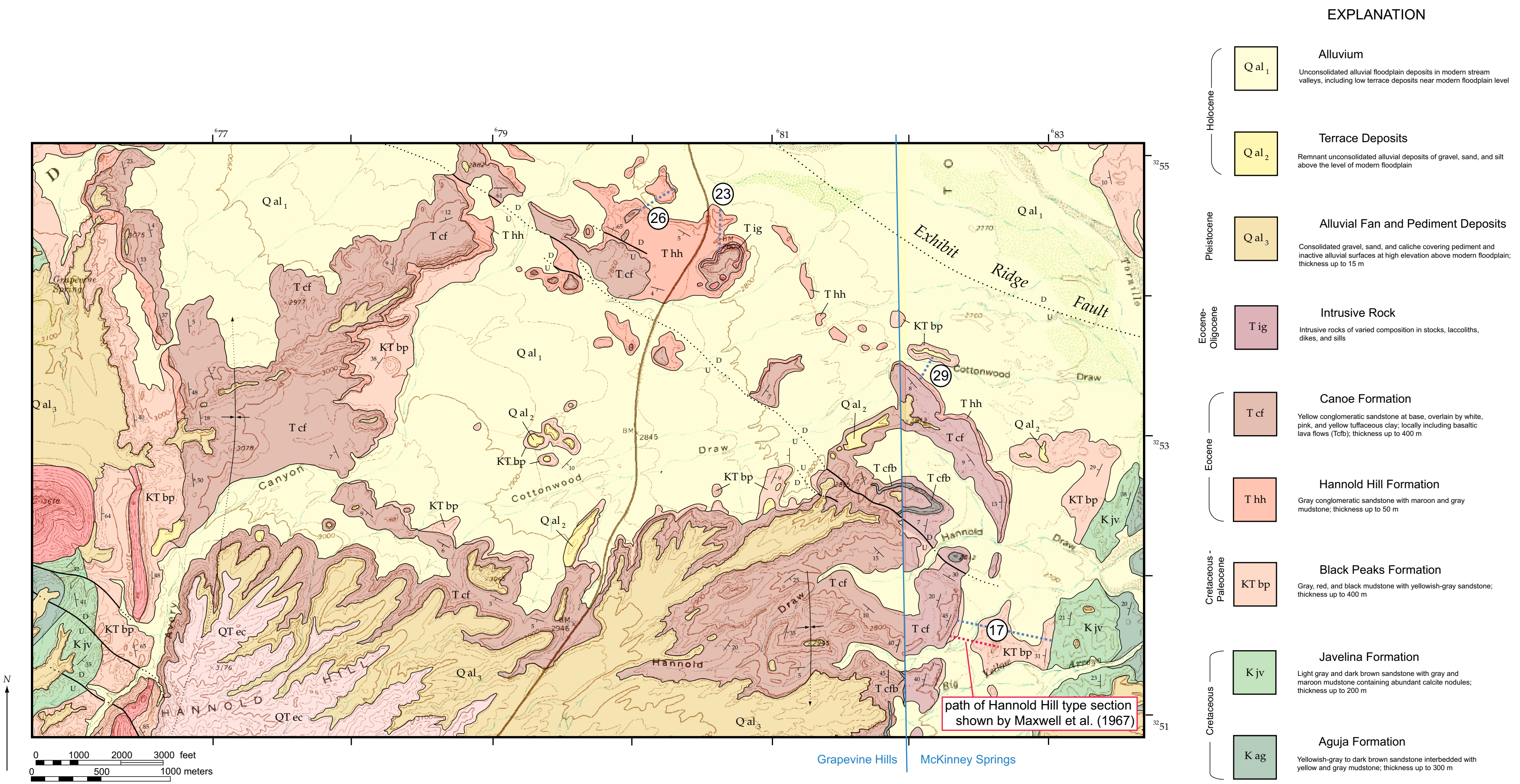


Figure 15. Geologic map of the type area of the Hannold Hill Formation on southern Tornillo Flat in Big Bend National Park, showing path of original type section measured by Maxwell et al. (1967), the principal reference section measured for the present study, and exposures identified as Hannold Hill Formation in the present study.

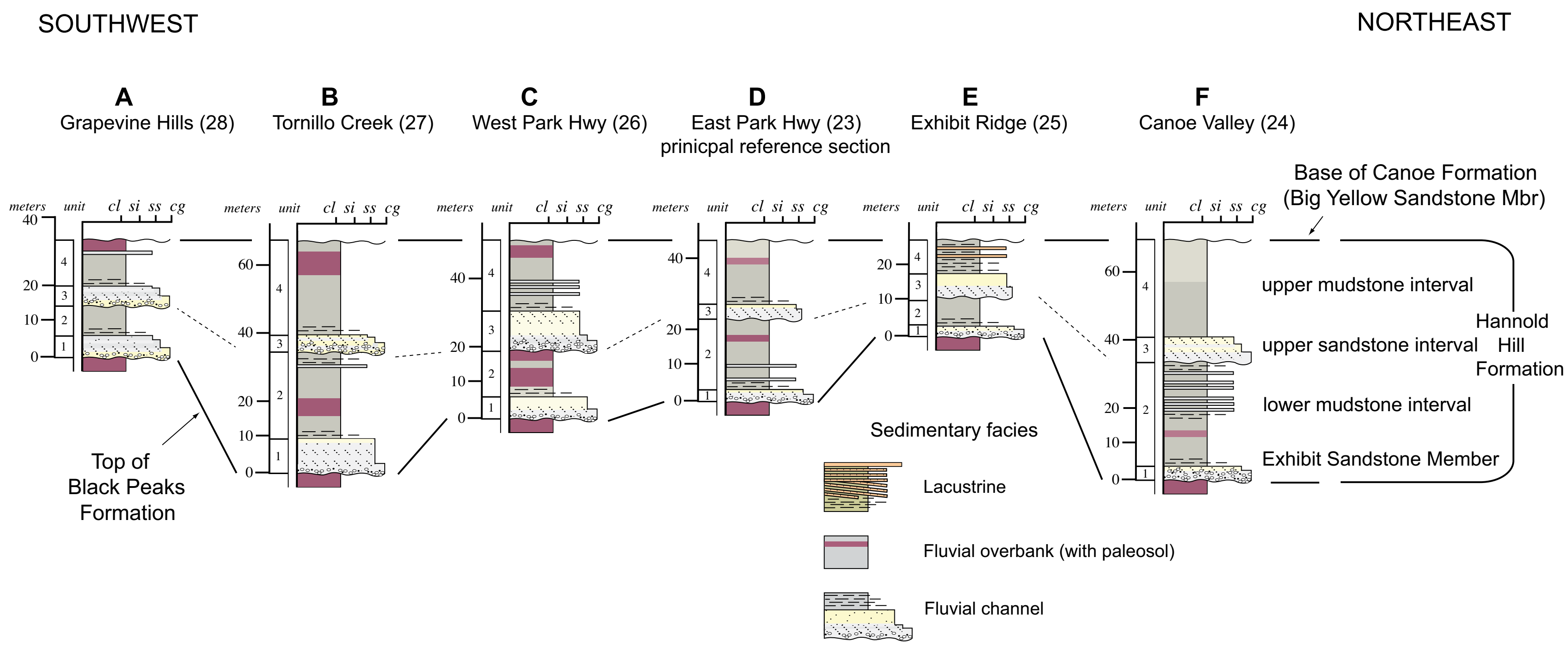


Figure 16. Correlation of key stratigraphic sections of the Hannold Hill Formation in Big Bend National Park, Texas (see Supplemental Material, section III [text footnote 1] for detailed descriptions of sections). cl—claystone; si—siltstone; ss—sandstone; cg—conglomerate.

break may not occur at the series boundary, and fossils are scarce in the critical part of the section regardless. For recent mapping of the Park (Turner et al., 2011), the base of the Exhibit Sandstone Member is mapped as the base of the formation (see above; Beatty, 1992; Lehman, 2002). This provides the only easily recognizable contact practical for mapping purposes. The Exhibit Sandstone Member is a coarse-grained sandstone with pebble-cobble conglomerate containing clasts of Lower and Upper Cretaceous limestone, chert, and sandstone, reworked Cretaceous oyster shells, and rounded cobbles of Paleocene petrified wood; conglomerates of this composition do not occur in the underlying Black Peaks or Javelina formations. The Exhibit Sandstone Member records an abrupt increase in channel paleoslope and/or increase in stream competence compared to fluvial channel deposits in the underlying Black Peaks Formation, including the sandstone interval (Fig. 11; unit 18 of section 12) that Schiebout et al. (1987) and Bataille et al. (2016) identified with the Paleocene/Eocene boundary, which does not contain such coarse extrabasinal detritus. Even so, there is no striking physical evidence for a regional unconformity at the base of the Exhibit Sandstone (see below). There is apparently no dramatic erosional truncation of the underlying Black Peaks Formation, although the upper part of the formation does thin to the northeast. Regardless, the Exhibit Sandstone Member certainly marks the base of a distinct depositional sequence. The upper sandstone unit in the Hannold Hill Formation, however, also contains coarse conglomerate of similar composition, and the two sandstone intervals cannot be distinguished from one another in isolated exposures.

Upper Contact

The upper boundary of the Hannold Hill Formation is consistently placed at the base of the Big Yellow Sandstone Member of the overlying Canoe Formation (named for the "Canoe" Valley), as originally designated by Maxwell et al. (1967). This contact is easily recognized. The base of the Canoe Formation is a thick, laterally extensive, cliff-forming yellow fluvial sandstone bed (the Big Yellow Sandstone Member) that weathers to form picturesque hoodoos and rock monuments and rests on a marked erosional truncation surface.

Rigsby (1982, 1986), Walton (1986), and Runkel (1988) conducted thorough studies of the Canoe Formation and correlative units in the Devil's Graveyard and Chisos formations. On Tornillo Flat, the Big Yellow Sandstone is readily distinguished from sandstone beds in the underlying Hannold Hill Formation due to its vivid yellow color and cliff-forming habit. In some areas, the Big Yellow Sandstone also has large limonite-encrusted petrified logs and conglomerate beds with clasts that are much larger (boulder grade) than those in the Hannold Hill Formation and composed of angular sedimentary rock fragments derived from the underlying Aguja Formation and Tornillo Group. Although conglomerate in the Big Yellow Sandstone also contains pebbles of rounded Lower Cretaceous limestone and reworked petrified wood like those observed in Hannold Hill conglomerate beds, in addition there are pebbles of Paleozoic chert and metamorphic rocks that are not present in underlying strata (Lehman, 1991). These features make it possible to identify isolated remnants of the Big Yellow Sandstone, such as those that rest on the Javelina Formation (near Mailbox Tank) and on the Aguja Formation (at "the sphinx" butte on Cottonwood Creek).

As advocated by Runkel (1988), Lehman (1988), and Wilson and Runkel (1989), and contrary to the suggestion of Schiebout et al. (1989), the Big Yellow Sandstone Member is retained herein as the base of the overlying Canoe Formation, rather than including the unit within the underlying Tornillo Group. A regional angular unconformity is present at the base of the Big Yellow Sandstone, which rests on strata as old as the Aguja Formation in places (see below). Tuffaceous strata and volcanic rocks in the overlying part of the Canoe Formation are conformable with the Big Yellow Sandstone. Hence, the Big Yellow Sandstone is retained as the basal member of the Canoe Formation. These strata were shown to be correlative with the lower part of the Devil's Graveyard Formation in the Agua Fria region west of the Park (Runkel, 1988; Wilson and Runkel, 1989), and beyond the limited area of Tornillo Flat, the strata rest on a marked regional unconformity surface. In the Tornillo Flat area, the Big Yellow Sandstone appears to be conformable with the underlying Hannold Hill Formation; however, in at least one place (see below), the base of the Big Yellow Sandstone rests on a truncated fold in the Hannold Hill Formation, and the most recent assessment of the vertebrate fauna of the Big Yellow Sandstone (Robinson et al., 2004) suggests that it is early Uintan (Ui1) in age. If this assessment is correct, the unconformity at the base of the Big Yellow Sandstone, even on Tornillo Flat, may represent some part or all of Bridgerian time.

Key Beds

Maxwell et al. (1967) recognized that the Exhibit Sandstone was sufficiently extensive to warrant designation as a formal member. Beatty (1992) also studied the internal stratigraphy of the Hannold Hill Formation and observed that the formation consists of four laterally extensive units: the basal conglomeratic sandstone (Exhibit Sandstone Member), a lower mudstone interval, an upper conglomeratic sandstone, and an upper mudstone interval. All four of these units can be traced around the southern part of Tornillo Flat and are also present in the Canoe syncline on north Tornillo Flat (Fig. 16).

The lower mudstone interval varies markedly in thickness, from a minimum of 8 m on Exhibit Ridge up to a maximum of 35 m in the Canoe Valley area. The upper mudstone interval also varies in thickness, from less than 5 m up to 27 m in Canoe Valley. This thickness variation is likely due in part to higher sedimentation rates to the northeast during deposition. However, it also reflects reciprocal thickness variation due to channeling in the sandstone intervals above and below the mudstones. The Exhibit Sandstone varies from 2 m to 10 m, and the upper sandstone varies from 5 m to 22 m in thickness. The lower mudstone exhibits alternating thick gray and red color bands; the upper mudstone is more uniformly gray, lacks marked color bands, and typically has a distinctive nodular white calcareous concretionary zone immediately below its contact with the overlying Big Yellow Sandstone Member of the Canoe Formation.

Distribution

Maxwell et al. (1967) mapped a broad area of Hannold Hill Formation resting unconformably on the Javelina Formation north of Grapevine Hills in the valley of Tornillo Creek, and east of Grapevine Hills in Avery Canyon. These exposures actually consist of Black Peaks Formation in its normal stratigraphic relationship with the underlying Javelina Formation, and the Hannold Hill Formation has a much more limited distribution than shown by Maxwell et al. (1967). The Hannold Hill Formation is also not present in the area northwest of Pulliam Peak mapped by Maxwell et al. (1967). Strata exposed in that area are within the upper part of the Black Peaks Formation.

The Hannold Hill Formation may be traced in outcrop southward along Tornillo Creek, where the upper mudstone and sandstone units are progressively truncated at the base of the Canoe Formation, and the entire Hannold Hill Formation is absent south of Hannold Draw, where the Canoe Formation rests directly on Black Peaks Formation (Fig. 15). No exposures of the Hannold Hill Formation exist anywhere west of Tornillo Flat or south of the Chisos Mountains. Instead, in these areas, the Canoe Formation (or equivalent strata in the base of the Chisos Formation) rests directly on the Black Peaks Formation or on underlying strata. An isolated exposure of Hannold Hill Formation, not recognized by Maxwell et al. (1967), exists northwest of the Black Peaks intrusions adjacent to the Exhibit Ridge fault on the north bank of Tornillo Creek (Fig. 12).

The Hannold Hill Formation appears to be entirely restricted to Tornillo Flat. The widespread occurrence, however, of abundant well-rounded limestone pebbles, otherwise so distinctive of the Hannold Hill conglomerates, also within the base of the Canoe Formation and base of the Devil's Graveyard Formation (the so-called "basal Tertiary conglomerate" of Stevens et al., 1984), suggests that strata of the Hannold Hill Formation may once have been more extensive but were largely removed by erosion or exhumed and incorporated into these younger strata prior to middle Eocene (Bridgerian to early Uintan) time.

Thickness Variation

On Exhibit Ridge and south of Tornillo Creek on either side of the Park highway, the entire thickness of the formation is 39–50 m (Fig. 16). However, beyond this area, there are significant variations in thickness over relatively short distances. A complete section of the formation, where all four units are present (Exhibit Sandstone, lower mudstone, upper sandstone, and upper mudstone) is exposed northeast of Grapevine Hills but is slightly thinner (33 m); while in the valley of Tornillo Creek only 4 km east of there, the thickness is much greater (65 m). A complete section exposed at Canoe Valley (71 m) is also nearly twice the thickness observed in the type area. The section measured by Maxwell et al. (1967; plate IX, section 32) on the southwest side of Canoe syncline only includes the upper sandstone and upper mudstone intervals (16 m). The same section measured for the present study is 26 m (section 25). Much or all of the greater thickness of the Hannold Hill Formation at Canoe Valley and northeast of Grapevine Hills is accounted for by substantial thickening of the lower and upper mudstone units. For example, in most other areas, the lower mudstone is from 8 m to 10 m in thickness; however, at Canoe Valley, it is 35 m thick. Outside of the central Tornillo Flat area, the Hannold Hill Formation was partly or completely truncated by erosion prior to deposition of the Canoe Formation, and it is missing one or more of its stratigraphically highest constituent units. As a result, in these areas, the formation is thinner than the typical ~50 m, or is absent entirely.

Maxwell et al. (1967, p. 104) discussed post–Hannold Hill truncation, and they noted "angular relations are conspicuous at several places in central Tornillo Flat." One such outcrop north of Grapevine Hills exposes the gently dipping upper sandstone interval of the Hannold Hill Formation resting directly on an upturned and truncated section of steeply dipping Exhibit Sandstone Member, with the intervening lower mudstone interval removed by erosion (Beatty, 1992; see discussion below). This particular outcrop shows striking evidence for deformation of Hannold Hill strata during deposition (see discussion below). Similarly, an area just west of the Park highway exposes the upper sandstone and upper mudstone interval of the Hannold Hill Formation in a monoclinal fold that is truncated and overlain by flat-lying Canoe Formation (see below). The entire upper mudstone interval is absent on the south side of this fold. Therefore, syndepositional deformation is at least in part responsible for the striking thickness variations observed within the formation.

Facies Variation

The four units that comprise the Hannold Hill Formation are present consistently wherever the entire formation is exposed (Supplemental Material, section III [footnote 1]). However, both the Exhibit Sandstone Member and upper sandstone interval have marked lateral variation in thickness and facies due to channeling at their base. In some areas, these units consist almost entirely of pebble-cobble conglomerate; in other areas, the units comprise sparsely conglomeratic sandstone or exclusively trough–cross bedded sandstone (Fig. 16). For example, the base of the Exhibit Sandstone includes very coarse cobble conglomerate at the Canoe syncline (section 24), but elsewhere, the conglomerate does not exceed small pebble grade. In contrast, the upper sandstone interval includes coarse cobble conglomerate at Grapevine Hills and Tornillo Creek (sections 27 and 28) but only coarse sandstone or small pebble-grade conglomerate elsewhere. These facies variations could record a southward shift in the axis of the main trunk stream during deposition of the Hannold Hill Formation.

Biostratigraphy

Schiebout (1974) reported that an early Eocene (Wasatchian) fauna (TMM 41221) may occur within a sandstone interval near the top of the Black Peaks Formation, above the highest black mudstone bed in the outcrop (marker bed "G" of Schiebout, 1970, 1974) and below the Exhibit Sandstone Member of the Hannold Hill—which yields a definitive in situ Wasatchian fauna (reviewed by Wilson and Runkel, 1989). However, it is possible that failure to recognize the "Exhibit Ridge fault" (Lehman, 2004), which results in a partially repeated section of the Black Peaks–Hannold Hill contact interval in that vicinity, may have led to problems in defining the contact between the two formations there and in determining the stratigraphic position of this site (TMM 41221), which occurred in a float block (Schiebout, 1995).

Localities within the Exhibit Sandstone (e.g., TMM 40143, aka "Exhibit" site or T4 of Maxwell et al., 1967) include *Coryphodon*, *Hyracotherium*, *Phenacodus*, and *Phenacolemur*, which likely place the base of the Hannold Hill in the late Wasatchian (Wa7; Robinson et al., 2004). Several localities in the upper mudstone interval of the Hannold Hill (e.g., TMM 40144, aka "TT Jack's" or T5 of Maxwell et al., 1967) yield a similar fauna but also include *Hyopsodus* and *Paramys* (Hartnell, 1980). A specimen initially identified by J. Wilson (in Maxwell et al., 1967) as *Lambdotherium* (TMM 40181-1) from a site believed to be in the base of the Hannold Hill, instead pertains to *Phenacodus cf. primaevus* (J. Wilson, note dated 1975 with specimen), an identification that accords with the lower stratigraphic position of the site within the middle of the Black Peaks Formation as determined in the present study (Fig. 14).

If the late Wasatchian (Wa7; Robinson et al., 2004) age assessment for the Hannold Hill vertebrate fauna is correct, then the base of the Exhibit Sandstone Member may mark a significant disconformity. Faunas of Clarkforkian and possibly earliest Wasatchian age have not been recovered anywhere in the underlying Black Peaks section on Tornillo Flat or elsewhere in the Park. This part of the section is, however, poorly fossiliferous, and it remains possible that sites of this age are yet to be discovered, and that the base of the Hannold Hill Formation is conformable with the underlying Black Peaks Formation (e.g., Bataille et al., 2016).

DEPOSITIONAL HISTORY OF THE TORNILLO GROUP

During deposition of the Tornillo Group, stream flow was generally toward the southeast. Paleocurrent data for the Javelina Formation (Lawson, 1972; Lehman, 1985), the Black Peaks Formation (Schiebout, 1970), and the Hannold Hill Formation (Hartnell, 1980; Beatty, 1992) consistently indicate a southeastward sediment transport direction. This, along with the general similarity in fluvial sedimentary facies among the three formations indicates that the Tornillo Group comprises a compatible sequence of strata, resulting from a common depositional system (Fig. 17).

Several observations suggest that the Aguja/Javelina formational contact, which marks the base of the Tornillo Group, resulted from a significant tectonic event—most likely the regional onset of Laramide tectonism during early Maastrichtian time. The transition from northeastward sediment transport and shoreline progradation during deposition of the underlying Aguja Formation to southeastward sediment transport in the Javelina Formation records a shift in paleoslope at that time (Lehman, 1986). The occurrence of coarse chert gravel in the base of the Javelina Formation (probably derived from erosion of nodular chert in Lower Cretaceous strata) indicates that nearby sedimentary source rock terrains outside the Tornillo Basin were exposed for the first time. Sandstone in the Javelina Formation also contains abundant carbonate rock fragments and reworked marine foraminifera derived from erosion of Upper Cretaceous marine strata (Lehman, 1991). The progressively lower stratigraphic position of the Aguja/Javelina contact from west to east may indicate pre-Javelina truncation of the upper part of the underlying Aguja Formation, although this could be due at least in part to original depositional thinning of the upper shale member of the Aguja to the east (Lehman, 2009, Lehman's figure 45). The Aguja/Javelina contact does not appear to reflect a simple stratigraphic sequence boundary (for example, one resulting from a change in base level alone), but instead results from a regional tectonic event that changed the paleoslope, exposed underlying strata to erosion, and began to confine sedimentation within the margins of the Tornillo Basin (Wilson, 1970; Lehman, 1991).

The present preserved limits of the Tornillo Group lie between Mesa de Anguila to the southwest and Sierra del Carmen to the northeast (Figs. 17 and 18). Both of these ranges are thought to have formed initially as monoclinal folds during the Laramide orogeny (Cobb and Poth, 1980; DeCamp, 1985). It seems likely therefore that these two structures, facing each other, may have formed the original margins of the Tornillo Basin; however, there is only slight evidence for intraformational thinning of units within the Tornillo Group toward their preserved limits.

Western Basin Margin

The westernmost exposures of the Tornillo Group indicate abrupt thinning, primarily due to erosional truncation along the western margin of the basin. A section exposed in the valley of Alamo Creek southeast of Pena Mountain, although largely covered, is over 300 m thick and includes the entire Javelina Formation and lower part of the Black Peaks Formation up to the "log jam sandstone" and at least 100 m above that (Fig. 17). The Tornillo Group section here is comparable in thickness to that measured nearby on Rough Run Creek at Dogie Mountain (230 m), and much thicker than that present on Dawson Creek (190 m), where the Black Peaks Formation is truncated at the base of the Canoe Formation at a level ~60 m below the "log jam sandstone" (Fig. 17). The interval between the top of the Javelina Formation and the K/Pg boundary is also much thinner at Dawson Creek (~20 m) than it is at Rough Run Creek (~80 m). The intraformational thinning and more deeply truncated section on Dawson Creek may indicate that uplift of the Terlingua monocline occurred at least in part there prior to Paleocene time, and certainly before deposition of the Canoe Formation. A small reverse fault that cuts the Canoe Formation (Fig. 5), and the southerly dip of the strata here, indicate that deformation continued along the Terlingua monocline at least into middle Eocene (early Uintan) time.

Only a short distance (8 km) west of the Pena Mountain exposure is the westernmost remnant of the Tornillo Group at Sierra Aguja, where less than 30 m of Javelina Formation remain beneath the Chisos Formation (Figs. 17 and 18). So, over a distance of about eight kilometers, at least 270 m of Tornillo Group strata were removed by erosion from the westernmost edge of the basin prior to deposition of the Chisos Formation (Alamo Creek Basalt Member).

The section preserved at Sierra Aguja appears to represent only the lower part of the Javelina Formation, not a condensed section resulting from intraformational thinning of the unit. This remnant of Javelina Formation lies along the base of Mesa de Anguila and exhibits no facies contrast with typical Javelina fluvial channel and overbank deposits. If Mesa de Anguila was the site of a major Laramide monoclinal fold (e.g., DeCamp, 1985) that defined the western margin of the Tornillo Basin, then this structure must have formed after deposition of the Javelina Formation, or initially produced little topographic relief, and it was not a source terrain for sediment in either the Javelina or Black Peaks formations. Locally at many of these western exposures are channel-fill deposits of Canoe Formation (Big Yellow Sandstone or equivalent basal units of the Devil's Graveyard Formation) conformable with the overlying Chisos Formation and resting on the truncated Tornillo Group. These channel deposits indicate that uplift and truncation of the Tornillo Group occurred over much of the western Park area prior to middle Eocene time.

Eastern Basin Margin

The Javelina Formation appears to thicken to the east, from ~120 m on Dawson Creek to 180 m on eastern Tornillo Flat (Fig. 17). There is also a subtle facies change, with the distinctive lacustrine facies within the Javelina largely restricted to the eastern exposures. These observations could indicate that subsidence rates were higher along the eastern side of the Tornillo Basin or that uplift within the central part of the basin itself restricted sedimentation in some way between western and eastern sides of the basin. Evidence for the

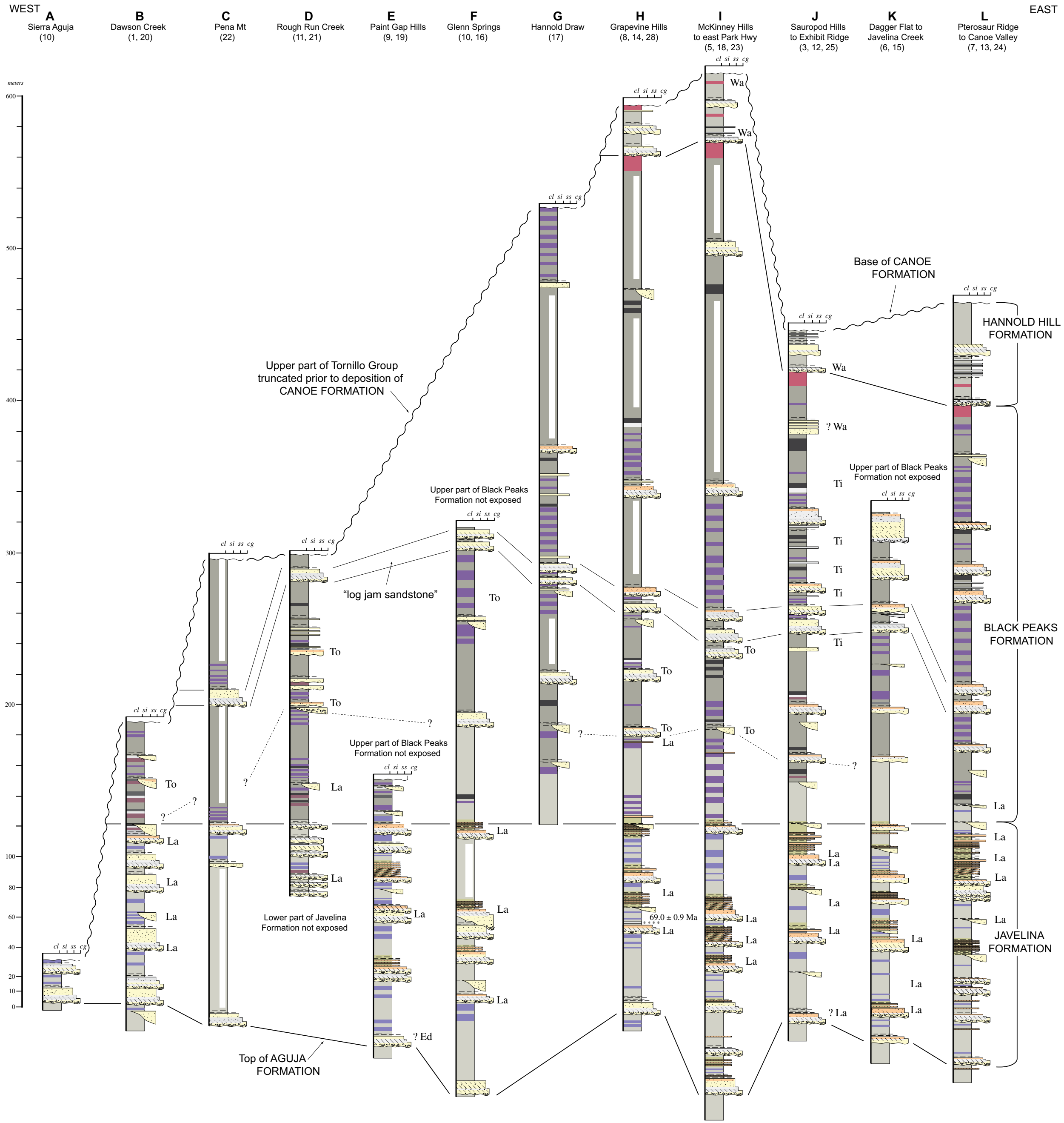


Figure 17. Correlation of key stratigraphic sections of the Tornillo Group across Big Bend National Park, using top of Javelina Formation as a datum, showing ages and positions of biostratigraphically significant vertebrate fossil localities. cl—claystone; si—siltstone; ss—sandstone; cg—conglomerate.

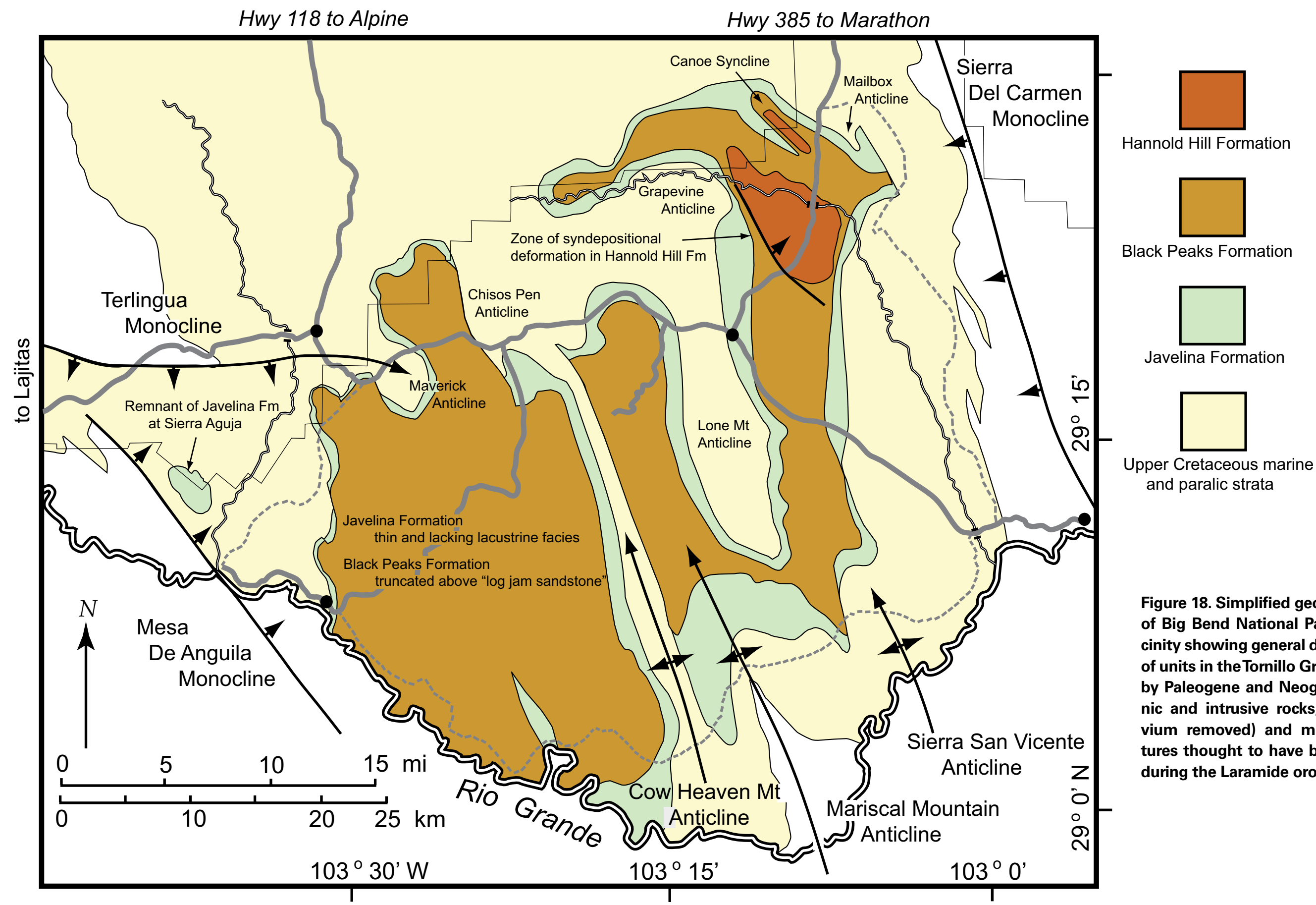


Figure 18. Simplified geologic map of Big Bend National Park and vicinity showing general distribution of units in the Tornillo Group (cover by Paleogene and Neogene volcanic and intrusive rocks, and alluvium removed) and major structures thought to have been active during the Laramide orogeny.

latter of these is the thin section of the Javelina Formation (122 m) measured along the eastern limb of a fold, herein referred to as the "Grapevine anticline" northwest of Grapevine Hills (Fig. 19; section 8). This unusually thin section might be attributable to obscure faulting (e.g., Straight, 1996) or "tectonic" thinning of one or more of the mudstone intervals within the formation along the eastern limb of the fold during deformation (see above); however, on the Rosillos Mountain Ranch ~3 km northwest of the Grapevine anticline (Fig. 19), Adams (2014) also found a markedly thinned (114 m) section for the Javelina Formation in an exposure lacking structural complexity (Fig. 20). Adams (2014) also observed that the lower interval of the Black Peaks Formation (to the base of the "log jam sandstone") is also unusually thin (45 m) in the same area. Elsewhere in the Park, the same interval is nearly three times thicker (see below). Collectively, these observations suggest that sedimentation rates in that vicinity were either lower than elsewhere in the Tornillo Basin, or that intermittent uplift in that area—perhaps development of the Grapevine anticline itself—led to erosion and thinning of the Javelina and lower Black Peaks formations over the area where the anticline would later form (Fig. 20). Regardless, net sediment accumulation in the vicinity of Grapevine anticline was less than in nearby areas to the east and west.

The Black Peaks Formation also thickens to the east; however, this is largely a result of the complete absence of the upper half of the formation in all areas west and south of Tornillo Flat (Fig. 17). The lower half of the formation (from the Javelina contact to the base of the "log jam sandstone") is relatively uniform in thickness (120–180 m) and present over most of the region. Much of

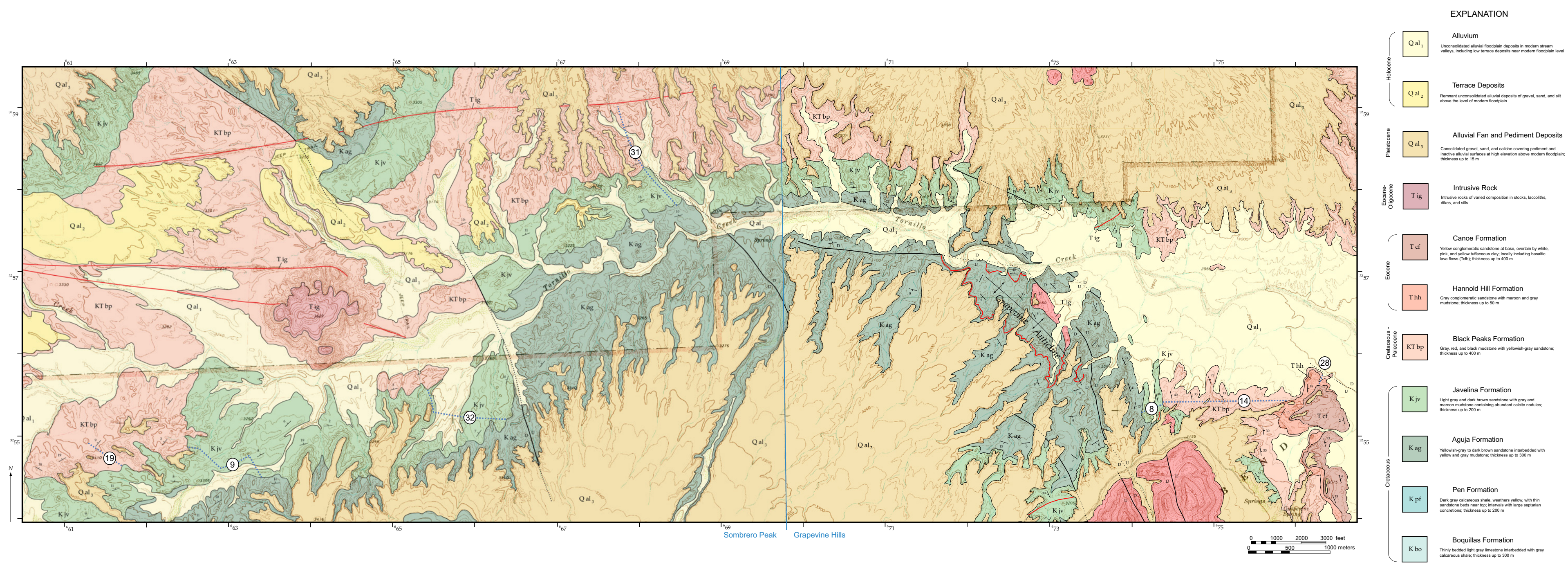


Figure 19. Geologic map of the region northwest of Grapevine Hills showing distribution of formations in the Tornillo Group and location of stratigraphic sections; part of map on Sombrero Peak quadrangle (vicinity of section 31) adapted from Adams (2014).

the 60 m variation in thickness of this interval could reflect inconsistency in placement of the gradational contact with the underlying Javelina Formation. However, in the northernmost section of the Black Peaks Formation (north of Canoe Valley), this lower interval is only 60 m thick; whereas in sections of the formation at Grapevine Hills and McKinney Hills, the lower interval is 110–120 m thick. The interval between the top of the Javelina Formation and the approximate K/Pg boundary also thins from ~60 m down to ~20 m over the same area. The reduced thickness probably reflects actual intraformational thinning within the lower part of the Black Peaks Formation toward the northeastern margin of the Tornillo Basin.

The upper Black Peaks Formation is preserved in depositional contact with the Hannold Hill Formation only on Tornillo Flat (Fig. 17). Elsewhere, the upper half of the formation was either not deposited or removed by erosion prior to deposition of the Canoe Formation (or equivalent parts of the Devil's Graveyard and Chisos formations). There are no obvious facies changes to indicate that the 200–300 m thickness reduction in the upper part of the Black Peaks Formation over the western part of the basin was a result of intraformational thinning, and so this is instead most likely attributable to erosional truncation. Where preserved in depositional contact with the Hannold Hill Formation, the upper half of the Black Peaks varies in thickness from a minimum of ~170–200 m on northern Tornillo Flat (type section and north of Canoe Valley) to a maximum of 240–340 m on eastern and southern Tornillo Flat (Grapevine Hills to McKinney Hills). This may also reflect original depositional thinning of the Black Peaks toward the northern margin of the basin; however, it could in part reflect truncation of the upper Black Peaks at the base of the overlying Hannold Hill Formation or inaccurate thickness estimates for extensive local covered intervals in the upper part of the formation (Fig. 17).

The Hannold Hill Formation is restricted to the Tornillo Flat area, and there is little evidence that its original depositional limits were extensive much or at all beyond that area (Fig. 17). However, the distinctive, well-rounded limestone pebbles observed in Hannold Hill conglomerates are also present in the base of the younger Devil's Graveyard Formation to the west and may indicate that the formation was originally more extensive to the west but was removed by erosion prior to middle Eocene time. The Hannold Hill Formation varies in thickness from ~30 m to 70 m. All four units recognized within the formation are present at most exposures, and so the thickness differences are

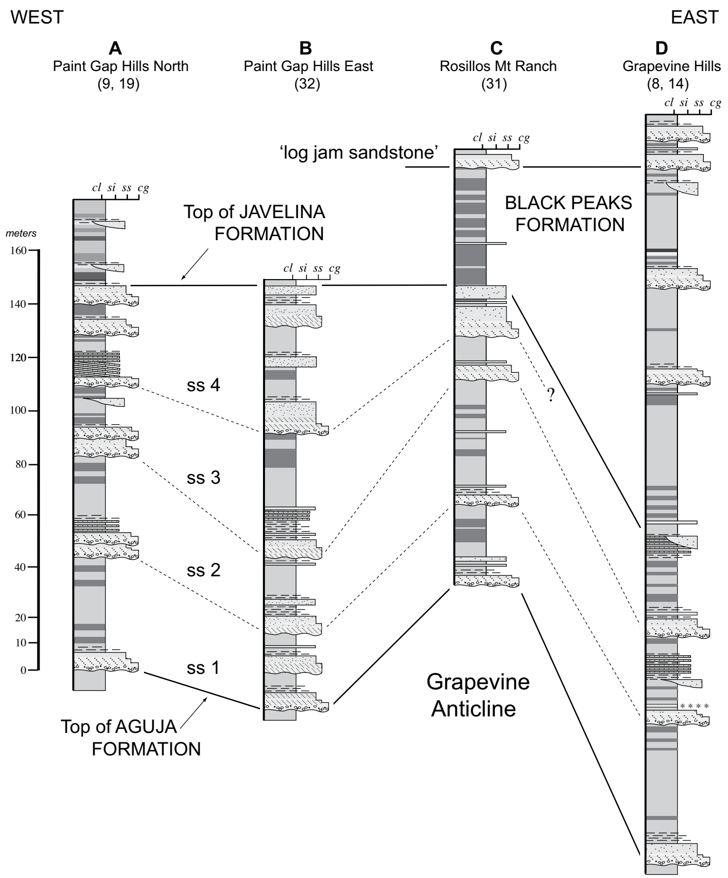


Figure 20. Correlation of stratigraphic sections in the area surrounding "Grapevine anticline" showing suggested correlation of four major ridge-forming sandstone intervals (ss1 through ss4), thinning of the Javelina Formation and thinning of lower Black Peaks Formation in vicinity of the anticline; section C is adapted from Adams (2014). cl—claystone; si—siltstone; ss—sandstone; cg—conglomerate.

for the most part due to original depositional variations. The thickest section observed is at Canoe Valley, suggesting that the Canoe syncline was either actively folded at that time or otherwise an area of more rapid subsidence during deposition of the Hannold Hill. In contrast, a very thin section of the formation exists immediately southwest of Canoe Valley on Exhibit Ridge. Reduced sedimentation in that area may also be compatible with syndepositional folding of underlying strata that produced the Canoe syncline to the northeast. The upper half of the formation appears to be absent on the northeast flank of the syncline, where the Canoe Formation (Big Yellow Sandstone) rests on the lower mudstone interval of the Hannold Hill. Although it is clear that the present geometry of the Canoe syncline may reflect drag along the fault that bounds its southwestern limb, thickness variation within the Hannold Hill Formation across the structure suggests that the syncline was initiated as a Laramide fold in early Eocene time.

Local Small-Scale Deformation

Apart from the regional intraformational thinning of stratigraphic units in the vicinity of Laramide structures described above, there is also clear evidence for small-scale contractional deformation (within the Tornillo Basin) that must have occurred during or shortly after deposition of the Tornillo Group. For example, on the south side of Tornillo Creek, the upper half of the Hannold Hill Formation (upper sandstone and mudstone interval) is deformed within a northeastward-dipping monoclinal fold; a reverse fault slightly displaces the limb of the fold (Figs. 21 and 22). The fold is truncated and overlain by undeformed Canoe Formation (Big Yellow Sandstone), indicating that this structure must have formed between early and middle Eocene time. At a second site, along the northeastern flank of Grapevine Hills, instead the lower half of the formation (Exhibit Sandstone and lower mudstone) is truncated, dips steeply to the northeast, and is overlain by the upper half of the formation (upper sandstone and mudstone units) that remains nearly horizontal (Fig. 23). The deformation observed at this outcrop is also compatible with a northeastward-dipping monoclinal fold that affects the lower Hannold Hill and underlying strata. The structure here must have formed, however, during early Eocene time (prior to deposition of the upper part of the Hannold Hill Formation). Due to extensive alluvial cover, it is not possible to trace the deformation observed at either of these outcrops much beyond the limited exposures.

Continuing southeastward from these exposures, the Hannold Hill Formation thins and is progressively truncated at the base of the Canoe Formation (Big Yellow Sandstone) near the mouth of Hannold Draw. South of Big Yellow Arroyo, the Canoe Formation rests directly on the Black Peaks Formation (Fig. 15). Similarly, in Avery Canyon, the upper half of the Hannold Hill Formation is missing; the Canoe Formation rests on the lower mudstone and Exhibit Sandstone, and farther to the south, rests directly on the Black Peaks Formation. Collectively, these observations indicate that deformation along the southern margin of Tornillo Flat occurred both during and shortly after deposition of the Hannold Hill Formation, prior to deposition of the Canoe Formation.

On the northern side of Tornillo Flat, there are small remnants of Canoe Formation conglomerate resting on a truncated asymmetric anticline that involves the underlying Aguja and Javelina formations (Figs. 24 and 25). This fold (referred to here as the "Mailbox anticline") is bounded by a steeply dipping reverse fault along its northeastern limb (Fig. 24). There are no apparent facies changes in either the Javelina or Black Peaks formations adjacent to this structure, suggesting that deformation here postdates both units. There are no nearby exposures of Hannold Hill Formation. The remnants of Canoe Formation are nearly horizontal and rest both atop the truncated fold and on

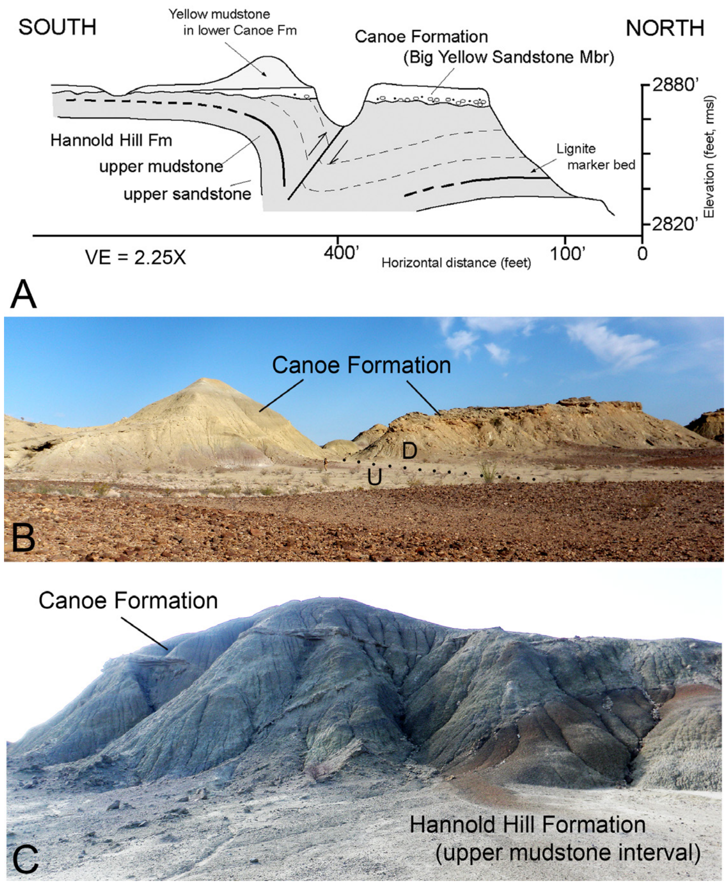


Figure 21. Field sketch and photographs of unnamed monocline on south side of Tornillo Flat, west of the Park Highway (see Fig. 15) with adjacent Tornillo Group strata (Hannold Hill Formation). (A) Field sketch showing monocline in upper part of Hannold Hill Formation, relationship to reverse fault along north limb of fold, and overlying undeformed Canoe Formation resting unconformably on truncated fold; (B) view to west of same structure showing trace of reverse fault and overlying Canoe Formation; (C) detailed view to east of same structure showing inclined stratification in upper Hannold Hill Formation on hanging wall of fault truncated at base of overlying Canoe Formation. VE—vertical exaggeration; rmsl—relative to mean sea level; U and D refer to up and down sides of fault.

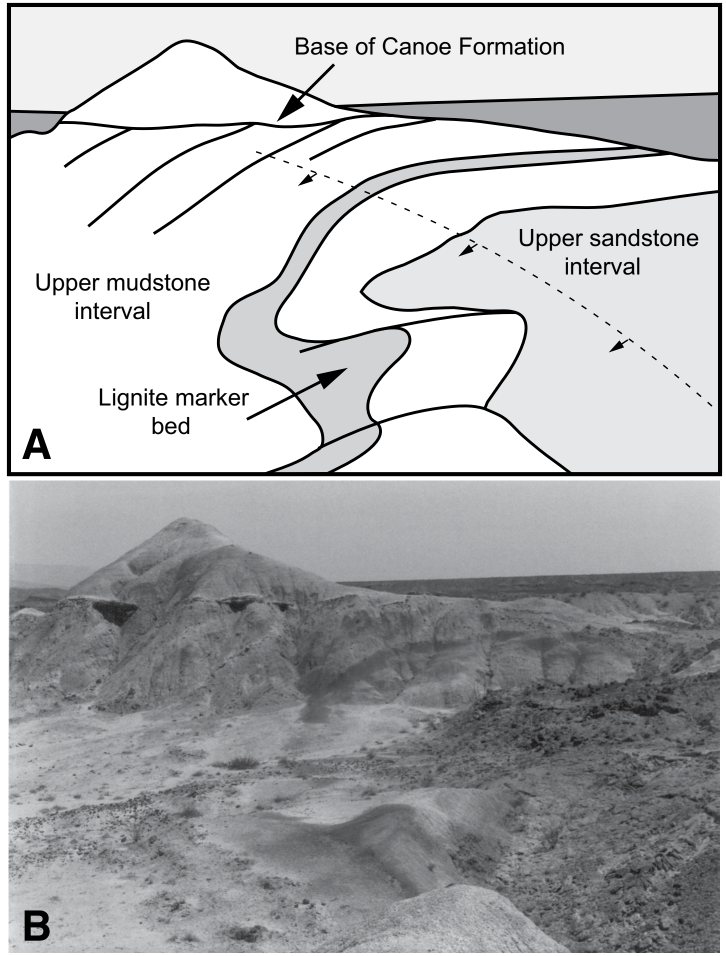


Figure 22. Field sketch and photograph showing unnamed monocline on south side of Tornillo Flat, west of the Park Highway (see Figs. 15 and 21) in Hannold Hill Formation. (A) Field sketch showing monocline in upper sandstone and mudstone intervals of Hannold Hill Formation, and overlying undeformed Canoe Formation resting unconformably on truncated fold; (B) photograph taken from same vantage point.

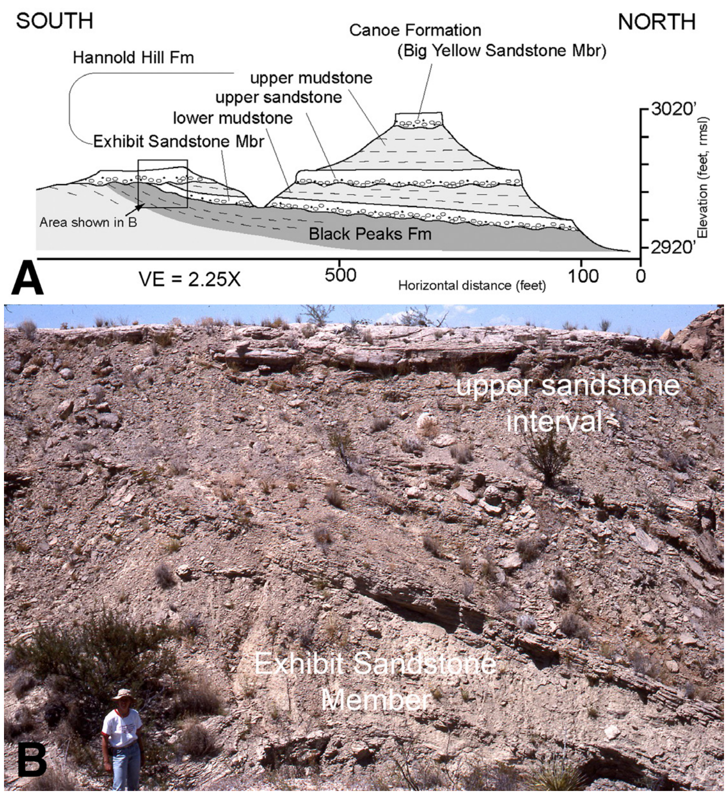


Figure 23. Field sketch and photograph showing fold within Hannold Hill Formation north of Grapevine Hills. (A) Field sketch showing relationship of folded units within the Hannold Hill Formation and underlying Black Peaks Formation with overlying undeformed strata in the upper Hannold Hill and Canoe formations; (B) photograph of area (box outlined in A showing inclined strata within the Exhibit Sandstone Member overlain by undeformed strata in the upper sandstone interval of the Hannold Hill Formation. VE—vertical exaggeration; rmsl—relative to mean sea level.

surrounding undeformed strata. This exposure indicates that folding and erosional truncation of the Tornillo Group along the northern margin of Tornillo Flat must also have occurred prior to deposition of the Big Yellow Sandstone Member in middle Eocene time.

Chronology of Deformation

The observations above provide a general chronology for deformation within the Tornillo Basin (Fig. 26). Initially, during deposition of the Javelina Formation, uplift in the vicinity of Grapevine anticline and/or a greater rate of subsidence in the region east of that, led to restricted lacustrine sedimentation in the northeastern part of the basin. Early during deposition of the Black Peaks Formation, the Grapevine anticline, and both southwestern and northeastern sides of the basin also experienced lower sedimentation rates (Fig. 26). This suggests that uplift of the Mesa de Anguila and Sierra del Carmen monoclines began to define the basin margins at that time. A similar pattern of intraformational thinning in the Javelina and lower Black Peaks formations along the south flank of Terlingua monocline indicates that this structure was also active at the same time. This pattern continued during deposition of the upper Black Peaks Formation, at least along the northeastern margin of the basin, where lower sediment accumulation rates continued. During deposition of the Hannold Hill Formation and shortly thereafter (prior to deposition of the Canoe Formation), folds (e.g., Canoe syncline and Mailbox anticline) began to develop within the basin along both the southwestern and northeastern margins of Tornillo Flat, sedimentation became mostly or entirely restricted to the limited area of Tornillo Flat, and much of the older Tornillo Group strata was removed by erosion over the western part of the basin (Fig. 26).

Although some other major structures within the Tornillo Basin (Cow Heaven anticline, Mariscal Mountain anticline, and Sierra San Vicente anticline) are believed to have formed during the Laramide orogeny (e.g., Muehlberger, 1980), these areas have been eroded to deeper structural levels such that only the lower part of the Tornillo Group is preserved along the limbs of the folds, or in close proximity, and so it is not possible to establish the timing of their development on the basis of stratigraphic or sedimentological criteria (Fig. 18). For example, the Javelina Formation and lower part of the Black Peaks Formation (up to the "log-jam sandstone") are preserved along the plunging nose of Mariscal Mountain anticline (Glenn Spring sections 4 and 16, Supplemental Material, section I [footnote 1]), but these strata have a thickness and character here comparable to that typically observed elsewhere in the Tornillo Basin. This indicates only that Mariscal Mountain anticline must have formed sometime after deposition of the middle part of the Black Peaks Formation.

SUMMARY

The threefold stratigraphic division of the Tornillo Group into Javelina, Black Peaks, and Hannold Hill formations originally proposed by Maxwell et al. (1967) continues to serve well for mapping purposes in Big Bend National Park and the surrounding vicinity. Although the boundaries between the three units were initially placed so as to coincide with the Cretaceous/Paleocene and Paleocene/Eocene series boundaries, fossils are so scarce in these strata that it subsequently proved impractical, if not impossible, to identify the contacts on this basis in most areas. Minor adjustments in the stratigraphic positions of the formational contacts, however, allow each of the units to be recognized more readily on the basis of lithologic and physiographic criteria and to be depicted more consistently in recent mapping efforts (Collins et al., 2006; Cooper, 2011; Turner et al., 2011).

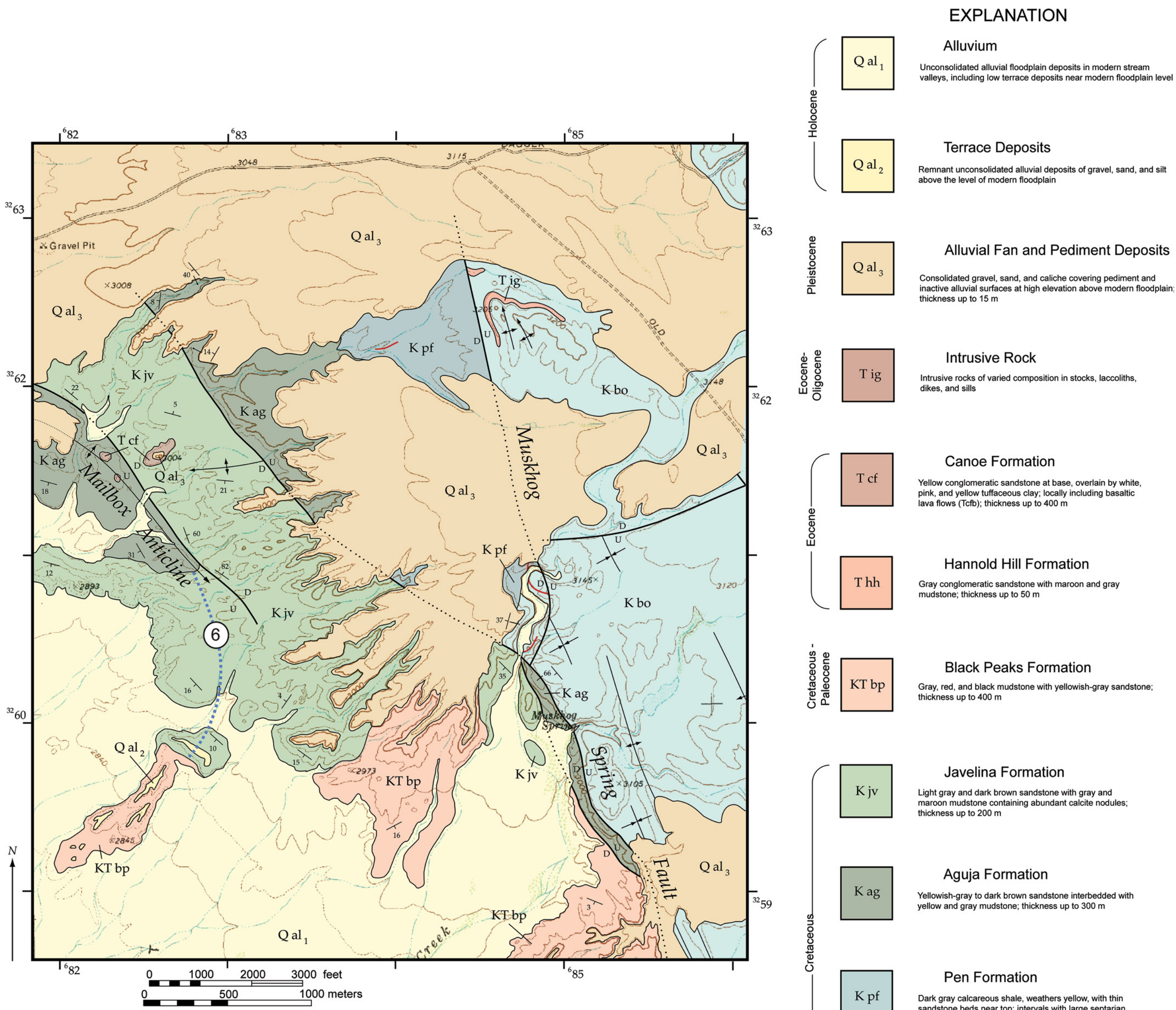


Figure 24. Geologic map of the region south of Dagger Flat showing distribution of formations in the Tornillo Group and location of stratigraphic sections.

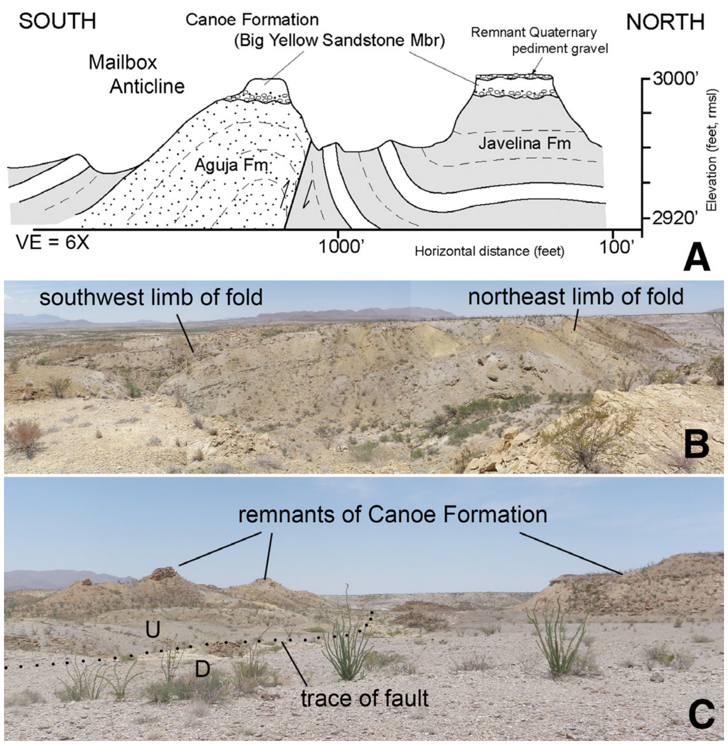


Figure 25. Field sketch and photographs of the "Mailbox anticline" south of Dagger Flat (see Fig. 24) and adjacent Tornillo Group strata (Javelina Formation). (A) Field sketch showing anticline in Aguja and Javelina Formations, relationship to reverse fault along northeast limb of fold, and overlying undeformed Canoe Formation resting unconformably on truncated fold; (B) view to northwest along axis of "Mailbox anticline" showing truncated surface overlain by Quaternary alluvium; (C) view to northwest of "Mailbox anticline" showing trace of reverse fault in valley northeast of the fold and position of remnant Canoe Formation outcrops on the fold (to left) and on footwall strata (to right). VE—vertical exaggeration; rmsl—relative to mean sea level; U and D refer to up and down sides of fault.

Several emendations in the formation contacts used in recent mapping are justified and documented in the present report. Although no changes in stratigraphic nomenclature are required, principal reference sections are designated for each of the formations, because the original type sections for each formation inadvertently included parts of the other units as they were mapped at that time. The revised stratigraphy, and recognition of key beds within each unit, allow for more confident correlation of isolated exposures and stratigraphic placement of significant vertebrate fossil sites throughout the Tornillo Group. As the units are currently mapped, the Cretaceous/Paleocene boundary lies within the lowermost part of the Black Peaks Formation. The Paleocene/Eocene boundary has not been confidently identified but must lie within the uppermost part of the Black Peaks Formation or at the base of the Hannold Hill Formation.

The more consistent identification of formation contacts provides a means to assess intraformational thickness variations and the chronology of deformation within the Tornillo Basin. The Javelina Formation is thinner in the southwestern part of the basin, but the Black Peaks Formation thins toward both the southwestern and northeastern sides of the basin, suggesting that the Terlingua, Mesa de Anguila, and Sierra del Carmen monoclines bounding those sides of the basin began to develop in latest Cretaceous through Paleocene time (Fig. 26).

Several observations indicate that structures within the Tornillo Basin affected sedimentation during deposition of these strata. One or more structures extending from the vicinity of Grapevine anticline southeastward to San Vicente anticline roughly mark a division between northeastern and southwestern parts of the basin. The Javelina Formation is thinner southwest of this line and lacks the distinctive lacustrine facies present to the northeast; and, the upper half of the Black Peaks Formation (above the "log-jam sandstone") is nearly or completely absent southwest of this line due to erosional truncation prior to deposition of the Canoe Formation (Fig. 26). The Hannold Hill Formation is also completely absent southwest of this line. Small northeast-facing monoclinal folds that affect parts of the Hannold Hill Formation in that same vicinity are truncated at the base of the overlying Canoe Formation, suggesting that the structure in this area restricted sedimentation and that the original depositional limits of the Hannold Hill Formation probably did not extend much beyond the northeastern part of the basin. The Canoe Formation is largely unaffected by any deformation that resulted in erosional thinning and truncation of the Tornillo Group. Collectively, these observations indicate that, while incipient deformation along Laramide-age structures broadly defined the Tornillo Basin during latest Cretaceous through Paleocene time and influenced sediment accumulation rates in the vicinity of these structures, the conspicuous Laramide-age deformation here occurred almost entirely during early to middle Eocene time.

ACKNOWLEDGMENTS

This paper reflects a collaborative effort and continual "learning process" spanning over 30 years of on-again off-again efforts. Although the initial work was part of the lead author's dissertation research, many students, advisors, colleagues, and fellow devotees of the Big Bend have been involved in small and large ways helping to create the current "progress" report. The authors of this report represent only those few that participated in seemingly most significant ways, but in particular we also gratefully acknowledge W. Langston, Jr., G. Kocurek, and W. Muehlberger for their advice and support during the formative stages of the research; T. Shiller, N. LaFon, M. Sander, J. Browning, D. Evans, C. Macon, R. Record, C. Vines, A. Coulson, and E. Wheeler for participating in fieldwork over the years. In addition, we have benefited tremendously from the insightful research on the Tornillo Group by A. Busbey, D. Lawson, D. Schmidt, A. Adams, and J. Cobb. The Science and Resource Management office in Big Bend National Park and, in particular, D. Corrick, P. Koepp, V. Davila, and M. Fleming, provided assistance with the research planning and permitting process in the Park, and A. Runkel and C. Bataille provided helpful reviews of the manuscript. Most importantly, we thank E. Lehman, J. Wick, and all "significant others" for their enduring patience over the years. The Geosciences Department at Texas Tech provided support for preparation and publications of the manuscript, and the Texas Tech Faculty Development Leave Program and the U.S. Geo-

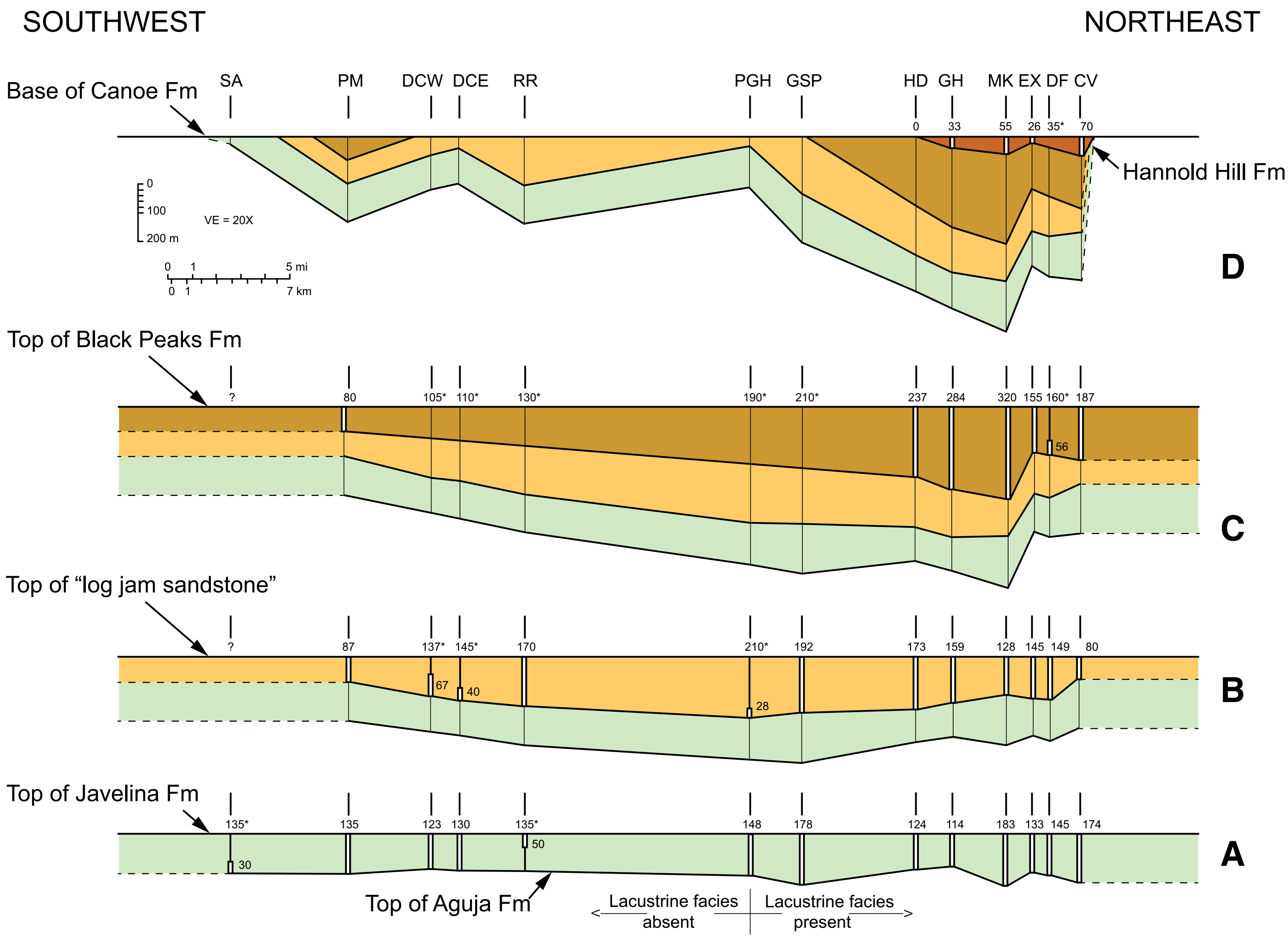


Figure 26. Diagrams showing sequential deposition of units within the Tornillo Group across the Tornillo Basin: (A) following deposition of Javelina Formation; (B) following deposition of the "log jam sandstone" bed in the Black Peaks Formation; (C) at end of deposition of the Black Peaks Formation; (D) prior to deposition of Canoe Formation; sections shown are CV—Canoe Valley (sections 7, 13, and 24); DCE—Dawson Creek east (section 2); DCW—Dawson Creek west (sections 1 and 20); DF—Dagger Flat (sections 6 and 15): EX—Exhibit Ridge (sections 3, 12, and 25); GH—Grapevine Hills (sections 8, 14, and 28); GSP—Glenn Spring (sections 10 and 16); HD—Hannold Draw (section 17); MK—McKinney Hills (sections 5, 18, and 23); PGH—Paint Gap Hills (sections 9 and 19); PM—Pena Mountain (section 22); RR—Rough Run Creek (sections 11 and 21); SA—Sierra Aguja (section 10); numbers with boxed columns for each section indicate actual total thickness measured for each unit; numbers with asterisks show estimated total thickness (based on average of two nearest complete sections). VE—vertical exaggeration.

logical Survey National Geologic Mapping Program (assistance Award No. 03HQAG0077) provided support for T. Lehman to conduct much of the mapping from 2002 through 2007. The views and conclusions contained in this document are those of the authors and should not be interpreted as necessarily representing the official policies, either expressed or implied, of the U.S. Government.

REFERENCES CITED

Adams, A.L., 2014, Stratigraphy and paleontology of Upper Cretaceous to Paleocene strata on the western Rosillos Mountain Ranch, Brewster County, Texas [M.S. thesis]: Fort Worth, Texas Christian University, 99 p.

Atchley, S.C., Nordt, L.C., and Dworkin, S.I., 2004, Eustatic control on alluvial sequence stratigraphy: A possible example from the Cretaceous–Tertiary transition of the Tornillo Basin, Big Bend National Park, West Texas, U.S.A: Journal of Sedimentary Research, v. 74, p. 391–404, https://doi.org/10.1306/102203740391.

Bataille, C.P., Watford, D., Ruegg, S., Lowe, A., and Bowen, G.J., 2016, Chemostratigraphic age model for the Tornillo Group: A possible link between fluvial stratigraphy and climate: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 457, p. 277–289, https://doi.org/10.1016/j.palaeo.2016.06.023.

Beatty, H.L., 1992, Fluvial sedimentology and sandstone petrography of the Hannold Hill Formation (Eocene), Big Bend, Texas [M.S. thesis]: Lubbock, Texas Tech University, 113 p.

Befus, K.S., Hanson, R.E., Lehman, T.M., and Griffin, W.R., 2008, Cretaceous basaltic phreatomagmatic volcanism in West Texas: Maar complex at Pena Mountain, Big Bend National Park, Texas: Journal of Volcanology and Geothermal Research, v. 173, p. 245–264, https://doi.org/10.1016/j.jvolgeores.2008.01.021.

Breyer, J.A., Busbey, A.B., Hanson, R.E., Befus, K.E., Griffin, W.R., Hargrove, U.S., and Bergman, S.C., 2007, Evidence for Late Cretaceous volcanism in Trans-Pecos, Texas: The Journal of Geology, v. 115, p. 243–251, https://doi.org/10.1086/510640.

Cobb, J., 2016, Sedimentology of the Cretaceous–Paleogene boundary interval in the Tornillo Group of West Texas [M.S. thesis]: Lubbock, Texas Tech University, 161 p.

Cobb, R.C., and Poth, S., 1980, Superposed deformation in the Santiago and northern Del Carmen mountains, Trans-Pecos Texas, *in* Dickerson, P.W., Hoffer, J.M., and Callender, J.F., eds., New Mexico Geological Society Guidebook, 31st Field Conference, Trans-Pecos Region, p. 71–75.

Collins, E.W., Muehlberger, W.R., and Dickerson, P.W., 2006, Geologic map of the Glenn Spring Quadrangle, Big Bend National Park, Texas: University of Texas, Bureau of Economic Geology, Open-File Map, scale 1:24,000, 1 sheet.

Cooper, R.W., compiler, 2011, Geologic maps of the Upper Cretaceous and Tertiary strata, Big Bend National Park, Texas: Bureau of Economic Geology, Miscellaneous Maps No. 50, scale 1:24,000, 6 sheets.

Coulson, A.B., 1998, Sedimentology and taphonomy of a juvenile Alamosaurus site in the Javelina Formation (Upper Cretaceous), Big Bend National Park, Texas [M.S. thesis]: Lubbock, Texas Tech University, 103 p.

Davies, K., 1983, Hadrosaurian dinosaurs of Big Bend National Park [M.S. thesis]: Austin, University of Texas at Austin, 231 p.

DeCamp, D.W., 1985, Structural geology of Mesa de Anguila, Big Bend National Park, Texas, *in* Dickerson, P.W., and Muehlberger, W.R., eds., Structure and Tectonics of Trans-Pecos Texas: West Texas Geological Society Publication 85-81, p. 127–135.

Fronimos, J.A., and Lehman, T.M., 2014, New specimens of a titanosaur sauropod from the Maastrichtian of Big Bend National Park, Texas: Journal of Vertebrate Paleontology, v. 34, p. 883–899, https://doi.org/10.1080/02724634.2014.840308.

Geologic Atlas of Texas, 1979, Emory Peak–Presidio Sheet: University of Texas, Bureau of Economic Geology, scale 1:250,000, 1 sheet.

Hartmann, B.M., and Scranton, D.F., 1992, Geologic Map of Texas: University of Texas, Bureau of Economic Geology, scale 1:500,000, 2 sheets.

Hartnell, J.A., 1980, The vertebrate paleontology, depositional environment and sandstone provenance of Early Eocene rocks on Tornillo Flat, Big Bend National Park, Brewster County, Texas [M.S. thesis]: Baton Rouge, Louisiana State University, 174 p.

Hunt, R.K., and Lehman, T.M., 2008, Attributes of the ceratopsian dinosaur *Torosaurus*, and new material from the Javelina Formation (Maastrichtian) of Texas: Journal of Paleontology, v. 82, p. 1127–1138, https://doi.org/10.1017/S0022336000055335.

Lawson, D.A., 1972, Paleoecology of the Tornillo Formation, Big Bend National Park, Texas [M.S. thesis]: Austin, University of Texas at Austin, 182 p.

Lawson, D.A., 1976, *Tyrannosaurus* and *Torosaurus*, Maastrichtian dinosaurs from Trans-Pecos, Texas: Journal of Paleontology, v. 50, p. 158–164.

Lehman, T.M., 1985, Stratigraphy, sedimentology, and paleontology of Late Cretaceous (Campanian-Maastrichtian) sedimentary rocks in Trans-Pecos Texas [Ph.D. thesis]: Austin, University of Texas at Austin, 310 p.

Lehman, T.M., 1986, Late Cretaceous sedimentation in Trans-Pecos Texas, *in* Pause, P.H., and Spears, R.G., eds., Geology of the Big Bend area and Solitario Dome, Texas: West Texas Geological Society Fieldtrip Guidebook, Publication 86-82, p. 105–110.

Lehman, T.M., 1987, Late Maastrichtian paleoenvironments and dinosaur biogeography in the western interior of North America: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 60, p. 189–217, https://doi.org/10.1016/0031-0182(87)90032-0.

Lehman, T.M., 1988, Stratigraphy of the Cretaceous–Tertiary and Paleocene–Eocene transition rocks of Big Bend [discussion]: The Journal of Geology, v. 96, p. 627–631, https://doi.org/10.1086/629258.

Lehman, T.M., 1989, Upper Cretaceous (Maastrichtian) paleosols in Trans-Pecos Texas: Geological Society of America Bulletin, v. 101, p. 188–203, https://doi.org/10.1130/0016-7606(1989)101<0188:UCMPIT>2.3.CO;2.

Lehman, T.M., 1990, Paleosols and the Cretaceous/Tertiary transition in the Big Bend region of Texas: Geology, v. 18, p. 362–364, https://doi.org/10.1130/0091-7613(1990)018<0362:PATCTT>2.3.CO;2.

Lehman, T.M., 1991, Sedimentation and tectonism in the Laramide Tornillo Basin of West Texas: Sedimentary Geology, v. 75, p. 9–28, https://doi.org/10.1016/0037-0738(91)90047-H.

Lehman, T.M., 2002, Revisions to the Tornillo Group (Upper Cretaceous–Eocene), Big Bend National Park, Texas: Geological Society of America Abstracts with Programs, v. 34, no. 3, p. A10.

Lehman, T.M., 2004, Mapping of Upper Cretaceous and Paleogene strata in Big Bend National Park, Texas: Geological Society of America Abstracts with Programs, v. 36, no. 5, p. A129.

Lehman, T.M., 2007, Upper Cretaceous and Paleogene strata south of the Chisos Mountains, Big Bend National Park, Texas: Geological Society of America Abstracts with Programs, v. 39, no. 6, p. A510.

Lehman, T.M., 2009, West park entrance: Upper Cretaceous and Paleogene stratigraphy, *in* Cooper, D.A., ed., Geology of Trans-Pecos and the Big Bend Area, Texas: Houston Geological Society and Geological Society of America, Fieldtrip Guidebook for 2008 Joint Annual Meeting, p. 17–19.

Lehman, T.M., and Busbey, A.B., 2007, Big Bend Field Trip Guidebook: Society of Vertebrate Paleontology, 69 p.

Lehman, T.M., and Coulson, A.B., 2002, A juvenile specimen of the sauropod dinosaur *Alamosaurus sanjuanensis* from the Upper Cretaceous of Big Bend National Park, Texas: Journal of Paleontology, v. 76, p. 156–172, https://doi.org/10.1666/0022-3360(2002)076<0156:AJSOTS>2.0.CO;2.

Lehman, T.M., and Langston, W., Jr., 1996, Habitat and behavior of *Quetzalcoatlus*: Paleoenvironmental reconstruction of the Javelina Formation (Upper Cretaceous), Big Bend National Park, Texas: Journal of Vertebrate Paleontology, v. 16, p. 48A.

Lehman, T.M., and Wheeler, E.A., 2001, A fossil dicotyledonous woodland/forest from the Upper Cretaceous of Big Bend National Park, Texas: Palaios, v. 16, p. 102–108, https://doi.org/10.1669/0883-1351(2001)016<0102:AFDWFF>2.0.CO;2.

Lehman, T.M., McDowell, F., and Connelly, J., 2006, First isotopic (U-Pb) age for the Late Cretaceous *Alamosaurus* vertebrate fauna of West Texas, and its significance as a link between two faunal provinces: Journal of Vertebrate Paleontology, v. 26, p. 922–928, https://doi.org/10.1671/0272-4634(2006)26[922:FIUAFT]2.0.CO;2.

Lehman, T.M., Wick, S.L., and Wagner, J.R., 2016, Hadrosaurian dinosaurs from the Maastrichtian Javelina Formation, Big Bend National Park, Texas: Journal of Paleontology, v. 90, p. 333–356, https://doi.org/10.1017/jpa.2016.48.

Leslie, C.E., Peppe, D.J., Williamson, T.E., Heizler, M., Jackson, M., Atchley, S.C., Nordt, L., and Standhardt, B., 2018, Revised age constraints for Late Cretaceous to early Paleocene terrestrial strata from the Dawson Creek section, Big Bend National Park, west Texas: Geological Society of America Bulletin, https://doi.org/10.1130/B31785.1.

Lofgren, D.L., Lillegraven, J.A., Clemens, W.A., Gingerich, P.D., and Williamson, T.E., 2004, Paleocene biochronology: The Puercan through Clarkforkian Land Mammal Ages, *in* Woodburne, M.O., ed., Late Cretaceous and Cenozoic Mammals of North America: New York, Columbia University Press, p. 43–105, https://doi.org/10.7312/wood13040-005.

Maxwell, R.A., Lonsdale, J.T., Hazzard, R.T., and Wilson, J.A., 1967, Geology of Big Bend National Park, Brewster County, Texas: University of Texas Bureau of Economic Geology, Publication 6711, 320 p.

Muehlberger, W.R., 1980, Texas lineament revisited, *in* Dickerson, P.W., Hoffer, J.M., and Callender, J.F., eds., Trans-Pecos Region: New Mexico Geological Society Guidebook, 31st Field Conference, p. 113–121.

Nordt, L., Atchley, S., and Dworkin, S., 2003, Terrestrial evidence for two greenhouse events in the latest Cretaceous: GSA Today, v. 13, p. 4–9, https://doi.org/10.1130/1052-5173(2003)013<4:TEFTGE>2.0.CO;2.

Rapp, S.D., MacFadden, B.J., and Schiebout, J.A., 1983, Magnetic polarity stratigraphy of the early Tertiary Black Peaks Formation, Big Bend National Park, Texas: The Journal of Geology, v. 91, p. 555–572, https://doi.org/10.1086/628804.

Retallack, G.J., 1990, Soils of the Past: London, Unwin Hyman, Inc., 520 p., https://doi.org/10.1007/978-94-011-7902-7.

Rigsby, C.A., 1982, Provenance and depositional environments of the middle Eocene Canoe Formation, Big Bend National Park, Brewster County, Texas [M.S. thesis]: Baton Rouge, Louisiana State University, 200 p.

Rigsby, C.A., 1986, The Big Yellow Sandstone: A sandy braided stream, *in* Pause, P.H., and Spears, R.G., eds., Geology of the Big Bend Area and Solitario Dome, Texas: West Texas Geological Society Publication 86-82, p. 111–116.

Robinson, P., Gunnell, G.F., Walsh, S.L., Clyde, W.C., Storer, J.E., Stucky, R.K., Froehlich, D.J., Ferrusquia-Villafranca, I., and McKenna, M.C., 2004, Wasatchian through Duchesnean biochronology, *in* Woodburne, M.O., ed., Late Cretaceous and Cenozoic Mammals of North America: New York, Columbia University Press, p. 106–155, https://doi.org/10.7312/wood13040-006.

Runkel, A.C., 1988, Stratigraphy, sedimentation, and vertebrate paleontology of Eocene rocks in the Big Bend region of southwest Texas [Ph.D. thesis]: Austin, University of Texas at Austin, 283 p.

Runkel, A.C., 1990, Lateral and temporal changes in volcanogenic sedimentation; analysis of two Eocene sedimentary aprons, Big Bend region, Texas: Journal of Sedimentary Petrology, v. 60, p. 747–760.

Schiebout, J.A., 1970, Sedimentology of Paleocene Black Peaks Formation, western Tornillo Flat, Big Bend National Park, Texas [M.S. thesis]: Austin, University of Texas at Austin, 114 p.

Schiebout, J.A., 1974, Vertebrate paleontology and paleoecology of Paleocene Black Peaks Formation, Big Bend National Park, Texas: Texas Memorial Museum, Bulletin, 88 p.

Schiebout, J.A., 1995, The Paleocene/Eocene transition on Tornillo Flat in Big Bend National Park, Texas: National Park Service Paleontological Research, v. 2, Technical Report NPS/NRPO/NRTR-93/11.

Schiebout, J.A., Rigsby, C.A., Rapp, S.D., Hartnell, J.A., and Standhardt, B.R., 1987, Stratigraphy of the Cretaceous–Tertiary and Paleocene–Eocene transition rocks of Big Bend National Park, Texas: The Journal of Geology, v. 95, p. 359–375, https://doi.org/10.1086/629135.

Schmidt, D.R., 2009, Stable isotope geochemistry of Upper Cretaceous and Paleocene strata in Big Bend National Park, Texas [Ph.D. thesis]: Lubbock, Texas Tech University, 202 p.

Shiller, T.A., 2017, Stratigraphy and paleontology of Upper Cretaceous–Paleogene strata in northern Coahuila, Mexico [Ph.D. thesis]: Lubbock, Texas Tech University, 268 p.

Standhardt, B.R., 1986, Vertebrate paleontology of the Cretaceous/Tertiary transition of Big Bend National Park, Texas [Ph.D. thesis]: Baton Rouge, Louisiana State University, 298 p.

Standhardt, B.R., 1995, Early Paleocene (Puercan) vertebrates of the Dogie locality, Big Bend National Park, Texas: National Park Service Paleontological Research, v. 2, Technical Report NPS/NRPO/NRTR-93/11.

Stevens, J.B., Stevens, M.S., and Wilson, J.A., 1984, Devil's Graveyard Formation (New), Eocene and Oligocene Age, Trans-Pecos Texas: Texas Memorial Museum, Bulletin 32, 137 p.

Straight, W.H., 1996, Stratigraphy and paleontology of the Cretaceous-Tertiary boundary, Big Bend National Park, Texas [M.S. thesis]: Lubbock, Texas Tech University, 102 p.

Tomlinson, S.L., 1997, Late Cretaceous and early Tertiary turtles from the Big Bend region, Brewster County, Texas [Ph.D. thesis]: Lubbock, Texas Tech University, 194 p.

Turner, K.J., Berry, M.E., Page, W.R., Lehman, T.M., Bohannon, R.G., Scott, R.B., Miggins, D.P., Budahn, J.R., Cooper, R.W., Drenth, B.J., Anderson, E.D., and Williams, V.S., 2011, Geologic Map of Big Bend National Park, Texas: U.S. Geological Survey, Scientific Investigations Map No. 3142, scale 1:75,000, pamphlet 84 p.

Tykoski, R.S., and Fiorillo, A.R., 2016, An articulated cervical series of *Alamosaurus sanjuanensis* Gilmore, 1922 (Dinosauria, Sauropoda) from Texas: New perspective on the relationships of North America's last giant sauropod: Journal of Systematic Palaeontology, v. 15, p. 339–364, https://doi.org/10.1080/14772019.2016.1183150.

Udden, J.A., 1907, A sketch of the geology of the Chisos country: University of Texas Bureau of Economic Geology, Bulletin, v. 93, 101 p.

U.S. Geological Survey, 1971, McKinney Springs, Texas: 7.5′ topographic quadrangle, scale 1:24,000, 1 sheet.

Vines, C.M., 2000, Mineralogy and geochemistry of paleosols in the Javelina and Black Peaks Formations (Late Cretaceous–Paleocene) Big Bend National Park, Texas [M.S. thesis]: Lubbock, Texas Tech University, 114 p.

Wagner, J.R., 2001, The hadrosaurian dinosaurs (Ornithischia: Hadrosauria) of Big Bend National Park, Brewster County, Texas, with implications for Late Cretaceous paleozoogeography [M.S. thesis]: Lubbock, Texas Tech University, 417 p.

Walton, A.H., 1986, Magnetostratigraphy and the ages of Bridgerian and Uintan faunas in the Lower and Middle members of the Devil's Graveyard Formation, Trans-Pecos Texas [M.S. thesis]: Austin, University of Texas at Austin, 135 p.

Wheeler, E.A., 1991, Paleocene dicotyledonous trees from Big Bend National Park, Texas: Variability in wood types common in the Late Cretaceous and Early Tertiary, and ecological inferences: American Journal of Botany, v. 78, p. 658–671, https://doi.org/10.1002/j.1537-2197.1991.tb12590.x.

Wheeler, E.A., and Lehman, T.M., 2000, Late Cretaceous woody dicots from the Aguja and Javelina Formations, Big Bend National Park, Texas, USA: International Association of Wood Anatomists Journal, v. 21, p. 83–120.

Wheeler, E.A., and Lehman, T.M., 2005, Upper Cretaceous–Paleocene conifer woods from Big Bend National Park, Texas: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 226, p. 233–258, https://doi.org/10.1016/j.palaeo.2005.05.014.

Wheeler, E.A., and Lehman, T.M., 2009, New Late Cretaceous and Paleocene dicot woods of Big Bend National Park, Texas and review of Cretaceous wood characteristics: International Association of Wood Anatomists Journal, v. 30, p. 293–318.

Wheeler, E.A., Lehman, T.M., and Gasson, P.E., 1994, *Javelinoxylon*, an Upper Cretaceous dicotyledonous tree from Big Bend National Park, Texas, with presumed malvalean affinities: American Journal of Botany, v. 81, p. 703–710, https://doi.org/10.1002/j.1537-2197.1994.tb15504.x.

White, P.D., and Schiebout, J.A., 2003, Paleogene paleosols of Big Bend National Park, Texas, *in* Wing, S.L., Gingerich, P.D., Schmitz, B., and Thomas, E., eds., Causes and Consequences of Globally Warm Climates in the Early Paleogene: Geological Society of America Special Paper 369, p. 537–550, https://doi.org/10.1130/0-8137-2369-8.537.

White, P.D., and Schiebout, J.A., 2008, Paleogene paleosols and changes in pedogenesis during the initial Eocene thermal maximum: Big Bend National Park, Texas, USA: Geological Society of America Bulletin, v. 120, p. 1347–1361, https://doi.org/10.1130/B25987.1.

Wick, S.L., 2014, New evidence for the possible occurrence of *Tyrannosaurus* in West Texas, and discussion of Maastrichtian tyrannosaurid dinosaurs from Big Bend National Park: Cretaceous Research, v. 50, p. 52–58, https://doi.org/10.1016/j.cretres.2014.03.010.

Wick, S.L., and Lehman, T.M., 2013, A new ceratopsian dinosaur from the Javelina Formation (Maastrichtian) of West Texas and implications for chasmosaurine phylogeny: Naturwissenschaften, v. 100, p. 667–682, https://doi.org/10.1007/s00114-013-1063-0.

Wick, S.L., and Lehman, T.M., 2014, A complete titanosaur femur from West Texas with comments regarding hindlimb posture: Cretaceous Research, v. 49, p. 39–44, https://doi.org/10.1016/j.cretres.2014.02.003.

Wiest, L.A., Lukens, W.E., Peppe, D.J., Driese, S.G., and Tubbs, J., 2018, Terrestrial evidence for the Lilliput effect across the Cretaceous–Paleogene (K-Pg) boundary: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 491, p. 161–169, https://doi.org/10.1016/j.palaeo.2017.12.005.

Williamson, T.E., 1996, The beginning of the age of mammals in the San Juan Basin, New Mexico: Biostratigraphy and evolution of Paleocene mammals of the Nacimiento Formation: New Mexico Museum of Natural History and Science, Bulletin 8, 141 p.

Wilson, J.A., 1970, Vertebrate biostratigraphy of Trans-Pecos Texas: West Texas Geological Society, Publication 71-59, p. 159–166.

Wilson, J.A., and Runkel, A.C., 1989, Field guide to the Paleogene stratigraphy and vertebrate paleontology of the Big Bend region, *in* Busbey, A.B., and Lehman, T.M., eds., Vertebrate Paleontology, Biostratigraphy, and Depositional Environments, Latest Cretaceous and Tertiary, Big Bend Area, Texas: Society of Vertebrate Paleontology, 49th Annual Meeting, Field Trip Guidebook, p. 47–59.

Woodward, H.N., and Lehman, T.M., 2009, Bone histology and microanatomy of *Alamosaurus sanjuanensis* (Sauropoda: Titanosauria) from the Maastrichtian of Big Bend National Park, Texas: Journal of Vertebrate Paleontology, v. 29, p. 807–821, https://doi.org/10.1671/039.029.0310.