New Mexico Geological Society

Downloaded from: https://nmgs.nmt.edu/publications/guidebooks/51



Aptian-Albian extensional faulting and subsequent Laramide inversion, central Peloncillo Mountains, southwestern NM

German Bayona and Timothy F. Lawton
2000, pp. 85-94. https://doi.org/10.56577/FFC-51.85

in:

Southwest Passage: A trip through the Phanerozoic, Lawton, T. F.; McMillan, N. J.; McLemore, V. T.; [eds.], New Mexico Geological Society 51 st Annual Fall Field Conference Guidebook, 282 p. https://doi.org/10.56577/FFC-51

This is one of many related papers that were included in the 2000 NMGS Fall Field Conference Guidebook.

Annual NMGS Fall Field Conference Guidebooks

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

Free Downloads

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

Copyright Information

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

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

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

APTIAN–ALBIAN EXTENSIONAL FAULTING AND SUBSEQUENT LARAMIDE INVERSION, CENTRAL PELONCILLO MOUNTAINS, SOUTHWESTERN NEW MEXICO

GERMAN BAYONA[1] and TIMOTHY F. LAWTON
Department of Geological Sciences, New Mexico State University, Las Cruces, NM 88003-8001; [1]Present address: Department of Geological Sciences, University of Kentucky, Lexington, KY 40506; e-mail: gbayo2@pop.uky.edu

Abstract—In southern New Mexico and Arizona, sedimentation patterns of Cretaceous and Paleogene deposits have been related to normal faulting and subsequent reverse faulting on the same structures, but specific inversion faults have not been identified. In the central Peloncillo Mountains, dramatic thickness changes in the Lower Cretaceous Bisbee Group and the Upper Cretaceous–middle Paleogene Bobcat Hill Formation between blocks bounded by high-angle, northwest-striking reverse faults suggest local control on deposition. Stratigraphic correlations of those deposits between blocks document at least three episodes of fault activity. The first episode of normal faulting in late Aptian–middle Albian time is recorded by fan-delta deposits restricted to the hanging-wall block and stratal thickening toward the hanging-wall block of the three lower formations of the Bisbee Group. The second episode of fault activity is documented by abrupt thickening on the hanging-wall block of the upper unit of the Bisbee Group. The third episode of fault activity, reverse movement along former normal faults, is recorded by clastic and tuffaceous deposits of the Upper Cretaceous?–Eocene Bobcat Hill Formation, which are restricted to the footwall block.

INTRODUCTION

Rift-related, basement-involved faults are weak zones within the continental lithosphere that may influence the subsequent location and architecture of some orogenic belts and basins (Butler et al., 1997; Holdsworth et al., 1997). The most extensively documented style of reactivation of former rift-related structures in compressional settings is positive inversion (i.e, Butler et al., 1997). Previous studies in the central Peloncillo Mountains (Fig. 1; i.e., Gillerman, 1958; Smith, 1987) have not recognized the importance of local changes in thickness and stratal architecture of Cretaceous–Paleogene deposits across basement-involved faults. The purpose of this paper is to document that northwest-striking, basement-involved faults in the central Peloncillo Mountains controlled internal architecture, thickness variations, distribution, and composition of Cretaceous–Paleogene strata adjacent to those faults. This paper demonstrates that Cretaceous–middle Paleogene strata record the history of two northwest-striking faults, the Goatcamp and Wood Canyon faults (Fig. 2), and their influence on deposition. These faults had an Early Cretaceous history as normal faults and were reactivated as reverse faults during the Laramide orogeny; therefore, the trends of Laramide basins were likely inherited from the older rift trend.

In southern New Mexico and Arizona, sedimentation patterns in the Bisbee Group have been related to normal faulting, but specific faults have proven difficult to find. In southeastern Arizona, west-northwest-striking, high-angle faults controlled deposition of the Glance Conglomerate, the basal unit of the Bisbee Group (Bilodeau, 1982; Klute, 1991). In southwestern New Mexico, Early Cretaceous normal faults have been predicted (e.g., Mack, 1987), but not previously identified. Similarly, reactivation of normal faults during the Laramide orogeny has been inferred by different authors. Davis (1979), Seager and Mack (1986), and Klute (1991) have suggested that some Laramide structures, basins, and uplifts in southeastern Arizona might be the result of reactivation of pre-Laramide structures. Laramide inversion of Jurassic–Early Cretaceous extensional faults has been described in the Little Hatchet Mountains (Lawton, 1996).

METHODS

Eleven stratigraphic sections of the Lower Cretaceous Bisbee Group and the Upper Cretaceous–Paleogene Bobcat Hill Formation were measured using a Jacob's staff and Brunton compass in the hanging-

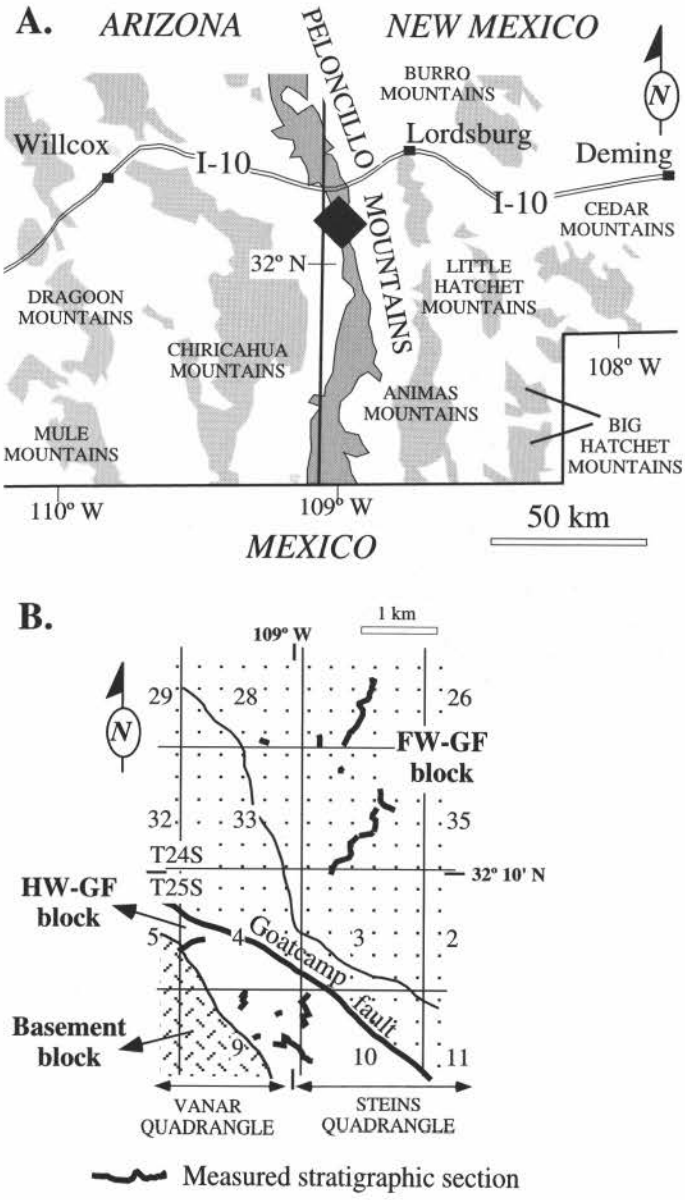


FIGURE 1. **A**, Map of location of the study area (black rectangle) and mountain ranges of southwestern New Mexico and southeastern Arizona. **B**, Locations of measured stratigraphic sections and definition of reference blocks: HW-GF, hanging-wall block of the Goatcamp fault; FW-GF, footwall block of the Goatcamp fault. Area of Figure 2 coincides with map of Figure 1B.

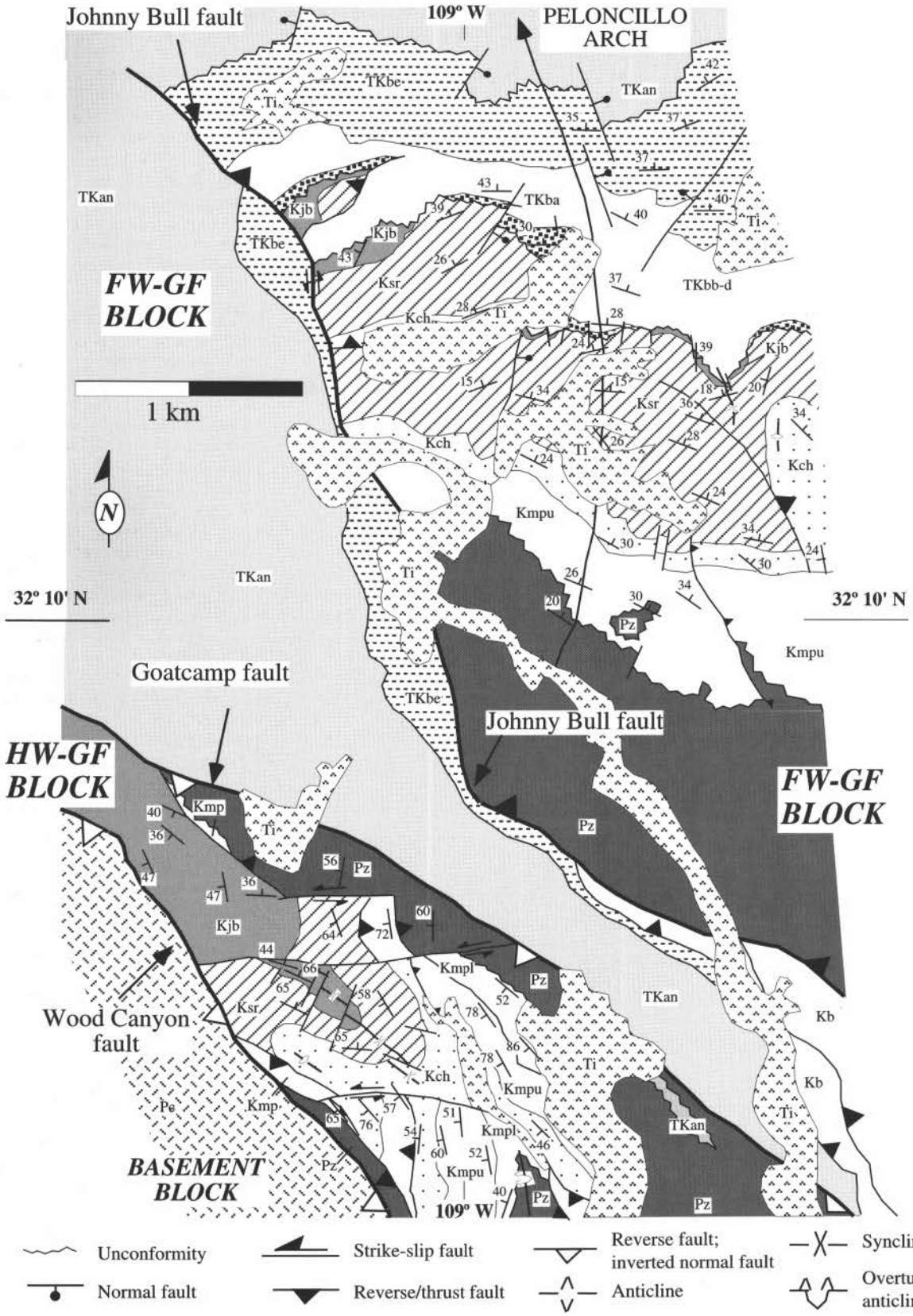


FIGURE 2. Geologic map of the central Peloncillo Mountains, showing in detail the distribution of Cretaceous-middle Paleogene units in the hanging-wall block of the Goatcamp fault (HW-GF) and footwall block of the Goatcamp fault (FW-GF). Stratigraphic sections were measured in areas with strike/dip data. Geology of surrounding areas from Smith (1987). **Pe**, undifferentiated Precambrian rocks; **Pz**, undifferentiated Paleozoic strata. Bisbee Group: **Kb**, undifferentiated Bisbee Group; **Kmpl**, lower member of McGhee Peak Formation; **Kmpu**, upper member of McGhee Peak Formation; **Kch**, Carbonate Hill Formation; **Ksr**, Still Ridge Formation; **Kjb**, Johnny Bull Formation. Bobcat Hill Formation: **TKba**, member A; **TKbb–d**, members B to D; **TKbe**, member E. **TKan**, andesite of Steins Pass; **Ti**, intrusive rocks. Quaternary surficial alluvial deposits are not shown.

wall and footwall blocks of the Goatcamp fault (HW-GF and FW-GF blocks in Figs. 1, 2). The geologic map of Smith (1987) was modified on the basis of stratigraphic and structural control in areas near the stratigraphic sections (Fig. 2) and based on analysis of aerial photos. Areas with less structural complexity and better exposure were selected for measured sections and rock descriptions. Descriptions of siliciclastic rocks employ Wentworth grain-size terminology. Where carbonate constituents predominate over siliciclastic grains, the textural maturity classification of Dunham (1962) was used. Descriptions of volcaniclastic rocks employ the textural classification of Schmid (1981). The internal and external geometry, nature of contacts, texture, and composition of each lithologic body were described in each stratigraphic section. Paleocurrent data were collected mainly from planar cross-beds and axes of channel structures. Depositional environment analysis was performed following designation of individual lithofacies and lithofacies associations, an approach similar to that of Miall (1996) for fluvial deposits.

Stratigraphic correlation across the Goatcamp fault was supported by identification of stratigraphic surfaces, which correspond to unconformities, flooding surfaces, or depositional contacts of units with contrasting petrofacies or lithofacies assemblages. Identification of flooding surfaces and depositional environments was refined with published biostratigraphic data. Details of petrofacies and provenance analyses of clastic units are found in Bayona (1998); Figure 3 shows the stratigraphic position and modal composition of each sample. All stratigraphic, paleocurrent, and compositional data were integrated in order to identify changes of thickness, lithofacies, composition, and depositional environments of correlative strata between blocks. In order to assign the age for stratigraphic units and significant stratigraphic surfaces identified in the central Peloncillo Mountains, a tectonostratigraphic correlation with equivalent units in southeastern Arizona and southwestern New Mexico was accomplished by reference to existing literature (Fig. 4; Bayona, 1998).

GEOLOGY OF THE CENTRAL PELONCILLO MOUNTAINS

The Lower Cretaceous Bisbee Group and an overlying conglomerate and volcaniclastic succession of Late Cretaceous–Paleogene age (Gillerman, 1958; Drewes and Thorman, 1980; Smith, 1987) comprise the two major tectonostratigraphic units of the central Peloncillo Mountains. Gillerman (1958) divided the Bisbee Group into four formations, in ascending order, the McGhee Peak Conglomerate, Carbonate Hill Limestone, Still Ridge Formation, and Johnny Bull Sandstone. The post-Bisbee succession has been defined in unpublished theses (Hudson, 1984; Smith, 1987), and includes the Bobcat Hill Conglomerate and the andesite of Steins Pass. We used the stratigraphic divisions of Gillerman (1958) and Smith (1987) for mapping purposes, but the term formation was applied to each unit because each is composed of a complex lithofacies assemblage rather than a distinct and dominant lithofacies.

Three major northwest-striking reverse faults, the Wood Canyon, Goatcamp, and Johnny Bull faults, are present in the study area (Fig. 2). The Wood Canyon and Goatcamp faults dip moderately to steeply southwest. Smith (1987) reported local evidence of left-lateral strike slip movement on these faults. The Wood Canyon fault on the southwest juxtaposes megacrystic Precambrian granite (basement block in Fig. 2) against Bisbee and Paleozoic strata. The Goatcamp fault places Paleozoic rocks against the andesite of Steins Pass and Bisbee Group (Gillerman, 1958; Smith, 1987). The Johnny Bull fault dips steeply northeast, bends abruptly to a north-northwest strike (Fig. 2), and decreases in stratigraphic throw abruptly northward (Smith, 1987). The Johnny Bull fault affects the youngest strata in the study area, although andesitic and rhyolitic intrusive rocks cross-cut strata and structures on both sides of the Goatcamp and Johnny Bull faults (Smith, 1987). Thickness changes of Laramide volcanic rocks across the Johnny Bull fault indicate that it had a Laramide history, but this fault was not the main focus of this study.

This paper interprets the history of the Wood Canyon and Goatcamp faults from stratigraphic relations of Bisbee Group strata on the footwall and hanging wall of the Goatcamp fault and composition of Laramide deposits on the hanging wall. In the hanging-wall block of the Goatcamp fault, the Bisbee Group is at least 840 m thick, Laramide deposits are absent, and all strata are deformed by folds and thrust, normal, and strike-slip faults. The Bisbee Group in the footwall block is only 287 m thick, Laramide deposits of the Bobcat Hill Formation are at least 600 m thick, and the andesite of Steins Pass is more than 2500 m thick (Hudson, 1984). The Bobcat Hill Formation thickens and is finer grained eastward (Gillerman, 1958; Smith, 1987). Strata in the footwall block of the Goatcamp fault (FW-GF block in Figs. 1 and 2) occupy a regional, north-plunging anticline, termed the Peloncillo arch, the axis of which is offset by the Johnny Bull fault. The southwest limb of the Peloncillo arch is truncated by the Goatcamp fault.

STRATIGRAPHY AND DEPOSITIONAL ENVIRONMENTS

Description and interpretation of Bisbee and Bobcat Hill deposits are organized according to intervals defined by stratigraphic surfaces (Fig. 3). Deposits between stratigraphic surfaces accumulated in a single depositional system and had common source areas (Bayona and Lawton, 1998). Stratigraphic surface 1 corresponds to the basal unconformity of the Bisbee Group in the hanging-wall block. Surface 2 corresponds to the basal unconformity of the Bisbee Group in the footwall block, but the equivalent level in the hanging-wall block is a conformable contact. Surfaces 3 and 4 are within the Bisbee Group. Surface 3 represents the maximum record of marine transgression, and surface 4 corresponds to an abrupt change in clastic supply and composition. Surface 5 corresponds to an unconformity overlying the Bisbee Group in the footwall block. Surface 6 divides the Bobcat Hill Formation into two units with different lithofacies and petrofacies associations, and surface 7 corresponds to the unconformity between the Bobcat Hill Formation and the overlying andesite of Steins Pass.

The ages of the Bisbee Group and the Bobcat Hill Formation have been assigned primarily by correlation of major stratigraphic surfaces and deposits with better-dated Cretaceous–Paleogene successions in the Big and Little Hatchet Mountains (Figs. 1, 4) (Gillerman, 1958; Mack et al., 1986; Bayona, 1998). Except for the upper part of the Carbonate Hill Formation, the ages of lower and upper units of Bisbee Group in the study area remain uncertain. Faunal data indicate that the Aptian-Albian boundary (surface 3 in Figs. 3–5) lies within the upper part of the Carbonate Hill Formation (Gillerman, 1958; LeMone and Sandidge, 1991; Goodspeed and Lucas, 1992).

Ages of the Bobcat Hill Formation and the andesite of Steins Pass are controversial. Drewes and Thorman (1980) reported fission-track ages of 27.5 ± 4.8 Ma (apatite) and 32.7 ± 1.5 Ma (zircon) of a quartz latite porphyry identified by Smith (1987) and Bayona (1998) as stratified volcaniclastic deposits of the Bobcat Hill Formation, and a zircon fission-track age of 44.7 ± 2.7 Ma in a sample collected low in the section assigned to the andesite of Steins Pass by Smith (1987). Lucas (1992) described a mammalian bone from the top of the Bobcat Hill Formation (member E in this study) that indicates a late Eocene age. Hudson (1984) and Smith (1987) concluded that the apparently young radiometric ages obtained from rocks of the Bobcat Hill Formation and andesite of Steins Pass were reset by 31.6 Ma (Oligocene) intrusive rocks. Because the fission-track age in the andesite of Steins Pass is older (middle Eocene) than the mammalian bone in underlying deposits (late Eocene), the ages of the igneous rocks need to be re-evaluated with more appropriate dating techniques, such as zircon U-Pb, and more biostratigraphic data are also required to resolve this problem.

Bisbee Group between surfaces 1 and 4

Deposits of the Bisbee Group between surfaces 1 and 2 include only the lower member of the McGhee Peak Formation (Fig. 3). This member is restricted to the hanging-wall block and unconformably overlies several Upper Permian formations (Gillerman, 1958; Smith, 1987). The lower part consists of clast- to matrix-supported conglomerate with clasts of limestone and subordinate chert and quartzarenite. This basal conglomerate is overlain by an upward-coarsening succession of mixed

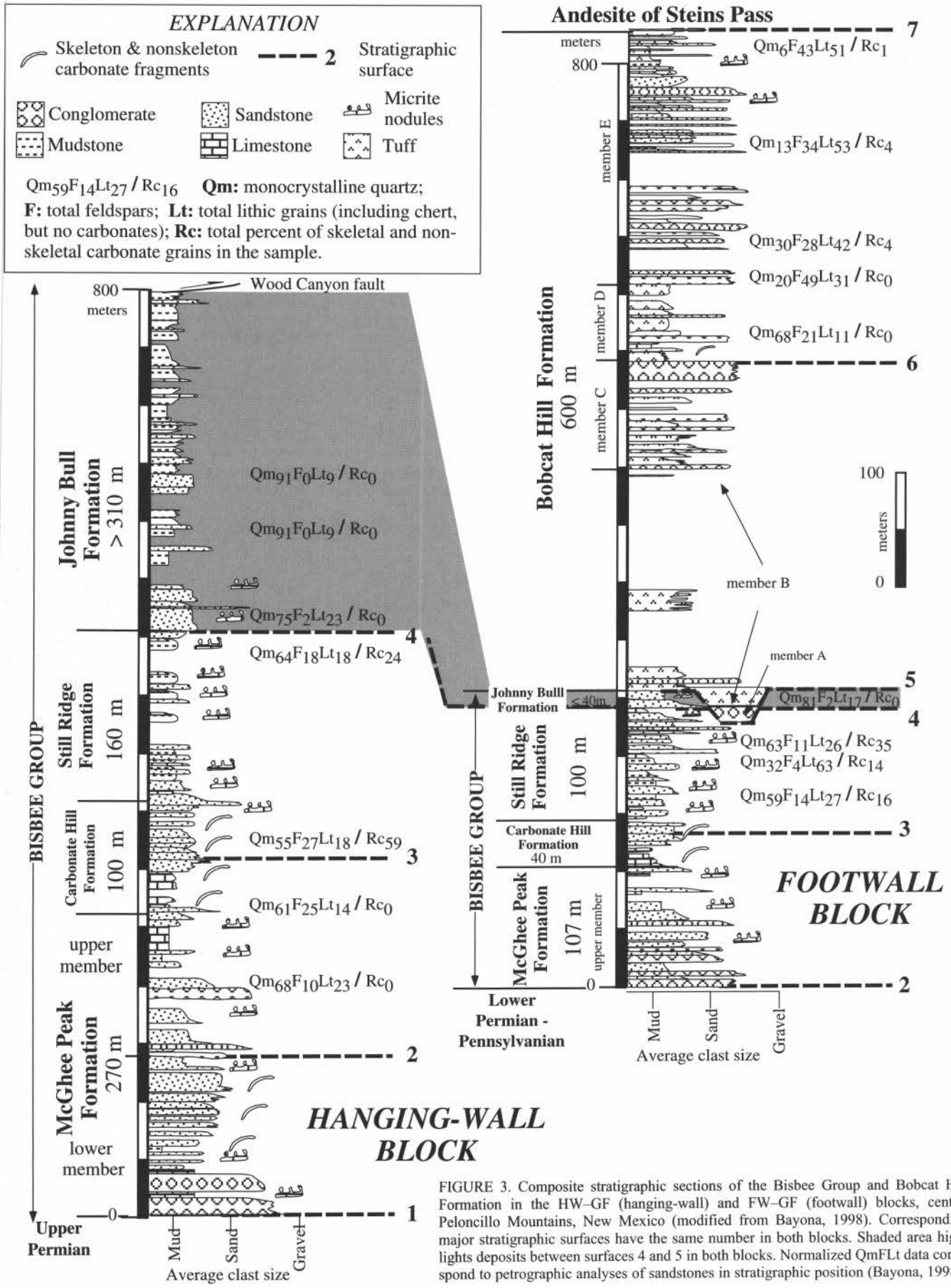


FIGURE 3. Composite stratigraphic sections of the Bisbee Group and Bobcat Hill Formation in the HW–GF (hanging-wall) and FW–GF (footwall) blocks, central Peloncillo Mountains, New Mexico (modified from Bayona, 1998). Corresponding major stratigraphic surfaces have the same number in both blocks. Shaded area highlights deposits between surfaces 4 and 5 in both blocks. Normalized QmFLt data correspond to petrographic analyses of sandstones in stratigraphic position (Bayona, 1998).

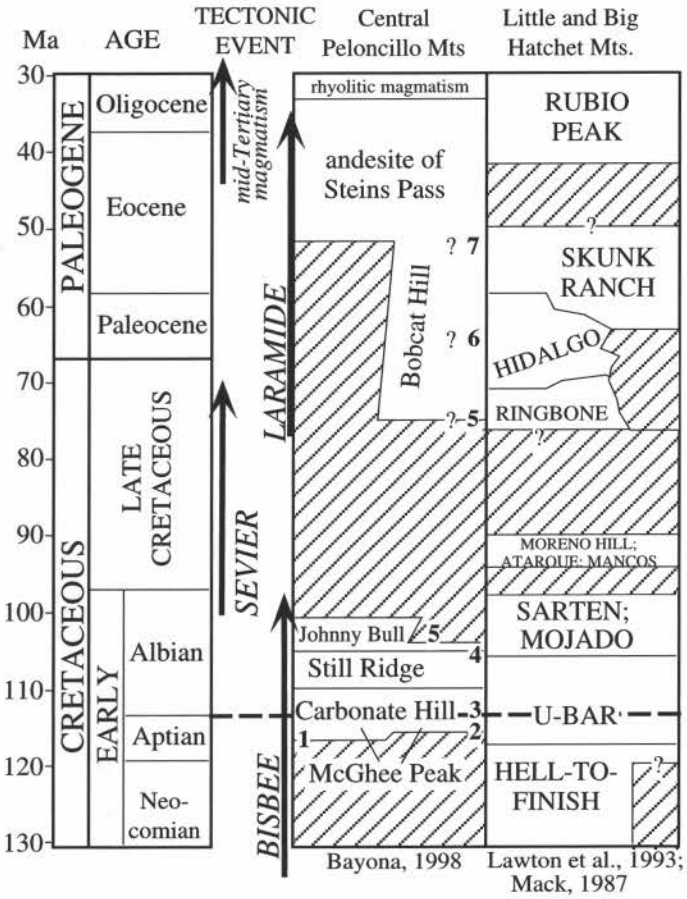


FIGURE 4. Correlation chart of Cretaceous–middle Paleogene strata in southwestern New Mexico. Dashed line is the Aptian-Albian boundary; ruled areas represent periods of no record. Numbers 1 through 7 are the major stratigraphic surfaces identified in the study area. Question mark indicates stratigraphic surface of uncertain age.

siliciclastic and carbonate rocks with oyster fragments and scattered clasts of chert, quartz, and limestone. In this succession, massive to ripple-laminated sandstone with micrite nodules predominates at the bottom, whereas cross-bedded sandstone predominates at the top. Conformable contacts among those deposits indicate interbedding of deposits of alluvial fans and brackish-water environments. Similar assemblages of environments are described in modern and ancient fan deltas (e.g., McPherson et al., 1987).

Bisbee deposits above surface 2 and below 4 encompass strata of the upper member of the McGhee Peak, the Carbonate Hill, and Still Ridge formations (Fig. 3). The upper member of the McGhee Peak Formation consists of siliciclastic upward-fining successions that conformably overlie the lower member in the hanging-wall block and unconformably overlie Permian–Pennsylvanian strata in the footwall block. Individual upward-fining successions consist of, in ascending order, massive conglomerate with quartz, chert, and limestone clasts; cross-bedded conglomerate and coarse-grained subarkose; and cross-bedded and ripple-laminated subarkose with abundant micrite nodules and irregular layers of sandy micrite. Changes of lithofacies within the upward-fining succession are abrupt, both laterally and vertically. The uppermost part of this member includes beds of sandy mudstone.

The Carbonate Hill Formation is a mixed carbonate-siliciclastic succession that overlies the McGhee Peak Formation on a gradational contact. The lower part of the formation consists of sandy mudstones and wackestones with micrite nodules and coarse oyster and gastropod fragments. The middle and upper parts of the formation consist of sandy packstones and wackestones with oyster fragments, gastropods, corals, foraminifera, encrusting algae, ooids, peloids, and intraclasts. Massive bedding and ripple lamination predominate in sandstone beds of the footwall block, whereas cross-bedding predominates in the hanging-wall block.

The Still Ridge Formation is gradational above the Carbonate Hill Formation and is defined by three types of lithologic successions. The first is present locally near the base in the footwall block and consists of cross-bedded, well-sorted, fine-grained quartzose sandstone interbedded with ripple-laminated quartzose sandstone and massive, nodular sandy mudstone. Kolins (1986) reported charophyta within this succession. The second succession, dominant in both blocks, is an upward-fining succession of gray, cross-bedded, coarse-grained to conglomeratic sandstone overlain by cross-bedded and ripple-laminated, fine-grained sublitharenite with abundant micrite nodules. The third lithologic succession is restricted to the footwall block and is present only near the top of the formation. It consists of massive to crudely bedded conglomerate with clasts of pedogenic micrite, and subordinate quartz and chert clasts. The conglomerate changes laterally to cross-bedded, coarse-grained sandstone, and grades vertically to cross-bedded and ripple-laminated, fine-grained sandstone with micrite nodules. Sandstone composition in the Still Ridge Formation is dominantly sublitharenite (Bayona, 1998).

Deposits of the upper member of the McGhee Peak Formation uniformly covered the entire study area. Channel-fill successions in the upper member of the McGhee Peak Formation are interpreted from the upward-fining trend and the variation in depositional structures as deposits of deep, gravel-bed braided channels (e.g., Miall 1996). Cross-bedded packstone with ooids and a high diversity of fossil fragments in the Carbonate Hill Formation are interpreted as shallow, nearshore shoals that separated brackish and normal marine waters. Deposits in the transition between the McGhee Peak and the Carbonate Hill formations accumulated in conditions similar to those depicted by McPherson et al. (1987) for coarse braid-deltas. Ripple-laminated sandstones with calcic paleosol development characterize supratidal areas, whereas massive, sandy mudstone and wackestone with oysters and gastropod fragments accumulated in intertidal and lagoonal–subtidal conditions.

Encroachment of a tidal-flat environment above surface 3 is suggested by the vertical assemblage of lithofacies in the Still Ridge Formation. These deposits have characteristics of hypothetical vertical profiles of siliciclastic tidal flats (e.g., Dalrymple 1992) and carbonate tidal flats traversed by creeks (e.g., Pratt et al., 1992). Quartzose deposits in the lower succession accumulated as tidal bars and sand flats in subtidal and lower intertidal conditions, respectively. The dominant mixed siliciclastic-carbonate succession of the Still Ridge Formation accumulated in intertidal and supratidal conditions, where brackish and fresh waters mixed and calcic paleosols developed during protracted episodes of subaerial exposure. Progradation of coastal-plain environments combined with reworking of calcic paleosols is interpreted from mixed siliciclastic-carbonate deposits at the top of the Still Ridge Formation.

Provenance analysis and south- to west-oriented paleocurrent indicators (Kolins, 1986; Mack et al., 1986; Bayona, 1998) of clastic units between surfaces 1 and 4 indicate that arkosic, cherty, and polycrystalline and monocrystalline quartz sand-size detritus was derived from basement and Paleozoic rocks exposed on the rift shoulder to the northeast (Mack et al., 1986; Bayona, 1998). Boulder- to cobble-size conglomerate clasts were derived from nearby, probably intrabasinal, uplifts (Bayona, 1998).

Bisbee Group between surfaces 4 and 5

The Johnny Bull Formation lies between surfaces 4 and 5. The lower contact of the formation is conformable and is defined beneath the lowermost thick, cross-bedded quartz arenite (surface 4 in Fig. 3). In the hanging wall and outside the study area, Smith (1987) reported a maximum thickness of 420 m for the Johnny Bull Formation. The lower part contains, in order of abundance, cross-bedded to ripple-laminated, well-sorted, fine-grained sandstone, and upward-fining sandstone beds with erosional lower contacts overlain by basal conglomeratic lags. The upper part of the Johnny Bull Formation is present only in the hanging-wall block and consists of laminated red mudstone interbedded with

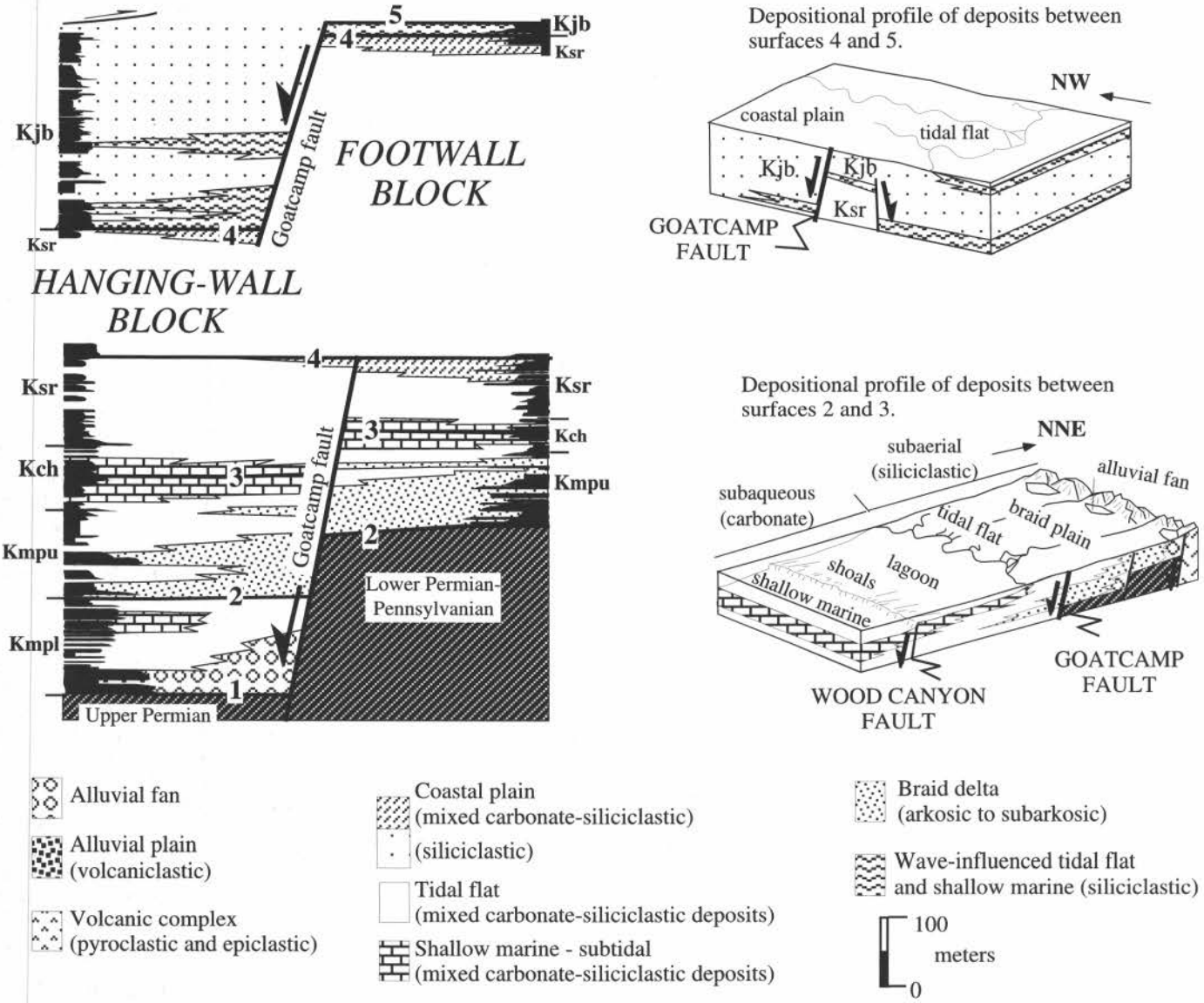


FIGURE 5. **Bottom**, Stratigraphic correlation and depositional environments of McGhee Peak (Kmpl and Kmpu), Carbonate Hill (Kch), and Still Ridge (Ksr) formations (Aptian–middle Albian). **Top**, Stratigraphic correlation and depositional environments of the Johnny Bull Formation (Kjb; Upper Albian).

fine- to medium-bedded quartzose sandstone with internal cross-bedding and thin lateral-accretion sets. Sandstone in this unit is dominantly quartzose (Bayona, 1998).

Sandy quartzose deposits at the bottom of the Johnny Bull Formation are interpreted as having been deposited in wave-influenced tidal-flat environments. The upsection increase in laminated mudstone and cross-bedded sandstone may represent a transition to coastal-plain deposition, with muddy deposition in floodplains and sandy deposition in crevasse splays and shallow, sinuous channels. Quartz-rich detritus and paleocurrent indicators of sandstones both near the base of the Still Ridge Formation and in the overlying Johnny Bull Formation (Galemore, 1986; Mack et al., 1986; Bayona 1998) suggest that early shallow-marine currents and a subsequent east-directed fluvial system transported terrigenous sediment supplied from new sources located to the west. The source of the quartzose detritus is controversial. Dickinson et al. (1989) and Klute (1991) proposed the following areas: highly weathered rocks exposed in the Mogollon highlands, cratonic North America, and magmatic arc lying to the west. Mack (1987) interpreted the Sevier thrust belt as the source of quartzose detritus.

The Bobcat Hill Formation

The Bobcat Hill Formation unconformably overlies the Bisbee Group in the footwall block and is divided into five informal members. Members designated A, B, and C are between surfaces 5 and 6, whereas members D and E are between surfaces 6 and 7 (Fig. 3). Member A is in discontinuous lenses 0–35 m thick and overlies strata of the Still Ridge Formation. Member B conformably overlies member A, or unconformably overlies the Johnny Bull Formation where member A is absent. Contacts between members are condordant.

Member A consists of matrix- and clast-supported, pebble to boulder conglomerate with quartzarenite clasts in the lower part, and granite, chlorite schist, limestone, and volcanic clasts in the middle and upper parts. Member B consists of massive to crudely stratified lapilli and ash tuff with crystals of altered feldspar and quartz. Medium to thick conglomerate beds, dominated by angular felsic volcanic clasts, are locally present in the lower part. Member C consists of interbedded volcanic-rich conglomerate and crudely stratified lapilli and ash tuffs. Conglomerate beds have indistinct horizontal stratification near their bases, thicken and coarsen upsection, and are massive and matrix-supported in their upper parts. Member D consists of stratified and locally cross-bedded ash tuff, interbedded with thin to medium beds of matrix- and clast-supported conglomerate that contain clasts of quartzarenite, limestone, and intermediate volcanic rocks. Angular quartz and volcanic lithic grains are the dominant grain types in the tuff (Bayona,

1998). The member D includes a meter-thick, sandy, ostracod-bearing micrite bed that extends laterally for more than 3 km (Smith, 1987).

Member E consists of conglomerate, sandstone, and mudstone. Conglomerate beds are clast-supported and massive in their lower parts, horizontally stratified in the middle part, and include cross-bedded sandstone lenses in the middle and upper parts. Conglomerate decreases in abundance upsection. Clast types include, in order of decreasing abundance, volcanic rocks, limestone, and quartzarenite. Sandstones are massive, horizontally stratified, and cross-bedded, whereas mudstones are internally massive. Sandstones are rich in volcanic lithic grains, and feldspar grains increase in abundance upsection as quartz abundance decreases (Bayona, 1998).

Coarse clastic deposits between surfaces 5 and 6 (members A to C) mainly accumulated by a variety of sediment-gravity flow processes. Massive conglomerates in members A and B have lithofacies assemblages similar to deposits interpreted as formed on alluvial fans dominated by debris flows (Blair and McPherson, 1994). In member C, the upsection change in fabric and conglomerate bedding structures indicates that hyperconcentrated-flow processes dominated at the bottom, but younger conglomerate beds accumulated by debris-flow processes. The upsection shift in depositional process suggests an increase in the sediment–water ratio (Smith and Lowe, 1991). These sediment-gravity flow deposits were derived from nearby sources and filled a pre-existing topography of valleys and interfluves. The presence of boulder- and cobble-sized clasts of basement, quartzarenite, and limestone in sediment-gravity flows of members A and C suggests derivation from the hanging-wall blocks of the Wood Canyon and Goatcamp faults, where basement and Paleozoic rocks are exposed (Fig. 2; Bayona, 1998).

In contrast, the epiclastic association of conglomerate, sandstone, and mudstone deposits in member E and above surface 6 is interpreted to represent deposition on alluvial plains. The absence of lateral-accretion surfaces and sharp transitions among lithofacies suggest that these deposits accumulated in gravel-bed braided channels (Miall, 1996). Massive and clast-supported conglomerate beds locally interbedded in this succession are interpreted as deposits of hyperconcentrated flows intercalated with alluvial-fan deposits. North- and northwest-oriented paleocurrent indicators (Bayona, 1998) and intermediate volcanic lithic grains present in sandstones of member E suggest that alluvial deposits were derived from areas toward the south and southeast, where intermediate volcanic rocks were exposed (Lawton et al., 1993).

Felsic tuffaceous deposits of the Bobcat Hill Formation show an upsection increase in the presence of primary depositional structures and decrease in grain-size that is most evident across surface 6. These upsection variations may be related to changes in the process of deposition and type of contributing eruption. According to models proposed by Cas and Wright (1987), massive and crudely bedded lapilli and ash tuffs of members B and C (below surface 6) may be interpreted as deposits of either pyroclastic flows or pyroclastic surges, whereas finer grained and cross-bedded tuffs in member D (above surface 6) likely originated as pyroclastic surges. Beds of accretionary lapilli in member D, the abundance of planar and cross-bedded structures up-section, and the higher fragmentation of pyroclastic components suggest increased interaction of water in volcanic eruptions (e.g., Sheridan and Wohletz, 1983) that contributed to higher parts of the section (Bayona, 1998).

In the footwall block, the contact between the Bobcat Hill Formation and the andesite of Steins Pass is angular, ranging in discordance from 15° to 50° (Smith, 1987). In the hanging-wall block, the andesite unconformably rests on Paleozoic strata. The andesite of Steins Pass consists of 2500–2700 m of andesitic lava and volcaniclastic rocks of calc-alkaline and high-potassium chemical composition (Hudson, 1984; Smith, 1987).

CONTROLS ON SEDIMENTATION BY FAULTING

In this section, we discuss stratigraphic patterns of deposits that were controlled dominantly by local faulting. Deposits restricted to a particular fault-bounded block and abrupt changes in thickness of correlative strata across a fault are considered as indicators of variable amounts of subsidence and uplift of fault-bounded blocks. The internal stratal architecture and clastic composition are the result of a complex interaction of allogenic conditions, such as tectonism, climate, eustatic sea-level changes, and magmatism (e.g., Van Wagoner et al., 1990; Christie-Blick and Driscoll, 1995). The reader should keep in mind that climate, sediment supply, and eustasy also played important roles in deposition of the Cretaceous–middle Paleogene succession in the study area. Although these factors are only briefly mentioned in this paper, the influence of climate, sediment-supply, eustasy, and magmatism on deposition are discussed more extensively in Bayona (1998).

Early Cretaceous extensional tectonism

Two major episodes of extensional activity on the Goatcamp fault are evidenced by restricted distribution of Bisbee units and by thickening of Bisbee units in the hanging-wall block. The localized distribution of the lower member of the McGhee Peak Formation records the onset of the first episode of faulting (Fig. 5). Debris flows were derived from the footwall block and accumulated on the hanging-wall block near the footwall scarp. Stacking patterns and difference in thickness of deposits between surfaces 2 and 4 indicate a variable offset rate along the fault. Intervals of increased normal fault activity may have contributed to the retrogradation of depositional systems (e.g., Leeder and Gawthorpe, 1987), recorded by deposits between surfaces 1 and 2, and between 2 and 3 (Fig. 5). In contrast, a decline in rate of normal faulting might have produced a drop of base level and/or progradation of the system, as represented by abrupt progradation of braided-channel deposits above surface 2, and by encroachment of tidal-flat deposition during deposition of the Still Ridge Formation. The second episode of extensional activity corresponds to down-to-southwest reactivation of the Goatcamp fault (Fig. 5). The extreme difference in thickness of the Johnny Bull Formation between fault-bounded blocks, 35 m in the footwall block and >420 m in the hanging-wall block (Smith, 1987), documents this episode of normal faulting. In addition, the early aggradational and subsequent progradational patterns of Johnny Bull deposits suggest that the rate of sediment supply exceeded the rate of creation of space through time. Syndepositional stratigraphic offset of the second episode (>380 m of stratigraphic surface 4) is greater than the stratigraphic offset of the first episode (ca. 280 m of stratigraphic surface 1).

In a regional framework, retrogradation resulted from a combination of extensional tectonism operating adjacent to the rift shoulder of the Bisbee basin (Mack, 1987), Aptian–Albian marine transgression (Scott and Warzesky, 1993), and low terrigenous influx from the basement-cored Mogollon-Burro uplift (Mack, 1987). Initial extensional tectonism in the Bisbee basin is recorded by Jurassic deposits (Bilodeau, 1982; Dickinson, 1989; Lawton and Olmstead 1995; Lawton and Harrigan, 1998). Extension continued to control the distribution of subsiding and uplifted areas through early Albian time (Mack et al., 1986; Klute 1991). Normal faulting also contributed to the late record of Aptian–Albian marine transgression in the central Peloncillo Mountains, as well as the earlier progradation of continental deposits over shallow-marine deposits near the rift shoulder (Mack, 1987; Dickinson et. al., 1989; Bayona, 1998). The late Albian down-to-southwest fault reactivation identified in the central Peloncillo Mountains may have tectonic counterparts in surrounding areas. Although exposures of upper Albian deposits are uncommon in southern New Mexico and Arizona, upper Albian deposits as much as 1500 m thick in the Little Hatchet Mountains (Mack et al., 1986) record a new episode of rapid tectonic subsidence (Mack, 1987), which we interpret as a result of thickening across Early Cretaceous normal faults.

Late Cretaceous–middle Paleogene inversion

The Bobcat Hill Formation records several episodes of basement-cored uplift accompanied by felsic volcanism (Bayona and Lawton, 1998). Gravel-size granite clasts in debris-flow deposits of member A indicate that Precambrian basement was already exposed in nearby western blocks. The uplift of western blocks (e.g., basement block in Figs. 2, 6) record the onset of inversion and likely enhanced the relief of the Bisbee-Bobcat Hill unconformity. A second episode of uplift, result-

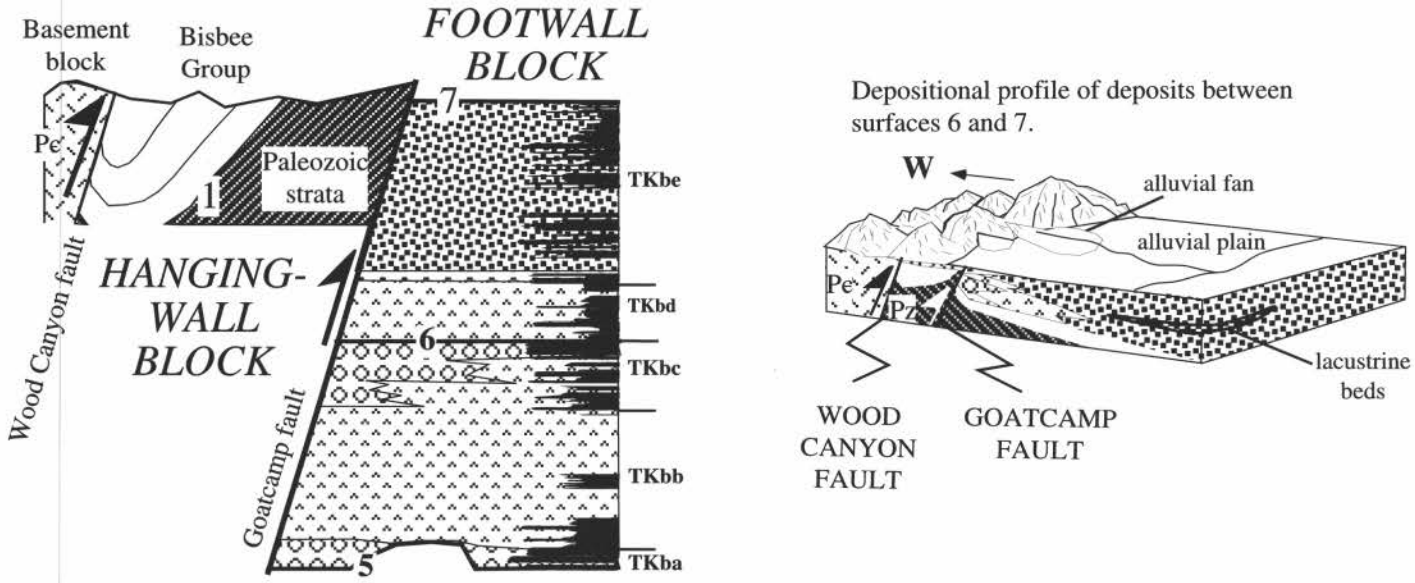


FIGURE 6. Stratigraphic correlation and depositional environments of the Bobcat Hill Formation (TKba through TKbe; Upper Cretaceous?–Eocene). See Figure 5 for explanation of symbols.

ing in reverse movement along the Goatcamp fault, is recorded in member C (deposits below surface 6). Up-section changes in clast population, increases in bed thickness, and increases in clast size of sediment-gravity-flow deposits indicate that uplift approached the study area with time. Deposition of gravel and fine-grained alluvial-plain deposits above surface 6 record intermittent reverse movement on the Goatcamp fault and fill of the complementary basin. The absence of basement clasts and widespread presence of gravel-size volcanic clasts in this interval suggests that uplifted blocks were regularly covered by volcanic deposits.

Stratigraphic patterns and clast composition of Laramide deposits in adjacent ranges record the uplift of northwest-trending basement-cored blocks and accumulation in complementary intermontane basins (Keith and Wilt, 1985; Seager and Mack, 1986; Miller et al., 1992), similar to what is documented here for the central Peloncillo Mountains. In the study area and Little Hatchet Mountains, basement-cored uplift is recorded by basement clasts in lower conglomerate beds of the Bobcat Hill Formation and Ringbone Formation, respectively (Fig. 4; Lawton et al., 1993). Laramide clastic deposition was interrupted and modified by volcanic activity, as indicated by volcanic deposits of members B, C, and D of the Bobcat Hill Formation, and the Hidalgo Formation in the Little Hatchet Mountains (Lawton et al., 1993). In addition, the lithofacies associations and stratigraphic position of the Skunk Ranch Formation in the Little Hatchet Mountains (Lawton et al., 1993) and member E of the Bobcat Hill Formation are similar. Both units contain conglomerate and sandstone beds deposited by alluvial fans and braided rivers. A broad connection of fluvial systems between those areas has been inferred from paleocurrent indicators and the up-section increase of basaltic volcanic fragments in volcaniclastic sandstones of member E, which may have been supplied from andesitic deposits present in the Little Hatchet Mountains (Bayona, 1998).

DISCUSSION AND CONCLUSIONS

In the central Peloncillo Mountains, stratigraphic correlation of Cretaceous–middle-Paleogene strata, supported by matching seven stratigraphic surfaces across the Goatcamp fault, indicates that depositional patterns and composition of clastic detritus were primarily controlled by fault activity on northwest-striking faults (Figs. 5, 6). In addition to depositional patterns and composition, distribution and internal stratal architecture of Cretaceous–middle-Paleogene strata document two episodes of normal faulting during Aptian–Albian time and inversion of those structures during Late Cretaceous–middle Paleogene time.

Cretaceous and Paleogene fault activity in the central Peloncillo Mountains was the result of regional tectonism. Onset of normal faulting in the study area is documented by restricted deposition on hanging-wall sites of fan-delta and shallow-marine strata of the lower member of the McGhee Peak Formation. Intermittent pulses and later decline of normal fault activity are documented in braided-delta, shallow-marine, and tidal-flat strata of the upper member of the McGhee Peak, Carbonate Hill, and Still Ridge formations (Fig. 5). This first episode of normal fault activity was related either to extensional tectonism adjacent to the rift shoulder of the Bisbee basin (Mack, 1987), or to thermal contraction of the lithosphere. Dickinson et al. (1989) suggested that thermotectonic subsidence controlled deposition in the Bisbee basin during Neocomian–Albian time.

The abrupt change in thickness of the Johnny Bull Formation across the Goatcamp fault suggests down-to-the-southwest fault reactivation during late Albian time. Normal reactivation was accompanied by deposition of voluminous quartzose detritus in tidal-flats and east-flowing fluvial systems (Fig. 5; Mack, 1987; Bayona, 1998). Tectonism must have played, at least in the study area, an important role since syndepositional stratigraphic offset recorded by upper Albian strata is greater than that recorded by any other Bisbee units in the central Peloncillo Mountains. Late Albian tectonics in the former rift shoulder may have been influenced either by Aptian–Albian plate reorganization at the Cordilleran margin (Dickinson and Lawton, 1999), or by the cratonward advance of the Sevier thrust belt (Mack, 1987).

The Bobcat Hill Formation, preserved only in the northeastern (footwall) block, records a third episode of fault activity that corresponds to inversion during the Late Cretaceous–Paleogene Laramide orogeny (Fig. 6). Gravel-sized basement and sedimentary clasts in gravity-flow deposits of the lower half of the Bobcat Hill Formation resulted from uplift of southwestern (hanging-wall) basement-cored blocks along the former normal fault. Sedimentary structures and bed geometry of volcaniclastic deposits in the upper half of the Bobcat Hill Formation, in conjunction with the presence of lacustrine beds, indicate a transition to an alluvial-plain setting. Inversion of southwestern (hanging-wall) blocks was accompanied by emplacement of felsic pyroclastic flows and surge deposits.

Basement-cored uplift took place along the Wood Canyon and Goatcamp faults, which are oriented nearly perpendicular to the proposed southwest–northeast Laramide compression (Seager and Mack, 1986; Miller et al., 1992). Connate fluids and magmatic activity may

have contributed to inversion of steeply dipping normal faults, facilitating offset along the otherwise unfavorable normal orientation of horizontal stresses and the fault (e.g., Sibson, 1995). Overpressure may have resulted from fluids stored during extension and then confined during the compressional regime that inversion caused (Sibson, 1995). Weak materials precipitated in fault gouges as a result of hydrothermal fluids and host rock interaction also reduce the shear strength necessary to overcome friction and allow reactivation (Sibson 1995; Wintsch et al., 1995).

ACKNOWLEDGMENTS

This research was partially supported by National Science Foundation grant EAR-9304759, and by scholarships from the Department of Geological Sciences of New Mexico State University, the Roswell Geological Society, and the New Mexico Geological Society (NMSU). The first author acknowledges COLCIENCIAS (Instituto Colombiano para el Desarrollo de la Ciencia y la Technología–Francisco José de Caldas) for the financial support provided during his M.S. research at NMSU. We thank S. A. Hodgson, W. R. Seager, and W. A. Thomas for reviews that led to significant improvements.

REFERENCES

Bayona, G., 1998, Stratigraphic relationships of Cretaceous and Paleogene deposits, and their tectonic implications; central Peloncillo Mountains, Hidalgo County, southwestern New Mexico [M.S. thesis]: Las Cruces, New Mexico State University, 151 p.

Bayona, G. and Lawton, T. F., 1998, Tectonic control on deposition of Cretaceous–Paleogene deposits, central Peloncillo Mountains, New Mexico (abs.): New Mexico Geology, v. 20, p. 51.

Bilodeau, W. L., 1982, Tectonic models for Early Cretaceous rifting in southeastern Arizona: Geology, v. 10, p. 466–470.

Blair, T. C. and McPherson, J. G., 1994, Alluvial fans and their natural distinction from rivers based on morphology, hydraulic processes, sedimentary processes, and facies assemblages: Journal of Sedimentary Research, v. A64, p. 450–489.

Butler, R., Holdsworth, R. and Lloyd, G., 1997, The role of basement reactivation in continental deformation: Journal of the Geological Society, London, v. 154, p. 69–71.

Cas, R. A. F. and Wright, R. A., 1987, Volcanic successions—modern and ancient: Allen and Unwin, London, 528 p.

Christie-Blick, N. and Driscoll, N. W., 1995, Sequence stratigraphy: Annual Reviews of Earth and Planetary Science, v. 23, p. 451–478.

Dalrymple, R. W., 1992, Tidal depositional systems; *in* Walker, R. G. and James, N. P., eds., Facies models—response to sea level change: Geological Association of Canada, St. Johns, Newfoundland, p. 195–218.

Davis, G. H., 1979, Laramide folding and faulting in southeastern Arizona: American Journal of Science, v. 279, p. 543–569.

Dickinson, W. R., 1989, Tectonic setting of Arizona through geologic time: Arizona Geological Society Digest, v. 17, p. 1–16.

Dickinson, W. R. and Lawton, T. F., 1999, Post-mid-Paleozoic tectonic assembly of Mexico: Geological Society of America, Abstracts with Programs, v. 31, n. 7, p. 125.

Dickinson, W. R., Fiorillo, A. R., Hall, D. L., Monreal, R., Potochnik, A. R. and Swift, P. N., 1989, Cretaceous strata of southern Arizona: Arizona Geological Society Digest, v. 17, p. 447–461.

Dunham, R. J., 1962, Classification of carbonate rocks according to depositional texture: American Association of Petroleum Geologists, Memoir 1, p. 108–122.

Drewes, H. D. and Thorman C. H., 1980, Geologic map of the Steins quadrangle, and the adjacent part of the Vanar quadrangle, Hidalgo County, New Mexico: U.S. Geological Survey, Miscellaneous Geologic Investigations Map I-1220, scale 1:24,000.

Galemore, J. A., 1986, Stratigraphy, depositional environments, and provenance of the Mojado Formation (middle Albian–early Cenomanian), southwestern New Mexico [M.S. thesis]: Las Cruces, New Mexico State University, 103 p.

Gillerman, E., 1958, Geology of the central Peloncillo Mountains, Hidalgo County, New Mexico, and Cochise County, Arizona: New Mexico Bureau of Mines and Mineral Resources, Bulletin 57, 152 p.

Goodspeed, T. and Lucas S. P., 1992, Early Cretaceous (Aptian) ammonites from the central Peloncillo Mountains, southwestern New Mexico (abs.): New Mexico Geology, v. 14, p. 78.

Holdsworth, R., Butler, C. and Roberts, A., 1997, The recognition of reactivation during continental deformation: Journal of the Geological Society, London, v. 154, p. 73–78.

Hudson, J. S., 1984, Geology and hydrothermal alteration of the San Simon mining district south of Steins Pass, Peloncillo Mountains, Hidalgo County, New Mexico [M.S. thesis]: Albuquerque, University of New Mexico, 125 p.

Keith, S. B. and Wilt J. C., 1985, Late Cretaceous and Cenozoic orogenesis of Arizona and adjacent regions—a strato-tectonic approach; *in* Flores, R. M. and Kaplan, S. S., eds., Cenozoic paleogeography of west-central United States: Rocky Mountain section, Society of Economic Paleontologists and Mineralogists, Denver, Colorado, p. 403–437.

Klute, M. A., 1991, Sedimentology, sandstone petrofacies, and tectonic setting of the late Mesozoic Bisbee basin, southeastern Arizona [Ph.D. dissertation]: Tucson, University of Arizona, 268 p.

Kolins, W. B., 1986, Stratigraphy, depositional environments, and provenance of Lower Cretaceous sedimentary rocks, Peloncillo and Animas mountains, southwestern New Mexico [M.S. thesis]: Las Cruces, New Mexico State University, 214 p.

Lawton, T. F., 1996, Laramide inversion of Late Jurassic–Early Cretaceous extensional faults, SE Arizona and SW New Mexico (abs): Geological Society of America, Abstracts with Programs, v. 28, no. 6, p. 509–510.

Lawton, T. F., Basabilvazo, G. T., Hodgson, S. A., Wilson, D. A., Mack, G. H., McIntosh, W. C., Lucas, S. G. and Kietzke, K. K., 1993, Laramide stratigraphy of the Little Hatchet Mountains, southwestern New Mexico: New Mexico Geology, v. 15, p. 9–15.

Lawton, T. F. and Harrigan, P. J., 1998, Broken Jug Formation—redefinition of lower part of the Bisbee Group, Little Hatchet Mountains, Hidalgo County, New Mexico: New Mexico Geology, v. 20, p. 69–77.

Lawton, T. F. and Olmstead, G. A., 1995, Stratigraphy and structure of the lower part of the Bisbee Group, northeastern Chiricahua Mountains, Arizona: Geological Society of America, Special Paper 301, p. 21–39.

Leeder, M. R. and Gawthorpe, R. L., 1987, Sedimentary models for extensional tilt-block/half-graben basins: Geological Society, Special Publication 28, p. 139–152.

Lemone, D. V. and Sandidge M. H., 1991, The middle Cretaceous Carbonate Hill Formation, Hidalgo County, New Mexico: Geological Society of America, Abstracts with Programs, v. 23, n. 4, p. 41–42.

Lucas, S. G., 1992, Eocene mammal from the Bobcat Hill Conglomerate, Peloncillo Mountains, southwestern New Mexico: New Mexico Geology, v. 14, p. 9–12.

Mack, G. H., 1987, Mid-Cretaceous (late Albian) change from rift to retroarc foreland basin in southwestern New Mexico: Geological Society of America Bulletin, v. 98, p. 507–514.

Mack, G. H., Kolins, W. B. and Galemore, J. A., 1986, Lower Cretaceous stratigraphy, depositional environments and sediment dispersal in southwestern New Mexico: American Journal of Science, v. 286, p. 309–331.

McPherson, J. G., Shanmugam, G. and Moiola, R. J., 1987, Fan-deltas and braid-deltas—varieties of coarse-grained deltas: Geological Society of America Bulletin, v. 99, p. 331–340.

Miall, A. D., 1996, The geology of fluvial deposits: Springer-Verlag, Berlin, 582 p.

Miller, D. M., Nilsen, T. H. and Bilodeau, W. L., 1992, Late Cretaceous to early Eocene geologic evolution of the U.S. Cordillera; *in* Burchfield, B. C., Lipman, P. W. and Zoback, M. L., eds., The Cordilleran orogen—conterminous U.S.: Geological Society of America, The Geology of North America, v. G-3, p. 205–260.

Pratt, B. R., James, N. P. and Cowan, C. A., 1992, Peritidal carbonates; *in* Walker, R. G. and James, N. P., eds., Facies models—response to sea level change: Geological Association of Canada, St. Johns, Newfoundland, p. 303–322.

Schmid, R., 1981, Descriptive nomenclature and classification of pyroclastic deposits and fragments—recommendations of the IUGS subcomission on the systematics of igneous rocks: Geology, v. 9, p. 41–43.

Scott, R. W. and Warzesky, E. R., 1993, An Aptian–Albian shelf ramp, Arizona and Sonora;: American Association of Petroleum Geologists, Memoir 56, p. 71–79.

Seager, W. R. and Mack G. H., 1986, Laramide paleotectonics of southern New Mexico: American Association of Petroleum Geologists, Memoir 41, p. 669–685.

Sheridan, M. F. and Wohletz, K. H., 1983, Hydrovolcanism—basic considerations and review: Journal of Volcanology and Geothermal Research, v. 17, p. 1–29.

Sibson, R., 1995, Selective fault reactivation during basin inversion—potential for fluid redistribution through fault-valve action: Geological Society, London, Special Publication 88, p. 3–19.

Smith, F. C., 1987, Geology, mineralization, and exploration potential of the McGhee Peak area, San Simon mining district, Hidalgo County, New Mexico [M.S. thesis]: Albuquerque, University of New Mexico, 176 p.

Smith, G. A. and Lowe, D. R., 1991, Lahars—volcano-hydrologic events and deposition in the debris flow-hyperconcentrated flow continuum: Society for Sedimentary Geology, Special Publication 45, p. 59–70.

Van Wagoner, J. C., Mitchum, R. M., Campion, K. M. and Rahmanian, V. D., 1990, Siliciclastic sequence stratigraphy in well logs, cores, and outcrops—concepts for high-resolution correlation of time and facies: American Association of Petroleum Geologists, Methods in Exploration Series 7, 55 p.

Wintsch, R., Christoffersen, R. and Kronenberg, A., 1995, Fluid-rock reaction weakening of fault zones: Journal of Geophysical Research, v. 100, n. B7, p. 13,021–13,032.

