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THE CRETACEOUS FORELAND BASIN IN SOUTHWESTERN NEW MEXICO

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Abstract—Early Cretaceous sedimentation in southwestern New Mexico began in a west–northwest-trending rift basin that was bordered on the north by a basement-cored rift shoulder. By late Albian and early Cenomanian time, the crest of the rift shoulder was substantially reduced in relief and was onlapped by the Sarten and Beartooth Formations, which consist of about 120 m of sandstone and shale derived from sedimentary source rocks located north of the basin. The Sarten Formation consists of two regressive cycles, the upper of which displays a change from offshore to fluvial facies. As the rift shoulder was onlapped, up to 1500 m of sandstone and shale of the Mojado Formation was deposited along the former axis of the rift basin. The Mojado Formation consists of lower and upper shallow-marine and shoreline members and a middle member composed of fluvial sediment. The Mojado Formation contains primarily monocrystalline quartz, but some sandstones also contain volcanic rock fragments and plagioclase, indicating a mixed sedimentary and volcanic source terrane. Eastward-directed fluvial paleocurrents suggest that the source terrane was located west of the basin.

By middle to late Cenomanian time, the rift shoulder was no longer a barrier to sedimentation, and foreland basin deposition was continuous across New Mexico. From middle Cenomanian to Campanian time up to 1000 m of marine and nonmarine sandstone and shale were deposited in at least two major transgressive and regressive cycles. Fluvial paleocurrent data suggest a northeastward paleoslope, and the presence of volcanic rock fragments, plagioclase, chert, pelitic rock fragments, and a high percentage of monocrystalline quartz indicate a mixed sedimentary and volcanic source terrane. The foreland basin was disrupted by Laramide deformation in latest Cretaceous and early Tertiary time.

INTRODUCTION

During Cretaceous time the Western Interior of North America underwent a period of compressional deformation known as the Sevier orogeny (Armstrong, 1968). In the central and northern Rocky Mountains of the United States, Precambrian, Paleozoic, and Mesozoic sedimentary rocks were transported cratonward along low-angle thrust faults (Royse et al., 1975). East of the fold and thrust belt a complementary foreland basin subsided in response to thrust loading and infilled with siliciclastic detritus derived from the orogenic belt (Beaumont, 1981; Jordan, 1981). Eustatic sea-level changes were superimposed on local tectonic and climatic events, resulting in a series of transgressive and regressive cycles within the foreland basin (Kauffman, 1977; Weimer, 1984).

The Sevier fold and thrust belt can be traced with some degree of confidence to the vicinity of Las Vegas, Nevada. Although Cretaceous deformation has been recognized south of Las Vegas, it is not clear whether these structures are a continuation of the Sevier belt or whether they define a structural domain unique in age and style (Burchfiel and Davis, 1972, 1977; Rangin, 1978; Reynolds et al., 1980; Hamilton, 1982). Similarly, the foreland basin is generally assumed to end at the southern margin of the San Juan Basin in New Mexico and the Black Mesa Basin in Arizona (McGookey et al., 1972; Dickinson, 1981). However, it is now evident that Upper Cretaceous strata can be traced southward from the San Juan and Black Mesa Basins into southern New Mexico and southeastern Arizona, implying that the foreland basin extended throughout the state of New Mexico and into at least the southeastern part of Arizona (Molenaar, 1983). The primary goal of this paper is to describe the stratigraphy, depositional environments, and provenance of the foreland basin rocks in southwestern New Mexico.

An understanding of the Cretaceous foreland basin in southwestern New Mexico is complicated by the existence in Early Cretaceous time of a rift basin, known in Mexico as the Chihuahua trough and in Arizona as the Bisbee basin (Greenwood et al., 1977; Bilodeau, 1982; Bilodeau and Lindbergh, 1983; Dickinson et al., 1986). The rift basin evolved in mid-Cretaceous time into a foreland basin, a transition that was discussed by Mack (1987a) and will be amplified upon in this paper.

The emphasis in this paper is on data collected by the authors from the Mojado, Sarten, and Colorado Formations. Measured sections of these formations are presented here for the first time. In addition, previously published work is integrated into the regional interpretations, but is not discussed in detail. This work includes the depositional environments of the Beartooth Formation by Chafetz (1982), the stratigraphy and depositional environments of Upper Cretaceous rocks in the Engle Coal Field by Wallin (1983), and the thickness of Cretaceous rocks in the Grimm and others well described by Thompson and Bieberman (1975), Uphoff (1978), and Thompson (1982).

STRATIGRAPHY

Cretaceous sedimentary rocks in southwestern New Mexico range in age from Aptian to Campanian and were examined at 16 different locations (Figs. 1, 2). Lower Cretaceous rocks are thickest in the southern part of the study area, where they are divided into the Hell-to-Finish, U-Bar and Mojado Formations (Fig. 2; Zeller, 1965, 1970; Zeller and Alper, 1965; Mack et al., 1986). The Hell-to-Finish Formation consists of a basal conglomerate less than 40 m thick that is overlain by as much as 700 m of conglomerate, sandstone, siltstone, and minor amount of limestone. All but the uppermost part of the Hell-

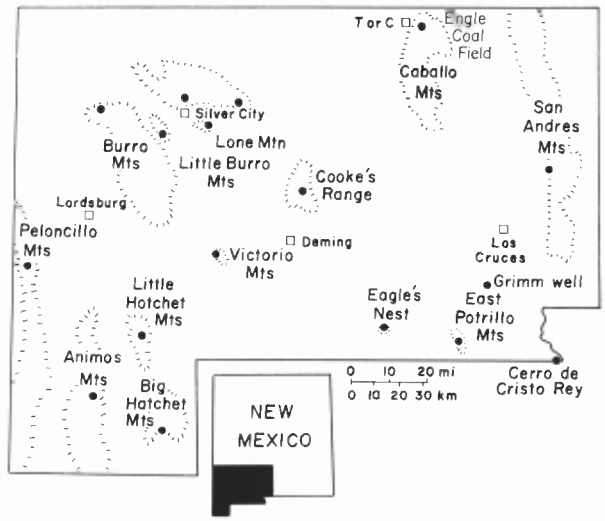


FIGURE 1. Location of Cretaceous outcrops examined in this study. Also shown is the location of the Grimm and others Arctic Limited Number 1 Mobil 32 well, which penetrated Cretaceous rocks.

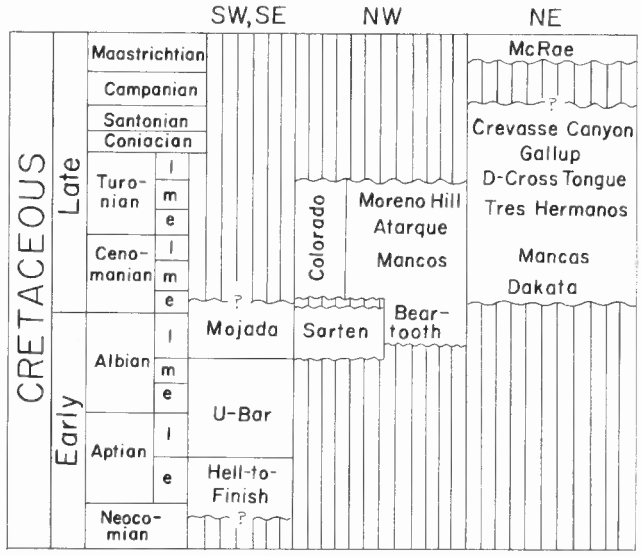


FIGURE 2. Correlation chart for Cretaceous rocks in southwestern New Mexico, adapted from Mack et al. (1986) and Wallin (1983). SW refers to the Little Hatchet, Big Hatchet, Animas and Victorio Mountains; see Mack et al. (1986) for correlation of stratigraphic names used in the Peloncillo Mountains; SE refers to Eagle's Nest and East Potrillo Mountains; see Mack et al. (1986) for correlation of stratigraphic names used at Cerro de Cristo Rey; NW includes the Big and Little Burro Mountains, Lone Mountains, Cooke's Range and the area around Silver City; NE includes the Caballo and San Andres Mountains.

to-Finish Formation in the Big Hatchet, Little Hatchet and Animas Mountains is nonmarine, whereas in the East Potrillo Mountains only the basal conglomerate is nonmarine (Mack, 1986; Mack et al., 1986). The Hell-to-Finish Formation is conformably overlain by the U-Bar Formation, which consists of up to 1200 m of interbedded marine limestone, shale, and sandstone, with the amount of sandstone and shale decreasing upsection (Zeller, 1965; Weise, 1982; Mack et al., 1986; Kolins, 1986). The Mojado Formation conformably overlies the U-Bar Formation and is composed of 1500 m of sandstone and shale with a few limestones at the base (Zeller, 1965, 1970; Zeller and Alper, 1965; Mack et al., 1986; Galemore, 1986; Kolins, 1986). The age of the U-Bar Formation is constrained by fossils as late Aptian through middle Albian (Zeller, 1965; Weise, 1982). A conformable lower contact and index fossils at the top provide an age range for the Mojado Formation of late Albian to early Cenomanian (Zeller, 1965). The conformable upper contact of the Hell-to-Finish Formation suggests that it is probably in part early Aptian, but the age of the base is not known (Zeller, 1965; Mack et al., 1986).

In the northern part of the study area, the only rocks which have been determined to be Early Cretaceous in age belong to the Sarten Formation, which outcrops in the Cooke's Range and San Andres Mountains (Figs. 1, 2). The Sarten Formation ranges in age from middle late Albian to early Cenomanian (Cobban, 1987). The Sarten Formation is lithologically similar to the Mojado Formation, but is an order of magnitude thinner (Hyde, 1984; Mack et al., 1986). Although it lacks index fossils, the Beartooth Formation, exposed in the Burro Mountains and near Silver City, is generally assumed to be Cenomanian in age because of its conformable upper contact with the Cenomanian Colorado Formation (Figs. 1, 2; Molenaar, 1983; Mack et al., 1986). However, the Beartooth Formation is similar in thickness and lithology to the Sarten Formation and may be as old as late Albian.

The Sarten and Beartooth Formations are overlain by the Colorado Formation, which ranges in age from middle or late Cenomanian to middle Turonian and consists of about 150 m of sandstone and shale (Hook and Cobban, 1977; Hook, 1981; Clemons, 1982). Molenaar (1983) recommends abandonment of the name Colorado Formation in favor of Mancos, Atarque, and Moreno Hill Formations, which are used in central New Mexico (Fig. 2). The most complete section of Upper Cretaceous rocks in southwestern New Mexico is exposed in the Engle Coal Field, east of Truth or Consequences (Fig. 1; Wallin, 1983). This section consists of, in ascending order, the Dakota, Mancos, Tres Hermanos, D-Cross Tongue of the Mancos, Gallup and Crevasse Canyon Formations, totaling just over 1000 m in thickness (Fig. 2; Wallin, 1983). The Dakota, Mancos, Tres Hermanos, and Gallup Formations range in age from middle Cenomanian to early Coniacian, based upon a few marine index fossils and a comparison with similar rocks farther north (Hook, 1983). The pollen species *Labrapollis* sp., *Pseudoplicapollis cuneata,* and *Aquilapollenites* from one bed near the middle of the Crevasse Canyon Formation indicate a lower Campanian age (A. R. Sweet, written commun., 1988). The Crevasse Canyon Formation is unconformably overlain by the McRae Formation of late Maastrichtian and early Tertiary age (Wolberg et al., 1986).

EARLY CRETACEOUS RIFT BASIN

The Early Cretaceous rift basin, known as the Chihuahua trough in Mexico and the Bisbee basin in Arizona, is briefly summarized here in order to provide a basis for understanding the change from rift to foreland basin. A more detailed discussion of the rift is given in Bilodeau (1982), Bilodeau and Lindbergh (1983), Dickinson et al. (1986) and Mack (1987a). The rift sequence in southwestern New Mexico is represented by the Hell-to-Finish and U-Bar Formations, which were deposited along the northern edge of the west–northwest-trending basin (Fig. 3; Bilodeau and Lindbergh, 1983; Mack, 1987a). The principal source terrane was located north of the basin and was composed of Paleozoic carbonates, sandstones and shales, and Precambrian crystalline basement. This interpretation is supported by south–southwestward-directed paleocurrent data, by southward decrease in grain size and by lithic and arkosic sandstones composed of chert, pelitic rock fragments, carbonate rock fragments and a high percentage of K-feldspar, including perthite (Fig. 3; Mack, 1987a). The northern source terrane was originally called the Burro uplift by Elston (1958) and was subsequently referred to as a rift shoulder by Bilodeau and Lindbergh (1983). As the rift basin subsided, the sea transgressed westward along the basin axis, and by late Aptian time marine deposition prevailed throughout southwestern New Mexico south of the rift shoulder (Mack, 1986; Mack et al., 1986; Mack, 1987a). The end of the rift phase in middle Albian time is indicated by marked decreases in the rates of siliciclastic influx and tectonic subsidence (Mack, 1987a).

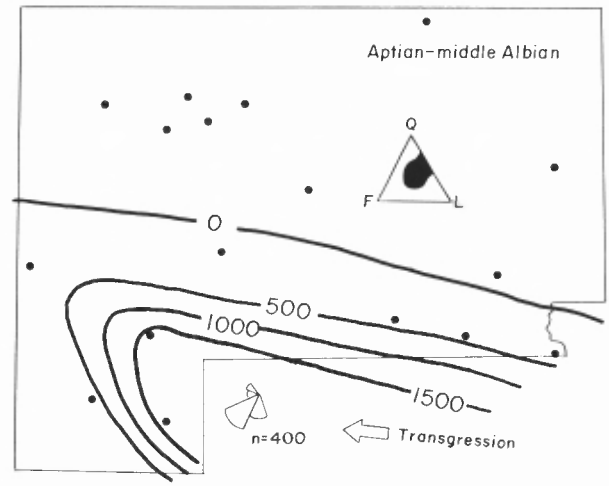


FIGURE 3. Isopach map for the Hell-to-Finish and U-Bar Formations (CI = 500 m). Paleocurrent rose diagram represents 400 imbrication measurements from the fluvial Hell-to-Finish Formation in the Little Hatchet Mountains (Mack et al., 1986). QFL sandstone compositional diagram is based on 41 samples of the Hell-to-Finish and U-Bar Formations in the Little Hatchet, Big Hatchet, Animas and East Potrillo Mountains. Q = quartz plus chert; F = total feldspar; L = total rock fragments, including carbonate rock fragments. Details of detrital modes appear in Mack (1987a).

TRANSITION FROM RIFT TO FORELAND BASIN

In southwestern New Mexico the transition from rift to foreland basin took place in late Albian and early Cenomanian time and is represented by the Mojado, Sarten, and Beartooth Formations (Fig. 4).

Mojado Formation

The Mojado Formation is exposed in the Little Hatchet and Big Hatchet Mountains, where it can be divided into three members that reflect changing depositional environments (Fig. 5; Galemore, 1986). The lower member, which is approximately 250 m thick, is composed primarily of gray, silty, bioturbated shale that is interbedded with thin (<2 m) beds of sandstone, thick (average 5 m) beds of limestone and a few thin (<0.1 m) beds of rip-up clast conglomerate. Sandstones are fine- to medium-grained and commonly display horizontal laminations or hummocky cross-stratification in the lower part and symmetrical ripples and burrows in the upper part. Silty wackestones and packstones contain gastropods, pelecypods, echinoderm columnals, echinoid spines, ostracods, foraminifera, and one bed near the top of the member contains dasycladacean algae. Deposition of the lower member took place in a shallow marine environment between normal and storm wave base. Upward-shoaling is indicated by the dasycladacean limestone near the top of the member.

The middle member of the Mojado Formation, which ranges from 547 to 764 m thick, was deposited by an eastward-flowing fluvial system (Mack et al., 1986; Galemore, 1986). Channel sandstone bodies are up to 10 m thick and commonly consist of a basal lag conglomerate of granules, pebbles, and petrified wood that is overlain by fine- to medium-grained sandstone with trough crossbeds and horizontal laminations with parting lineation, which provide paleocurrent data with a strong eastward mode (Fig. 4). The upper part of some channel sandstones have asymmetrical ripple laminations. Floodplain deposits, totaling about 20 percent of the section, are characterized by red mudstone and siltstone with root traces and calcareous nodules, as well as a few thin (<1 m), rippled, bioturbated fine sandstone beds interpreted to be crevasse splay deposits (Galemore, 1986). Near the top of the middle member are a few thin (<2 m) oyster-bearing fine sandstone beds that were probably deposited in brackish water and are transitional into the marine rocks of the upper member.

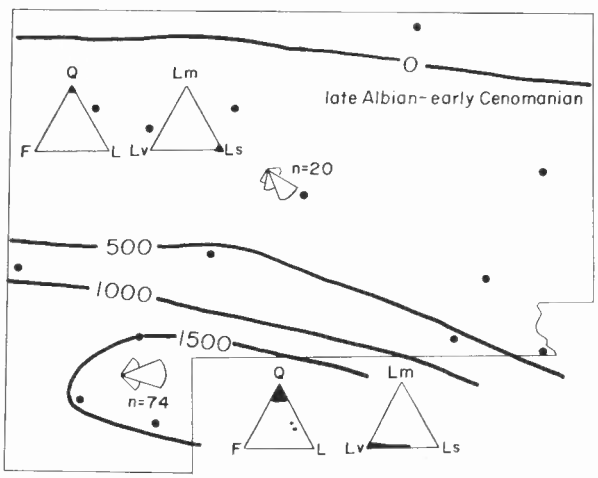


FIGURE 4. Isopach map for the Mojado, Sarten and Beartooth Formations (CI = 500 m). Paleocurrent rose in lower left represents trough crossbeds from the fluvial middle member of the Mojado Formation in the Little Hatchet, Big Hatchet and Animas Mountains; paleocurrent rose in the upper part of diagram represents planar crossbeds from a fluvial interval of the Sarten Formation in the Cooke's Range; sandstone compositional diagrams in upper left represent 20 samples of the Sarten Formation in the Cooke's Range and 5 samples of the Beartooth Formation near Silver City; sandstone compositional diagrams in lower right represent 67 samples of the Mojado Formation in the Little Hatchet, Big Hatchet and Animas Mountains; Q = quartz plus chert; F = total feldspar; L = total rock fragments; Lm = metamorphic rock fragments; Lv = volcanic rock fragments; Ls = sedimentary rock fragments.

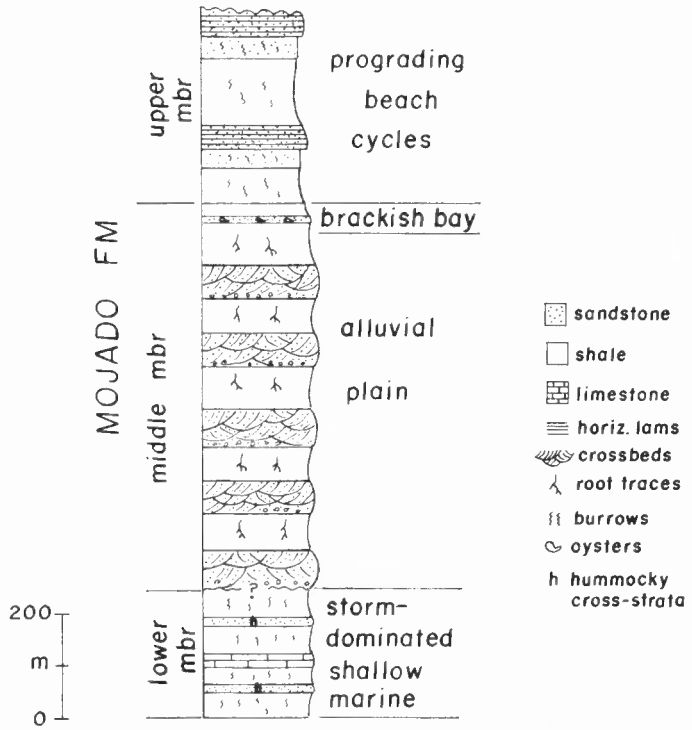


FIGURE 5. Schematic measured section of the Mojado Formation in the Big and Little Hatchet Mountains. Individual beds are designed to illustrate the range of lithologies in each member and not the actual abundance of lithologies nor the actual thickness or stratigraphic position of the beds.

The nature of the contact between the lower and middle members is uncertain due to poor exposure. However, the abrupt transition from offshore marine facies to fluvial facies, without intervening shoreline facies, may indicate an unconformable contact. Weimer (1984) describes a similar sequence in Cretaceous rocks of Colorado that he interprets to have resulted from a basin-wide drop in sea level. A similar interpretation may be possible for the Mojado Formation, because a middle late Albian regression has been reported in the western U.S. and in the Arabian Peninsula (Harris et al., 1984; Mack, 1987b), as well as on the eustatic sea-level curves of Haq et al. (1987).

The upper member of the Mojado Formation is poorly exposed and is estimated to be about 400 m thick. The upper member consists of at least two coarsening-upward sequences that are interpreted to be regressive beach cycles (Fig. 5; Galemore, 1986). Brown silty, bioturbated shale comprises the lower part of each cycle and represents deposition below normal wave base. The shale grades upward into fossiliferous, bioturbated fine- to very fine-grained sandstone, which represents lower shoreface deposition (Howard and Reineck, 1981). Each cycle is capped by horizontally laminated medium sandstone that probably was deposited in the upper shoreface and/or foreshore zone. The absence of a distinct contact between upper shoreface and foreshore facies suggest that the shoreline was of low energy, analogous to the modern coast of Georgia described by Howard and Reineck (1981).

Sarten and Beartooth Formations

The Sarten Formation in the Cooke's Range unconformably overlies the Abo Formation (Permian) and is unconformably overlain by the Colorado Formation. The Sarten Formation is about 120 m thick and consists of gray shale and siltstone, sandstone, and a minor amount of pebble conglomerate, and is arranged into 3 or 4 trangressive and 2 regressive sequences (Fig. 6).

The base of the Sarten consists of a ravinement surface (T_1) that is overlain by a 1-m-thick transgressive lag composed of limestone- and chert-pebble conglomerate with a bioturbated sandstone matrix (Fig. 6;

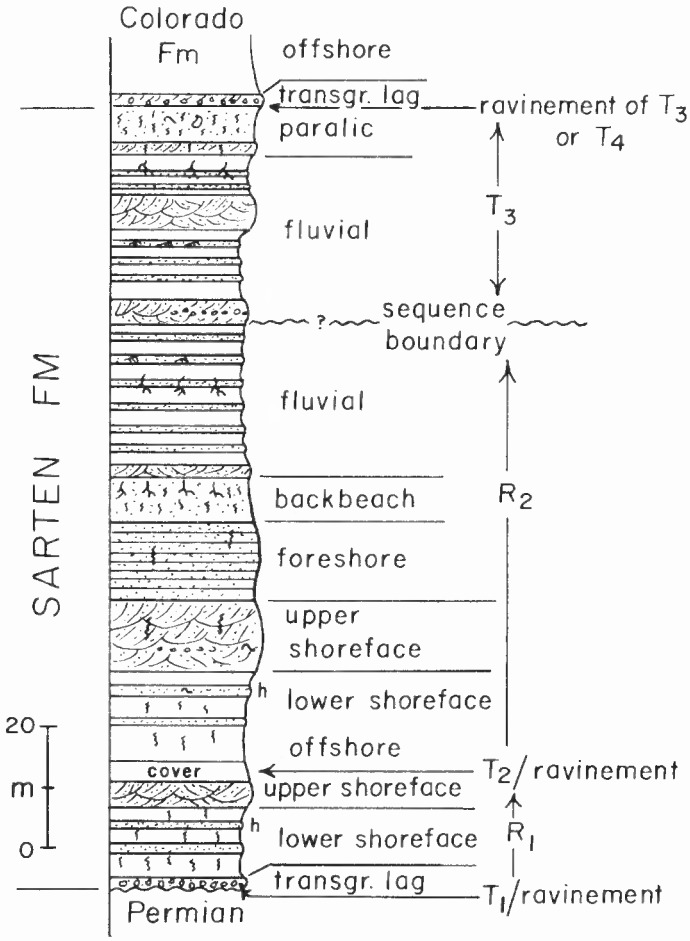


FIGURE 6. Measured section of the Sarten Formation at Rattlesnake Ridge in the Cooke's Range. Key to symbols appears in Figure 5. T = transgression; R = regression.

Swift, 1968). In this case the sequence boundary (top of the Permian) and ravinement surface are the same, and the lack of marine sediment between the sequence boundary and ravinement suggests either low rate of sediment influx or an upland setting (Demarest and Kraft, 1987; Nummedal and Swift, 1987). The transgressive lag is overlain by a regressive sequence (R_1) that coarsens upward from lower shoreface to upper shoreface facies. The lower shoreface is represented by interbedded bioturbated gray siltstone and laminated to hummocky cross-stratified fine sandstone, whereas the upper shoreface consists of cross-bedded fine- to medium-grained sandstone with a few vertical burrows including *Ophiomorpha* (Howard and Reineck, 1981; Clifton, 1981).

A covered interval a few meters thick separates dark, fissile shale of offshore marine origin from the underlying upper shoreface sandstone (Fig. 6). This facies change indicates another transgression (T_2), but the details are obscured by the covered interval. The second transgression is followed by a thick regressive sequence (R_2) that represents prograding beach and alluvial plain environments. The offshore shale is overlain by lower and upper shoreface facies, which are similar to those of the first regressive sequence. The upper shoreface sediment is overlain by foreshore facies, which consists of horizontally laminated and low-angle laminated medium sandstone with a few *Ophiomorpha* burrows. The foreshore facies is overlain by mottled, fine- to medium-grained sandstone and siltstone that contain many burrows, including *Ophiomorpha,* and root traces. This sediment was deposited in an environment transitional between marine and nonmarine and is called back-beach facies (Fig. 6). The back-beach facies probably does not represent a lagoon, because of the coarse grain size and the lack of brackish-water fauna. The second regressive sequence is capped by fluvial rocks, consisting of channel and floodplain facies. Channel bodies are up to 5 m thick and are composed of planar and trough cross-bedded medium to coarse sandstone. One channel bed near the middle of the fluvial section truncates several meters into the underlying strata and contains several pebbly horizons up to 1 m thick. Crossbed paleocurrent data from the channel facies indicate south–southeastward transport (Fig. 4). Floodplain facies consist of interbedded gray, blocky, silty shale and thin beds (<1 m) of massive to ripple cross-laminated fine sandstone, some of which display numerous root traces. The shale was deposited from suspension during floods and the sandstone represents crevasse-splay deposition (Miall, 1985).

The fluvial facies is overlain by paralic and marine rocks, indicating a transgression (T_3). Along modern transgressive coastlines, stream aggradation and back-filling of valleys is the initial response to sea-level rise. In this case the sequence boundary that separates the top of the regressive sequence from the base of the transgressive sequence is within a fluvial section (Demarest and Kraft, 1987; Nummedal and Swift, 1987). A likely location in the Sarten for such a sequence boundary is beneath the pebbly channel body (Fig. 6). Above this sequence boundary, fluvial facies are overlain by paralic facies, which include crossbedded, *Ophiomorpha*-bearing, medium sandstone that probably represents a beach, dark carbonaceous shale of probable coastal marsh origin, and heavily bioturbated, oyster- and pelecypod-bearing, silty and clayey fine sandstone that was deposited in a lagoon or estuary (Demarest and Kraft, 1987).

The contact between the Sarten and Colorado Formations is an unconformity that is overlain by a transgressive lag composed of pebbly, bioturbated, fossiliferous sandstone. Is this unconformity the ravinement surface associated with the third transgression (T_3), or does it represent a major lowstand of sea level? The unconformity has the correct stratigraphic position to be the T_3 ravinement. However, apparently there is a significant hiatus across the unconformity (3 to 4 ammonite zones missing; Lucas et al., 1988), supporting the idea of a lengthy period of erosion due to a sea-level drop. If this is the case then the transgressive lag above the unconformity represents yet another transgressive event (T_4).

The Beartooth Formation northwest of Silver City has been interpreted by Chafetz (1982) to have been deposited by a delta, and includes strandline, delta front and distributary mouth bar deposits that are arranged into an initial transgressive sequence and an overlying regressive sequence. The initial transgression of the Sarten and Beartooth Formations probably is a response to long-term eustatic sea-level rise (Kauffman, 1977; Mack, 1987b; Haq et al., 1987). Subsequent transgressive and regressive cycles may not represent basin-wide or eustatic sea-level changes but rather autocyclic shifting of the locus of deposition or tectonically- or paleoclimatically-induced variations in the rate of sediment influx with respect to basin subsidence or sea-level rise (Ryer, 1977).

Paleogeographic setting

Sediment deposited during the transitional stage displays similarities and dissimilarities to sediment deposited during the rift stage. The most obvious similarity is the west–northwest trend of the basin, delineated by isopach data (cf. Figs. 3 and 4). However, significant differences between the rift and transitional stages are apparent. During the transitional stage, the crest of the rift shoulder was onlapped by the Sarten and Beartooth Formations (cf. Figs. 3 and 4). In the Burro Mountains, the Beartooth Formation directly overlies Precambrian crystalline rocks that must have been at or near the crest of the rift shoulder (Elston, 1958). That Precambrian crystalline and Paleozoic carbonate rocks were no longer supplying sediment to the basin during the transitional stage is further indicated by the lack of feldspar and carbonate rock fragments in Sarten and Beartooth sandstones (Fig. 4).

Sediment dispersal in the southwestern part of the basin also changed between the rift and transitional stages. Whereas the Hell-to-Finish Formation was dispersed southward, paleocurrents in the middle member of the Mojado Formation indicate eastward sediment transport (Fig. 4). The Mojado Formation also has a significant component of andesitic

volcanic rock fragments and plagioclase, which were probably derived from arc volcanic rocks located west or southwest of the basin (Mack, 1987a).

The paleogeographic setting during late Albian and early Cenomanian time in southwestern New Mexico may have been similar in style, if not in magnitude, to the modern Amazon system in Brazil. The Amazon River runs parallel to the axis of an inactive rift, whose last movement was related to the opening of the Atlantic Ocean (Burke, 1976). The bulk of the sandy bedload of the Amazon River, however, is derived from the Andes orogenic belt, and only minor quantities of quartz-rich detritus is fed into the Amazon by tributaries draining the surrounding craton (Franzinelli and Potter, 1983). Similarly, detritus of the Mojado Formation was transported eastward along the axis of the former rift basin, but the source of the sediment was a mixed sedimentary and volcanic terrane located to the west of southwestern New Mexico. Only a minor amount of quartz-rich detritus, represented by the Sarten and Beartooth Formations, was derived from the erosional remnant of the rift shoulder to the north.

LATE CRETACEOUS FORELAND BASIN

Sediments deposited in the Late Cretaceous foreland basin in southwestern New Mexico include the Colorado Formation in the northwest part of the study area and the Mancos, Tres Hermanos, D-Cross Tongue, Gallup and Crevasse Canyon Formations in the northeastern part of the study area (Figs. 1, 2, 7). Cretaceous rocks of post-Cenomanian and pre-Laramide age were presumably removed by Laramide and younger erosion in the southern part of the study area (Fig. 7).

Colorado Formation

The Colorado Formation, which ranges in age from middle or late Cenomanian through middle Turonian, is best exposed near Santa Rita, where it consists of about 180 m of sandstone and shale (Fig. 8; Kaczmarek, 1987). A 2-m-thick bed of granular to pebbly, heavily bioturbated sandstone at the top of the Beartooth Formation is interpreted to be a transgressive lag that overlies a ravinement surface, and may correlate with the transgressive lag at the Sarten-Colorado contact in the Cooke's Range (Figs. 6, 8). The overlying Colorado Formation was deposited during a single regressive cycle (Fig. 8).

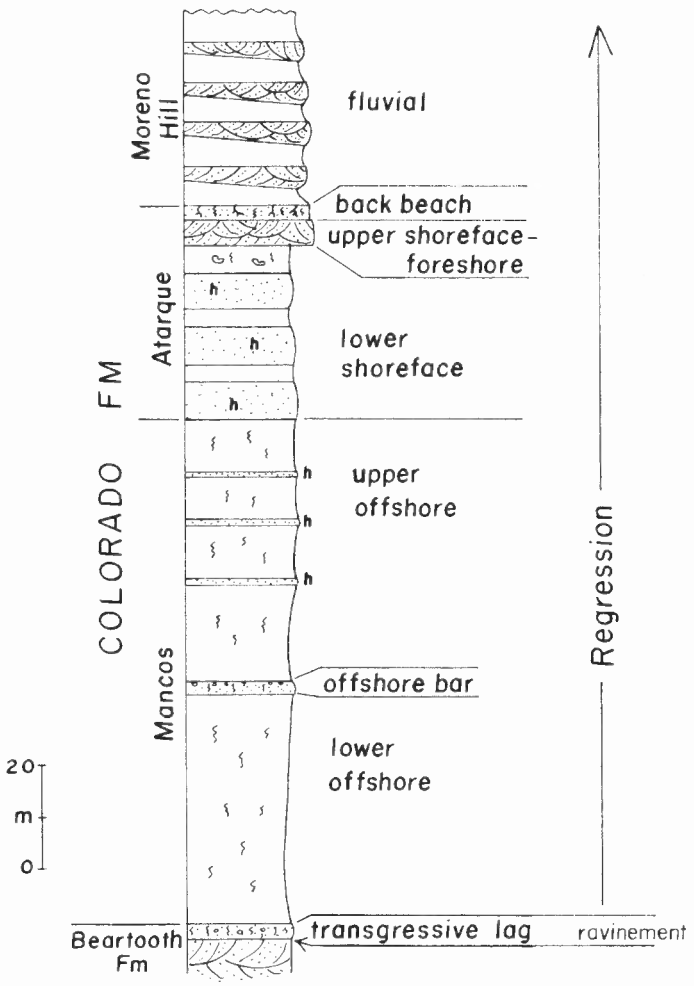


FIGURE 8. Measured section of the Colorado Formation near Santa Rita. The stratigraphic names Mancos, Aratque and Moreno Hill are from Molenaar (1983). Key to symbols appears in Figure 5.

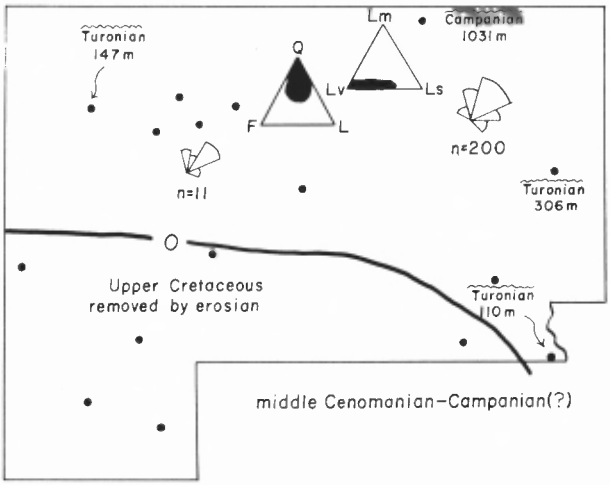


FIGURE 7. Location of outcrops of post-middle Cenomanian rocks examined in this study. Sections south–southwest of zero line do not have Cretaceous rocks younger than the Mojado Formation. At four locations the thickness of Upper Cretaceous rocks and the younger rocks beneath the disconformity are shown. Paleocurrent rose on the left represents fluvial trough crossbeds from the Colorado Formation near Santa Rita; paleocurrent rose on the right is a composite of several rose diagrams appearing in Wallin (1983). Sandstone compositional diagrams represent 25 samples of the Colorado Formation and 15 samples of the Tres Hermanos, Gallup and Crevasse Canyon Formations. See Figure 4 for description of compositional diagrams.

The lower 100 m of the Colorado Formation consists of gray, flaggy shale and siltstone that exhibit horizontal laminations, horizontal burrows, shell fragments and ammonite molds (Fig. 8). Shale and siltstone are interbedded with several thin (0.5 m) very fine- to fine-grained sandstones that contain horizontal laminations, hummocky cross-stratification and symmetrical ripple marks. The lower 100 m of the section was deposited in a marine environment between normal and storm wave base. One thicker (1.5 m) sandstone bed near the base coarsens upward from fine to granular medium sand and may represent an offshore bar (Swift and Field, 1981).

The offshore facies is overlain by fine-grained sandstone with thin (<1 m) interbeds of gray shale and siltstone. Horizontal and vertical burrows, including *Ophiomorpha*, hummocky cross-stratification, horizontal laminations and bivalve fragments are present in the sandstones and suggest deposition in the lower shoreface (Fig. 8; Howard and Reineck, 1981; Clifton, 1981). The lower shoreface facies is overlain by 4 m of planar crossbedded and horizontally laminated medium sandstone deposited in the upper shoreface and foreshore zones (Fig. 8). A 3-m-thick bed of heavily bioturbated and root mottled fine sandstone overlies the upper shoreface/foreshore sandstone and represents backbeach facies (Fig. 8).

The section is capped by 37 m of poorly exposed fine and medium sandstone and brown shale (Fig. 8). The sandstone beds are lenticular, up to 4 m thick, and contain trough crossbeds, shale rip-up clasts and plant molds, and are interpreted to represent fluvial channels. Paleocurrent data indicate northeastward sediment transport (Fig. 7).

Upper Cretaceous rocks in the Engle Coal Field

The most complete section of Upper Cretaceous rocks in the study area is in the Engle Coal Field northeast of Truth or Consequences (Fig. 1). This section was studied by Wallin (1983) and his interpretations are summarized below. The Mancos Formation and the lower two members of the Tres Hermanos Formation (Atarque and Carthage members) were deposited in a regressive cycle that correlates with the Colorado Formation exposed in the northwest part of the study area. The upper member of the Tres Hermanos Formation, the Fite Ranch member, is a thin (3 m) transgressive shoreline deposit. The transgression reached its peak during deposition of the 73-m-thick D-Cross Tongue of the Mancos Shale. The overlying Gallup and Crevasse Canyon Formations, totaling 727 m thick, were deposited during a regressive cycle. Crossbed paleocurrent data from nonmarine portions of the section indicate northeastward sediment transport (Fig. 7). The Crevasse Canyon Formation is unconformably overlain by the McRae Formation of late Maastrichtian and early Tertiary age (Fig. 2; Wolberg et al., 1986).

Paleogeographic setting

The Colorado Formation and the formations in the Engle Coal Field are similar to rocks exposed in central New Mexico and in the San Juan basin of northwestern New Mexico (Molenaar, 1983). This suggests that the rift shoulder that separated southwestern New Mexico from the Midcontinent foreland basin in Aptian, Albian and early Cenomanian time was not a significant barrier by middle to late Cenomanian and that the foreland basin occupied virtually all of New Mexico. The paleoslope of the foreland basin was probably northeastward, based on northeastward-directed paleocurrent data and northwestward-trending shorelines interpreted by Molenaar (1983). The line of maximum transgression moved northeastward through time, according to Molenaar (1983), and the section in the Engle Coal Field coarsens upward (Wallin, 1983), suggesting that the clastic wedge was prograding northeastward through time.

The source terrane of the sediment was composed primarily of intermediate volcanic rocks and sedimentary rocks (Mack, 1987b). Volcanic source rocks are indicated by volcanic rock fragments with microlitic and porphyritic textures and by oscillatory zoned plagioclase, whereas sedimentary source rocks are reflected in the presence of chert, pelitic rock fragments and a large percentage of monocrystalline quartz. Provenance and dispersal data suggest that the source terrane was probably located southwest of the basin. The exact nature of the source terrane is not known. Andesitic volcanic rock fragments suggest that the source area included volcanic arc rocks. The sedimentary component may have come from a fold-thrust belt, unroofing of a foreland-style uplift, or the sedimentary cover eroded during batholith emplacement.

CONCLUSIONS

Cretaceous sedimentation in southwestern New Mexico began in Aptian time in a west–northwest-trending rift basin that was part of the Chihuahua/Bisbee basin. Siliciclastic sediment was transported southward into the basin from a rift shoulder composed of Paleozoic sedimentary rocks and Precambrian crystalline basement. As the rift shoulder wore down and as the sea transgressed westward along the axis of the basin, siliciclastic sedimentation was replaced by shallow-marine carbonate deposition.

Late Albian and early Cenomanian was a transitional time between the rift and foreland basins. The rift shoulder was onlapped by the Sarten and Beartooth Formations, which consist of quartzarenites and shales derived from the northwest. The Mojado Formation was deposited along the former axis of the rift basin and consists of up to 1500 m of siliciclastic detritus that was transported eastward into the basin. A significant volcanic component in the Mojado Formation suggests that the source terrane included arc rocks and was located to the west or southwest of the basin.

By middle or late Cenomanian time, the rift shoulder was no longer a significant barrier to sedimentation and foreland basin deposition was continuous across New Mexico until late Campanian time. As much as 1000 m of sandstone and shale were deposited in two major transgressive and regressive cycles. The source terrane for the sediment deposited in the foreland basin was composed of sedimentary and volcanic rocks and was probably located to the southwest of the basin.

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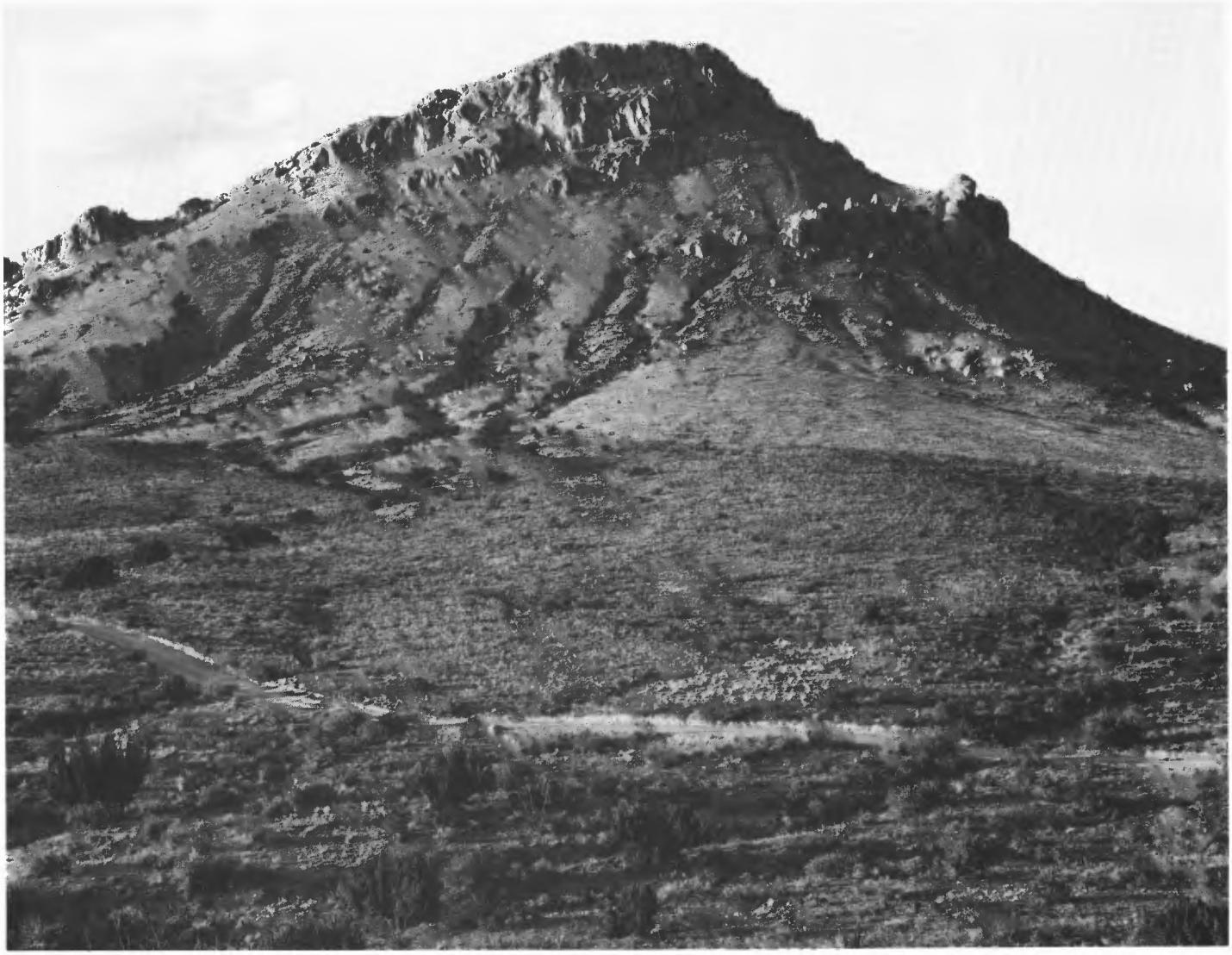
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Playas Peak, Little Hatchet Mountains. View is N25°E. Oligocene(?) ash-flow tuffs dip gently west at east end of Playas Peak. Road and low rolling terrain in foreground is on Ringbone Formation arkosic beds dipping about 30° west. Site of Stop 3, Day 2. Numerous rills and gullies on the middle and lower slopes of the peak are accentuated by the low sun angle. Juniper is present in the foreground and in several of the larger gullies at the base of the peak. Camera station is in SE¼ NW¼, sec. 8, T28S, R16W. Altitude about 1448 m. W. Lambert photograph No. 87L49. 24 July 1987, 7:36 p.m., MDT.