Stratigraphic Revision and Depositional Environments of the Upper Cretaceous Toreva Formation in the Northern Black Mesa Area, Navajo and Apache Counties, Arizona

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By KAREN J. FRANCZYK

Stratigraphic revision, sedimentology, and depositional history of Upper Cretaceous units in northern Arizona

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Stratigraphic Revision and Depositional Environments of the Upper Cretaceous Toreva Formation in the Northern Black Mesa Area, Navajo and Apache Counties, Arizona

By Karen J. Franczyk

Abstract

Detailed examination of the Upper Cretaceous Toreva Formation resulted in recognition of six mappable lithologic units previously included in the Toreva Formation. Three of these units present at the type locality on the southwest side of Black Mesa are, in ascending order, the lower sandstone, the middle carbonaceous, and the upper sandstone members of the Toreva Formation; three of these units formerly assigned to the Toreva on the northeast side of Black Mesa are assigned to the lower carbonaceous member of the Wepo Formation, the Wind Rock Tongue (new name) of the Mancos Shale, and the Rough Rock Sandstone (new name) of the Mesaverde Group. These six stratigraphic units record two episodes of marine regression separated by a period that included (1) base level lowering and channel erosion, (2) fluvial deposition, and (3) marine transgression.

During the first regressive event, a prograding, wave-dominated deltaic system deposited the lower sandstone member of the Toreva Formation. This regressive delta-front sandstone is overlain by delta-plain deposits of the middle carbonaceous member of the Toreva Formation. A lowering of base level, possibly initiated by both tectonic uplift and eustatic drop, caused a period of channel erosion that removed a significant thickness of the middle carbonaceous member in the study area. When deposition resumed, northeast-flowing, meandering and braided rivers deposited the upper sandstone member of the Toreva Formation. During deposition, a gradually rising sea level caused the change from higher to lower energy fluvial systems, the landward shift in alluvial and coastal-plain environments, and the transgression of the sea into the Black Mesa area. The lower carbonaceous member of the Wepo Formation shows an upward change from alluvial to coastal-plain depositional environments. The transgression of the sea back into the Black Mesa area resulted in the deposition of the newly named Wind Rock Tongue of the Mancos Shale. During the regressive event following this transgression, the newly named Rough Rock Sandstone was deposited along a prograding barrier-island complex, which may have been flanked on the northwest by a deltaic system.

INTRODUCTION

Interpretation of depositional environments and mapping of facies changes within the Upper Cretaceous Toreva Formation from the southwestern part of Black Mesa to the northeastern part of Black Mesa have resulted in revised correlations of the Toreva across the mesa, the renaming of strata that were formerly included in the upper part of the Toreva in northern Black Mesa, and the establishment of better correlations of Cretaceous rock units between the Black Mesa basin and the San Juan Basin to the east and the Kaiparowits basin to the northwest. Also, this study of rock sequences within the Toreva has provided information on the response of depositional systems to regional events such as tectonism, eustatic changes, and recurrent transgression and regression of the Cretaceous sea.

Nomenclatural problems have plagued the Toreva Formation since Repenning and Page (1956) formally named it. The problems resulted from correlating the rock units at the type locality of the Toreva (in the southwestern part of Black Mesa), across an area of more than 60 mi (97 km) where numerous facies changes occur, to the northern part of Black Mesa. Repenning and Page's (1956) interpretation of the facies changes across Black Mesa led them to include in the Toreva Formation the rock units in the northern part of Black Mesa that are not present at the type locality and to assign different member names to the Toreva units in the northern part of the mesa. When the depositional environments and the sequence of depositional events of these rock units are known, the correlation problems caused by the facies changes are more easily understood and solved.

LOCATION AND ACKNOWLEDGMENTS

Black Mesa, located in the northeastern corner of Arizona, is a southwest-dipping cuesta, nearly circular in plan, and approximately 60 mi (97 km) in diameter. The study area is in the northeastern part of Black Mesa and covers parts of Apache and Navajo Counties (fig. 1). In the northern and eastern parts of the study area, the Toreva Formation is exposed along a continuous cliff that forms the edge of the mesa. In the southern part of the study area, numerous canyons incised into the mesa provide additional exposures. Access to the Toreva Formation within the study area is very limited; only two unimproved dirt roads provide access to the top of the mesa, and there are few dirt roads to the cliffs at the base of the mesa. Most of the outcrops in the study area are accessible only on foot.

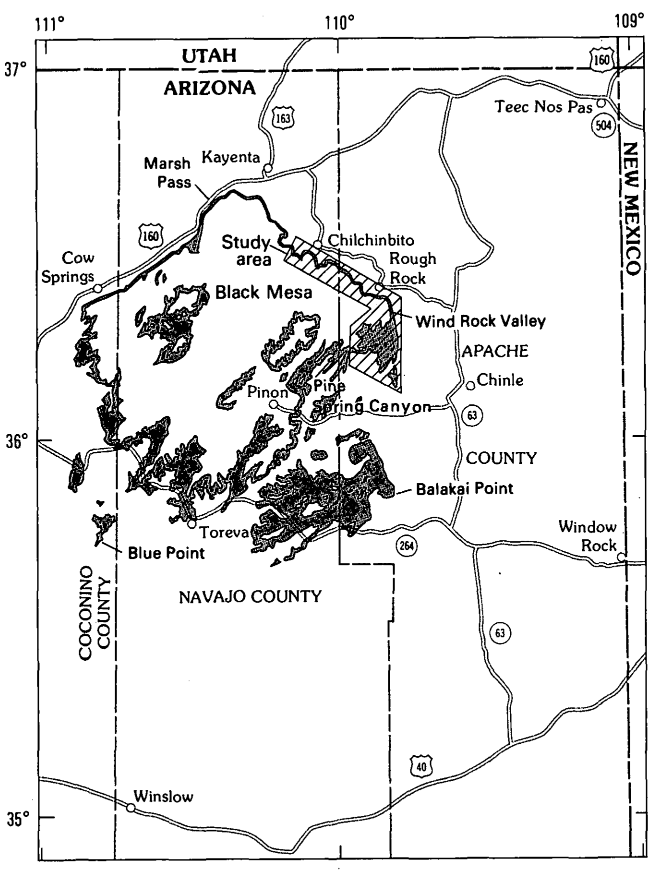


Figure 1. Locations of Black Mesa, the study area (dashed line), and the outcrop of the Toreva Formation (dark pattern) on and adjacent to Black Mesa. Outcrop distribution is from O'Sullivan and others, 1972.

The Navajo Tribe granted permission to conduct field studies on their land. Margaret Traylor and Alice Gross assisted in collecting the field data, and A. R. Kirk and Fred Peterson of the U.S. Geological Survey and R. J. Weimer and J. C. Horne of the Colorado School of Mines provided helpful discussion and advice throughout the study. W. A. Cobban of the U.S. Geological Survey identified the fossils collected during this study, and D. J. Nichols of the U.S. Geological Survey conducted palynological analysis of coal samples. C. M. Molenaar, Fred Peterson, and C. A. Repenning of the U.S. Geological Survey provided helpful suggestions for improving this manuscript.

METHODS OF STUDY

The field data for this study consist of observations and data from measured sections, which include the upper part of the Mancos Shale, the Toreva Formation, and the lower part of the Wepo Formation, and from laterally tracing units within these formations. Because the cliff face is inaccessible in many places, the presence of both continuous exposure and access through the formations determined the location of the ten measured sections (fig. 2; table 1). Most of these sections average about 350 ft (107 m) in thickness, and the distances between sections range from 1.5 to 10 mi (2.5 to 16 km). Where possible, genetic units were traced laterally between sections on foot; and oblique aerial photographs and binoculars were used to trace these units on inaccessible cliff faces.

Table 1. Location of measured sections

Measured section	Latitude	Longitude
Chilchinbito Canyon	36°28'36"	110°04'54"
Red Tree Springs	36°25'08"	109°55'25"
Needle	36°23'22"	109°54'49"
Yale Point	36°22'48"	109°50'06"
Wind Rock Valley	36°21'30"	109°49'36"
Sweathouse Peak	36°18'54"	109°48'39"
Tse Da Ahoodza Peak	36°15'57"	109°48'29"
Lohali Mesa	36°11'00"	109°50'14"
Waterfall Spring Canyon	36°16'01"	109°50'29"
Tah Chee Wash	36°14'43"	109°53'36"

Sections were measured with tape and Abney level and Jacobs staff. Sedimentologic data from each genetic unit were obtained; lateral tracing of these units, where possible, helped to determine their geometry, distribution, and lateral relationships. This information was used to model depositional environments and facies relationships between genetic units.

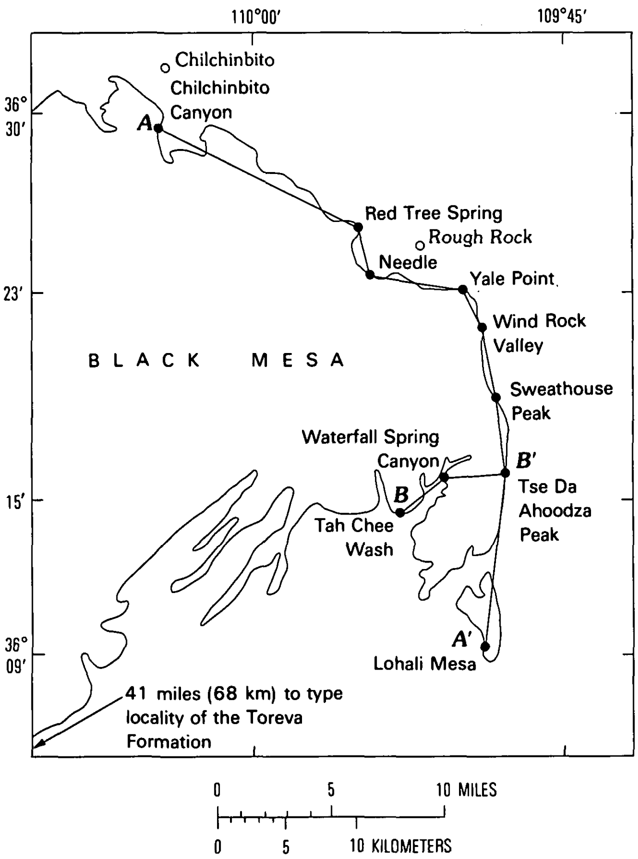


Figure 2. Locations and names of measured sections and lines of stratigraphic sections (see pl. 1).

Marine fossils collected during this study and by previous workers provided ages for the marine parts of the section. Coal samples from units within the Toreva and Wepo Formations were collected and sampled for palynomorphs to help determine the age of the nonmarine deposits.

Petrographic analyses of thin sections from samples collected from measured sections provided additional information on mineralogy and texture of the genetic units. The petrographic study consisted of mineral identification: 300 point counts on each section to determine modal mineralogy, and 100 point counts on each section to determine grain size and sorting.

GEOLOGIC AND STRUCTURAL SETTING

During Late Cretaceous time, the Black Mesa area was part of the large Western Interior depositional basin that extended across the Western United States from the present Gulf of Mexico northward through Canada (Gill and Cobban, 1966; Kauffman, 1977). Repeated transgressions and regressions of the Cretaceous sea into the Black Mesa area throughout the Late Cretaceous produced at least three cycles of marine, coastal, and continental sedimentation. The oldest Late Cretaceous unit is the Dakota Sandstone, which was deposited unconformably on Jurassic rocks. Lithologic units in the Dakota show vertical changes in depositional environments from fluvial to coastal marine; these units record the first transgression of the Cretaceous sea into the Black Mesa area. The Dakota Sandstone is overlain by the Mancos Shale, which was deposited in an offshore marine environment when the Cretaceous sea covered the entire Black Mesa area. As the Cretaceous sea regressed for the first time from the Black Mesa area, the lower part of the Toreva Formation was deposited. A second, less extensive transgression and regression of the Cretaceous sea in northern Black Mesa is indicated by units identified by Repenning and Page (1956) as the uppermost units of the Toreva Formation. These units are designated as individual formations (the Wind Rock Tongue of the Mancos Shale and the Rough Rock Sandstone) in this report. The Wepo Formation, which overlies the Toreva Formation, was deposited while the Cretaceous sea was located to the northeast of Black Mesa. The last known incursion of the sea into the Black Mesa area is represented by the Yale Point Sandstone, which overlies the Wepo Formation. Erosion has removed any younger Cretaceous or Tertiary deposits that may have existed on Black Mesa.

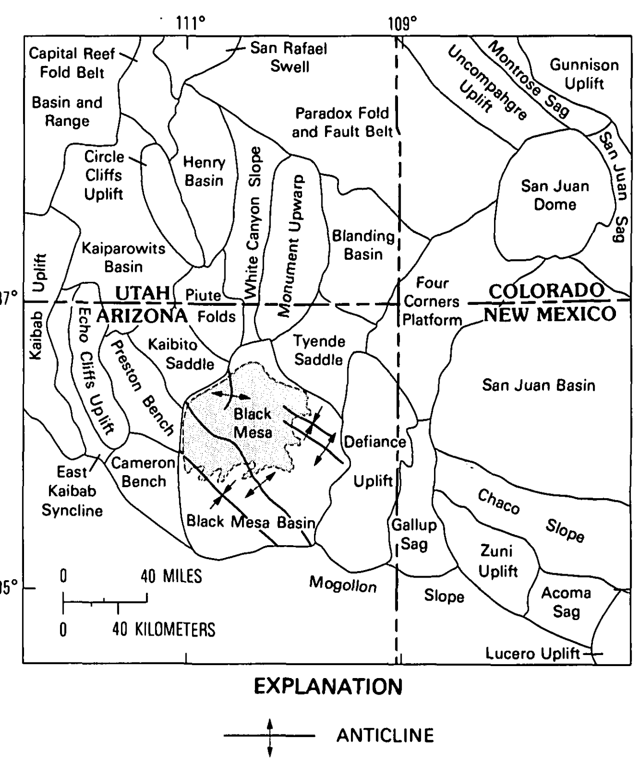


Figure 3. Structural setting of the Black Mesa basin, trend of fold axes within the basin, and location of Black Mesa within the basin (after Kelley, 1955 and 1958).

The Laramide orogeny in Late Cretaceous to early Tertiary time accompanied the final withdrawal of the Cretaceous sea from the Western Interior of the United States and produced or rejuvenated the structural features present in the Black Mesa area today (fig. 3; Tweto, 1975). Black Mesa is located within the Black Mesa basin—a shallow, nearly circular structural depression about 90 mi (145 km) in diameter, with low regional dips (Kelley, 1958). Only 1,500 ft (457 m) of structural relief is present in Black Mesa basin (Haynes and Hackman, 1978). Numerous, parallel, northwest-trending, open folds are the most prominent structural features in the basin, but less common north-trending folds also are present (fig. 3). The dip on the limbs of these folds is usually only a few degrees. Faults are rare in the Black Mesa basin, and only one fault, having 20 ft (6 m) of displacement, was noted in the study area.

The boundary between the Black Mesa basin and many of the surrounding structural provinces is seldom sharp. As a structural element, the Black Mesa basin changes almost imperceptibly into many of the surrounding benches and saddles that separate it from the Kaiparowits basin to the northwest. To the east, the Defiance uplift is the major structural feature that separates the Black Mesa basin from the San Juan Basin and the Gallup Sag.

PREVIOUS WORK AND NOMENCLATURAL HISTORY OF THE TOREVA FORMATION

Newberry (1861), Campbell and Gregory (1911), Gregory (1917), Reagan (1925), Reeside and Baker (1929), and Williams (1951) described and assigned formation or group names to the Cretaceous sequence in the Black Mesa basin. All of these authors except Newberry (1861) and Reagan (1925) used the threefold Dakota Sandstone, Mancos Shale, and Mesaverde Formation or Group classification for the entire Cretaceous sequence. Rocks now assigned to the Toreva Formation were always included as the basal part of the Mesaverde Formation or Group. However, in Reagan's (1925) classification scheme, the Toreva Formation is equivalent to his entire Mesaverde sandstone. Using fossil evidence, Reeside and Baker (1929) showed that the Mesaverde Formation was older than the Mesaverde sequence in western Colorado, where the name was first used. However, they continued to apply the name Mesaverde Formation to the sequence above the Mancos Shale in the Black Mesa basin. Williams (1951) followed this usage, but he designated the Mesaverde a group rather than a formation.

Repenning and Page (1956) first subdivided the Mesaverde on Black Mesa into three formations that include, in ascending order, the Toreva Formation, the Wepo Formation, and the Yale Point Sandstone. However, the stratigraphy and nomenclature of the Toreva Formation, as defined by Repenning and Page (1956) is confusing because (1) they included two units in the northern part of Black Mesa, which are not present at the type section in the southwestern part of the mesa, in the Toreva Formation; (2) they miscorrelated these two units with units of the type section; and (3) they used a different nomenclature for Toreva units in the northern and southern parts of the mesa (fig. 4).

The type locality of the Toreva Formation is near Toreva, a Hopi Indian village in the southwestern part of Black Mesa (fig. 1; Repenning and Page, 1956). At this locality, the Toreva Formation consists of three informal members: a lower sandstone member, a middle carbonaceous member, and an upper sandstone member (fig. 4). A fourth unit, Repenning and Page's (1956) sandstone tongue of the Toreva Formation, is present within the upper part of the underlying Mancos Shale below the lower sandstone member of the Toreva Formation at Blue Point southwest of Black Mesa (fig. 1). This sandstone tongue pinches out northward into the Mancos Shale and is not present at the type locality of the Toreva.

The lower sandstone member is a fine- to medium-grained, regressive, coastal-marine sandstone that characteristically forms sheer, smooth-faced, massive cliffs. It has a gradational contact with the underlying Mancos Shale and a sharp but conformable, and locally intertonguing, contact with the overlying middle carbonaceous member. Repenning and Page (1956) reported that the lower sandstone member is present everywhere on Black Mesa except in a small area near Balakai Point (fig. 1). J. I. Kirkland (personal commun., 1984) stated that the lower sandstone member is present at Balakai Point, but it weathers into a slope-forming unit.

The middle carbonaceous member consists of interbedded siltstone, carbonaceous mudstone, coal, and lenticular sandstone. This member is 106 ft (32 m) thick at the type locality of the Toreva and thins to the northeast. Repenning and Page (1956) interpreted this thinning to be the result of a depositional pinchout (nondeposition) and therefore believed that the middle carbonaceous member was not present in the northern part of Black Mesa. However, remnants of this member are present within the study area; and erosion prior to deposition of the overlying upper sandstone member, rather than a depositional pinchout, caused the thinning and local absence of the middle carbonaceous member.

The upper sandstone member is an arkosic, fine to very coarse grained fluvial sandstone unit that is internally composed of channel sandstone deposits interbedded with less abundant, fine-grained, slope-forming, overbank material. In southern Black Mesa, the upper part of the fluvial sandstone unit is coarser grained than the lower part; locally, in the southwest part of the mesa, cobbles of silicified limestone that have Paleozoic fossils

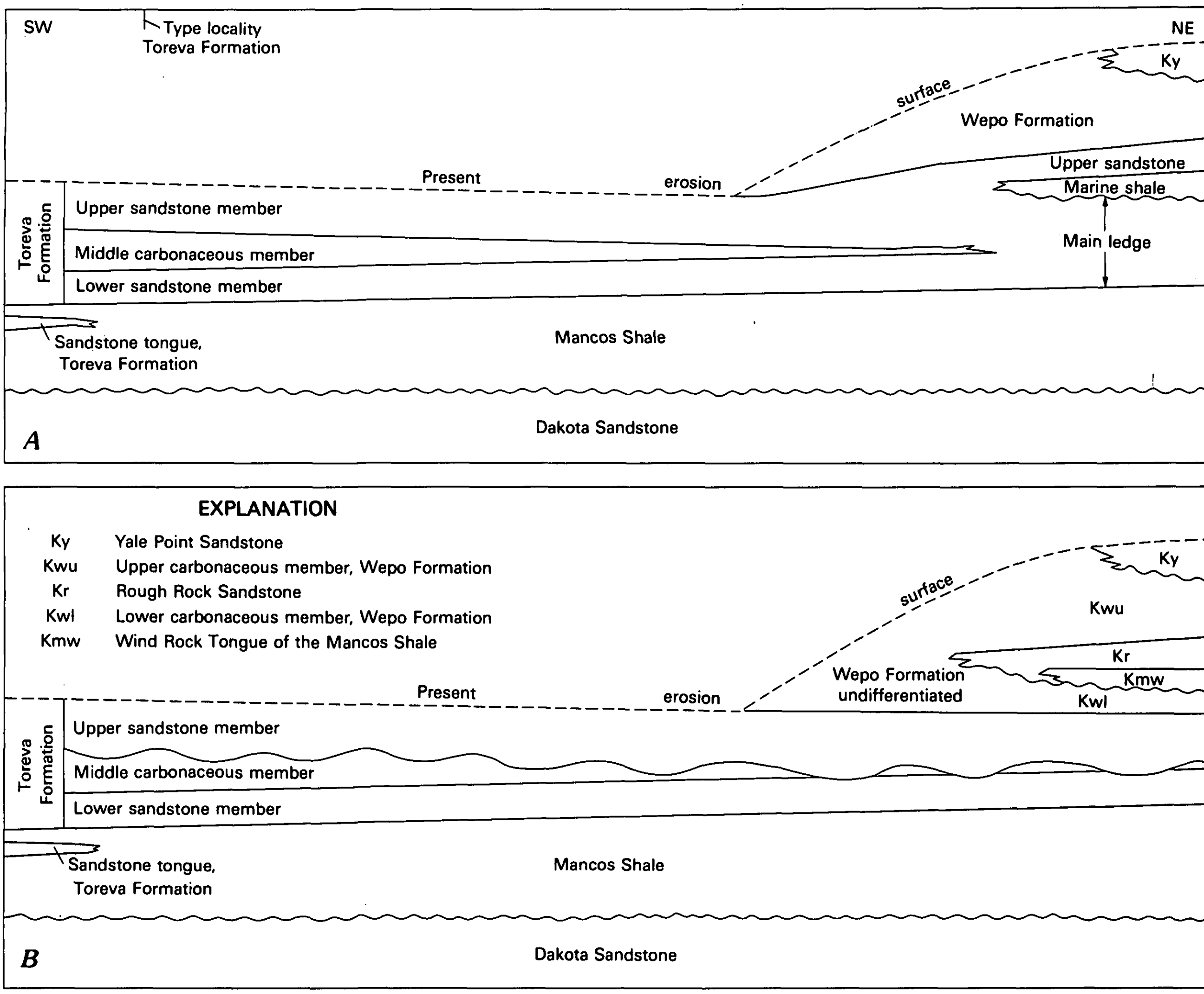


Figure 4. *A*, Repenning and Page's (1956) correlation and nomenclature of the Toreva Formation of Black Mesa. *B*, nomenclatural changes and recorrelation of the Toreva Formation resulting from this study.

occur in the uppermost part of the unit (Repenning and Page, 1956). To the north, the upper sandstone member becomes finer grained and granules and small pebbles are the largest grains. A scour contact is present between the upper sandstone member and the middle carbonaceous member.

Locally, in the northern part of the mesa, where the middle carbonaceous member has been removed, the upper sandstone member lies directly on the lower sandstone member. Even when these sandstones are in contact they have distinctly different weathering characteristics, grain-size distributions and trends, and sequences of sedimentary structures. Repenning and Page (1956) felt that without the intervening fine-grained unit, a detailed examination was necessary to separate the two sandstone members, so they applied the name "main ledge" to the combined upper and lower sandstone members in the northern part of the mesa (fig. 4).

Repenning and Page (1956) included two other units in the Toreva that are only present in the northern part of Black Mesa: the marine shale and the upper sandstone units (fig. 4). They included these two units in the Toreva Formation because they believed the upper sandstone coalesced southward with the upper part of the main ledge, which is equivalent to the upper sandstone member. This study shows that Repenning and Page's (1956) upper sandstone unit of northern Black Mesa can be traced to a depositional pinchout within the Wepo Formation and that it does not coalesce with the top of the main ledge (fig. 4). In the northern part of Black Mesa, Beaumont and Dixon (1965) recognized an additional unit that they named a tongue of the Wepo Formation below Repenning and Page's (1956) marine shale unit of the Toreva Formation. This tongue of the Wepo consists predominately of coal, carbonaceous shale, and lenticular sandstone beds, and it is present throughout the study area.

Figure 5. Outcrop of Cretaceous units in the study area excluding the Dakota Sandstone. Photo taken at the Chilchinbito Canyon section (fig. 2). Km-Mancos Shale; Ktl, Ktm, Ktu-lower sandstone, middle carbonaceous, and upper sandstone members, respectively, of the Toreva Formation; Kwl-lower carbonaceous member of the Wepo Formation; Kmw-Wind Rock Tongue of the Mancos Shale; Kr-Rough Rock Sandstone; Kwu-upper carbonaceous member of the Wepo Formation; and Ky-Yale Point Sandstone.

Where the marine shale unit pinches out, this tongue of the Wepo underlies the upper sandstone unit of the Toreva.

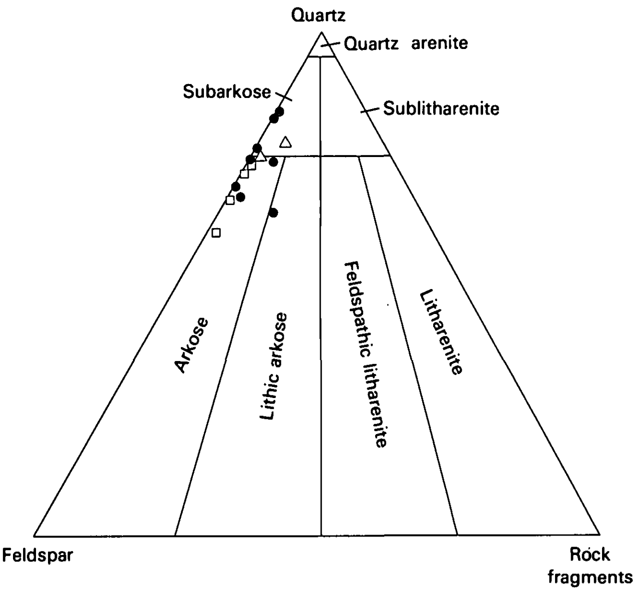
The local presence of the middle carbonaceous member of the Toreva Formation in the northern part of the mesa, the presence everywhere of a tongue of the Wepo above the main ledge and below the marine shale, and the recorrelation of the upper sandstone (fig. 4) lead me to suggest a restriction of the Toreva Formation nomenclature in northern Black Mesa to what Repenning and Page (1956) referred to as the main ledge. Also, the member names used at the type locality (lower sandstone member, middle carbonaceous member, and upper sandstone member) should be used throughout Black Mesa and the name "main ledge" should be abandoned. Beaumont and Dixon's (1965) tongue of the Wepo Formation is renamed the lower carbonaceous member of the Wepo Formation, the upper sandstone is herein named the Rough Rock Sandstone, and the intervening marine shale tongue is herein named the Wind Rock Tongue of the Mancos Shale. Where the Rough Rock Sandstone is present, the overlying unit is named the upper carbonaceous member of the Wepo Formation. Where the Rough Rock Sandstone is absent, the upper and lower carbonaceous members of the Wepo are not differentiated. These changes are shown on figure 4. Figure 5 shows a typical outcrop expression of these units within the study area.

UPPER PART OF THE MANCOS SHALE AND LOWER SANDSTONE MEMBER OF THE TOREVA FORMATION

Description

Upper Part of the Mancos Shale

The contact between the Mancos Shale and the lower sandstone member of the Toreva Formation is gradational. Therefore, an examination of the sedimentary characteristics of the upper part of the Mancos Shale is essential to understanding the origin of the lower sandstone member of the Toreva Formation. In the upper 50 ft (15 m) of the Mancos Shale a transition zone occurs in which the lithology shows a gradual change upward from



EXPLANATION

- ● Sandstone in lower sandstone member of the Toreva Formation
- △ Sandstone in upper part of the Mancos Shale
- □ Channel-form sandstone within the middle carbonaceous member of the Toreva Formation

Figure 6. Mineral composition and classification (Folk, 1974) of sandstone within the lower sandstone and the middle carbonaceous members of the Toreva Formation.

dark-gray shales to very thinly interbedded siltstone and mudstone, which in turn change to interbedded very fine grained sandstone and siltstone. The sandstone beds gradually increase in thickness from less than 0.5 in. (1 cm) to 1.5 ft (0.5 m), and the siltstone beds decrease in thickness until they occur as laminations between the sandstone beds. Mica and comminuted carbonaceous material are concentrated along the bedding planes between the sandstone and siltstone; minor amounts of glauconite and rare, reworked silicified fossil fragments occur within the fine- to very fine grained, subarkosic sandstone beds (fig. 6).

A characteristic vertical sequence of sedimentary structures is present within the sandstone beds in the uppermost part of the Mancos Shale. The basal contact of these beds is sharp and flat to slightly undulatory. Rare hummocky cross-stratification is present in the lower part of the beds, but the dominant stratification types in this part of the sandstone bed are very low-angle cross-stratification and horizontal to low-angle parallel stratification; ripple stratification is common in the upper part of these beds. Locally, the stratification was disrupted and obscured by burrowing organisms. Trace fossils are most abundant in the siltstone beds and at the top of the sandstone beds. The most common type of trace fossil in the upper part of the Mancos Shale is *Planolites*; *Rhizocorallium* burrows are present locally in the uppermost beds of the Mancos Shale. Overall, the number of trace fossils decrease upward toward the base of the lower sandstone member of the Toreva Formation.

The most striking sedimentary structures in the upper part of the Mancos Shale are soft sediment deformation features. Ball and pillow structures, which range from 1 to 17 ft (0.3 to 5 m) in thickness, are the most common type of deformation feature (fig. 7). These structures result from the vertical and lateral displacement of sand layers into underlying mud and indicate rapid sedimentation rates. Observations made during reconnaissance surveys outside the study area indicate that those structures are also abundant in the upper part of the Mancos Shale throughout Black Mesa. Faulting contemporaneous with sedimentation also occurred during deposition of the upper part of the Mancos Shale. Faults having displacements of as much as 5 ft (2 m) offset the interbedded sandstone and siltstone sequence but do not extend into the lower sandstone member of the Toreva Formation.

Lower Sandstone Member of the Toreva Formation

Because of the gradational contact with the underlying Mancos Shale, the base of the lower sandstone member is arbitrarily defined at the top of the last thick (greater than 3 ft (1 m)) siltstone bed, which generally corresponds to the base of the first massive cliff-forming sandstone above the Mancos Shale. The lower sandstone member extends across the study area as sheetlike sandstone bodies. In some areas, only one sandstone body is present, but two or more stacked sheetlike sandstone bodies may occur locally. Where the sandstone is stacked within the study area, the lowest sandstone body is designated unit I and the upper sandstone body unit II (fig. 8; pl. 1). In the northern part of the study area, units I and II are separated by a sequence of interbedded sandstone and siltstone that is 10 ft (3 m) thick. Where unit I underlies the interbedded sequence, the upper 1-3 ft (0.3-1 m) is intensely burrowed and locally bioturbated. South of the Yale Point section (pl. 1), this interbedded sequence becomes sandier and grades laterally into unit II, and a notch in the cliff face is all that separates unit I from unit II. Unit II then thins southward to a depositional pinchout between the Wind Rock Valley and Sweathouse Peak sections (pl. 1), and unit I thickens southward. Where unit I is not overlain by unit II, the top of unit I contains abundant root casts and underlies beds of coal and carbonaceous shale. The thickness of the lower sandstone member is usually 35-50 ft (11-15 m); however, where units I and II are stacked, the thickness ranges from 60 to 90 ft (18 to 27 m).

Each sheetlike sandstone body in the lower sandstone member has a characteristic grain-size trend and sequence of sedimentary structures. Locally, there are

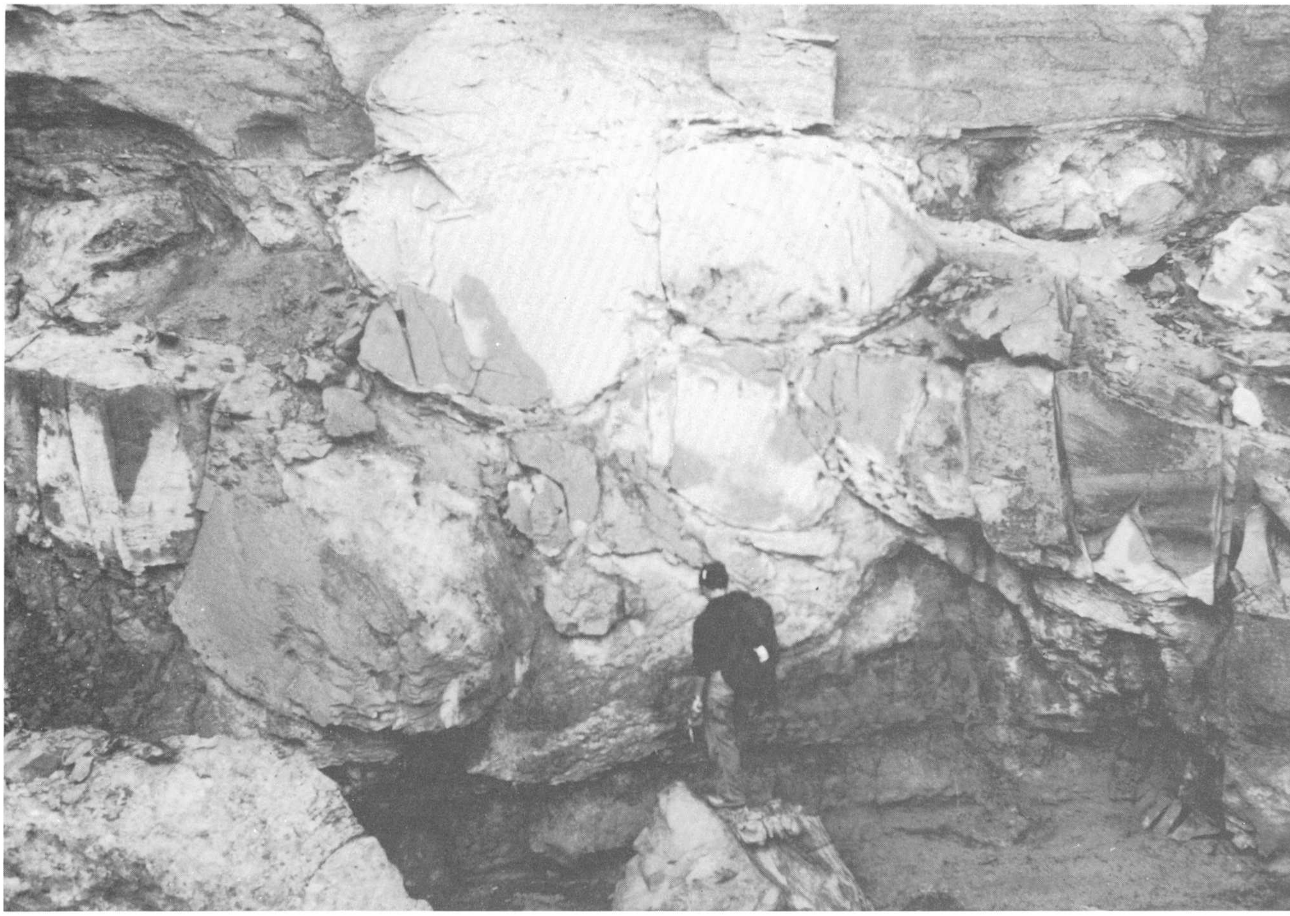


Figure 7. Large ball and pillow structures in the transition zone of the upper part of the Mancos Shale at the Tah Chee Wash section. Field assistant is 5 ft 2 in. tall.

some differences in these characteristics between units I and II, which will be discussed later. A coarsening-upward grain-size trend occurs within the sheetlike sandstone bodies: very fine to fine-grained sandstone at the base changes gradually upward to medium-grained sandstone with local coarse-grained and granule-sized material in the upper part of the unit. The sandstone within these sheetlike units is well to moderately sorted, subrounded, and arkosic to subarkosic (fig. 6) with an average feldspar content of 23 percent.

The lower part of the sheetlike sandstone units contains beds of very low angle cross-stratification and parallel laminations alternating with burrowed to bioturbated beds. Trace fossils are most common in the lower part of the unit and consist primarily of *Planolites*, *Rhizocorallium*, and *Ophiomorpha*. In the upper part of the sheetlike sandstone units, medium-angle trough and wedge-planar cross-stratification are the dominant bedding types with local, less abundant, tabular-planar cross-stratification. Trace fossils within this sequence are rare, vertical *Ophiomorpha*. A change to very low angle trough cross-stratification and inclined parallel laminations occurs in the upper 2–5 ft (0.6–1.5 m) of the sheetlike units, and the uppermost 0.5 ft (15 cm) commonly contains root casts and carbonaceous material.

Some deviations in these grain-size trends and sedimentary structure sequences occur in unit II at the Yale Point and Wind Rock Valley sections (pl. 1). At these sections, medium- to coarse-grained sandstone with scattered granule-sized material occurs near the base of unit II, and a slight fining-upward trend to medium-grained with some fine-grained sandstone occurs at the top of the unit. Another difference is that the alternating burrowed to stratified zone at the base of the sandstone body is thin to locally absent, and trough and tabular-planar cross-stratification are present close to the base of unit II.

Sediment transport directions also show differences between unit II at the Yale Point and Wind Rock Valley sections and unit I (figs. 9 and 10). These sediment transport directions were obtained from orientation measurements of trough axes and, where troughs were not present, from foreset orientations in tabular-planar cross-sets. Unit II shows both northeast and southeast dominant components of transport, and unit I shows northest through southeast components of transport.

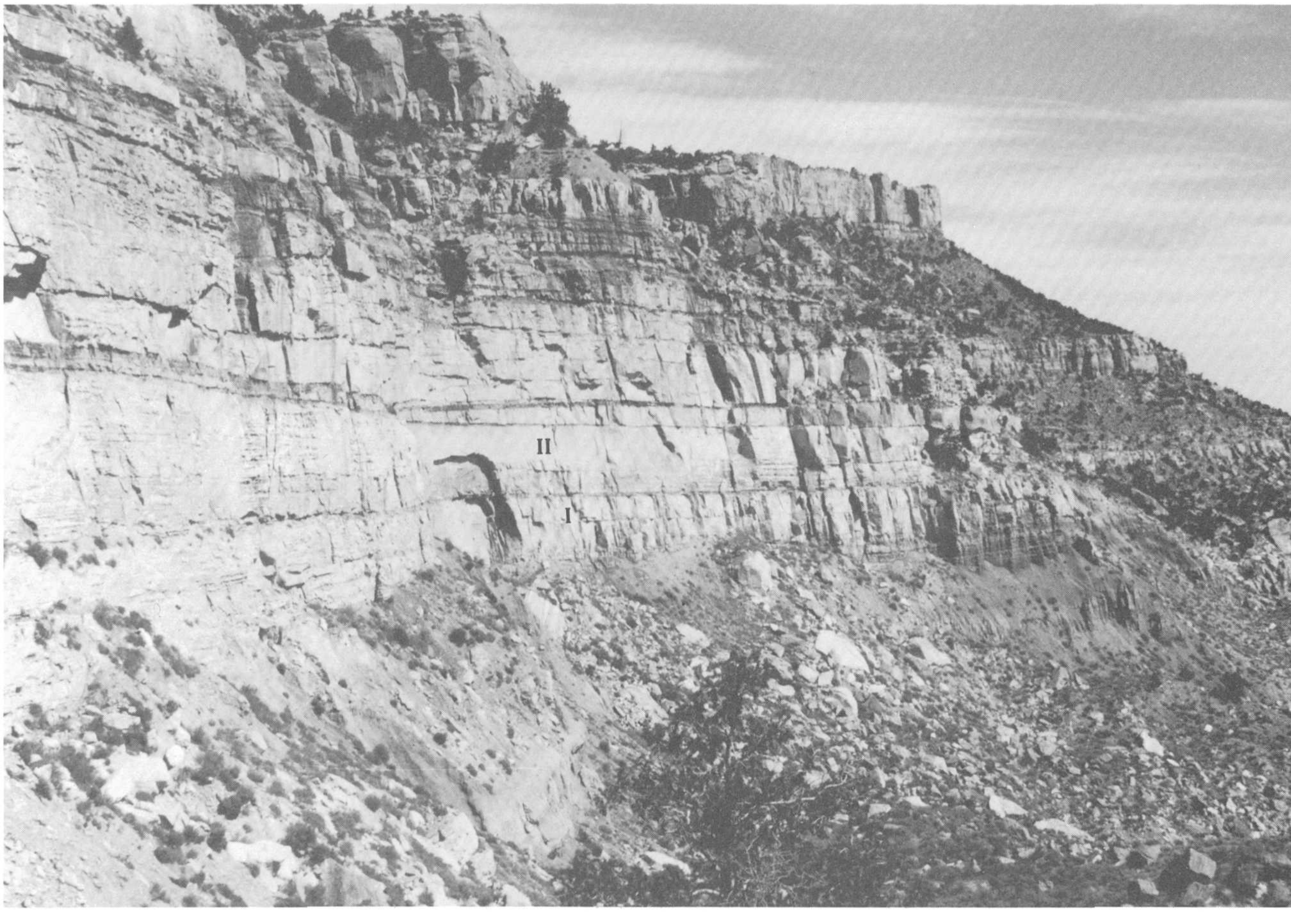


Figure 8. Sheetlike sandstone bodies (units I and II on pl. 1) within the lower sandstone member of the Toreva Formation. Photo is looking north from the Wind Rock Valley section. Unit I is 25 ft (8 m) thick and unit II is 30 ft (9 m) thick.

In the study area, an age-diagnostic fossil collection was not obtainable because of the scarcity of fossils in the lower sandstone member of the Toreva Formation. The age of the lower sandstone member can be approximated, however, from fossils collected from this member outside of the study area. The oldest fossils, which belong to the early middle Turonian *Collignoniceras woollgari* faunal zone, were found at Blue Point (fig. 1) in an outcrop southwest of Black Mesa (Repenning and Page, 1956). To the northeast, the fossil assemblages become progressively younger. Fossils collected from this member during this study at Pine Spring Canyon south of the study area (fig. 1) belong to the middle Turonian *Prionocyclus hyatti* faunal zone (W. A. Cobban, personal commun., 1982). At Marsh Pass in the northernmost part of Black Mesa, the basal Toreva sandstone was reported to contain fossils of the late Turonian *Prionocyclus macombi* zone (Repenning and Page, 1956), but J. I. Kirkland (oral comm., 1987) believed they were misidentified and should be placed in the *Prionocyclus hyatti* zone. Therefore, within the study area, the lower sandstone member of the Toreva Formation is late middle Turonian in age.

Interpretation

The gradual increase in abundance of siltstone and sandstone beds through the upper part of the Mancos Shale, the gradational contact between the Mancos Shale and the lower sandstone member of the Toreva, and the coarsening-upward grain-size trend and vertical changes in sedimentary structures within the lower sandstone member indicate that these units were deposited in a marine environment under increasingly higher energy conditions and shallower water depths during a progradation of the shoreline. As the shoreline prograded, silt and very fine sand-sized material was introduced during storm events into the deeper parts of the basin where finer grained sediments were being deposited. Mud settled out of suspension and burrowing organisms mixed the sediment during periods of calm between storm events. These alternating storm and calm events produced the

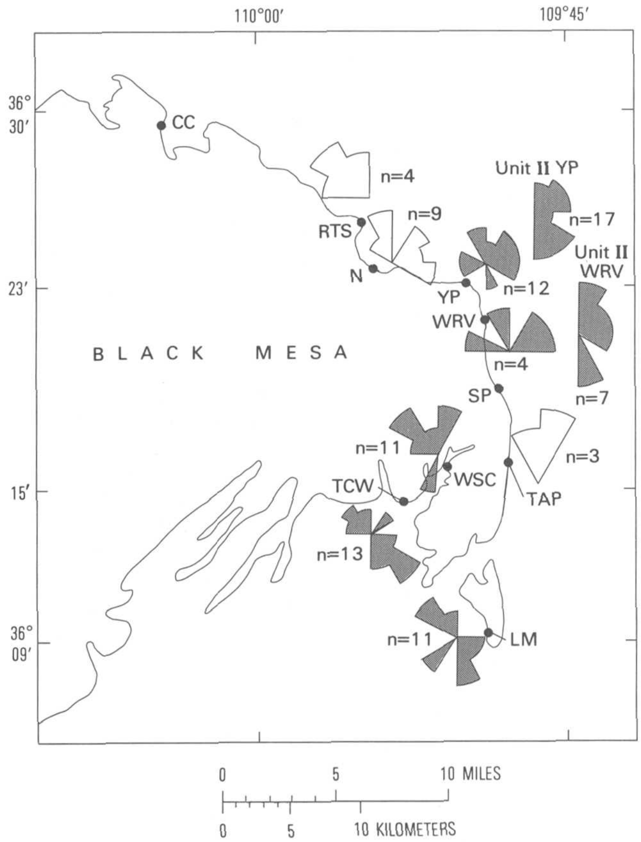


Figure 9. Transport directions obtained from trough and tabular planar cross-stratified beds within the lower sandstone member of the Toreva Formation shown by black rose diagrams. Open rose diagrams show directions from trough cross-stratified beds in the channel-form sandstone of the middle carbonaceous member of the Toreva Formation that are incised into the lower sandstone member; n is the number of readings. Measured section abbreviations are shown on plate 1.

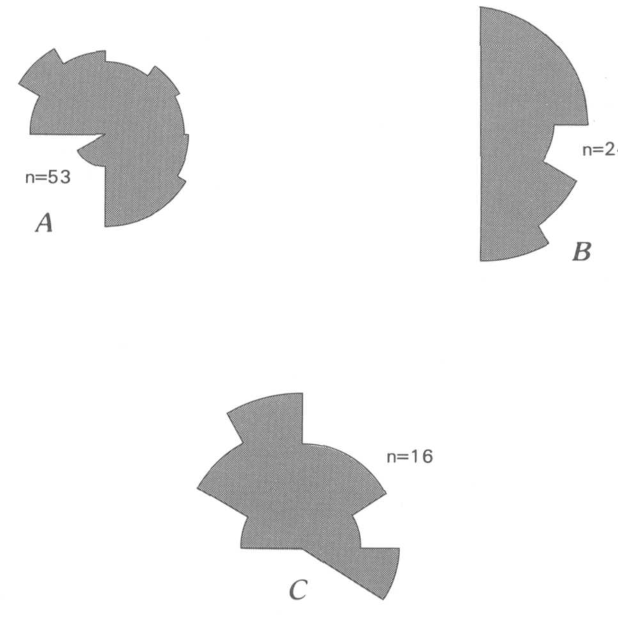


Figure 10. *A*, combined transport directions from the lower sandstone member of the Toreva, unit I. *B*, combined transport directions from lower sandstone member, unit II. *C*, combined transport directions from channel-form sandstone of the middle carbonaceous member that are incised into the lower sandstone member; n is the number of readings.

interbedded sequence in the upper part of the Mancos Shale. Continual progradation of the shoreline resulted in progressively shallower water conditions accompanied by a higher energy regime as storm wave base and finally daily effective wave base extended to the sediment interface. Sediments deposited under these higher energy conditions formed the lower sandstone member. The sedimentary structures within the sheetlike sandstone bodies show the change to increasingly higher energy conditions, which correspond to Reading's (1978) and Reineck and Singh's (1980) models of the depositional sequences forming along modern coastlines. The low-angle cross-beds and laminated beds alternating with burrowed beds in the lower part of the sandstone reflect the deeper water sand depositional zone where storm waves periodically reworked the sediment, but burrowing organisms disturbed parts of the stratified beds during calm periods. In the upper part of the sheetlike sandstone, the increase in grain size and the medium-angle trough and tabular-planar cross-stratification reflect sand deposition in the shallower, higher energy surf and breaker zone. The upper 2–5 ft (0.6–1.5 m) that contains the low-angle, parallel-bedded sequence formed in the swash, or beach zone, and root casts at the top of the sandstone indicate the beginning of deposition in a subaerial environment.

The type of coastal environment in which these deposits accumulated can be inferred from the characteristics of the upper part of the Mancos Shale and the lower sandstone member of the Toreva Formation. In the upper part of the Mancos Shale, the abundant transported carbonaceous material concentrated along bedding planes, the lack of intense reworking of the sediments by burrowing organisms, and the abundant penecontemporaneous deformation structures indicate a nearby terrigenous source area and rapid rates of sedimentation. Both of these conditions are indicative of a deltaic coastline, and all of these features in the upper part of the Mancos Shale are present in the transition zone between prodelta and deltafront deposits in modern deltaic systems (Fisher, 1969; Coleman and Prior, 1980). Ryer (1982), Flores and Erpenbeck (1981), Flores and Tur (1982), and other workers have described these same features from the transition zone (upper prodelta to lower delta front) of deltas that existed along the Cretaceous seaway.

The character and distribution of the sediments deposited in the delta front can indicate the type of deltaic system that existed. Galloway (1975) has classified deltaic systems according to three end-member types: tide dominated, wave dominated, and river dominated. Deposits of both wave- and river-dominated deltaic systems have been identified in Cretaceous rocks of the Western Interior (Balsley, 1982; Ryer, 1982), but there is no evidence that tidal energy along the Western Interior Cretaceous seaway was strong enough to produce tide-dominated deltas.

Along coastlines with high wave energy, sediments deposited at the mouth of distributary channels are reworked by waves and longshore current into extensive strand plains and coastal marine sand bodies whose depositional axes parallel the coastline. In this setting, discrete distributary mouth bar complexes, which characterize river-dominated deltas like the Mississippi (Coleman and Prior, 1980), are not preserved. The lateral extent of the sheetlike sandstone bodies of the lower sandstone member and the lack of discrete distributary mouth bar complexes flanked by interdistributary bay deposits suggest that the lower sandstone member was deposited along a wave-dominated coastline. Peterson (1969a) inferred a northwest-southeast orientation of the coastline during middle to late Turonian time in southern Utah and northern Arizona. The northwest and southeast transport directions obtained from unit I (fig. 10) in the lower sandstone member reflect transport by currents that paralleled the coastline and reworked the sediments deposited at the distributary mouths.

The northeast, offshore component of transport present in unit II (fig. 10) of the lower sandstone member and the differences in grain-size trends and sedimentary structures in this unit at the Yale Point and Wind Rock Valley sections suggest that fluvial currents may have been more dominant than marine wave and current action in deposition of parts of unit II. Unit II in the area of these two measured sections could have been deposited close to a distributary mouth where sedimentation rates were very high and the sand did not undergo extensive reworking by wave action.

The presence of two distinct delta-front deposits, unit I and II, in the lower sandstone member indicate sequences of constructional and destructional events in the delta-building process along the Toreva coastline (fig. 11). Unit I was deposited when a distributary channel in or near the study area was actively supplying sediment to a prograding deltaic complex. Abandonment of the distributary channel and shifting of the progradational center caused a period of local submergence and wave reworking of sediments along the part of the coastline where unit I was deposited. This period of local water deepening, wave reworking of delta-front deposits, and decrease in sediment supply is reflected by the burrowed to bioturbated top of unit I where it is overlain by the interbedded sandstone and siltstone sequence. Reestablishment of a prograding deltaic center in the

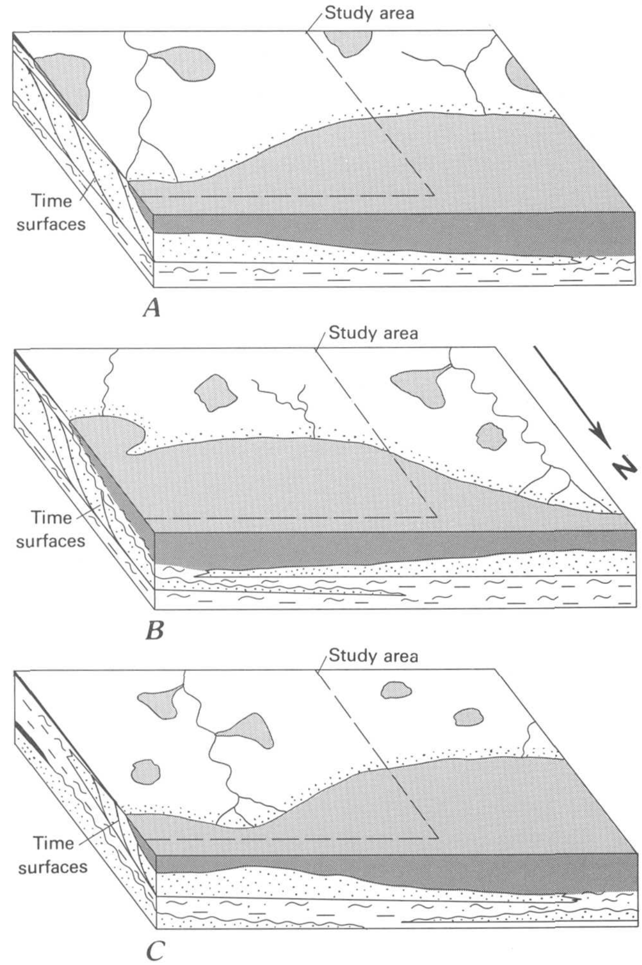


Figure 11. Schematic diagrams of the distribution of deltaic centers during deposition of the lower sandstone member of the Toreva Formation: *A*, deposition of unit I of the lower sandstone member; *B*, coastline in study area submerged and unit I reworked as a result of distributary-channel abandonment and deltaic depositional center shift; *C*, unit II deposited when distributary channels reintroduced into the study area. Coastline in all diagrams is prograding to the northeast.

study area resulted in the deposition of the delta-front deposits of unit II.

MIDDLE CARBONACEOUS MEMBER OF THE TOREVA FORMATION

Description

Within the study area, the middle carbonaceous member ranges in thickness from 0 to 70 ft (0 to 21 m) and has a sharp but conformable base with the underlying lower sandstone member. Where the middle carbonaceous member is missing, the upper sandstone member of the Toreva Formation rests with a scour base on the lower sandstone member. The lithologic units within the middle carbonaceous member can be divided into two groups: (1) channel-form sandstone units and (2) the coal, carbonaceous mudstone, siltstone, and sandstone units that surround the channel-form sandstone.

Arkosic (fig. 6) channel-form sandstone units occur in two settings: partly within the lower sandstone member and totally within the middle carbonaceous member. In the area between the Needles and Red Tree Springs measured sections (pl. 1) and in the area of the Tse Da Ahoodza Peak section (pl. 1), channel-form sandstone units extend from the middle carbonaceous member into the lower sandstone member. A zone of stacked or single channel-form sandstone units extends along the outcrop belt for 3–4 mi (5–6 km) in the Needles-Red Tree Spring area. At the Tse Da Ahoodza Peak section, a single, channel-form sandstone unit that is 30 ft (9 m) thick has been incised into the lower sandstone member. The channel-form sandstone units within the middle carbonaceous member are from 3 to 40 ft (1 to 12 m) thick, but most units are less than 10 ft (3 m) thick. These units occur as isolated bodies that extend laterally for about 200 ft (61 m), but the thickest units may have a lateral extent of up to 1,000 ft (305 m).

All of the channel-form sandstone units have similar grain-size trends and stratification sequences. Clay rip-up clasts, carbonaceous material, and granules are concentrated along the base of the unit. The grain size decreases upward from medium to coarse grained in the lower part of the sandstone to fine to medium grained in the upper part. Sorting improves upward through the unit from poorly sorted at the base to moderately or well sorted at the top.

The thickness of the cross-stratification sets within the channel-form sandstone units also decreases upward. Medium-angle trough and wedge-planar cross-stratification sets that have an average set thickness of 1–1.5 ft (30–46 cm) are the dominant sedimentary structures in the lower part of the unit. Measurement of trough axis orientations give sediment transport directions that range from northwest to southeast (fig. 9). Very low angle trough cross-stratification, ripple-stratification, and horizontal laminations occur in the upper 1–3 ft (0.3–1 m). Large-scale lateral accretion cross stratification is present within a few of the channel-form sandstone bodies.

The diversity and number of trace fossils within the channel-form sandstone units are low. The units that occur lower in the section commonly contain *Teredo*-bored logs at the base of the unit. *Ophiomorpha* and *Thalassinoides* burrows were observed only in the channel-form sandstone bodies immediately above the lower sandstone member at the Tah Chee Wash section (pl. 1).

The lithologic units that surround the channel-form sandstone bodies in the middle carbonaceous member include coal, carbonaceous mudstone, interbedded sandstone and siltstone, and tabular sandstone units. The lateral extent of each of these lithologic units is often difficult to determine because scouring at the base of an overlying channel-form sandstone has removed laterally equivalent parts of these units, and the slope-forming middle carbonaceous member is commonly covered by Quaternary talus, colluvium, or slumped material.

Coal deposits range in thickness from less than one foot (0.3 m) to a maximum observed thickness of 11 ft (3 m), but most coal beds are 1–3 ft (0.3–1 m) thick. Visual inspection of the cliff faces indicated many of these beds are less than a few hundred feet in lateral extent as they grade laterally into carbonaceous mudstone and siltstone, or they have been removed by erosion at the base of a sandstone unit. However, the coal bed at the Chilchinbito Canyon section which is 11 ft (3 m) thick could be traced for more than a mile along the cliff face before this interval was obscured. Root casts are present at the base of many, but not all, coal beds; and the coal beds are commonly split by thin interbeds of carbonaceous shale.

The carbonaceous mudstone units are less than 1 ft (0.3 m) to about 5 ft (2 m) thick and most commonly occur interbedded with coal and siltstone. The mudstone is generally laminated and contains abundant fine, disseminated, detrital organic material and numerous plant impressions; root casts are locally present at the top of the mudstone. Only rare, straight, horizontal and vertical burrows, which are undiagnostic of depositional environment, occur in these units, and no definitive marine or brackish water fossils or trace fossils were observed.

Interbedded sandstone and siltstone sequences are abundant within the middle carbonaceous member and generally occur above or adjacent to channel-form sandstone bodies. Within these sequences, the amount of sandstone decreases upward and the siltstone content increases proportionally. Although the sedimentary structures may show some variation between sequences, the sandstone beds are generally ripple laminated, and the siltstone beds are laminated, or locally, the sedimentary structures are disturbed by root casts and small, straight, burrows. The amount of organic material preserved in these sequences may vary greatly, and soft sediment deformation is locally present.

One interbedded sandstone and siltstone sequence, which occurs immediately above the lower sandstone member at the Waterfall Spring Canyon section (pl. 1), has very different characteristics from those previously described. In this sequence, the sandstone beds increase in thickness and abundance upward, and the sedimentary structures are similar to those in the interbedded sandstone and siltstone sequence at the top of the Mancos Shale. This sequence at Waterfall Spring Canyon pinches out depositionally and can not be traced to the adjacent measured sections (pl. 1).

Tabular sandstone units that are easily distinguishable from the channel-form sandstone units also occur within the middle carbonaceous member. These tabular sandstone bodies are very fine to fine grained, have planar lower and upper contacts, and range from 1 to 7 ft (0.3 to 2 m) in thickness. Locally, these units may grade laterally into sandy siltstone. The dominant sedimentary structure within the tabular sandstone beds is ripple stratification, but, locally, root casts or burrowing in the upper part of a unit have destroyed sedimentary structures. The only type of burrows observed within these units were simple, straight, vertical and horizontal burrows except in one tabular sandstone bed in the Lohali Mesa section (pl. 1) where *Ophiomorpha* burrows are present.

Interpretation

The middle carbonaceous member of the Toreva Formation was deposited on the delta plain that developed landward of the delta-front deposits of the lower sandstone member of the Toreva Formation. The inferred depositional environments within this delta plain include distributary channels flanked by interdistributary areas of well and poorly drained swamps, crevasse channels, crevasse splays, and freshwater lakes. Absence of marine and brackish-water fossils and observation of *Ophiomorpha* and *Thalassinoides* trace fossils in very few beds indicate a delta-plain setting that contained few marine to brackish-water interdistributary bays. This particular delta-plain setting developed along a cuspate or arcuate wave-dominated deltaic system where an extensive, laterally continuous, strand plain inhibited the formation of large interdistributary bays. The specific geographic distribution of environments on the delta plain that existed during deposition of the middle carbonaceous member is difficult to establish because of the thinness and local absence of this member.

The channel-form sandstone units were deposited within distributary channels. Several characteristics of these units indicate a distributary channel rather than a tidal channel origin: the presence of unidirectional trough cross-stratification throughout each sandstone body, the abundance of transported logs and terrigenous material at the base of each unit, the lack of brackish and marine fossils within the units, and the lack of shell lags at the base of the units. Also, evidence of other tidal environments, such as washover, flood tidal, ebb tidal, tidal flat, and lagoonal deposits, were not associated with the channel deposits or observed within the middle carbonaceous member.

On the lower delta plain, distributary channels that eroded into the delta front deposits produced the channel-form sandstone units that are partly within the lower sandstone member. Large-scale lateral accretion surfaces within some of the incised distributary channel deposits in the Needles-Red Tree Spring area indicate that some of these channels were meandering. It was probably the lateral migration of these channels that produced this extensive zone of deposits. Meandering distributary channels occur in modern wave-dominated deltaic systems, such as the Rhone delta (Fisher, 1969), where channels are transporting a high percentage of bedload material. Balsley (1982) has documented meandering distributary channels in Late Cretaceous, wave-dominated, deltaic deposits in the Book Cliffs of eastern Utah.

The only indicators of brackish-water conditions within the distributary channels of the middle carbonaceous member are the *Teredo*-bored logs at the base of the channel deposits and the spatially restricted *Ophiomorpha* and *Thalassinoides* burrows. Brackish-water environments occurred within the distributary channels when saltwater wedges formed periodically during low river discharge.

The characteristics of the lithologic units that surround the distributary channel deposits indicate deposition on a delta plain in flood-plain environments rather than in extensive interdistributary bays. Levees, well-drained swamps, poorly drained swamps, crevasse splays, and freshwater lakes all existed lateral to the distributary channels.

The interbedded sandstone and siltstone sequences represent deposition in the levees and well-drained swamps adjacent to the channels. Repeated flooding of these areas resulted in deposition of alternating thin beds of ripple-stratified sand and laminated silt. The vegetation that established itself on these areas produced the abundant root casts within these beds. Although vegetation was abundant in this setting, the position of the sediments above the water table resulted in oxidation of much of the organic material.

Farther away from the channels are the poorly drained swamps. Topographically, this area is lower and closer to the water table than the well-drained swamps. Therefore, most of the organic material that forms in the poorly drained swamps is preserved as peat. Two types of peat-forming environments were present on the delta plain: poorly drained swamps in areas where distributary channels are concentrated, and poorly drained swamps in areas removed from distributary channels. The thin coal deposits with carbonaceous shale interbeds formed in areas where channels were present. Frequent flood events interrupted peat formation by drowning the swamp and depositing very fine clastic material. The 11-ft (3 m)-thick coal bed at the Chilchinbito Canyon section (pl. 1) formed in an area away from distributary channels where peat deposition was uninterrupted by flood events, clastic sedimentation, or channel switching.

Both freshwater lakes and crevasse splays were present on the flood plains. The carbonaceous, laminated

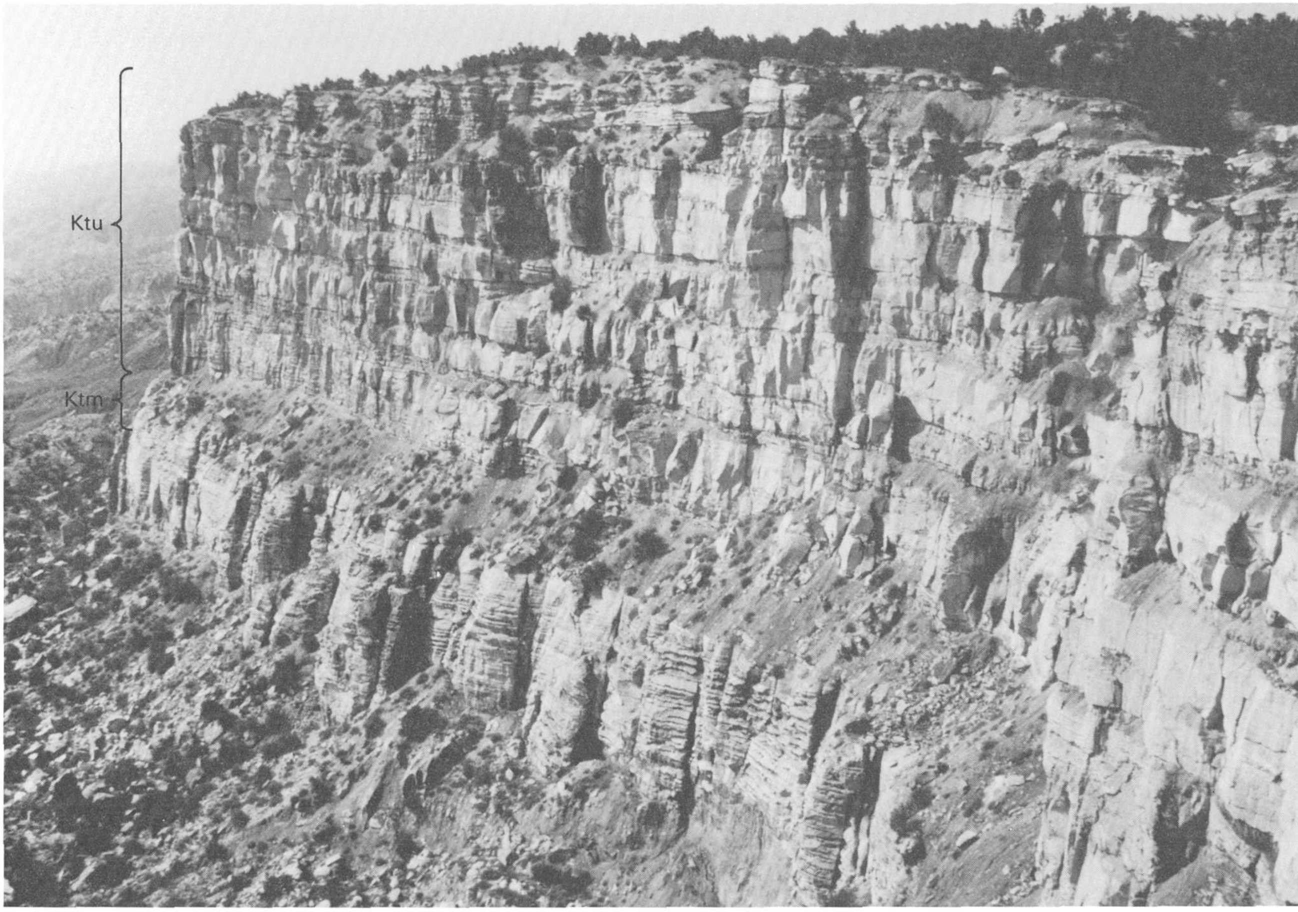


Figure 12. Sandstone geometries of the upper sandstone member of the Toreva Formation, **Ktu**. Sheetlike sandstones in the upper sandstone member overlie a thin slope-forming middle carbonaceous member, **Ktm**. In the uppermost part of the upper sandstone member, seen in the uppermost outcrop exposure in this photo, the sandstone units gradually become ribbonlike and lenticular (dependent on orientation of the sandstone body) and more fine-grained material is present. Photo taken west of the Lohali Mesa section.

mudstone that contains no brackish water fossils or trace fossils indicates slow rates of deposition in reducing, freshwater environments. These freshwater lakes occurred in the lowest parts of the floodplain or within abandoned channels. Crevasse splays formed when levees were breached during flood events. Sediment was deposited at the end of crevasse channels as broad, often extensive, lobes. The units whose geometry best corresponds to that of a splay are the tabular sandstone bodies. There is little grain-size variation among these units, but parts of the splay deposited closer to the crevasse channel are upper very fine to lower fine-grained sandstone, and the most distal parts of the splay contain a high percentage of silt.

Although there is no evidence of large embayments along the coastline, there is evidence for rare, small, laterally restricted embayments. The laterally restricted sandstone and siltstone sequence directly above the delta-front sandstone at the Waterfall Spring section is interpreted as an embayment fill deposit. The intensely burrowed and calcite-cemented upper 1 ft (30 cm) of the delta-front sandstone at this locality indicates the embayment formed after a period of local marine submergence and wave reworking of the delta-front deposits. The upward increase in the thickness of sandstone beds within the interbedded sandstone and siltstone sequence indicates a gradual infilling and shallowing of the embayment.

UPPER SANDSTONE MEMBER OF THE TOREVA FORMATION

Description

The upper sandstone member of the Toreva Formation is composed of two types of sandstone bodies that differ in geometry, grain size, and sedimentary structures: sheetlike sandstone bodies (internally composed of numerous channel-form units) that form the lower part of the

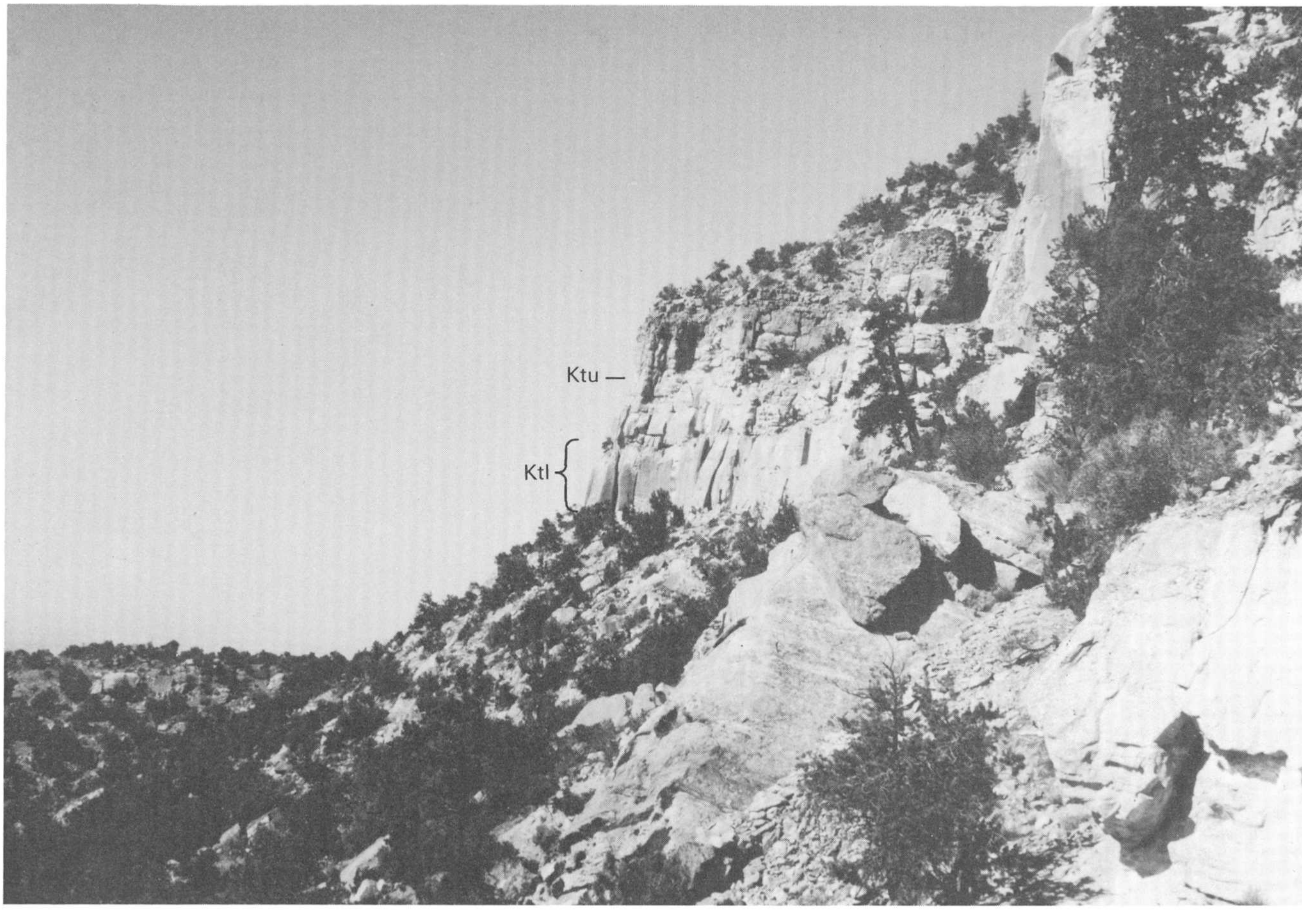


Figure 13. Fluvial sandstones of the upper sandstone member of the Toreva Formation, **Ktu**, that scour into the lower sandstone member of the Toreva Formation, **Ktl**. The middle carbonaceous member is absent. Photo taken at the Yale Point section.

member, and ribbonlike to lenticular sandstone bodies in the upper part of the member (fig. 12). This member rests with a sharp scour contact on the underlying middle carbonaceous member. Locally, however, it rests directly on the lower sandstone member (fig. 13). The sheetlike sandstone bodies in the lower part of the upper sandstone member are distinguished from sandstone units in the middle carbonaceous member by the types and sequences of sedimentary structures and the geometry of the sandstone bodies. However, the upper sandstone member of the Toreva Formation has a gradational contact with the overlying lower carbonaceous member of the Wepo Formation because the amount of interbedded fine-grained material gradually increases upward and the thickness and lateral extent of the sandstone bodies decrease upward. This upper contact is arbitrarily placed where the thickness of the interbedded fine-grained material is greater than the thickness of coarse- to medium-grained sandstone bodies. Although the upper sandstone member is present throughout the study area, its thickness ranges from about 25 ft (8 m) to slightly over 120 ft (37 m).

The sheetlike sandstone bodies are composed of numerous, discrete, stacked, channel-form sandstone sequences. These individual sandstone sequences range in thickness from 7 to 40 ft (2 to 12 m), but are most commonly 10–15 ft (3–5 m) thick. Where these sandstones are not scoured into by an overlying sandstone, they are commonly sharply overlain by thin sequences, usually less than 5 ft (2 m) thick, of siltstone, mudstone, or coal. Locally, lenticular siltstone, mudstone, and interbedded sandstone and siltstone sequences occur within the sheetlike sandstone bodies.

The lenticular sandstone bodies in the upper part of the upper sandstone member range in thickness from 5 to 30 ft (2 to 9 m) and are enclosed in fine-grained deposits. Although these sandstone units are often gradationally overlain by interbedded sandstone and siltstone sequences, they may be sharply overlain by coal beds or siltstone and mudstone. The types and sequences of sedimentary structures within the ribbonlike and lenticular sandstone units differ from those within the sheetlike sandstone bodies. These differences, and differences in lithology, mineralogy (fig. 14), and texture,

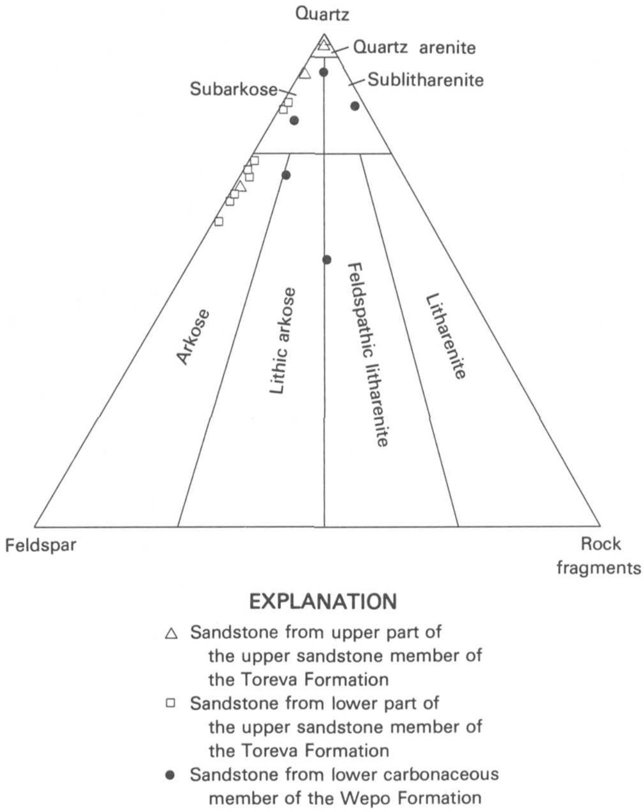


Figure 14. Mineral composition and classification (Folk, 1974) of sandstone (lower part, sheetlike sandstone bodies; upper part, lenticular sandstone bodies) within the upper sandstone member of the Toreva Formation and sandstone in the lower carbonaceous member of the Wepo Formation.

are summarized in table 2. Both the sheetlike and lenticular sandstones contain trough axes and tabular planar cross-stratification that indicates a dominantly northeast transport direction (fig. 15).

The fine-grained deposits within the lower part of the upper sandstone member are not laterally extensive because they are commonly scoured out by overlying sandstones. Coal beds within this member are rare and are usually less than 1 ft (0.3 m) thick. They also may contain thin interbeds of carbonaceous shale or siltstone. The siltstone and mudstone sequences that lie between the sheetlike sandstone bodies contain abundant carbonaceous material and root casts. Sedimentary structures were often not discernable within these units, but locally some siltstone units contain current ripple-stratification. The lenticular siltstone and mudstone units within the sheetlike sandstones are similar to the other siltstone and mudstone units except that they are thicker and were deposited on a scoured basal contact containing a lag of granules and coarse-grained sandstone.

Interpretation

The geometry of the sandstone bodies, the types and distributions of sedimentary structures, the grain size and textural characteristics, the presence of rooted coal beds, and the absence of marine or brackish-water fossils and trace fossils indicate that the upper sandstone member of the Toreva Formation was deposited in a continental fluvial environment. The grain-size trends, stratification types, and the sheetlike geometry of the sandstone in the lower part of the upper sandstone member are significantly different from those of the sandstone in the underlying middle carbonaceous member. A distinct and abrupt change in the depositional environment of these two members accounts for these differences.

The rivers that deposited the lower part of the upper sandstone member transported dominantly bedload material of granule- to medium-grained sand within channels that migrated extensively across an alluvial plain. Such rivers may have a braided or meandering morphology, and distinguishing between the two types of river morphology from the rock record can be difficult.

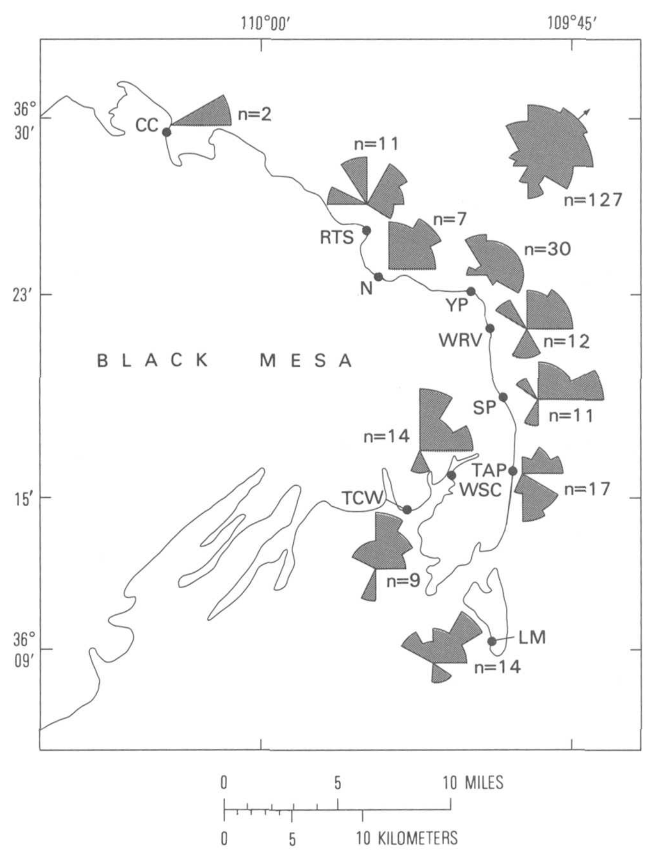


Figure 15. Transport directions taken on trough axes and tabular planar cross-stratified sets within the upper sandstone member of the Toreva Formation. Rose diagram at upper right shows combined readings from all sections. n is number of readings. Measured section abbreviations are shown on plate 1.

Table 2. Comparison of sheetlike sandstones and lenticular sandstones in the upper sandstone member of the Toreva Formation

Diagnostic characteristics	Sheetlike sandstones	Ribbonlike and lenticular sandstones
Lithology	Medium- to coarse-grained sandstone with granules and pebbles abundant in lower part of individual channel-form units and minor amounts of fine-grained sandstone in upper part of individual units; poor- to moderate-sorting; subangular to subrounded; subarkosic to arkosic (fig. 14), percentage of feldspar decreases upward; sequences may have slight fining-upward grain size trends or show no trend; carbonaceous material, logs, and clay rip-up clasts common at base of units	Fine- to medium-grained sandstone with coarse-grained and minor granule-sized material in lower part of each unit; sorting poor at base changes to moderate- to well-sorted toward top of each unit; subangular to subrounded; arkosic to quartz arenitic (fig. 14); most units show well-developed fining-upward grain size trends; carbonaceous material, logs, and clay rip-up clasts locally present at base of units; upper part of each unit commonly grades upward into interbedded fine-grained sandstone and siltstone
Stratification	Trough cross-stratification dominant in lower part of individual units; tabular planar, wedge planar, and trough cross-stratification present in middle to upper part of each unit; horizontal laminations locally interbedded with tabular planar sets in upper part of each unit; ripple-stratification usually present only in upper 0.5 to 1 ft (15 to 30 cm) of each unit or locally along foreset laminations in tabular planar sets; common grading of grain size from granule and coarse-grained to medium- and fine-grained along foresets of tabular planar cross sets; inverse grading present but less common; thickness of cross sets decreases upward from 0.5 to >3 ft (0.3 to >1 m) in lower part to 2 to 3 in. (5 to 8 cm) in upper part of each unit; local clay drapes within each unit	Trough cross-stratification dominant in lower part of units; horizontal laminations locally present above trough cross-stratification; ripple stratification common in upper parts of unit, contorted bedding and rare tabular planar cross-stratification also present in upper part of units; ripple-stratification within overlying sandstone and siltstone sequences that are often dipping at angles up to 15°; clay drapes within sandstone unit common
Biogenic constituents	Disseminated carbonaceous material; local zones of concentrations of carbonaceous material at top of a unit; common root casts at top of units that are sharply overlain by siltstone or mudstone	Disseminated carbonaceous material throughout unit; root casts and small vertical straight burrows present in upper part of units.

Locally, sandstone bodies in the lower part of the upper sandstone member contain some of the features in coarse-grained point bar deposits described by McGowen and Garner (1970), Levey (1978), and Nijman and Puigdefabregas (1978). These features include abandoned channel-fill deposits represented by lenticular siltstone and mudstone units that contain a thin granule lag above the basal scour contact; epsilon (large-scale lateral accretion) cross-stratification formed by lateral accretion of sediment on the point bar surface; and large-scale tabular planar cross-stratification sets deposited by lateral accretion on chute bars or on transverse bars attached to the point bar. However, characteristics of many of the channel-fill deposits, such as the abundance of tabular planar cross-stratification and the lack of distinct fining-upward grain-size trends, can be formed in both braided and bedload meandering rivers, and the sheetlike geometry of the sandstone bodies can also be formed by both of these fluvial systems (Jackson, 1978). It is possible that some sandstone sequences in the lower part of the upper sandstone member were deposited by braided rivers and other sequences were deposited by bedload meandering rivers. Rivers with different morphologies can exist within the same drainage area (Schumm, 1977), and braided and meandering morphologies can exist along different segments of the same river (Jackson, 1978). Knowing the exact morphology of the rivers that deposited the sheetlike sandstone bodies may not be as important as knowing the general paleodepositional characteristics of the fluvial system. The thin beds of siltstone and mudstone present between the sheetlike sandstone bodies indicate the rivers did transport some suspended material that accumulated by vertical accretion on the flood plains. But as the rivers migrated extensively across the alluvial plain, channel scouring removed much of the flood-plain deposits and produced the sheetlike sandstone bodies. Although some suspended material was present, the bedload-to-suspended-load ratio within the channels was high. The granule- and sand-sized material was transported along the floor of the channel as migrating sand waves or dunes and was deposited as trough and tabular planar cross-sets. Point bars or transverse bars also formed within or along the margins of channels.

The fluvial systems gradually changed during deposition of the upper sandstone member in response to a decrease in regional gradient. This change is reflected in the gradual change upward through the member in sandstone body geometry from sheetlike to ribbonlike and lenticular, a decrease in grain size, and an increase in the amount of siltstone and mudstone (fig. 12). The geometry, sedimentary structures, and vertical grain-size trends within the ribbonlike and lenticular sandstone bodies (table 2) in the upper part of the upper sandstone member correspond more closely to the classic model for meandering streams transporting sand and a high percentage of suspended material. This increase in the proportion of suspended material resulted in the deposition of thick flood-plain deposits that restricted the lateral migration of the rivers before the river avulsed. Because the rivers migrated less extensively, individual ribbonlike or lenticular channel-fill deposits (depending on outcrop orientation) were preserved within overbank deposits.

The gradual change in depositional environments through the upper sandstone member contrasts with the abrupt change in depositional environments between the middle carbonaceous and upper sandstone members of the Toreva Formation. This abrupt change, the great variation in thickness of the middle carbonaceous member, and the scoured basal contact of the upper sandstone member suggest that a disconformity, produced by an erosional period, separates these two members of the Toreva Formation. A drop in regional base level, initiated by a sea-level drop, tectonism in the source area, local uplift, or a combination of any of these conditions, would cause rivers to begin a period of degradation. Degradation continued until an equilibrium base level was established or until the base level began to rise.

The great variation in the thickness of the middle carbonaceous member and the location of the thickest sections of the upper sandstone member over areas where the middle carbonaceous member is thin or absent indicate paleovalley formation during the erosional event. When deposition resumed, sediment was first deposited in the deeper part of the valleys. The valleys were gradually filled until, finally, the divides between the valleys were covered. The gradual infilling of the erosional topography was accompanied by a regional decrease in gradient, which is reflected by the upsection changes in the upper sandstone member.

LOWER CARBONACEOUS MEMBER OF THE WEPO FORMATION

Description

A gradational contact occurs between the upper sandstone member of the Toreva Formation and the lower carbonaceous member of the Wepo Formation. An erosional contact is present at the top of the lower carbonaceous member where it is overlain by the Wind Rock Tongue of the Mancos Shale or by the Rough Rock Sandstone (pl. 1). There is, however, no apparent break within the lower carbonaceous member southwest of the depositional pinchout of the Rough Rock Sandstone. Within the study area, the resistant Rough Rock Sandstone protects the less resistant lower carbonaceous member from erosion, but where this sandstone is absent, recent erosion has left only isolated remnants of the lower carbonaceous member. The lower carbonaceous member progressively thickens across the study area from 40 ft (12 m) in the north to 100 ft (30 m) in the south.

The lithologic units in the lower carbonaceous member are very similar to those in the middle carbonaceous member of the Toreva Formation: coal, carbonaceous mudstone, siltstone, interbedded siltstone and sandstone, tabular sandstone, and channel-form sandstone. A distinct vertical change occurs through the lower carbonaceous member in the abundance, distribution, and characteristics of these lithologic units. In the upper part of the member, coal and mudstone units are more abundant than in the lower part, and indicators of brackishwater environments are present in the upper sandstone and siltstone units.

Coal beds within the lower carbonaceous member range from 1 to 5 ft (0.3 to 1.5 m) thick and increase in number both upsection and to the south of the study area. Many coal beds are rooted and occur in association with siltstone and mudstone units and tabular sandstone units. Lack of distinctive marker beds within the coal-bearing sequence and poor exposures prohibit correlation of coal beds between measured sections.

The carbonaceous mudstone, siltstone, and interbedded siltstone and sandstone units within the lower carbonaceous member of the Wepo Formation have the same sedimentary structures and biogenic constituents as those described for the same lithologies in the middle carbonaceous member of the Toreva Formation. The dominant sedimentary structures include parallel laminations and ripple stratification. Simple, straight, horizontal and vertical burrows are also present within these units, but none of the units has been bioturbated. The carbonaceous mudstone units commonly contain abundant impressions of ferns, leaves, and twigs. As with the coal beds, Quaternary slope cover prevented tracing these units to determine their lateral extent.

The tabular, fine-grained sandstone units also contain the same sedimentologic characteristics as the tabular sandstone units in the middle carbonaceous member of the Toreva Formation. In the lower carbonaceous member of the Wepo Formation, these tabular sandstone beds range from 2 to 12 ft (0.6 to 4 m) thick and may extend laterally for more than a mile. Straight, simple burrows are present in these sandstone units in the lower part of the member, but in the uppermost part of the member these units contain the marine to brackish-water trace fossils *Ophiomorpha* and *Thalassinoides*.

Channel-form sandstone bodies, which usually have a lateral extent of less than 1,000 ft (305 m), are also present in the lower carbonaceous member of the Wepo Formation. These sandstone bodies are composed of subrounded, medium- to fine-grained sandstone that contains less feldspar and more lithic fragments than sandstone units in the upper sandstone member of the Toreva Formation (fig. 14). Clay rip-up clasts, carbonaceous material, and small chert pebbles occur above the scoured base of the channel-form units. Within the unit, the sandstone changes upward from coarse and medium grained at and near the base to fine grained in the middle and upper parts, and the sorting changes from poorly sorted at the base to well sorted at the top of the unit. Sedimentary structures are difficult to discern in most places because many of these sandstone units are friable and weather back to a poorly exposed slope. Where exposures are good, the most commonly observed stratification sequence is medium- to low-angle troughs in the lower part and rippled beds in the upper part of the channel-form sandstone. Some of the sandstone units in the uppermost part of the lower carbonaceous member locally contain glauconite and sets of tabular-planar cross-stratification with opposing dip orientations.

Interpretation

The gradational contact between the upper sandstone member of the Toreva Formation and the lower carbonaceous member of the Wepo Formation indicates a gradual evolution in the depositional environments. The decrease in the number of sandstone units and the increase in number of fine-grained units from the upper sandstone member of the Toreva Formation to the lower carbonaceous member of the Wepo Formation reflect the continuing decrease in regional gradients and the transition from deposition higher on an alluvial plain to lower on an alluvial plain. Vertical changes through the lower carbonaceous member of the Wepo Formation show that the lower alluvial plain was subsequently replaced by a coastal plain.

The changes within the channel-form sandstone units in the lower carbonaceous member of the Wepo Formation provide evidence for this change in depositional environments. The channel-form geometry, the fining-upward grain-size trend, and the vertical sequence of sedimentary structures in these sandstone units in the lower part of the member indicate deposition by meandering rivers that transported sandy bedload material and a large percentage of suspended material. The rivers were flanked by extensive flood plains where the lithologic units adjacent to and surrounding the channel sandstone were deposited. Stratigraphically higher in the section, the presence of glauconite and bimodal dip directions on cross-stratified beds within the channel deposits indicate both the presence of tidal currents and the transport of marine sediment into a coastal plain. Thus, the coastal plain gradually replaced the lower alluvial plain.

This change is also reflected in the overbank flood-plain deposits. During deposition of the lower part of the lower carbonaceous member, well- and poorly drained swamps, freshwater lakes, and crevasse splays were present on the flood plains. Peat formed in poorly drained swamps, carbonaceous mudstone was deposited in freshwater lakes, tabular sandstone bodies were deposited as crevasse splays, and the interbedded sandstone and siltstone were deposited in levees and well-drained swamps. The rate of base level rise appears to have been too rapid to permit the formation of thick peat deposits. The thinness of the coal beds and the frequent occurrence of coal beds underlying lacustrine deposits indicate that the rate of deposition of organic material could not keep pace with the rate of subsidence. As the coastal plain shifted landward, freshwater lakes were replaced by brackish-water bays. Crevasse splays flowing into the brackish-water environments were reworked by the organisms that produced the *Ophiomorpha* and *Thalassinoides* burrows.

The depositional sequence that extends from the base of the upper sandstone member of the Toreva Formation through the lower carbonaceous member of the Wepo Formation was deposited during a gradual decrease in regional gradient that was accompanied by a rise in base level. The gradual upsection decrease in the amount and grain size of the sandstone through this sequence and the gradual change from high-energy fluvial environments to low-energy coastal environments correspond to the process of valley filling that accompanies a rise in sea level (Fisk, 1944; Schumm, 1977). As the sea level rises, the rivers adjust to the new higher base levels by rapidly alluviating the lower parts of the drainage areas (Leopold and others, 1964; Ryer, 1977). This process prohibits abundant sediment from reaching the coastline, and estuaries and bays commonly develop in the coastal areas behind the transgressing sea (Ryer, 1977). While the sea is transgressing, the depositional environments retreat landward and produce the vertical depositional sequence that is present in the upper sandstone member of the Toreva Formation and the lower carbonaceous member of the Wepo Formation. The eventual transgression of the sea into the study area eroded part of the coastal-plain deposits producing the transgressive unconformity at the top of the lower carbonaceous member.

WIND ROCK TONGUE OF THE MANCOS SHALE AND THE ROUGH ROCK SANDSTONE OF MESAVERDE GROUP

Description

Wind Rock Tongue of the Mancos Shale

The Wind Rock Tongue of the Mancos Shale is the new formal name applied to interbedded mudstone, siltstone, and sandstone sequences that Repenning and Page (1956) informally named the marine shale unit of the Toreva Formation. The stratigraphic relationships described previously show that this unit does not correlate to the Toreva Formation; however, the lithology and depositional origin of the Wind Rock Tongue indicates that it is a tongue of the Mancos Shale. The type section for the Wind Rock Tongue is located at lat. 36°21′30″N. and long. 109°49′36″W. along the eastern

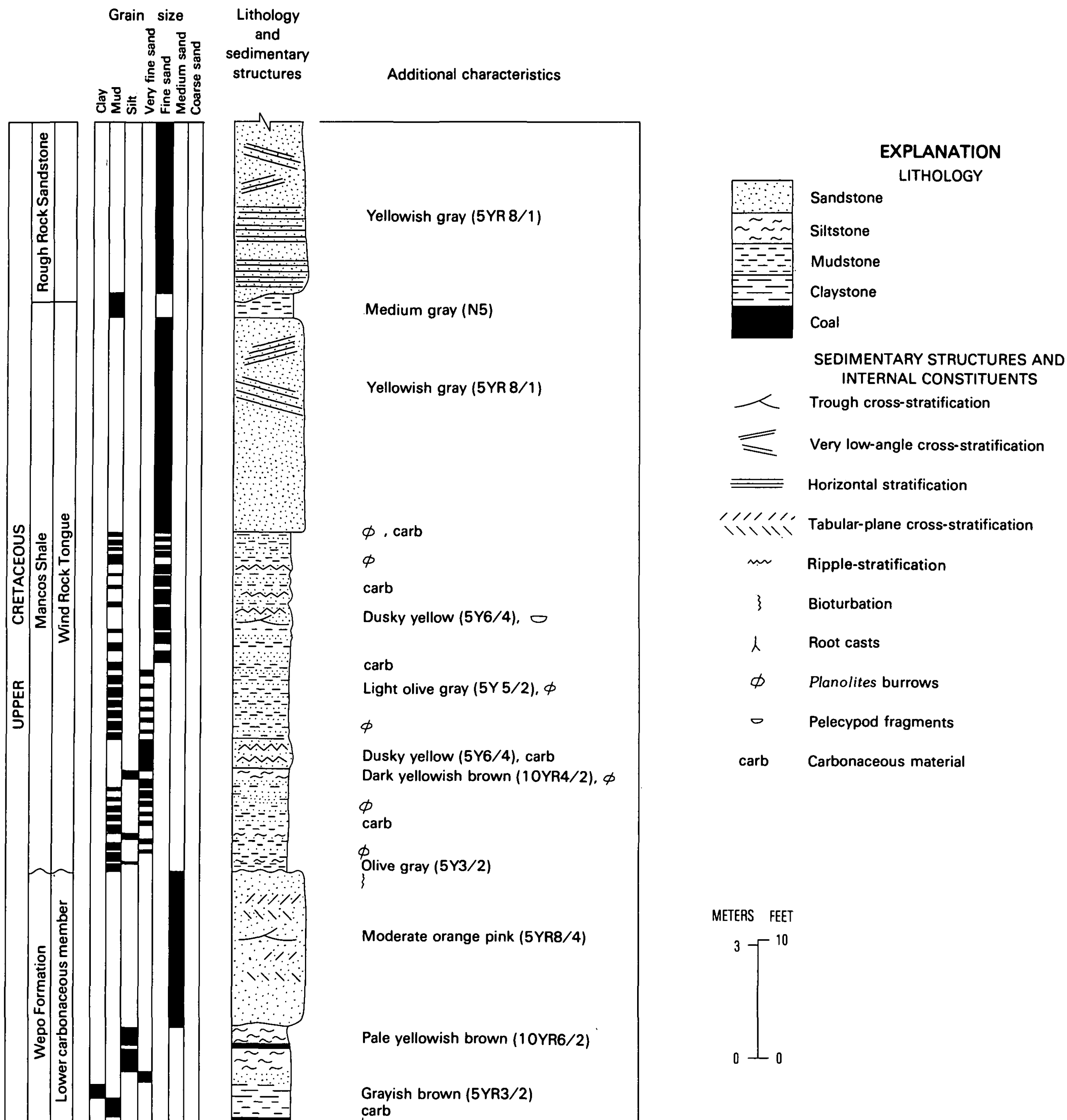


Figure 16. Graphic representation of the type section of the Wind Rock Tongue of the Mancos Shale, measured at the Wind Rock section. Location of section is shown in figure 2.

Figure 17. Photograph of intensely burrowed and bioturbated sandstone at the transgressive unconformity between the Wind Rock Tongue of the Mancos Shale and the lower carbonaceous member of the Wepo Formation at the Red Tree Spring section.

cliff face of Black Mesa at the head of Wind Rock Valley (fig. 16).

The erosional contact between the lower carbonaceous member of the Wepo Formation and the overlying Wind Rock Tongue is marked at the outcrop by a distinct color change from dark brown of the Wepo to olive gray of the Wind Rock. In most places, the interbedded mudstone and siltstone of the tongue lie directly on the lower carbonaceous member. Locally, however, an intensely burrowed and bioturbated sandstone or pebble bed, as much as 6 in. (15 cm) thick, lies directly above the contact (figs. 17 and 18). The tongue grades upward into the Rough Rock Sandstone; the contact between these two units is placed above the highest thick mudstone bed, which usually marks the base of the massive cliff-forming sandstone. The Wind Rock Tongue is present only in the northern part of Black Mesa (fig. 19); there is no subsurface continuation of this unit north of Black Mesa because of Tertiary erosion of the Cretaceous section. The Wind Rock Tongue is 48 ft (15 m) thick at the type section. It ranges in thickness from 0 to 75 ft (0 to 23 m) and thins progressively from north to south. A depositional pinchout of this unit occurs between the Tse Da Ahoodza Peak and Waterfall Spring Canyon sections. Fossils collected and identified by Repenning and Page (1956) from the Wind Rock Tongue belong to the *Inoceramus deformis* and the *Scaphites depressus* faunal zones, thus indicating a middle Coniacian to early Santonian age. However, new fossil data (J. I. Kirkland, oral comm., 1987) indicate that this sequence is no younger than Coniacian.

The vertical sequence of lithologies and sedimentary structures in the Wind Rock Tongue is very similar to that of the transition zone in the Mancos Shale underlying the Toreva Formation. However, the Wind Rock Tongue does not contain the penecontemporaneous deformation structures that are present in the upper part of the main body of the Mancos Shale. The tongue does contain abundant *Inoceramus* prisms and shells, and calcite-cemented siltstone and sandstone beds, two features that are lacking in the upper part of the Mancos Shale below the Toreva Formation. Tracks, trails, and syneresis cracks are evident along the base of sandstone beds in the Wind Rock Tongue. Although straight

Figure 18. *Chert and quartzite pebble lag marking the transgressive unconformity between the Wind Rock Tongue of the Mancos Shale and the lower carbonaceous member of the Wepo Formation at the Yale Point section.*

horizontal burrows are abundant in the mudstone and siltstone beds, and locally some beds are bioturbated, extensive bioturbation is not common in the Wind Rock Tongue.

Rough Rock Sandstone

The Rough Rock Sandstone is the new formal name given to the massive sandstone unit in the Mesaverde Group that overlies the Wind Rock Tongue of the Mancos Shale. Repenning and Page (1956) informally named this unit the upper sandstone of the Toreva Formation because they believed it joined the upper sandstone member of the Toreva where the sequence now

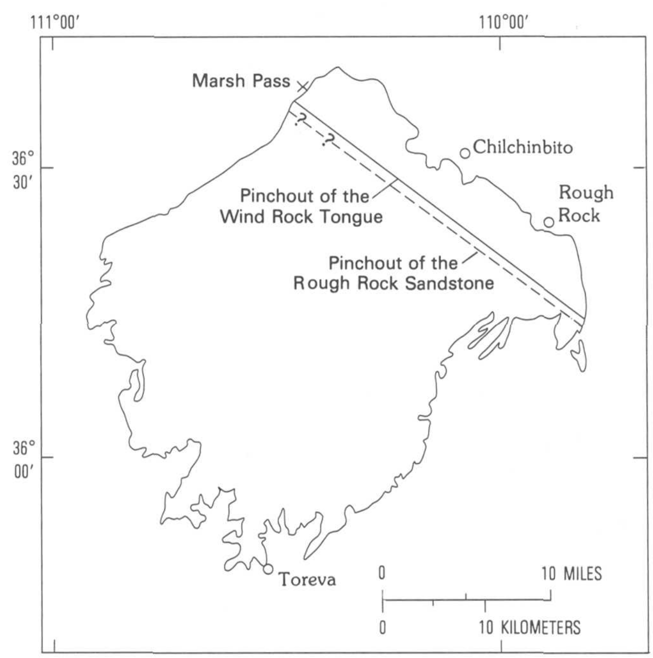


Figure 19. Distribution of the Wind Rock Tongue of the Mancos Shale and the Rough Rock Sandstone (northeast of pinchout edges) on Black Mesa. Location of the depositional pinchouts on the northwestern part of Black Mesa from Repenning and Page's (1956) maps.

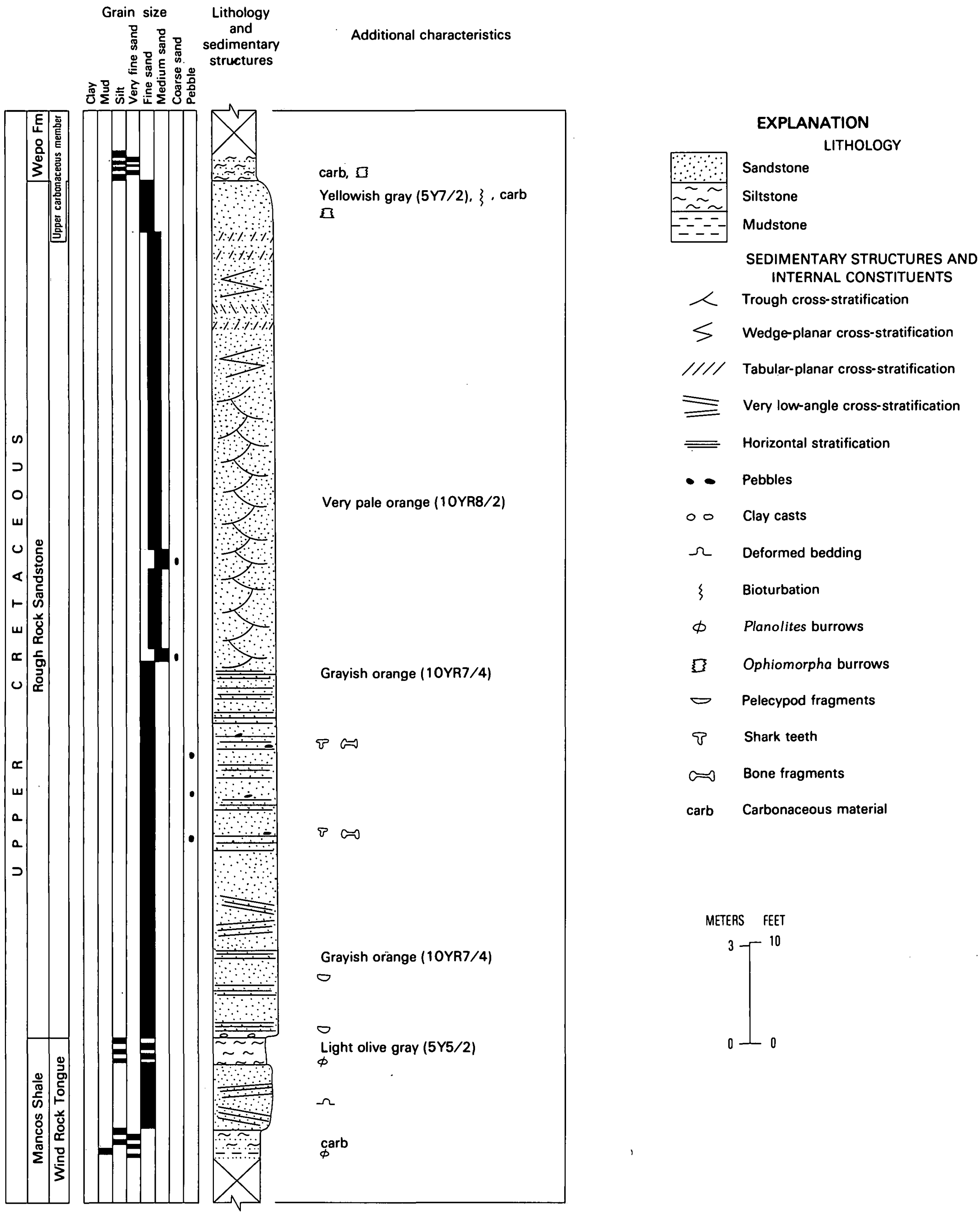


Figure 20. Graphic representation of the type section of the Rough Rock Sandstone, measured at the Needle section. Location of section is shown in figure 2.

assigned to the Wind Rock Tongue pinched out. However, the Rough Rock Sandstone pinches out southward into the Wepo Formation and cannot be correlated with the Toreva. There is no subsurface extension of the Rough Rock Sandstone outside of Black Mesa because of Tertiary erosion of the equivalent Cretaceous strata. The type section of the Rough Rock Sandstone is located at lat. 36°23′22″N. and long. 109°54′49″W. at the Needle measured section (fig. 20), 3.5 mi (5.6 km) southwest of the town of Rough Rock. Based on regional evidence, Molenaar (1983) concluded that deposition of this unit occurred during his R-3 regression in the late early to middle Santonian. Fossils recently collected from the base of the Rough Rock Sandstone indicate a Coniacian Age for this unit (J. I. Kirkland, oral comm., 1987); thus, this regression apparently began earlier in the Black Mesa area.

The Rough Rock Sandstone extends across most of the study area as a sheetlike, cliff-forming sandstone that locally contains channel-form sandstone bodies within the upper part of this formation (pl. 1). The basal contact of the Rough Rock Sandstone where it overlies the Wind Rock Tongue is gradational, but a sharp, erosional basal contact is present where the Rough Rock overlies the lower carbonaceous member of the Wepo Formation. A sharp, but conformable, contact also is present between the Rough Rock Sandstone and the overlying upper carbonaceous member of the Wepo Formation. The Rough Rock Sandstone thins progressively from 105 ft (32 m) in the north to a depositional pinch-out immediately south of the Tah Chee Wash section (pl. 1).

The sheetlike and channel-form sandstone beds in the Rough Rock are distinguished by different weathering characteristics (figs. 21 and 22), grain-size trends, and sequences of sedimentary structures. The sheetlike sandstone unit of the Rough Rock Sandstone is dominantly a well- to moderately sorted, subrounded, very fine to medium-grained sandstone. Like the lower sandstone member of the Toreva Formation, it has a coarsening-upward grain-size trend from very fine to medium grained. Locally, coarse-grained and granule-sized material occur in the middle to upper part of the Rough Rock Sandstone. There is, however, a distinct compositional difference between this part of the Rough Rock Sandstone and the lower sandstone member of the Toreva Formation; the Rough Rock Sandstone, which is dominantly a subarkose to a sublitharenite (fig. 23), contains a significantly lower feldspar and higher chert content than the lower sandstone member of the Toreva Formation (fig. 6).

This sheetlike part of the Rough Rock Sandstone also contains the same vertical sequence of sedimentary structures and trace fossil assemblages described for the sheetlike sandstone units of the lower sandstone member of the Toreva Formation. However, a distinctive lithologic sequence that is not present in the lower sandstone member of the Toreva occurs in the Rough Rock Sandstone in the area between the Red Tree Spring and Wind Rock Valley sections (pl. 1). Here, thin sequences of mudstone and siltstone are interbedded with sandstone in the interval where the sedimentary structures in the sandstone change from laminations and low-angle cross-stratification to medium-angle trough cross-stratification. Where coal beds overlie the Rough Rock Sandstone, root casts are present at the top of this unit; but where mudstone or siltstone overlies this sandstone, bioturbation of the top of the unit is common.

Sediment transport directions from the Wind Rock Tongue and the sheetlike part of the Rough Rock

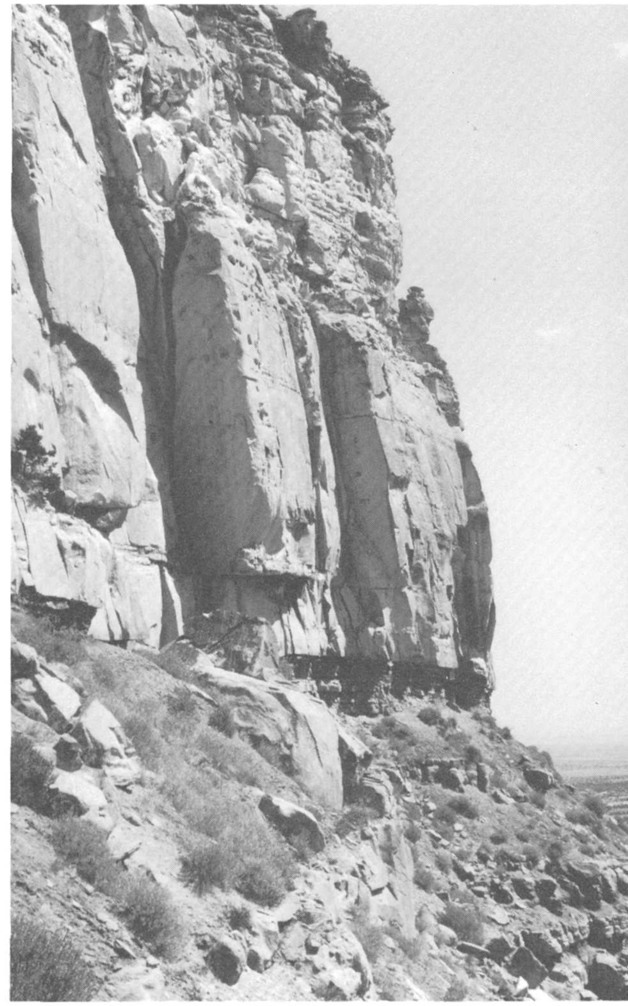


Figure 21. Weathering differences between the sheetlike and scour-based sandstones in the Rough Rock Sandstone at the Chilchinbito Canyon section. Pock-marked irregular weathering sandstone at top of the photo is a scour-based sandstone. The underlying sheetlike sandstone is 70 ft (21 m) thick.

Figure 22. Laterally extensive scour-based sandstone (darker ledge) at the top of the Rough Rock Sandstone between the Tse Da Ahoodza Peak and Sweathouse Peak sections.

Sandstone were obtained from the trough axes of trough cross-stratification and less frequently from tabular planar cross-stratification. North to northeast transport directions were measured in the Wind Rock Tongue at the Red Tree Spring section. The sheetlike part of the Rough Rock Sandstone shows a range of transport directions, but the combination of data from all the measured sections shows a dominant southeast component of transport (fig. 24).

The channel-form sandstone units in the upper part of the Rough Rock Sandstone (pl. 1) range in thickness from 5 to 30 ft (2 to 9 m), are subrounded to subangular and medium to fine grained, and contain clay rip-up clasts, carbonaceous material, and pebble- and granule-sized material concentrated along and above the basal scour surface. The units are also characterized by a fining-upward grain-size trend, a change from poorly sorted at the base to moderately or well sorted at the top, and a generally higher feldspar content than the sheetlike sandstone (fig. 23). Medium-angle trough and wedge-planar cross-stratification are the dominant sedimentary structures in these units. The uppermost part of the channel-form sandstone unit at the Yale Point section contains horizontal laminations and thin sets of tabular planar cross-stratification. However, the Yale Point section is the only locality where the uppermost part of a channel-form

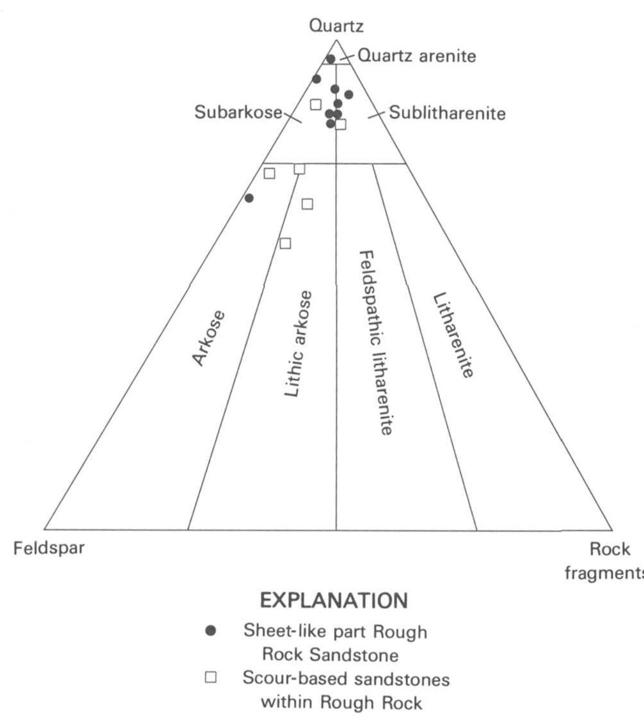


Figure 23. Mineral composition and classification (Folk, 1974) of sheetlike and scour-based sandstones in the Rough Rock Sandstone.

sandstone unit is preserved. At Chilchinbito Canyon, this upper part is scoured out by an overlying sandstone; and at both the Tse Da Ahoodza Peak and Sweathouse Peak sections, recent erosion has removed this part of the unit. *Ophiomorpha* burrows are abundant in the scour-based units at the Yale Point and Sweathouse Peak measured sections.

The scour-based channel-form sandstone unit at the Chilchinbito Canyon section differs slightly from the other channel-form units, as the upper part of this unit is stratigraphically higher than the Rough Rock Sandstone, and it does not contain marine and brackish-water trace fossils, which are abundant in the other scour-based sequences. Transport directions obtained from this sequence at the Chilchinbito section indicate flow to the northwest, while flow to the east and south occurred within the sequence at Yale Point (fig. 24). Cross-stratified beds with opposing dip directions were not observed in either of these scour-based units.

Interpretation

The same evidence that indicates deposition in a marine environment during a period of shoreline progradation for the upper part of the Mancos Shale and the lower sandstone member of the Toreva Formation (vertical changes in lithologies, grain size, and sedimentary structures) indicates that most of the Wind Rock Tongue and all of the Rough Rock Sandstone were also deposited by a similar depositional event. However, a deltaic system may not have developed in the study area during deposition of the Rough Rock Sandstone because, unlike the lower sandstone member of the Toreva Formation, there is no evidence in the Rough Rock Sandstone of distributary-channel abandonment and the resulting local marine submergence and reworking of nearshore and coastal plain deposits. The lack of penecontemporaneous deformation structures in the Wind Rock Tongue does not alone indicate the absence of a deltaic system. The Wind Rock Tongue was deposited on a stable platform and contains predominately fine sand and silt-sized material and little mud. The conditions conducive to the formation of penecontemporaneous deformation structures (high mud content, very high pore pressures in the mud deposits, and unstable slopes) were not present in the study area during deposition of the Wind Rock Tongue.

In the northern part of the study area, the Rough Rock Sandstone is much thicker than the sheetlike sandstone units in the lower sandstone member of the Toreva Formation. The thickness of the shoreface deposits of many coastal marine sands is equal to the depth of effective fair-weather wave base: usually about 25–30 ft (8–9 m) (Reineck and Singh, 1980). However, the thickness also

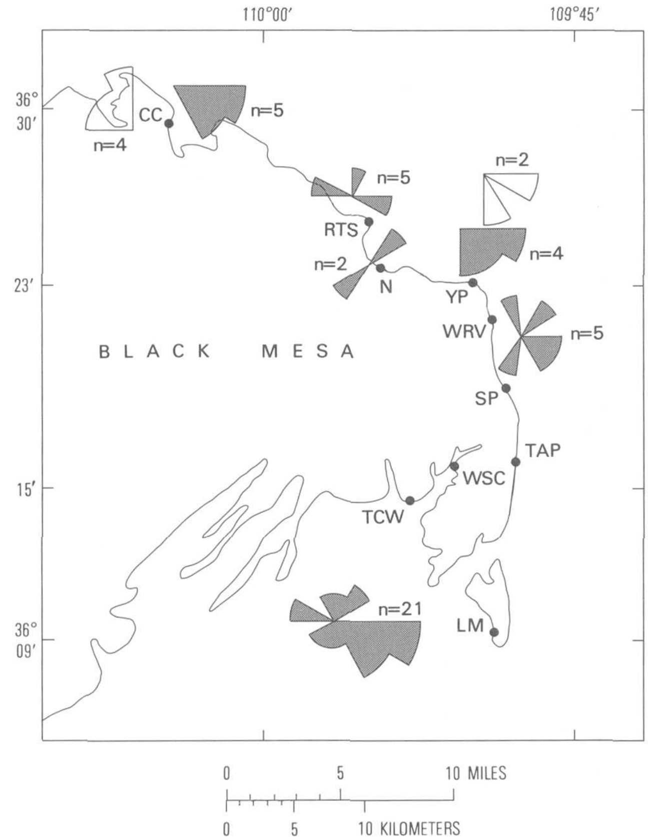


Figure 24. Transport directions taken on trough and tabular-planar cross-stratified sets within the Rough Rock Sandstone (directions from sheetlike units in black, channel-based units are unshaded). Composite diagram of all readings from the sheetlike units shown in lower part of the figure; n is the number of readings. Measured section abbreviations shown on plate 1.

depends on the relationship between rates of subsidence or submergence and rates of deposition (Vail and others, 1977). During some periods of Rough Rock deposition, the rate of subsidence or sea-level rise may have equaled the rate of deposition. When these conditions existed, the thicker shoreface sequences in the Rough Rock Sandstone were deposited.

The absence of a major deltaic system in the study area implies that most of the sediment was supplied to the coastline by longshore currents. Currents transporting sediment offshore during storm events produced the northeast transport directions in the sandstone beds of the Wind Rock Tongue. The strong southeasterly component of transport in the sheetlike sandstone of the Rough Rock Sandstone (fig. 24) corresponds to the flow direction of longshore current along the northwest-trending coastline that extended from southern Utah into northern Arizona during the time of Rough Rock Sandstone deposition (Peterson, 1969a). Extensive reworking of the sediment by current and wave energy produced a coastal sand deposit that was lower in feldspar and higher in quartz content than the delta-front sandstone of the lower sandstone member of the Toreva Formation (figs. 6 and 23).

The type of coastline that formed during deposition of the Rough Rock Sandstone was controlled by the relative intensities of tidal and wave action. If tidal energy is greater than wave energy, barrier island systems would form; if wave energy dominates, then unbroken strandplains would develop (Hayes, 1979). In the rock record, the presence or absence of deposits of tidal environments (such as tidal inlets, tidal channels, flood- and ebb-tidal deltas, tidal flats, and lagoons) provides clues to the type of coastline that existed.

With the exception of the unit at the Chilchinbito Canyon section, the abundant *Ophiomorpha* burrows in the scour-based sandstone units and the lateral coincidence of the top of these units with the top of the Rough Rock Sandstone suggest a tidal inlet or tidal channel origin rather than a distributary channel origin. The scour-based sandstone unit at the Tse Da Ahoodza Peak and Sweathouse Peak sections (fig. 22; pl. 1) can be traced along a north-trending cliff face for about 3 mi (5 km). The extensive development of this unit and the lateral accretion surfaces within it suggest that it was deposited in a meandering tidal channel behind the barrier. Such channels migrate rapidly and form extensive deposits when they erode into the barrier sands (Land, 1972). An extensive network of back-barrier tidal channels is characteristic of a meso-tidal barrier-island setting. However, inferring the exact type of barrier-island coastline present during Rough Rock deposition is difficult because of the lack of three-dimensional exposures; the inaccessability of the Rough Rock Sandstone cliffs, which prohibits detailed examination of lateral facies equivalents of the channel deposits; and the lack of a detailed study of the back-barrier deposits of the lower part of the upper carbonaceous member of the Wepo Formation. Tidal channel deposits suggest that barrier islands were present along the Rough Rock coastline, but knowing the back-barrier depositional environments is essential to distinguishing between micro- and meso-tidal barrier island systems.

The origin of the scour-based sandstone at the Chilchinbito Canyon section (pl. 1) is uncertain. It is a channel-fill deposit, but the top of the channel fill does not coincide with the top of the sheetlike sandstone, as do the other channel deposits in the northeastern part of the study area. In addition, the channel deposit at Chilchinbito does not contain marine or brackish-water trace fossils, and, locally, an intensely rooted and oxidized siltstone that was deposited on a levee or in a well-drained swamp is laterally equivalent to this channel deposit. These features suggest deposition in a distributary channel. However, a coastline that has both deltas and barrier islands is not unusual, and Flores and Erpenbeck (1981) have documented this relationship in the Upper Cretaceous Pictured Cliffs Sandstone of the San Juan Basin. The development of a delta system northwest of the study area along the Rough Rock coastline could produce an embayment that would both accentuate the tidal range and supply sediment through longshore drift to the barrier island shoreline inferred in the eastern part of the study area.

DEPOSITIONAL HISTORY AND REGIONAL CORRELATIONS

During the middle Turonian (fig. 25), there was a regional regression of the Cretaceous sea; and regressive marine sandstones were deposited in the present Black Mesa basin, Gallup Sag, and Kaiparowits basin along the margins of this sea (fig. 26). Within the Black Mesa area, the lower sandstone member of the Toreva Formation was deposited during this regressive event. When the Cretaceous sea regressed from the southwest to the northeast across the Black Mesa area during the time period of the *Collignoniceras woollgari* and *Prionocyclus hyatti* faunal zones (fig. 25), between 91 to 90 Ma, a deltaic system provided abundant feldspathic sediment to the prograding coastline. High wave energy and longshore currents along the Cretaceous shoreline redistributed the sediment that was deposited at the distributary mouths into extensive elongate sand bodies oriented parallel to the coastline. During the delta-building process, distributary channel switching produced stacked sand deposits that are separated by sequences deposited during periods of local submergence and marine reworking of delta-front deposits. As the deltaic shoreline prograded basinward, a delta-plain environment prograded over the delta-front deposits. The channel sandstone units and the carbonaceous fine-grained deposits of the middle carbonaceous member were deposited in distributary channel and interdistributary settings. The interdistributary areas contained freshwater lakes, poorly drained swamps, and crevasse splays. Marine embayments in the delta plain were rare.

The lower sandstone member south of the study area, toward the type locality of the Toreva Formation, contains many of the features characteristic of this unit in the study area: large penecontemporaneous deformation structures at the base of the delta-front sandstone and distributary channels incised into the delta-front sandstones. These features and their widespread distribution suggest that a major deltaic system prograded across the entire Black Mesa area during this middle Turonian regressive cycle.

In the Gallup Sag, southwest of the San Juan Basin in New Mexico, the same regressive event occurred during the time period represented by the *Collignoniceras woollgari* and possibly during the *Prionocyclus hyatti* faunal zones. The Atarque Sandstone Member of the Tres

Radiometric dates in m.y.		Stage	Substage	Faunal zone
	UPPER CRETACEOUS	Santonian	Middle	*Clioscaphites choteauenis*
				Clioscaphites vermiformis
			Lower	*Clioscaphites saxitonianus*
				Scaphites depressus
		Coniacian	Upper	*Scaphites ventricosus*
89.0			Middle	*Inoceramus deformis**
			Lower	*Inoceramus erectus*
				Inoceramus waltersdorfensis
		Turonian	? Upper	*Prionocyclus quadratus*
89.5				*Scaphites nigricollensis*
				Scaphites whitfieldi
				Scaphites warreni
				Prionocyclus macombi
90.0			Middle	*Prionocyclus hyatti*
				Collignoniceras woollgari (late form)
			Lower	*Collignoniceras woollgari* (late form)
				*Mammites nodosoides**
				Watinoceras coloradoense
91.5		Cenomanian	Upper	*Sciponoceras gracile*
				Dunveganoceras albertense
93.3				*Dunveganoceras pondi**
			Middle	*Plesiacanthoceras wyomingense*
94.1				*Acanthoceras amphibolum**
				Acanthoceras alvaradoense
				Acanthoceras muldoonense
95.0				*Acanthoceras granerosense*
				Calycoceras gilberti
			? Lower	

Figure 25. Faunal zones of the lower part of the Upper Cretaceous; stars indicate faunal zones with radiometric dates (from Weimer, 1983; after Obradovich and Cobban, 1975, and Fouch and others, 1983).

Hermanos Formation (fig. 27; Molenaar, 1983), a regressive, coastal marine sandstone, contains fossils of the *Collignoniceras woollgari* zone and is equivalent to the lower sandstone member of the Toreva Formation in the southern part of Black Mesa. Molenaar (1973, 1983) showed that clastic sediment input to the Gallup Sag area was low during this period of time and that the sandy coastline, represented by the Atarque Sandstone Member, changed to a dominantly mud coastline during the *Prionocyclus hyatti* faunal zone. This situation contrasts greatly with conditions in the Black Mesa area where there was high clastic imput to the coastline during this time.

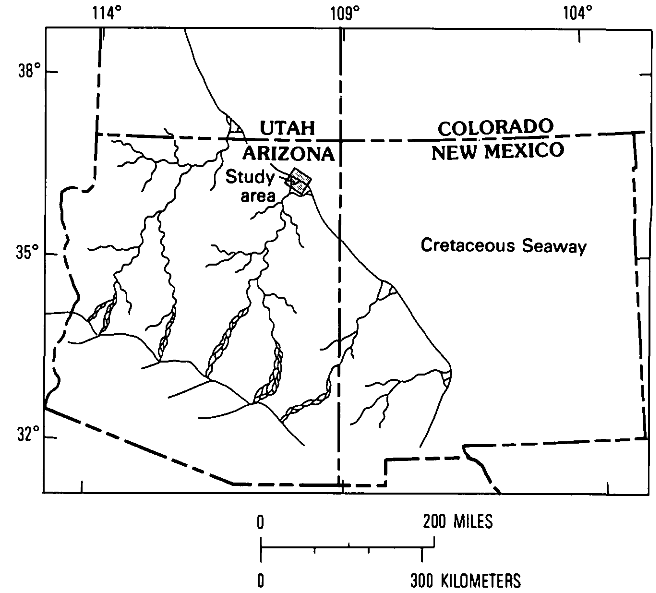


Figure 26. Schematic diagram of the paleogeography of the southwestern part of the Western Interior Cretaceous basin during the middle Turonian regressive cycle.

The sea began to transgress back into the Gallup Sag area (as represented by the Pescado Tongue of the Mancos Shale) during the time of the *Prionocyclus macombi* faunal zone (fig. 25), while the coastline in the Black Mesa area may have continued to prograde basinward. The Pescado Tongue in the Gallup Sag area (fig. 27) is a time equivalent of or slightly younger than the lower sandstone member of the Toreva Formation in the northern part of Black Mesa. After this time period, the clastic sediment supply into the Gallup Sag and southern San Juan Basin area increased markedly; and the Gallup Sandstone, which extends into the central part of the basin, was deposited along a prograding

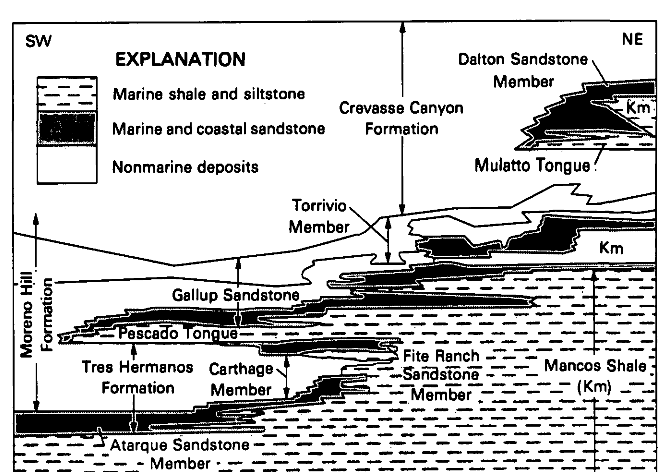


Figure 27. Schematic of middle Turonian through Coniacian units in the Gallup Sag area, New Mexico (from Molenar, 1983).

shoreline during late Turonian and early Coniacian time. Because there are no reliable age indicators in the nonmarine sequence between the lower sandstone member of the Toreva Formation and the Wind Rock Tongue of the Mancos Shale, the time-equivalent strata of the Gallup Sandstone in the Black Mesa area are not known. Although the upper sandstone member of the Toreva Formation has a similar mineralogy and depositional origin as the uppermost unit of the Gallup, the Torrivio Member, there are no available data to determine if these two units are time equivalent.

In the Kaiparowits region of southeastern Utah, the Tibbet Canyon Member of the Straight Cliffs Formation (fig. 28) contains fossils of the *Prionocyclus hyatti* faunal zone (Peterson, 1969b). In the Henry basin, east of the Kaiparowits basin, the lower unit of the Ferron Sandstone Member of the Mancos Shale contains fossils of the *Prionocyclus hyatti* and *Prionocyclus macombi* faunal zones (Peterson and Kirk, 1977). Both the Tibbet Canyon Member and the lower unit of the Ferron Sandstone Member are coastal marine sandstone bodies that formed during the same regressive event and are time equivalent to the lower sandstone member of the Toreva Formation.

The meandering and braided river deposits of the upper sandstone member of the Toreva Formation indicate an abrupt change in depositional environments from the delta-plain setting of the middle carbonaceous member to an alluvial-plain setting. There is no evidence of a gradational change in stream types from the distributary channels of the delta plain to the more proximal meandering and braided rivers on the alluvial plain. The lack of gradational facies changes and the thickness variations and local absence of the middle carbonaceous member of the Toreva Formation (pl. 1) suggest that a significant thickness of sediments may have been eroded beneath the upper sandstone member. Erosion may have occurred as a result of scouring at the base of the channels that deposited the upper sandstone member or during a distinct erosional event that occurred as a result of base level lowering prior to the deposition of the upper sandstone member. If one assumes that the middle carbonaceous member within the study area may originally have been as thick as at the type locality, over 100 ft (30 m), then channels that were 100 ft (30 m) deep would have been necessary to remove the middle carbonaceous member from the areas where it is now absent. However, none of the channel-fill sequences in the upper sandstone member are thicker than 40 ft (12 m). Erosion during a period of channel incisement prior to deposition of the upper sandstone member could have occurred if the base level was lowered by regional tectonic uplift in the source area, a local uplift, or sea level drop. Both tectonism and sea level fluctuations appear to have influenced deposition of the Toreva and Wepo Formations.

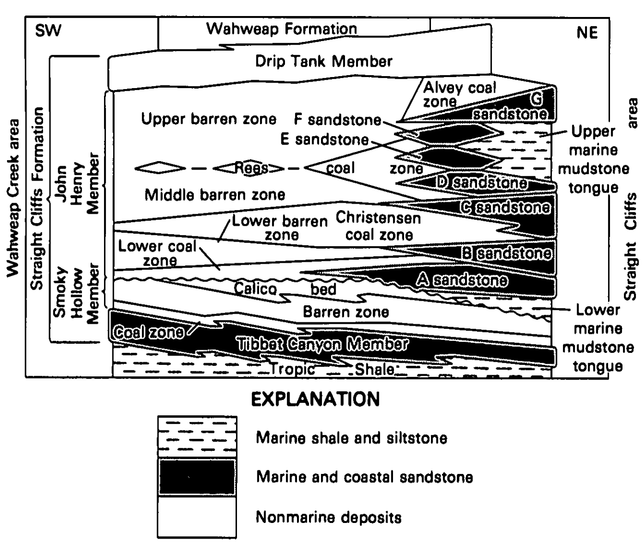


Figure 28. Relations of units within the Straight Cliffs Formation, southeastern Kaiparowits basin, Utah (from Peterson, 1969).

Precambrian crystalline and Jurassic plutonic rocks in southern Arizona were the source of much of the potassium-feldspar rich sediments in the Toreva Formation (Hayes, 1970). During late Turonian time, the first phases of compressional tectonism and uplift occurred in the source area (Hayes, 1970). The abundant arkosic to subarkosic sediment supplied to the Black Mesa area during deposition of the lower sandstone member of the Toreva Formation may indicate the onset of this uplift. During the height of tectonic activity, sediments were shed from the uplift, and regional gradients in areas surrounding the uplift increased. The regional extent of the gradient increase may have extended into the Black Mesa area if the source area was relatively close to Black Mesa. Another possibility is that stresses transmitted basinward during this tectonic event caused small, localized uplifts. In these uplifted areas, the gradient increase would cause a lowering of base level and channel incisement.

Uplift in a southern source area would explain the increase in clastic sediment supply to the Gallup Sag and San Juan Basin areas in the late Turonian that resulted in deposition of the thick and laterally extensive regressive Gallup Sandstone (fig. 27). Because the San Juan Basin area was farther from the uplifted source area than Black Mesa and the sea still occupied much of the San Juan Basin, a large part of the Gallup Sandstone was deposited in a nearshore marine environment. The Torrivio Member of the Gallup Sandstone (fig. 27; Molenaar, 1973) is a feldspathic, fluvial sandstone that is very similar to the upper sandstone member of the Toreva Formation. However, a regional erosion surface has not been documented at the base of the Torrivio. Molenaar (1973) and A. R. Kirk (oral commun., 1983) stated that the Torrivio Member intertongues with the nonmarine Dilco Coal Member of the Crevasse Canyon Formation and that some of the channel-fill sequences in the Torrivio represent distributary channels that provided sediment to the Gallup coastline.

A period of erosion also occurred in the Kaiparowits region during late Turonian or early Coniacian time. Peterson (1969b) described an unconformity at the top of the fluvial Calico bed (fig. 28), which he attributed to subaerial erosion caused by a period of local upwarping in the Kaiparowits region. Because this unconformity also occurs within a nonmarine sequence that contains no age-diagnostic fossils, the timing of this erosion event is not precisely known. Therefore, it is not known if the erosion events in the Black Mesa area and the Kaiparowits area occurred simultaneously.

A sea level drop could have produced a similar erosional event and a similar sequence of deposits on Black Mesa as a tectonic event. Worldwide sea level drops have been documented by Vail and others (1977), and eustatic drops that occurred during the Cretaceous would have affected the sea level in the shallow, epicontinental, Western Interior Cretaceous sea. Widespread unconformities present within a marine sequence, or the presence of a subaerial erosion surface that is marked by continental deposits overlying outer shelf deposits, are often good indicators of an eustatic drop. In a continental setting, the fluvial systems begin to incise to adjust to a lower base level. To relate an incisement event to sea level drop, the timing of the incisement must correspond to an established age for the eustatic drop. The numerous, well-documented and dated Cretaceous faunal zones of the Western Interior (Obradovich and Cobban, 1975) are excellent age indicators and have enough continuity to determine the presence of widespread unconformities within marine sequences. However, an accurate age determination for an erosional event within a continental sequence, in the absence of reliable age indicators, can be more difficult. In continental sequences lacking age-diagnostic fossils, the age can only be approximately determined by examination of palynomorphs within the section. Ages can also be bracketed by dating marine deposits that bound the continental sequence.

Fossil evidence from the lower sandstone member of the Toreva Formation and the Wind Rock Tongue of the Mancos Shale indicate that in the Black Mesa area, the period of erosion occurred sometime between the *Prionocyclus macombi* and *Inoceramus deformis* faunal zones (late Turonian to middle Coniacian): between 89 and 90 Ma ago (fig. 25). Weimer (1983) postulated a sea level drop at approximately 89.5 Ma ago based on evidence of erosion and missing faunal zones in marine sequences in central Wyoming and the Denver basin. The unconformity within the continental deposits in the Kaiparowits region appears to have occurred close to this time, but the exact time is uncertain. In the San Juan Basin, all faunal zones from *Prionocyclus macombi* to *Inoceramus erectus* are present within the nearshore marine Gallup Sandstone (Molenaar, 1983). At the top of the Gallup Sandstone in the northern San Juan Basin there is an unconformity that probably developed during *Inoceramus deformis* time during the Niobrara transgressive event (Molenaar, 1983). However, there have been no reports of unconformities that would have resulted from a sea level drop within the Gallup Sandstone or within the delta-plain deposits of the overlying Dilco Coal Member of the Crevasse Canyon Formation. If a sea level drop occurred during deposition of the Gallup Sandstone, extremely high subsidence rates in the Gallup Sag and San Juan Basin areas may have negated the effects of the drop; and a relatively high sea level would have been maintained along this part of the Cretaceous shoreline.

Palynological analysis of coal from the middle carbonaceous and the upper sandstone members of the Toreva Formation does not provide a precise age for either member. The coal beds within both members contained similar types of spores and pollen, and the upper sandstone member contains spores that are found in rocks of Turonian age in Utah and Wyoming (D. J. Nichols, oral commun., 1982).

Both the timing of the onset of tectonism in the source area and the timing of the postulated sea level drop fall into approximately the same time interval. Because both events may have occurred almost simultaneously, it is difficult to determine which event was primarily responsible for the inferred base level drop and resulting period of erosion. When deposition was renewed, northeast-flowing braided rivers and meandering rivers transporting large amounts of bedload material began to deposit the upper sandstone member of the Toreva Formation in paleovalleys that had been formed during fluvial incisement.

The vertical changes in lithologic sequences and types of sedimentary structures and in sandstone body geometry through the upper sandstone member reflect a gradual rise in base level that accompanied transgression of the Cretaceous sea back into the Black Mesa area. The depositional systems responded to the rise in base level by evolving from high energy to low energy fluvial systems. Braided and meandering rivers that deposited the lower part of the upper sandstone member gradually changed to fine-grained meandering rivers as the regional gradients became progressively lower. As the advancing sea drew closer, the landward shift in depositional environments continued. The stratigraphic sequence in the lower carbonaceous member of the Wepo Formation indicates that a lower alluvial plain containing extensive floodplains was replaced by a coastal plain containing tidal channels and brackish-water bays.

The transgressive event is documented throughout the southern and southwestern part of the Western

Interior Cretaceous basin. In the San Juan Basin area, the Mulatto Tongue of the Mancos Shale (fig. 27) was deposited as the sea transgressed, as was the lower marine mudstone tongue of the John Henry Member of the Straight Cliffs Formation (fig. 28) in the Kaiparowits region and the Wind Rock Tongue of the Mancos Shale in the Black Mesa area. The time of maximum extent of the transgressive event ranges from middle Coniacian in the Black Mesa area (J. I. Kirkland, oral comm., 1987) to late Coniacian in the San Juan Basin area and to early Santonian in the Kaiparowits area (Molenaar, 1983). The regional nature of this transgressive event suggests that it may have been caused by eustatic rise. If this transgression represents only a relative sea level rise, then regional subsidence rates must have increased rapidly or sedimentation rates decreased sharply to produce such a widespread effect.

As the sea transgressed across the northern Black Mesa area, wave action eroded the underlying coastal-plain deposits. Local beds of bioturbated coarse-grained, poorly sorted sand were left as erosional remnants. The origin of the pebble lags on the erosion surface is uncertain. There are no pebbles of the same size or composition in the underlying deposits; therefore, the pebbles must have been transported into the Black Mesa area after deposition of the underlying coastal plain deposits and prior to the development of the transgressive erosion surface. Because the unconformity is the result of a marine transgression, it does not extend past the line of maximum transgression. As the sea became shallower toward this line of maximum transgression, the Wind Rock Tongue of the Mancos Shale became sandier and thinner as it graded southwestward into the nearshore marine sand deposits.

A period of regression followed this transgressive episode. Sediment supplied to the Black Mesa area by longshore currents from local delta systems was deposited along a northwest-southeast-trending, dominantly barrier-island coastline. Tidal inlets and tidal channels were present between and behind the barrier islands, but the exact distribution of depositional environments in the back-barrier setting is unknown. The Rough Rock Sandstone formed in the nearshore marine environment as this coastline prograded basinward.

Marine regression in the Kaiparowits and San Juan basins occurred during the regression in the Black Mesa area. The A sandstone of the John Henry Member of the Straight Cliffs Formation in the Kaiparowits region and the Dalton Sandstone Member of the Crevasse Canyon Formation in the San Juan Basin are coastal marine sandstones that formed along a prograding coastline and are approximately time equivalents of the Rough Rock Sandstone.

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