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DEPOSITIONAL SYSTEMS AND PALEOGEOGRAPHIC EVOLUTION OF THE LATE PALEOZOIC TAOS TROUGH, NORTHERN NEW MEXICO

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ABSTRACT

The Taos Trough (Rowe-Mora Basin of some authors) of northern New Mexico was one of several tectonically active cratonic basins associated with the late Paleozoic Ancestral Rockies. As the basin and adjacent uplifts evolved structurally, the depositional systems and paleogeography evolved in conjunction with changing tectonic stability, fluctuating sediment input, evolution and integration of sediment dispersal systems, and varying water depth.

320-305

Morrowan time was marked by a widespread marine transgression in north-central New Mexico and the establishment of a shallow sea flanked by muddy strandplains. During periods of high sediment input, extensive mud and mixed mud-and-sand flats prograded into the shallow basin giving rise to 3 to 10 m (10 to 33 ft) thick coarsening-upward cycles. With sufficient shoaling, marsh conditions were established and thin lignite beds were deposited.

305-300

By Atokan time, vertical movements west of the trough elevated the Uncompahgre Uplift. As a result, coarse alluvial fan, braided stream, and fan-delta complexes prograded eastward into the basin. Alluvial fan and braided stream deposits are characterized by ribbon to sheet-like sandstone and conglomerate bodies which have sharp erosional bases and a dominance of trough and tabular cross-stratification. These units grade laterally into, and are frequently underlain by, coarsening-upward fan-delta sequences. Fan-delta cycles generally grade upward from dark gray siltstone into interbedded siltstone and thin sandstone beds and eventually into trough cross-bedded conglomeratic very coarse sandstone. Basinward, the fan-delta deposits become interbedded with thick sequences of dark gray calcareous siltstone which represent basinal mud. On the eastern side of the trough, finer-grained marine and marginal marine sediments were deposited on a relatively stable shelf.

This general depositional and paleogeographic pattern continued into Desmoinesian time. However, to the north, the Cimarron Arch had become a major positive feature by earliest Desmoinesian time and several braided stream and fan-delta systems prograded southward and southwestward into the basin. By middle Desmoinesian time an extensive coastal plain had developed along the western margin of the trough. Braided stream-dominated alluvial fans graded eastward into low-sinuosity, bed-load rivers which, in turn, fed lobate deltas. Lateral migration of the low-sinuosity fluvial channels gave rise to thick, sheet-like sandstone bodies. The dominant stratification in these sandstones is large-scale (2 to 10 m; 6.5 to 33 ft) sigmoidal cross-beds which represent accretion on alternate bank-attached bars. The fluvial sandstones grade eastward into coarsening-upward deltaic sequences which also have sheet-like geometries. Basinward, a clastic slope system developed in conjunction with continued subsidence of the basin.

A major middle to late Desmoinesian transgression inundated the western coastal plain, and shallow shelf deposition persisted throughout most of late Desmoinesian time. In latest Desmoinesian time, southward prograding fluvial-deltaic systems began filling the northern part of the basin, causing a net southward regression. By Early Permian time the basin was dominated by continental sedimentation with southward flowing braided streams.

INTRODUCTION

The Taos Trough (Rowe-Mora Basin) of northern New Mexico was one of several tectonically active cratonic basins associated with the Late Paleozoic Ancestral Rockies (Fig. 1). The basin was an asymmetric, fault-bounded feature flanking the Uncompahgre Uplift (Fig. 2). In the Taos area the basin received more than 2400 m (7800 ft) of coarse-grained clastic sediments (Fig. 2) while, farther south, shallow-water carbonates were deposited contemporaneously on the relatively stable Pecos Shelf (Sutherland, 1963).

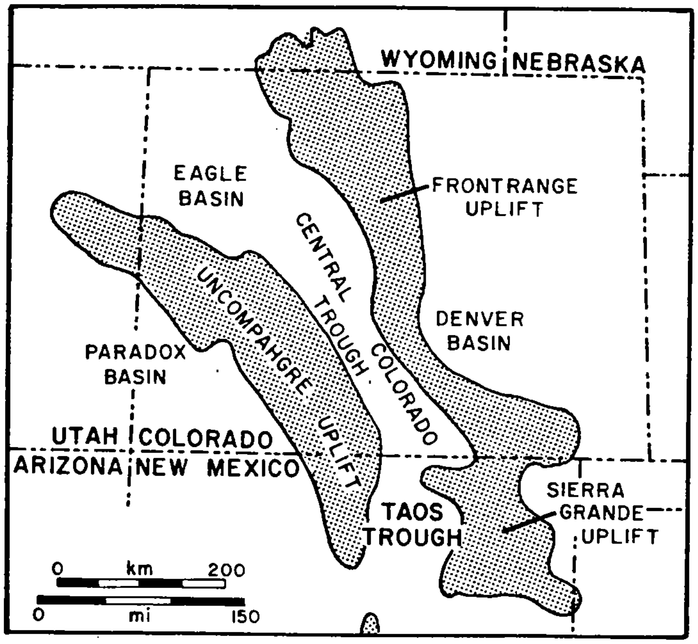

Figure 1. Major Late Paleozoic uplifts and associated basins of the Ancestral Rocky Mountains. After McKee and Crosby, 1975.

The objectives of this study were to delineate the major depositional systems of the Taos Trough and to demonstrate paleogeographic changes of the basin through time. Interpretation of depositional systems was based on a variety of criteria, including: sedimentary structures, spatial relationships of structures and textures, facies geometry, petrographic composition, and faunal content.

The study emphasizes the western part of the basin, where rocks are well exposed in the Sangre de Cristo Mountains (Fig. 3). A total of 85 sections were measured and, where possible, correlated by walking out limestone and sandstone marker beds. This aided in determining facies geometry and lateral facies associations, as well as enabling composite sections to be constructed which demonstrate the vertical stacking of facies. Paleocurrent directions were determined by taking compass bearings on cross-bedding. Corrections for structural dip were made graphically by rotating the data about a horizontal axis using a stereonet. Published data was then used to tie the depositional history of the western half of the trough to the geology of the rest of the basin.

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Previous work in this area has concentrated primarily on regional stratigraphy (Read and Wood, 1947; Brill, 1952; Baltz and Bachman, 1956; Sutherland, 1963; Baltz, 1965; Sutherland, 1972; Roberts, et al., 1976), geologic mapping (Bachman, 1953; Bachman and Dane, 1962; Miller, et al., 1963; Baltz, 1972; Johnson, 1973), and biostratigraphy (Thompson, 1942; Young, 1945; Sutherland and Harlow, 1973). However, details of facies distributions, environmental interpretations and sediment dispersal systems have received relatively little attention.

PENNSYLVANIAN STRATIGRAPHY

> *"Pennsylvanian strata have been riddled by a host of names converging from all directions so that merely attempting to unravel the nomenclature becomes a major part of any Pennsylvanian study."*
>
> (Foster, et al., 1972, p. 13)

Stratigraphic nomenclature of the Pennsylvanian rocks of north-central New Mexico has been controversial. Extreme lateral and vertical facies changes, coupled with structural complexities, make it difficult to subdivide strata on the basis of gross lithology alone. Sutherland (1963), Bachman and Meyers (1975), and Foster and others (1972) have summarized many of these problems and the various approaches used in regional studies of Pennsylvanian rocks in New Mexico.

One common approach, which involves naming thick, generalized lithostratigraphic units for regional mapping, has given rise to two systems of stratigraphic nomenclature (Fig. 4). The first adopts the lithostratigraphic terminology used in other areas, dividing the Pennsylvanian into the Sandia and Madera Formations (Baltz and Bachman, 1956). The second was proposed by Sutherland (1963) who realized the problems faced in using the terms Sandia and Madera. His formational names are also lithostratigraphic units, but were supplemented with extensive biostratigraphic control. Sutherland was able to demonstrate that the Flechado Formation, a thick, quartz-rich, clastic unit, is laterally equivalent in time to the predominantly carbonate La Pasada Formation of the Pecos area (Fig. 4).

[illegible] laterally

near [illegible] chronologically

The present study was conducted within the general biostratigraphic framework established by Sutherland and Harlow (1973), whose zonation is based on fusulinid and brachiopod fauna (fusulinids provided the primary basis or correlating upper Atokan and higher strata). They use a fusulinid zonation provided by Dwight E. Waddell, which recognizes seven zones. Waddell's zonation is used here to subdivide the Pennsylvanian into four informal time-stratigraphic divisions (Fig. 4). Fusulinid identifications were provided by George J. Verville of Amoco Production Company.

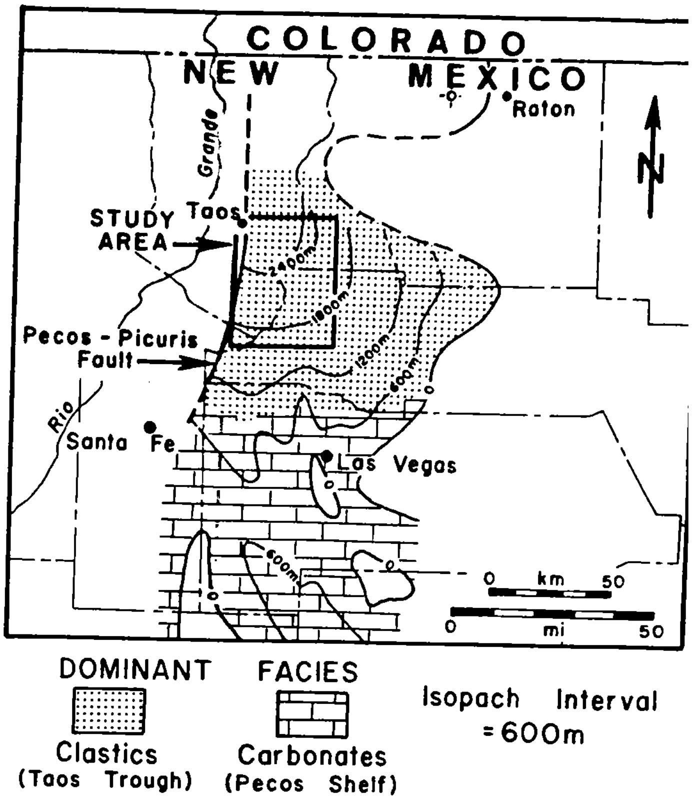

Figure 2. Isopachous map of Pennsylvanian rocks of the Taos Trough and Pecos Shelf, northern New Mexico. Based on maps by Baltz, 1965, and Roberts, et al., 1976.

PENNSYLVANIAN TECTONIC SETTING

The boundary between the Taos Trough and the Uncompahgre Uplift was formed by the Pecos-Picuris fault (Fig. 5), a reactivated Precambrian feature (Sutherland, 1963). During Pennsylvanian time, vertical movement on the west side of the fault elevated the Uncompahgre Uplift.

To the south lay an extensive carbonate shelf, which Sutherland (1963) named the Pecos Shelf. Within this shelf area, several northwest-trending anticlines have been recognized. Angular unconformities within the lower Pennsylvanian strata indicate that these anticlines were intermittently active throughout Early Pennsylvanian time and probably served as local sources of detritus (Baltz and Bachman, 1956). By late Desmoinesian age time the northern part of the Pedernal Uplift had also become ~~a~~ prominent ~~feature~~ and supplied sediment northeastward onto the Pecos Shelf (Kottlowski, 1968).

The eastern side of the Taos Trough sloped gently up onto the west flank of the northeast-trending ancestral Sierra Grande Arch (Fig. 5). Baltz (1965) suggested that a northwest extension of the Sierra Grande uplift, termed the "Cimarron Arch," was uplifted in Middle and Late Pennsylvanian time. Hills (1963) proposed a similar, although somewhat larger, feature which he called the Colfax Swell. Goodknight (1973) believed that the Cimarron Arch was narrower and more localized than originally conceived by Baltz. He further suggested that it was fault-bounded and had a northwesterly trend. Evidence presented in this study supports the hypothesis that the Cimarron "Arch" was periodically uplifted in Middle and Late Pennsylvanian time.

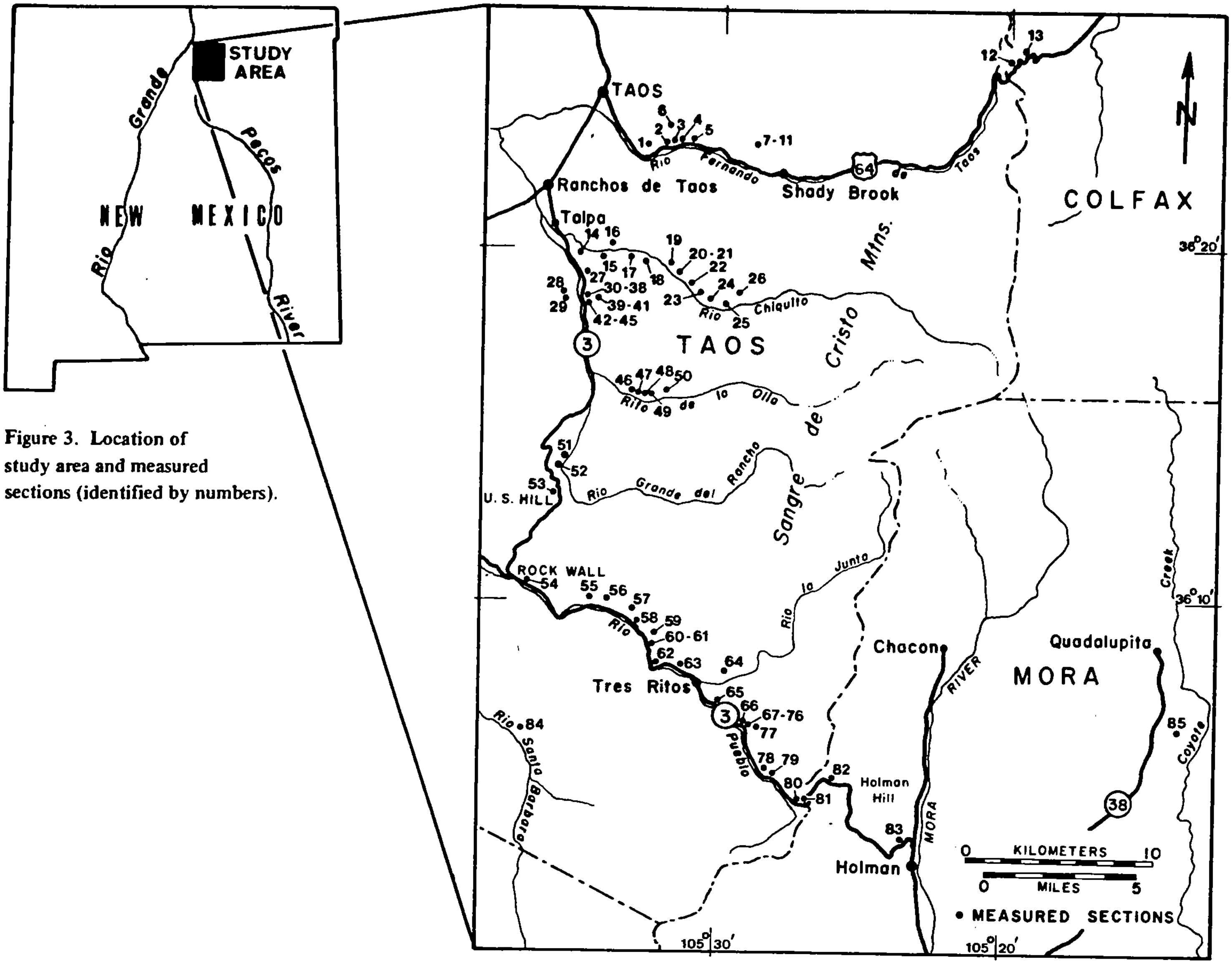

Figure 3. Location of study area and measured sections (identified by numbers).

		BALTZ & BACHMAN, 1956		SUTHERLAND, 1963		TIME-STRATIGRAPHIC DIVISIONS OF THIS STUDY	FUSULINID ZONES OF WADDELL (Sutherland & Harlow, 1973)
SYSTEM	SERIES	FORMATION		FORMATION			
PERMIAN		Sangre de Cristo		Sangre de Cristo			
PENNSYLVANIAN	VIRGILIAN	Arkosic Limestone Member	Madera	Alamitos		Late Desmoinesian and Younger	ZONE VII
	MISSOURIAN						ZONE VI
	DESMOINESIAN	Gray Limestone Member		La Pasada (south)	Flechado (north)	Early - Middle Desmoinesian	ZONE V ZONE IV ZONE III
	ATOKAN	Sandia				Atokan - Earliest Desmoinesian	ZONE II ZONE I
	MORROWAN					Morrowan	
MISS.				Tererro			

Figure 4. Stratigraphic nomenclature of the Taos–Las Vegas area and informal time-stratigraphic divisions used in this study.

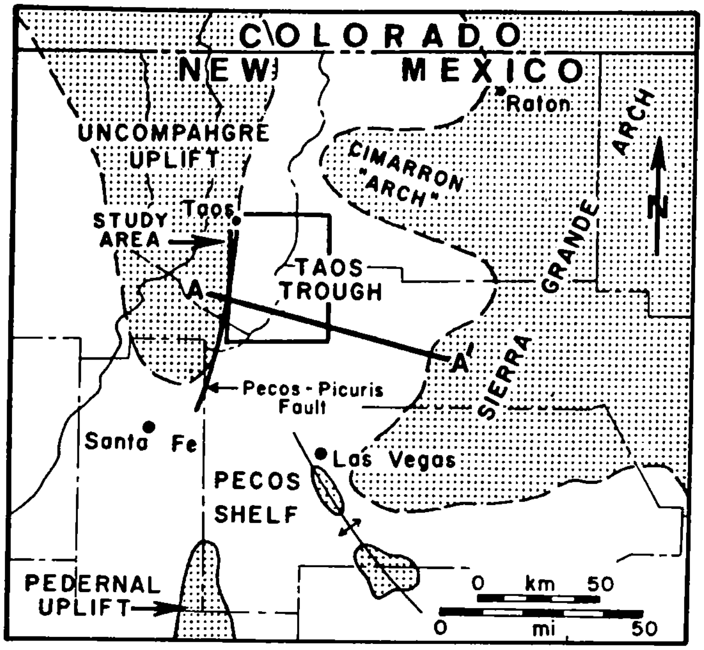

Figure 5. Pennsylvanian tectonic setting of north-central New Mexico. Based on maps by Baltz, 1965, and Roberts, et al., 1976.

DEPOSITIONAL SYSTEMS

A schematic cross-section of the Taos Trough shows the western margin dominated by an eastward prograding, coarse clastic wedge (Fig. 6). As this wedge prograded into the basin, the finer-grained shelf facies of the eastern margin onlapped the Sierra Grande Arch. The Upper Pennsylvanian strata represent a major marine regression as southeastward (and possibly southwestward) flowing fluvial-deltaic complexes filled the basin.

Morrowan Depositional Systems

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Exposures of Morrowan age rocks are limited in the study area. Sutherland (1963) and Sutherland and Harlow (1973) collected good Morrowan brachiopod faunas from two localities in the study area, which are similar to those in Morrowan formations of northwest Arkansas and northeast Oklahoma.

The best exposures of the lowermost Pennsylvanian system crop out high on a north-trending ridge west of Rio Grande del Rancho just south of Talpa, New Mexico, where Mississippian/Devonian and basal Pennsylvanian strata are nearly vertical. Sections 28 and 29 were measured along east-trending gullies from the top of the Precambrian up through the lower Pennsylvanian system. Sutherland and Harlow (1973, p. 122) measured a section in this area and reported Morrowan brachiopods from several horizons in the lower 150 m (500 ft).

poor usage?

Shallow Marine/Muddy Strandplain Facies

Facies Description

The entire Morrowan sequence is dominated by fine-grained clastic rocks with numerous thin, impure lignite beds and occasional sandy packstone (Fig. 7). These rocks are characterized by coarsening-upward cycles, usually capped by one or more impure lignite beds. Lignite beds are only a few centimeters thick and frequently have gray underclays. Coarsening-upward parts of the cycles ranges from 3 to 10 m (10 to 33 ft) in thickness. In the lower part of the sequence, these cylces generally grade upward from black shale into very fi to medium sandstone (Fig. 7). Higher in the sequence siltstone is tl dominant fine-grained facies and the sand content increases. Co glomeratic coarse sandstone units with erosional bases also becon more common higher in the section. These sandstone units are dom nated by trough cross-beds, frequently fine upward, and thin laterall indicating they are probably channel-shaped in cross-section.

Occasionally, sandy skeletal packstone beds cap coarsening-u ward sequences or overlie lignite units. Skeletal constituents of thes limestones are dominated by brachiopod, crinoid and bryozoan fra ments with occasional molluscan shells. Sand content of these lim stones varies from less than 5% to as much as 70%; thus, a complet gradation exists between the packstone facies and the sandston facies.

Interpretation

The Morrowan sequence of repetitive coarsening-upward cycle is interpreted to represent successive progradations of a muddy strand plain system similar to the Chenier Plain system of southwest Louisi ana (Byrne, et al., 1959; Coleman, 1966). The laminated shale an siltstone facies were deposited below wave base in shallow marin waters, where bioturbation by benthic organisms was restricted eithe by high turbidity or low salinity (Beall, 1968). Coarsening-upwar parts of the cycles represent shoaling by seaward progradation of extensive mud or mixed mud-and-sand flats. With sufficient shoaling marsh conditions were established and the thin lignites and associate underclays were deposited. During periods of temporary erosion o low mud supply, sand and shell debris was winnowed and deposited as beach ridges or cheniers. Conglomeratic sandstone channels higher in the sequence indicate that uplift of the Uncompahgre highlands had begun and coarser sediment was being supplied to the basin by small streams.

term?

Atokan-Earliest Desmoinesian Depositional Systems

Rocks of Atokan to earliest Desmoinesian age crop out along the western and northern margins of the study area. The upper boundary of this time-stratigraphic division is placed at a series of limestones containing zone III fusulinids (Fig. 4). Along Rio Chiquito and Rio Grande del Rancho this boundary is represented by several fossiliferous limestones. Farther to the south, along Rio Pueblo, at least two phylloid algal limestones occur 503 to 514 m (1650 to 1686 ft) above the base of the Pennsylvanian (measured section 56). The youngest limestone contains brachiopods belonging to Sutherland's brachiopod zone 3 which is equivalent to fusulinid zone III (Sutherland, 1963). These limestones are, therefore, considered to be correlative to the zone III limestones farther north.

Alluvial Fan—Braided Stream Facies

Facies Description

The clasts

bad usage

Atokan and earliest Desmoinesian rocks are characterized by very coarse clastics. These clastic ~~units~~ range in grain-size from coarse sandstone to boulder conglomerate; conglomeratic, very coarse sand is the most common grain-size. External geometry of the units ranges from narrow channel-shaped bodies with width-to-thickness ratios less than 10 to extensive sheets with width-to-thickness ratios much greater than 15. In the lower part of the sequence, broad ribbon-shaped sandstone bodies predominate. The thickness of individual ribbons ranges from a meter (3 ft) up to, and occasionally greater than, 10 m (33 ft). More extensive sheet sandstones and conglomerates are less common and tend to occur higher in the sequence. A few earliest Desmoinesian conglomerates can be traced for several kilometers to the east and south (Young, 1945). Almost all of the coarse sand and conglomerate bodies have sharp erosional bases and abrupt upper contacts.

includes everything

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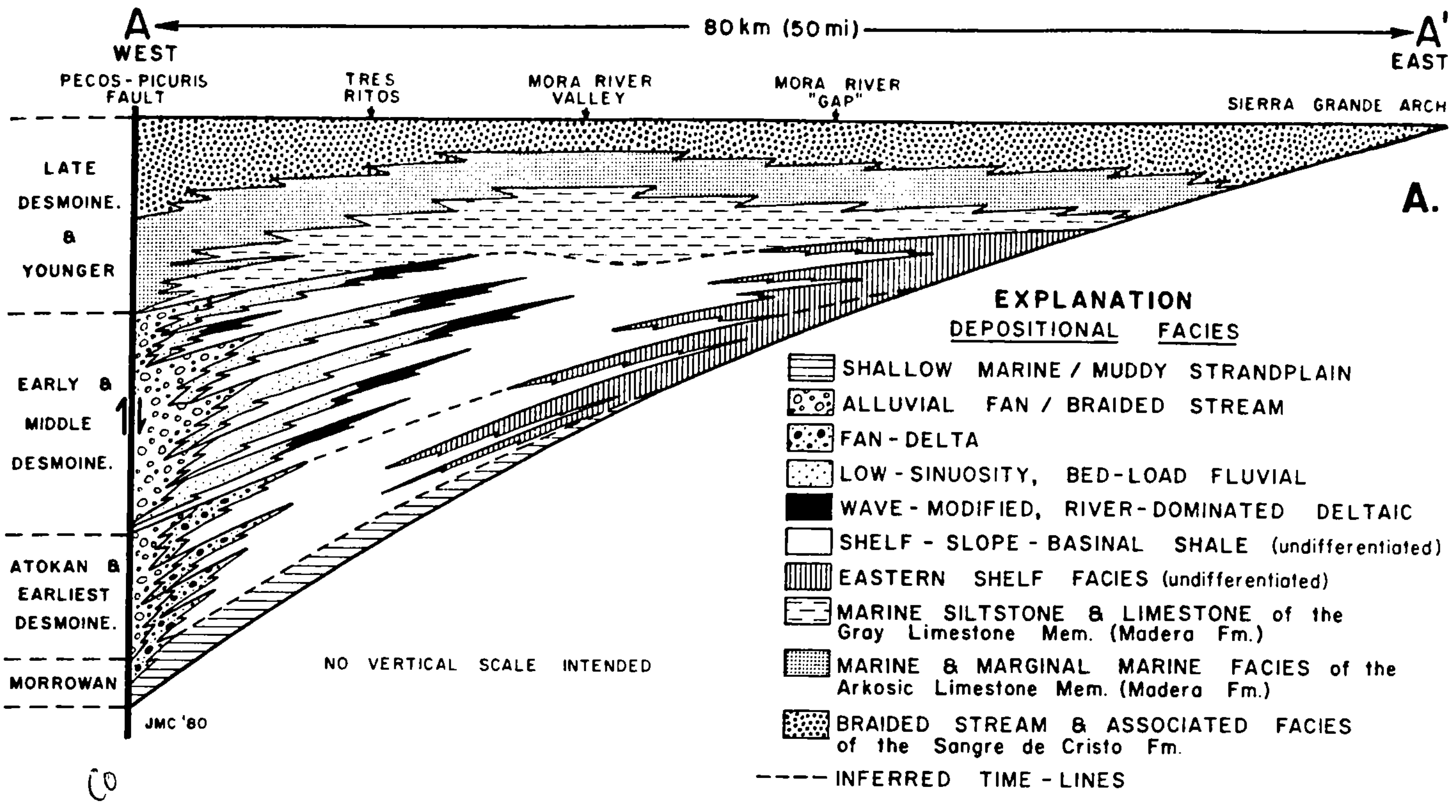


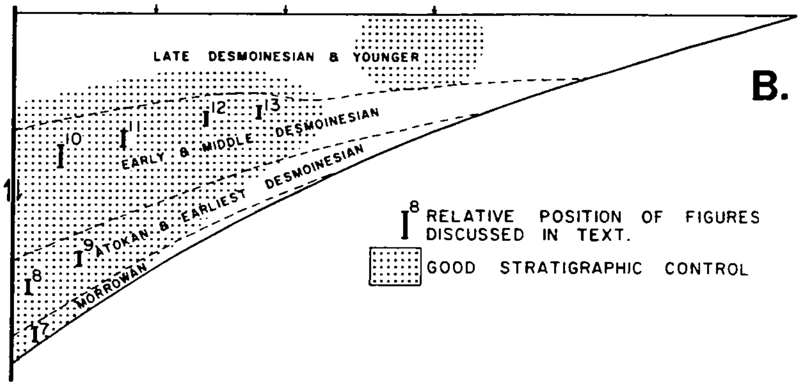


Figure 6. A—Distribution of component depositional facies of the Taos Trough sedimentary fill at the end of Pennsylvanian time. Approximate line of cross-section is indicated on Figure 5. Cross-section is strictly schematic and no vertical scale is intended.

B—Strata which are well exposed and have good fossil control or are physically correlatable to strata with fossil control. Relative positions of Figures 7 through 13 are also shown.

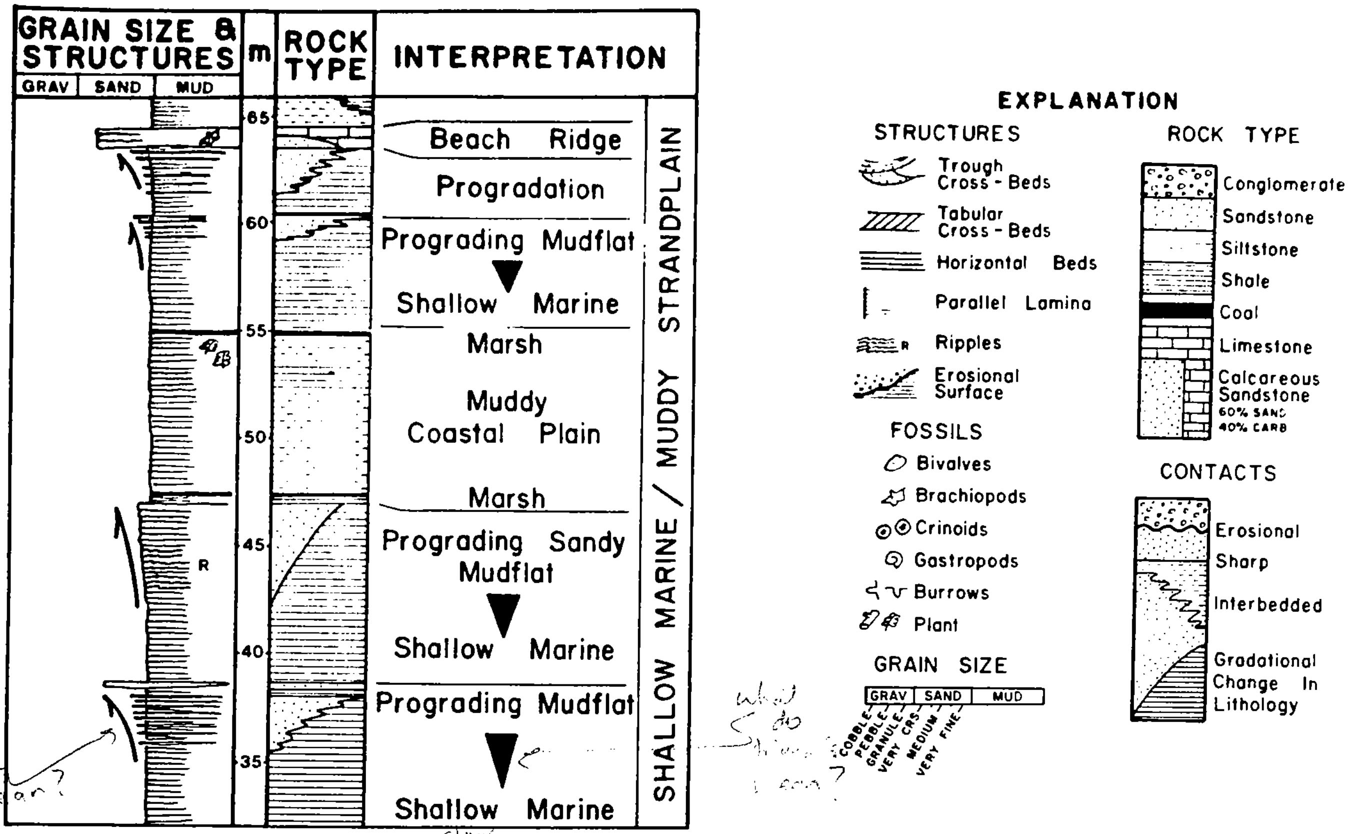
Internally, these sandstone bodies are composed of numerous overlapping, smaller-scale sedimentation units which may be characterized by trough cross-beds, tabular cross-beds, broad scour-surfaces with side fillings of the scour, or more rarely, horizontal beds. Figure 8 illustrates one of these coarse sandstone bodies. Individual sedimentation units are laterally discontinuous, cut into one another, and average 1 to 2 m (3 to 6.5 ft) in thickness. The most distinctive feature of these coarse sandstone bodies is that they exhibit no pronounced vertical trend or variation in grain-size or structures.

The more sheet-like sandstone bodies tend to be somewhat coarser and have less pronounced sedimentary structures. They vary from 2 to 6 m (6.5 to 33 ft) in thickness and contain quartzite clasts up to 40 cm (16 in) across. The cobble and boulder conglomerates are clast-supported with a matrix of coarse sand to granule-size gravel. Bedding is seldom apparent except in a few interbedded lenses of very coarse sandstone, which contain medium-scale cross-beds.

Interpretation

These coarse sandstone and conglomerate units are interpreted as braided stream and distal alluvial fan deposits. As Miall (1977) pointed out, the distinction between alluvial fan and braided stream deposits is somewhat arbitrary since sediment dispersal on alluvial fans, particularly on the distal parts, generally takes place by means of ephemeral braided streams.

Based on comparison with modern braided stream studies (e.g. Williams, 1971; Smith, 1972; Cant, 1978; also see excellent summary article by Miall, 1977), the broad ribbon-shaped sandstone bodies are interpreted as interfingering channel and bar deposits of relatively confined, small-to-moderate sized, sandy braided stream systems. Trough cross-beds formed on channel floors as trough-shaped scours were infilled by migrating dunes, whereas tabular cross-beds represent the foreset slopes of linguoid or transverse bars. Horizontal beds generally overlie tabular cross-beds and, therefore, were probably de-



what do arrows mean?

what do these mean?

Figure 7. Measured section of Morrowan rocks exposed south of Talpa, New Mexico (section 29). Explanation of symbols for sedimentary structures, fossils, and lithology is for all figures of measured sections discussed in text. Grain-size of clastic rocks is indicated by width of left-hand column—for example, a sandstone bed which extends half-way into the sand column is medium-grained sandstone. Coarsening- and fining-upward trends are shown by arrows.

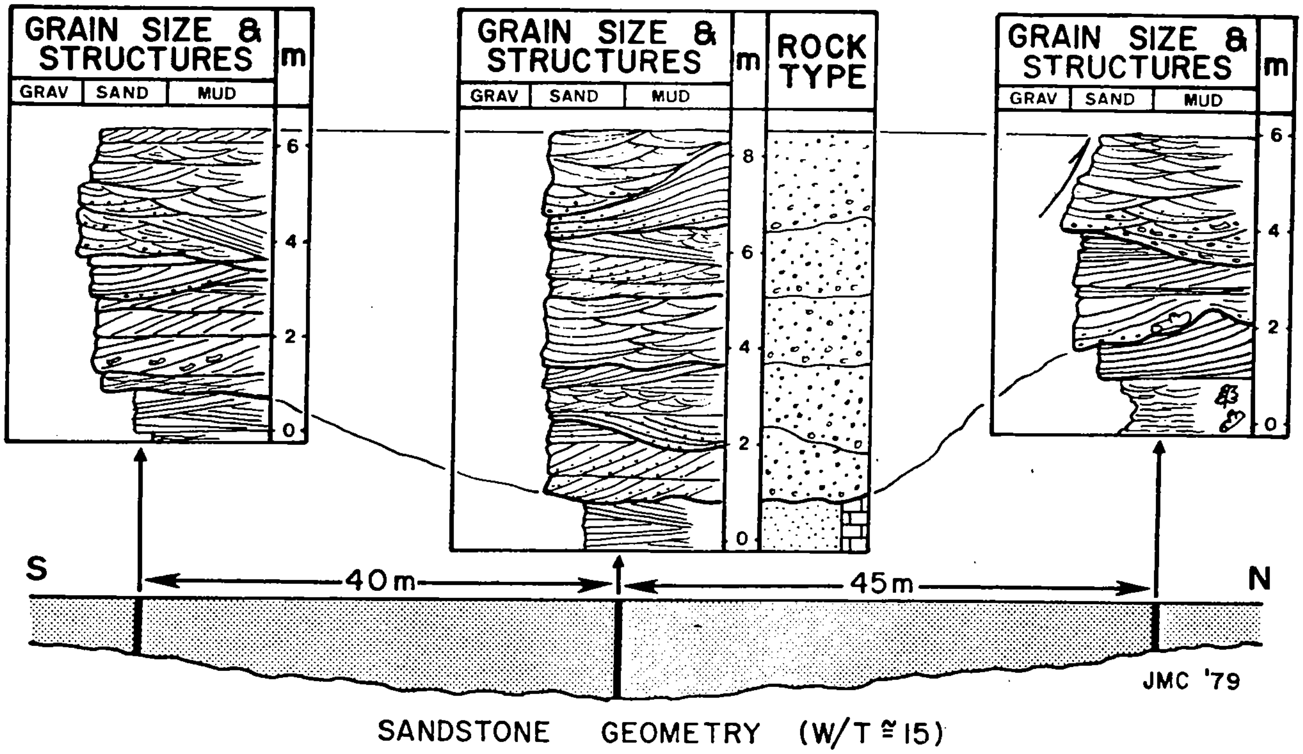


Figure 8. Earliest Desmoinesian, broad ribbon-shaped, braided stream channel exposed on east-facing wall of Capulin Canyon (measured sections 8 through 10). See Figure 7 for explanation of symbols.

posited during floods when water and sediment were transported across the tops of bars under upper flow-regime conditions. Asymmetrically filled scours formed as sediment moved downstream or laterally into small abandoned braid channels.

The narrow, ribbon-like geometry of many of these sandstone units indicates that the rivers probably shifted position by major avulsions rather than steady lateral migration. Friend and others (1979) suggested that this may be typical of streams with extremely flashy discharge. In contrast, the coarser conglomerates higher in the sequence tend to be laterally more persistent and were probably deposited on alluvial fans.

What does this mean?

intermittent?

Fan-Delta Facies

General Facies Description

Coarse ribbon and sheeet sandstones and conglomerates of the western part of the trough grade laterally into. and are frequently underlain by, coarsening-upward fan-delta sequences. Casey and Scott (1979) described one of these fan-delta complexes, and Casey (in prep.) discusses the inferred processes and variation of the fan-delta deposits in detail.

A typical coarsening-upward fan-delta cycle is shown in Figure 9. In general, these cycles grade upwards from dark gray siltstone into interbedded siltstone and thin sandstone beds and eventually, into trough cross-bedded conglomeratic very coarse sandstone. The coarse sandstone and conglomerate units which cap the sequences vary in geometry from narrow channel-like sandstone bodies to the broader ribbon-shaped, braided stream sandstones already described. Overlying the channel-like conglomeratic sandstone in Figure 9 is a 9 m (29.5 ft) thick interval of dark gray siltstone with a diverse molluscan-brachiopod fossil assemblage.

These coarsening-upward sequences are stacked vertically, giving rise to thick sequences of cyclically alternating fossiliferous mudstone and coarse conglomeratic sandstone. Young (1945) recognized 57 such cycles in the Taos Canyon area. Fossiliferous limestones ranging from a few centimeters to several meters in thickness are also common, generally occurring at the top of a cycle, and separated from the coarsening-upward part of the sequence by fossiliferous siltstone or shale. They may, however, occur at almost any position and are occasionally interbedded between conglomeratic sandstone lenses (Fig. 9).

Large-scale foreset-bedded sandstone units are also a common feature in these cyclic sequences. They either overlie coarsening-upward cycles or replace the interbedded sandstone-siltstone part of the cycle. Foresets are steeply dipping, with maximum dips of 27°. Individual beds making up the foresets average 25 cm (10 in) in thickness, thin towards their toes, show faint lamination parallel to bed boundaries, and are often texturally graded. Strongly tangential basal contacts give rise to steep foresets with nearly horizontal bottomsets which are finer-grained and often burrowed.

Fan-delta Model

Following uplift of the Uncompahgre highlands, small coarse-grained delta lobes prograded into the adjacent Taos Trough. These delta lobes were fed by fairly straight, symmetrical channels which graded landward into laterally more extensive braided stream systems. Stream discharge was flashy due to the proximity of the highlands, small drainage areas, and a climate dominated by seasonal or very sporadic rainfall. During periods of little or no discharge, bed-load sediment was stored in the distributary channels, whereas during flood discharge, this stored sediment was entrained and rapid seaward progradation occurred. This alternating sediment storage and transport gave rise to channel deposits dominated by large-scale trough cross-beds and numerous internal erosion surfaces. Variations in delta front sedimentation were dependent on many factors, including: channel size, amount and grain-size of sediment, discharge characteristics, and wave energy. Sediment influx into the delta front occurred during high discharge periods. If progradation was into areas with water depths greater than 4 meters, bed-load sediment would fan out on the delta slope forming fairly extensive fan-shaped frontal splays (Casey and Scott, 1979). During low discharge, very little sediment was deposited and so marine organisms would re-establish on the distal parts of the delta front. The fact that marine organisms occur in siltstones interbedded with the frontal splay sandstones is further evidence for flashy discharge and intermittent sedimentation. With successive flood events, these frontal splays prograded out to form a coarsening-upward wedge. Reworking by waves and other marine processes was minimal. As progradation continued, the distributary channel extended over these delta front sediments, forming an overall coarsening-upward sequence capped by conglomerates with erosional bases (Fig. 9). When deltas prograded into extremely shallow water (less than 4 m or 13 ft) delta-foresets similar to classical "Gilbert" deltas formed (Gilbert, 1882).

Carbonate Facies

A variety of shallow-water marine limestones are associated with the Atokan and earliest Desmoinesian fan-delta complexes, but the two most common are phylloid algal packstone-wackestone and silty brachiopod-crinoid packstone-wackestone. These two generally overlie fan-delta sequences, representing delta abandonment due to shifting delta lobes or major avulsions of the feeder fluvial systems.

Basinal Facies

To the east, the fan-delta facies become interbedded with thick sequences of dark gray calcareous siltstone and very fine to fine sandstone which represent basinal mud and sand deposition. This fine-grained facies is particularly well exposed in measured sections 22-26, along Rio Chiquito. The calcareous siltstone and fine sandstone units

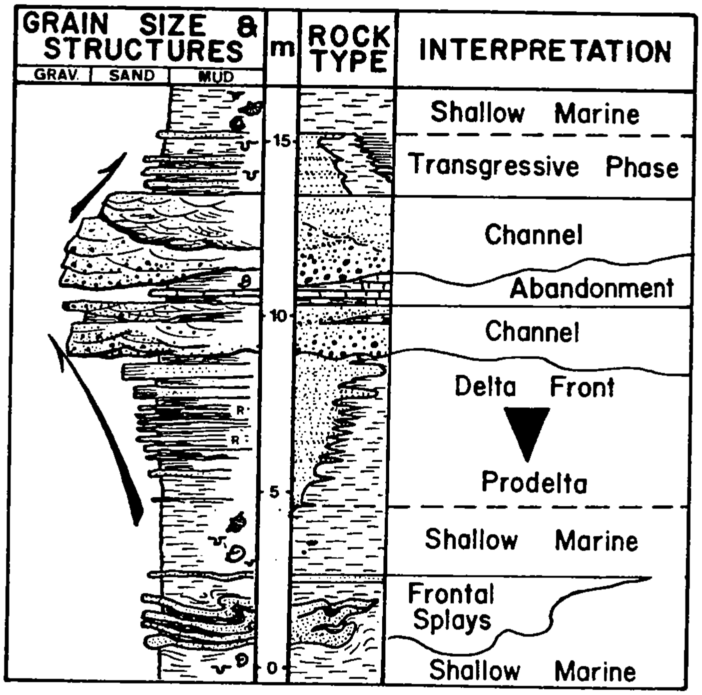


Figure 9. Measured section 43—typical earliest Desmoinesian, coarsening-upwards, fan-delta sequence. See Figure 7 for explanation of symbols. From Casey and Scott, 1979.

are very micaceous, often carbonaceous, and are marked by many surface grazing trace fossils. Invertebrate fossils are rare, with only occasional brachiopods, bivalves, and crinoid columnals. The siltstone units are up to 45 m (148 ft) thick, and alternate with fairly thick coarsening-upward sequences which represent progradations of unusually large fan-deltas into deeper parts of the basin. Shallow marine limestones usually overlie the progradational sequences. These limestones are thicker and laterally more extensive than the limestones farther west. The fact that basinal siltstone and fine sandstone are interbedded with deltaic sequences and shallow marine limestones indicates that deep water conditions did not exist during Atokan-earliest Desmoinesian time and water depths probably rarely exceeded 30 or 40 m (90 or 130 ft).

Eastern Shelf Facies

A thick sequence of limestone, siltstone, fine-grained sandstone and occasional coarse-grained sandstone or conglomerate is exposed in a series of roadcuts east of Palo Flechado Pass (measured sections 12 and 13) along U.S. Highway 64. Wanek and Read (1956, p. 90) referred to these sediments as the upper member of the Madera Formation. However, the occurrence of *Fusulina* cf. *F. taosensis* (fusulinid zone II) near the top of this sequence (Young, 1945, p. 57) indicates that these rocks are earliest Desmoinesian or older in age, and therefore, contemporaneous with the coarse fan-delta deposits further to the west. The high feldspar (particularly microcline) content of these sediments reflects a local granitic source, and does not justify correlation with the upper member of the Madera Formation to the southeast. Instead, these fine-grained, dominantly marine sediments represent deposition on a relatively stable shelf flanking the Sierra Grande Arch on the east side of the Taos Trough. Depositional environments include (in order of relative importance): shallow terrigenous shelf, carbonate banks, deltas, and braided streams (Casey, in prep.).

Early to Middle Desmoinesian Depositional Systems

Rocks of early to middle Desmoinesian age are best exposed in the southern half of the field area along Rio Pueblo. In this area, thick sequences of calcareous siltstone and shale alternate with thick, laterally persistent very coarse sandstone and conglomeratic sandstone units. The sandstone units represent extensive fluvial and fluvial-deltaic complexes that prograded eastward into the Taos Trough. Moving basinward, a middle Desmoinesian facies tract includes the following environments: (1) alluvial fans dominated by braided stream processes, (2) low-sinuosity bed-load rivers, (3) lobate deltas, (4) slope, and (5) "deep" basin. Locally, small phylloid algal mounds and cross-bedded shelf-edge carbonate shoals were associated with periods of delta abandonment.

Farther north the early-middle Desmoinesian depositional setting is less certain. Thick, very coarse sandstone units which crop out in the high peaks of this area may be of similar origin to those to the south, but exposures are poor because of the intense weathering at these higher elevations.

"Humid" Alluvian Fan Facies

Facies Description

The westernmost exposures of the early-middle Desmoinesian strata (measured section 57) are dominated by thick (up to 50 m; 164 ft) very coarse sandstone to granule or pebble conglomerate units interbedded with poorly exposed siltstone and shale. These sandstone units are similar to the Atokan-earliest Desmoinesian alluvial fan and braided stream facies except they are much thicker, laterally more continuous and, on average, somewhat coarser. They also include fewer tabular cross-beds and have more large-scale sigmoidal-shaped cross-beds (Fig. 10). The dominant stratification type is medium- to large-scale, low-angle trough cross-bedding (Fig. 10). Trough cross-beds fill broad, shallow channels that overlap and cut into one another. Horizontal stratification is also common.

Interpretation

These laterally persistent coarse units were probably deposited on the mid to distal reaches of fairly extensive "humid" alluvial fans. The term "humid" alluvial fan is used to describe alluvial fans that are dominated by braided streams which migrate without lateral confinement (Collinson, 1978). Humid fans have more gentle gradients and greater areal extent than arid fans (McGowen and Groat, 1971; Hayes and Kana, 1976). The large-scale sigmoidal cross-beds in Figure 10 may either represent side-filling of channels or lateral accretion of bank attached bars.

Low-Sinuosity Bed-Load Fluvial Systems

Sandstone Facies Description

Moving basinward (eastward) the dominant stratification type of the thick, laterally persistent sandstone bodies changes from trough cross-bedding to large-scale (2 to 10 m; 6.5 to 33 ft) sigmoidal cross-bedding. Sandstone units of measured sections 58 through 64 are dominated by this latter type of cross-bedding, which is extremely complex with numerous cross-cutting scour surfaces. In general, three major variations of sigmoidal cross-bedding have been observed in these units (Fig. 11). The first type (Fig. 11A) has relatively steep dips (up to 24°). Bed boundaries of this cross-bedding type represent erosional surfaces that cut down into the underlying beds, and mud drapes are rarely preserved. The second type (Fig. 11B) has gentle dips (4° to 18°), and individual sandstone beds are laterally more continuous than in the first type. These low-angle cross-beds tend to have well developed carbonaceous silt or fine sand drapes. A complete gradation exists between these first two types of sigmoidal cross-beds.

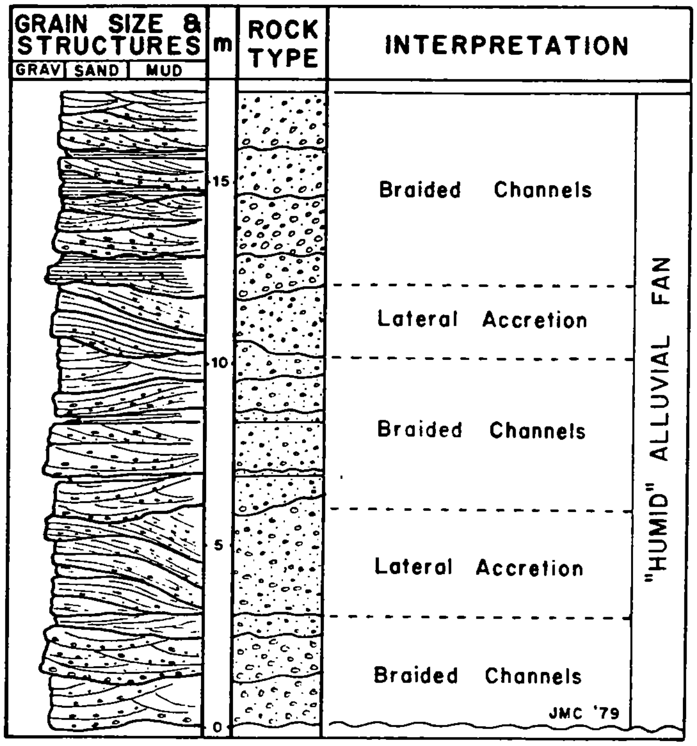


Figure 10. Mesaured section 57, north of Rio Pueblo—middle Desmoinesian, "humid" alluvial fan sequence. See Figure 7 for explanation of symbols.

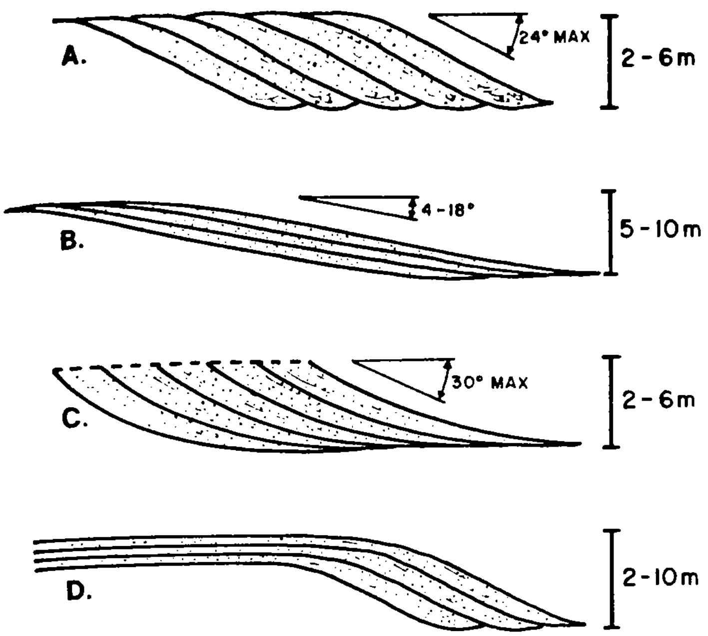


Figure 11. Major variations in sigmoidal cross-beds of the early and middle Desmoinesian fluvial sandstone bodies.

The third type (Fig. 11C) has steep dips (up to 30°), strongly tangential bases, and are usually truncated at the top (thus, this type is not truly sigmoidal-shaped).

Individual sigmoidal beds range in thickness from 10 to 150 cm (4 to 60 in) with an average thickness of 40 cm (16 in). Average grain-size is very coarse sand. Internal stratification is generally parallel to the bed boundaries, with occasional low-angle cross-stratification (particularly at the base of the units). Where present, internal cross-bedding dips at an oblique angle to the dip of the enclosing beds. Sigmoidal cross-beds often have gravel veneers on their upper surfaces and are separated from one another by micaceous, carbonaceous, sandy mudstone drapes.

Interbedded with the sigmoidal cross-bedded units are thin sheet sandstones with numerous carbonaceous siltstone drapes. These thin sandstone sheets are similar in grain-size and internal stratification to the sigmoidal sandstone beds. However, they are more uniform in thickness and can be traced for greater distances. In places, the upper ends of the first two types of sigmoidal beds (Fig. 11 A and B) grade laterally into thin sandstone sheets (Fig. 11D). Broad lens-shaped sandstone units are commonly associated with the sigmoidal bedding; however, some of these lenses may simply be low-angle sigmoidal cross-beds.

Interpretation

The best modern analogs for the Pennsylvanian rivers that deposited these sigmoidally cross-bedded sandstones are relatively straight rivers with alternate bank-attached bars. Little has been published about the deposits of modern straight rivers, although there are a few publications that deal with the hydrodynamics of straight reaches of rivers (e.g. Maddock, 1969). Straight rivers generally have a meandering thalweg, with alternate bars developed on the insides of bends (Collinson, 1978). Collinson distinguished between "side bars" which descend gradually into the channel with no slip face and "alternate bars" which are characterized by slip faces on their downstream side. Both types are roughly triangular in plan view and are attached with regular spacing on alternate sides of the channels. Allen (1970, p. 313) suggested that, since the thalweg of this type of stream is sinuous, downstream movement of the alternate bars inevitably involves lateral accretion and is essentially the same process active on point bars.

The alternation of very coarse sandstone and fine-grained drapes suggests that discharge during early and middle Desmoinesian time was still relatively flashy (unlike most fine-grained meandering streams). Each coarse unit was probably deposited during one major flood event. During floods the entire fluvial channel and a large part of the floodplain were covered with water. The result was essentially a straight fluvial channel with a meandering thalweg winding between alternate bank-attached bars. During this high discharge, sediment and water were transported across the bars under upper flow regime conditions as the bars migrated downstream. The entire fluvial channel system also migrated laterally giving rise to thick sheet sandstones.

The true sigmoidal cross-beds (Fig. 11 A and B) are interpreted as lateral accretionary surfaces of coarse-grained "side bars" which descended into the channels without slip faces. The slope of these sigmoidal beds is related to the original morphology of the bars and to stream size. Cross-beds with steep foresets and tangential bases (Fig. 11C) are indicative of avalanching down a slipface. These avalanche faces may have occurred on the downstream side of "alternate bars" or on chute bars such as those often associated with coarse-grained point bars (McGowen and Garner, 1970). Some of the "avalanche-type" cross-bedded sandstone units in the Tres Ritos area are gradational with underlying mudstones and may represent small deltas which prograded into lakes flanking the fluvial channels.

The extensive "tails" on the upper ends of some sigmoidal beds (Fig. 11D) and the thin sheet sandstone units suggest that sand deposition also occurred outside of the main channels. This process may be analogous to the Bijou Creek flood sedimentation described by McKee and others (1967) in which sand spread out more than 0.8 km (0.5 mi) beyond the channel. Deposits of both the channel and the floodplain were characterized by horizontal or near horizontal bedding. Large amounts of sand were probably deposited outside of the early-middle Desmoinesian channels in much the same way.

During the waning stages of floods, organic-rich fine sediment was deposited from suspension, forming thin drapes on the bar surfaces and somewhat thicker drapes on the overbank sheet sands. Preservation of planar bedding, both on the bars and in the overbank areas, suggests that rapidly waning flood conditions inhibited the formation of lower flow regime bedforms. Broad, shallow channelling and some smaller-scale cross-beds may represent reworking during falling discharge.

Wave-Modified River-Dominated Deltaic Facies

Facies Description

The coarse fluvial sheet sandstones grade eastward into extensive deltaic and fluvial-deltaic deposits. Casey (in prep.) distinguishes upper delta plain deposits dominated by fluvial sheet sandstones from distal deltaic deposits characterized by coarsening-upward progradational sequences.

On the upper delta plain, rapid delta progradation, coupled with lateral migration of low-sinuosity rivers, often caused erosion of the underlying deltaic progradational sequence and most of the fine-grained floodplain deposits. As a result, coarse fluvial sheet sandstone bodies may rest directly on marine mudstone, and evidence of delta progradation is only preserved on the outer margins of the fluvial-deltaic complexes.

In contrast, progradational sequences are well developed on the more distal parts of the deltaic packages. A typical distal deltaic coarsening-upward sequence is shown in Figure 12. Grain-size, scale of sedimentary structures, and thickness of sandstone beds all increase upwards. The vertical succession of delta subenvironments upwards through the sequence is:

shallow marine shelf: limestone and calcareous shale with a sparse bivalve fossil community (dominated by *Myalina* and *Aviculopecten*);
prodelta: siltstone and shale with abundant plant debris;
distal delta-front: thin horizontally bedded to rippled sandstone and siltstone with abundant plant debris;
delta-front sheet sandstone: coarse sandstone with horizontal bedding and low-angle cross-stratification;
distributary channel: very coarse sandstone with large-scale, low-angle trough cross-beds;
delta abandonment facies: bioturbated, calcareous sandstone;
shallow, storm-dominated shelf: calcareous siltstone and sandy limestone with abundant crinoid and brachiopod fragments.

Delta Type

The dominance of fluvial sandstone in the upper delta plain and coarse distributary channels in the lower delta plain suggests that these deltas were fluvial dominated. The sheet-like geometry of the delta-front sandstone, however, indicates that there was significant reworking of channel mouth sand by wave action. Using Galloway's terminology (1975) these deltas would be classified as wave-modified, fluvi dominated deltas. Modification by waves probably resulted in del that were lobate-shaped in plan view. Brown (1973) and Miall (19 suggested that lobate river-dominated deltas tend to have a less c tinuous discharge, and are often coarser than elongate river-dominat deltas. They also tend to have a greater number of distributaries (Mi 1979) and prograde over relatively thin mud sequences (Fisher, et 1969).

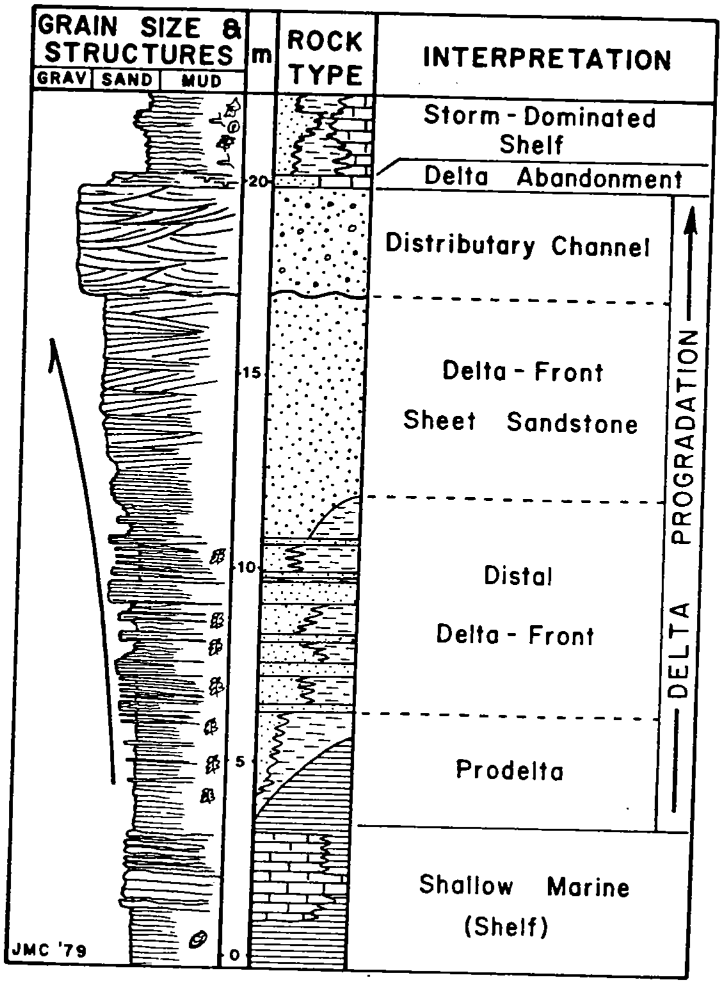


Figure 12. Measured section 78–typical middle Desmoinesian distal deltaic, coarsening-upward sequence. See Figure 7 for explanation of symbols.

Slope and Basin Facies

Facies Description

Basinward, the coarse early-middle Desmoinesian fluvial-delta sandstones grade into a thick sequence of calcareous shale and sil stone. Baltz and Read (1956, p. 76) referred to these dark, fissile shal as the shaly upper member of the Sandia Formation and noted th "just a short distance to the west of Holman Hill all evidence of th upper or shaly member of the Sandia Formation has disappeared." Th Mora River Valley between Holman and Chacon, New Mexico, is prob bly a topographic expression of this thick mudstone unit (Fig. 6).

On the slopes of Holman Hill (measured section 82) this uppe fine-grained member consists of calcareous shale and siltstone, locall with numerous sharp-based, thin sandstone beds. These thin, fine- t medium-grained sandstone beds have abundant sole marks and sedi mentary structures characteristic of "thin-bedded" or "distal" tur bidites (Walker, 1978). The sandstone beds occasionally have complet Bouma sequences (Bouma, 1962), but more commonly are dominated by either horizontal bedding or ripple-stratification. Locally, large-scale syndepositional folds occur (Fig. 13).

Interpretation

The shaly upper member of the Sandia Formation of the Mora River Valley is interpreted as the slope and basin equivalent of the coarse fluvial-deltaic complexes to the west. The thin sandstone beds are probably best explained by a prodelta turbidite model (Lundegard, 1979; Kepferle, 1978; Walker, 1978, p. 962-963; Moore and Clarke, 1970) rather than a submarine fan model. Prodelta turbidites differ from submarine fan turbidites in that they are fed by deltas rather than submarine canyons or upper fan channels. They accumulate on relatively smooth slopes and usually only contain classic turbidites without the coarser resedimented facies and channeling associated with submarine fans (Lundegard, 1979; Walker, 1978).

The early-middle Desmoinesian prodelta turbidites differ from those described by Lundegard (1979), Kepferle (1978), and Moore and Clarke (1970) in that they are coarser-grained and contain large submarine slump folds (Fig. 13). These slumps were probably the result of the unstable substrate caused by rapid deposition of turbidite sands.

Mud accumulated on areas of the slope were turbidite sands were not deposited and in the "deeper" parts of the basin. The resultant mudstones are often bioturbated and contain only a sparse bivalve fossil community.

Carbonate Facies

Minor carbonates are also associated with the extensive fluvial-deltaic complexes. These include both cross-bedded crinoidal grainstones and phylloid algal packstones and wackestones. The grainstones probably accumulated as carbonate shoals along the large eastward prograding delta platform during times of low clastic input. Phylloid algal limestones generally occur west of the grainstone and probably represent small algal mounds on abandoned parts of the delta platform.

Figure 13. Penecontemporaneous slump folds in middle Desmoinesian slope sediments exposed in Highway 3 roadcut near top of Holman Hill (measured section 82). Note that beds above and below contorted interval are undisturbed. Thickness of contorted interval is approximately 5m (15 ft).

Late Desmoinesian and Younger Depositional Systems

Overlying the coarse early–middle Desmoinesian strata is a thick sequence of calcareous siltstone and very fine sandstone interbedded with thick fossiliferous limestones. This unit is generally referred to as the "gray limestone member" of the Madera Formation (Sutherland, 1963, included it in the Alamitos Formation). In the Santa Barbara area (measured section 84) the unit is approximately 425 m (1400 ft) and contains upper Desmoinesian fusulinids (Sutherland and Harlow, 1973, p. 99), but farther east, its thickness is uncertain. Approximately 90 m (300 ft) of this member is exposed in the Mora River gap, but thrust faults may have removed an unknown thickness of the unit (Baltz and Bachman, 1956).

The gray limestone member of the Madera Formation grades upward into the upper arkosic limestone member of the formation. This upper member is not exposed in the western half of the field area (some of the arkoses in the Santa Barbara area may represent the lower part of the member). Thus, the latest Pennsylvanian depositional history for this area is not well known. Farther east, along Coyote Creek (measured section 85), at least 435 m (1425 ft) of the arkosic limestone member is well exposed. Zone V fusulinids occur in the lower part of these rocks (Fig. 4). The upper part of this sequence grades upward into the Sangre de Cristo Formation.

Late Desmoinesian Shelf Facies

Facies Description

In the Santa Barbara area (measured section 84) late Desmoinesian rocks (gray limestone member of the Madera Formation) consist of dark gray calcareous siltstone to very fine sandstone interbedded with thick, fossiliferous, impure limestones. Sutherland (1963) measured a section in this area and Sutherland and Harlow (1973, p. 99–102) gave petrographic descriptions of many of these rocks. The siltstones and very fine sandstones are usually bioturbated and contain a sparse brachiopod fossil assemblage. The impure limestones are nodular with thin silt or shale laminae. Most limestones are packstones or wackestones and are dominated by a brachiopod–crinoid fossil assemblage. Some of the less argillaceous limestones contain abundant phylloid algae.

Interbedded with these fossiliferous marine sediments are several arkosic granule to pebble conglomerate units. These range in thickness from 2 to 6 m (6.5 to 20 ft), have sharp erosional bases, and are dominated by broad, low-angle trough cross-beds. Coarse arkosic units become more numerous and thicker in the upper part of the sequence. Although Sutherland (1963) referred to the arkoses at the top of the sequence as the Sangre de Cristo Formation, they are similar in age and lithology to the upper arkosic limestone member of the Coyote Creek area (measured section 85).

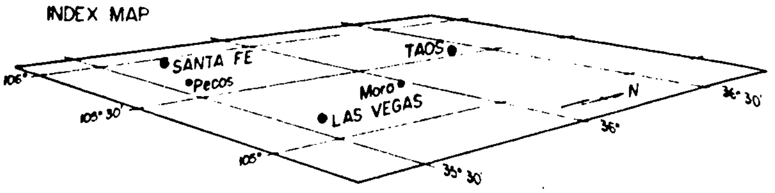
Interpretation

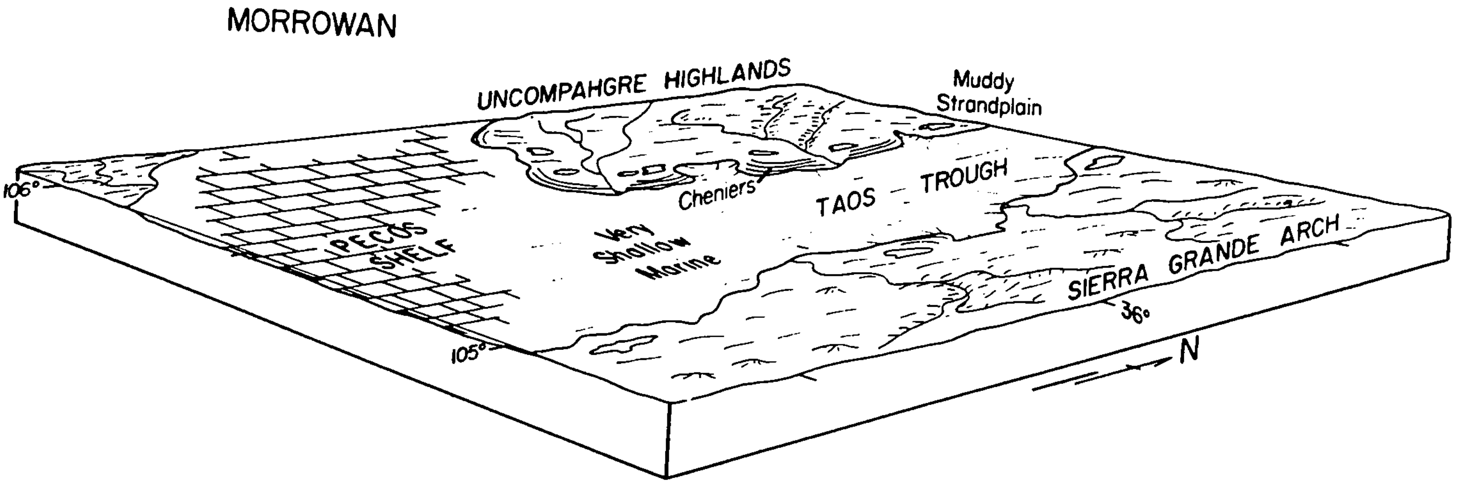
These predominantly marine sediments represent a major late Desmoinesian transgression of the northern part of the trough. The extensive, low-lying delta platform formed by the early–middle Desmoinesian fluvial–deltaic complexes was quickly inundated, and shallow shelf conditions prevailed during most of late Desmoinesian time. The shelf was dominated by rapid deposition of silt and very fine sand. Benthic organisms were restricted primarily to productid brachiopods. During periods of low clastic input, extensive shelf carbonates were deposited and a fairly diverse brachiopod–crinoid community was established. Where clastic influx was extremely low, phylloid algae also flourished. Occasional conglomerates may record episodic movements along the Pecos–Picuris fault and rapid eastward progradation of braided streams across this shallow shelf.

Depositional Environments of the Upper Madera and Sangre de Cristo Formations

In the Coyote Creek area (measured section 85) the lower part of the arkosic limestone member of the Madera Formation consists of calcareous siltstone and sandstone interbedded with impure limestone and numerous coarse arkosic sandstone units. The coarse sandstone units are characterized by abundant channeling and trough cross-

Figure 14. Morrowan paleogeography of the Taos Trough and surrounding areas.





bedding. Higher in the section, coarse arkosic sandstone beds become more numerous and there are fewer marine sandstones and limestones. Eventually the marine units die out as the Madera Formation grades upward into the red beds of the Sangre de Cristo Formation.

The lower part of the arkosic limestone member represents a variety of marine and marginal marine environments including: shallow shelf (both terrigenous and carbonate), deltaic, delta plain, interdeltaic, and fluvial (Casey, in prep.). In the upper part of the member there is a gradual change to predominantly coastal plain and fluvial environments. The red beds of the Sangre de Cristo Formation represent a final Late Pennsylvanian regression and deposition of braided stream sand with associated floodplain mud and lacustrine limestone (Brown, in prep.).

SUMMARY OF PALEOGEOGRAPHIC EVOLUTION

age

Morrowan ~~time~~ was marked by a widespread marine transgression in north-central New Mexico and the establishment of an extensive shallow epicontinental sea. The Uncompahgre Uplift and Sierra Grande Arch were both low-relief landmasses which supplied fine-grained sediment to the Taos Trough (Fig. 14). Other slightly emergent areas may also have been local sources of sediment. During periods of high sediment input, muddy strandplains prograded into the shallow marine basin. To the southeast of the trough, in the Santa Fe area, shallow water carbonates accumulated on the western part of the Pecos Shelf.

By Atokan time, vertical movements elevated the Uncompahgre Uplift to the west of the trough and coarse alluvial fan, braided stream, and fan-delta complexes prograded eastward into the basin (Figs. 15 and 16). During this period of fairly intense diastrophism along the western margin of the basin, the eastern side remained fairly stable. A broad, shallow-marine shelf sloped gently off the Sierra Grande Arch (Fig. 16). Sediment was probably supplied to this shelf by streams draining the Sierra Grande Arch. Farther eastward a shallow nearshore marine-to-continental depositional setting persisted during much of this time (Siemers, 1979). To the south, the entire Pecos Shelf was dominated by shallow-water carbonate deposition.

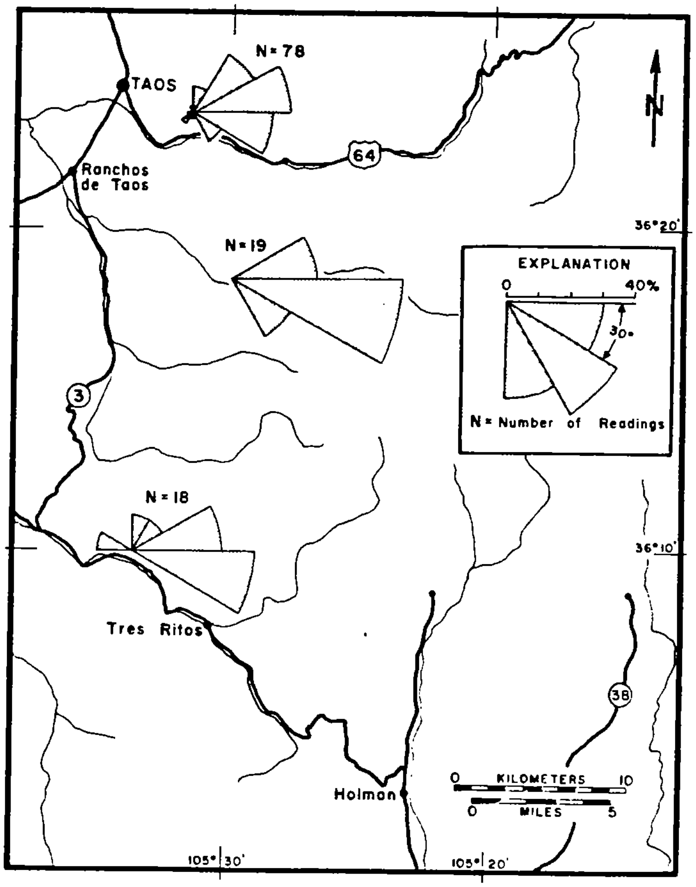


Figure 15. Atokan directional features. Measurements primarily on fan-delta foresets.

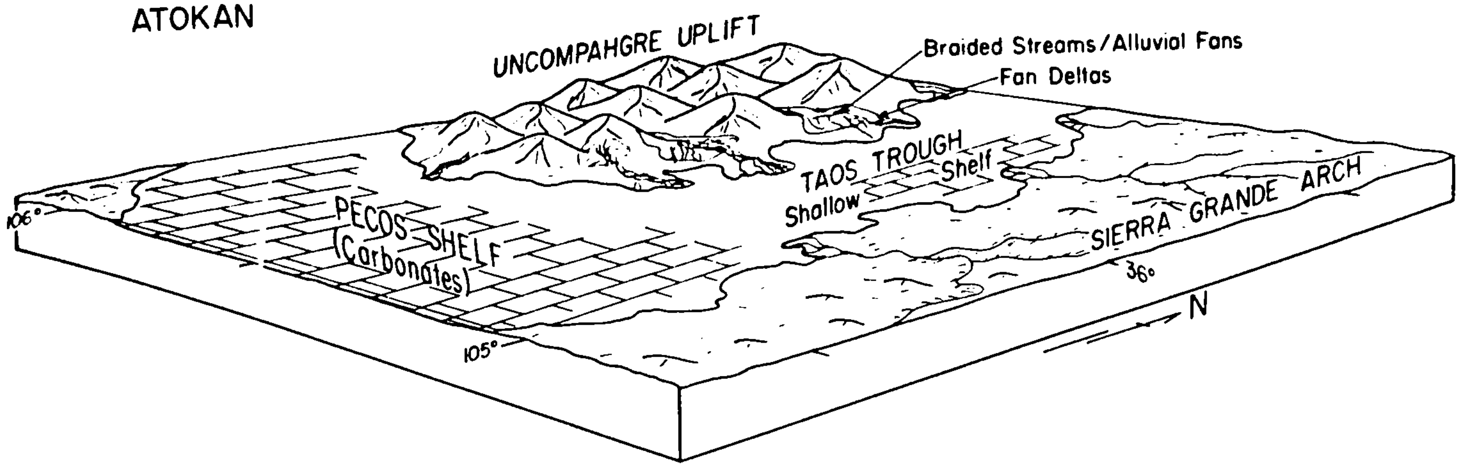


Figure 16. Atokan paleogeography of the Taos Trough and surrounding areas.

This general depositional and paleogeographic pattern continued into Desmoinesian time. However, to the north, the Cimarron Arch had become a major positive feature by earliest Desmoinesian time and coarse braided stream and fan-delta systems prograded southward and southwestward into the trough (Figs. 17 and 18). Locally, westward flowing braided streams joined streams flowing southeastward off the Uncompahgre Uplift to form fairly large southward flowing fluvial systems. By early to middle Desmoinesian time an extensive coastal plain had developed along the western margin of the basin. Humid alluvial fans flowed eastward into low-sinuosity, bed-load rivers which in turn, fed lobate deltas (Fig. 19). Basinward, a terrigenous slope system developed in conjunction with continued basin subsidence. As this delta platform prograded eastward, the axis of the trough also migrated eastward. As a result, the nearshore and coastal-plain environments flanking the Sierra Grande Arch shifted eastward and the basin widened.

Throughout middle to late Desmoinesian time the relief of the highlands diminished and a major transgression began. By late Desmoinesian time, the western delta platform and the eastern shelf had become inundated and shallow shelf conditions prevailed in the north (Fig. 20). Farther south, the Pedernal Uplift was supplying coarse arkosic sediment to Pecos Shelf (Kottlowski, 1968). In latest Desmoinesian time the Sierra Grande Arch, and possibly the Uncompahgre Uplift, were rejuvenated and coarse fluvial-deltaic complexes began filling the northern part of the basin (Fig. 21). During the remainder of the Pennsylvanian Period the seas gradually withdrew to the south. By the end of Pennsylvanian time the Taos Trough was dominated by southward flowing braided streams (Sangre de Cristo Formation); farther south, on the Pecos Shelf, deltaic deposition continued until early Permian time.

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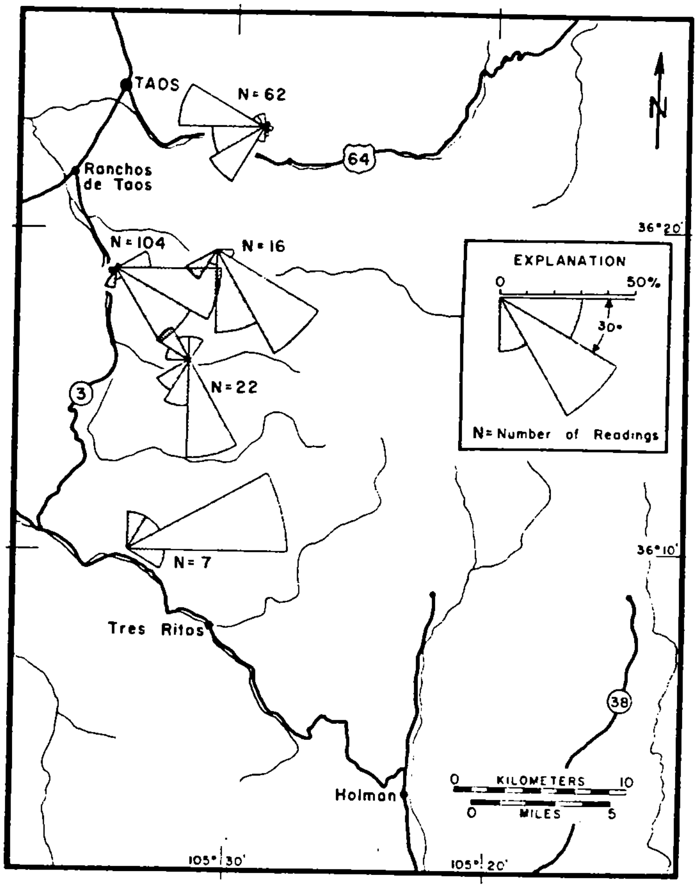

Figure 17. Earliest Desmoinesian directional features. Measurements on braided stream cross-beds (northern rose) and fan-delta foresets (four central roses).

I am particularly grateful to George J. Verville of Amoco Production Company for identifying the Pennsylvanian fusulinids. I also thank Bob Blodgett for his comments on parts of the manuscript. R. A. Morton and Bob Suchecki reviewed the manuscript and made many helpful suggestions. I especially thank Esther Magathan for her editorial comments.

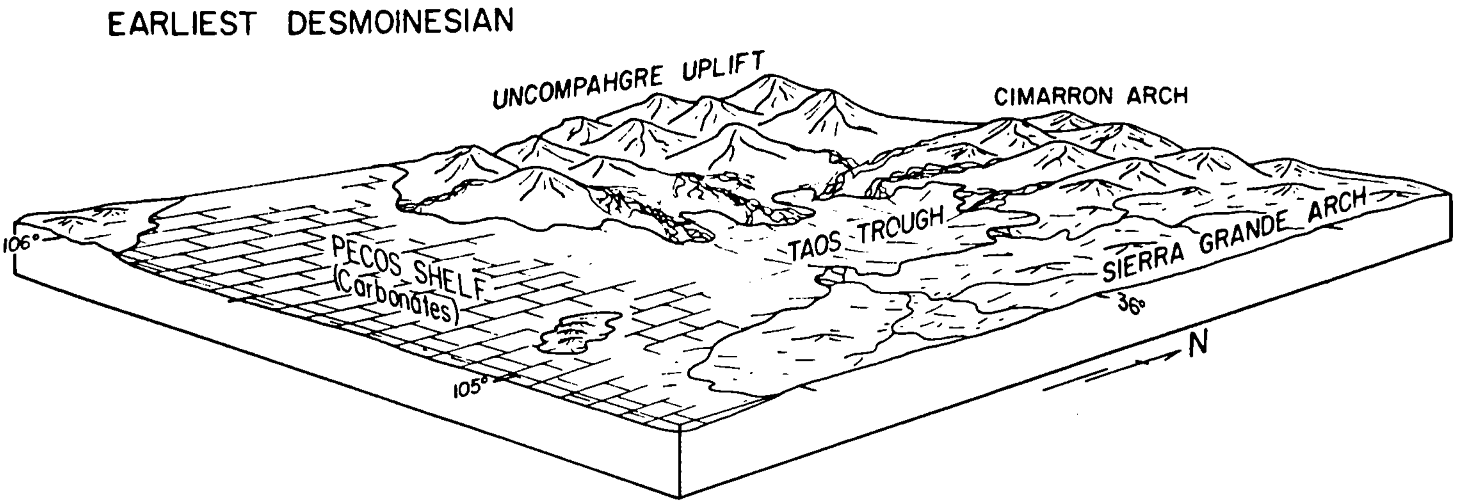

Figure 18. Earliest Desmoinesian paleogeography of the Taos Trough and surrounding areas.

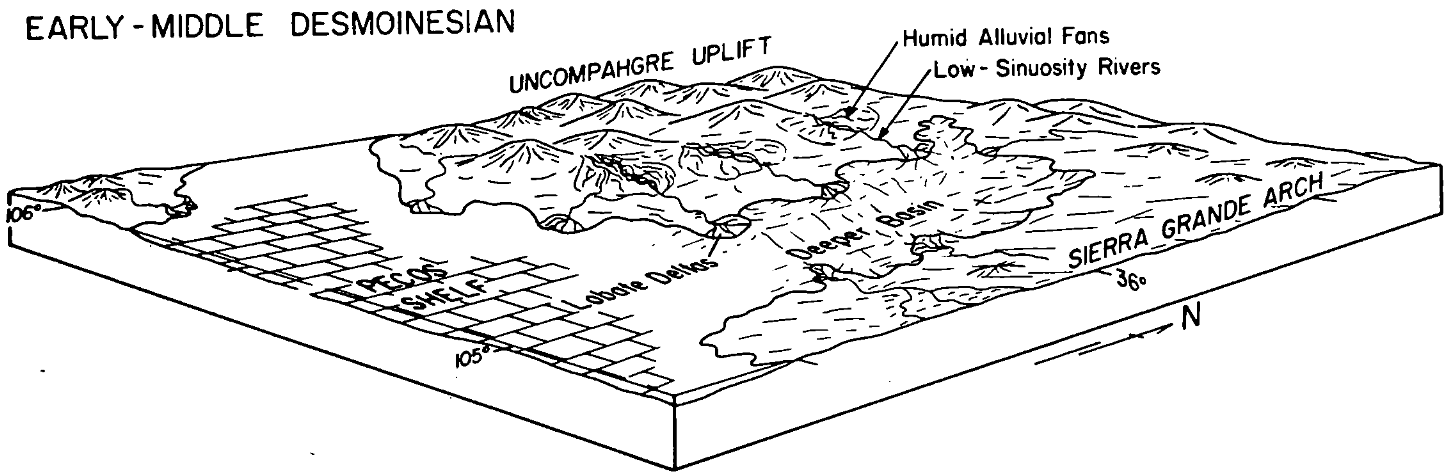

Figure 19. Early to middle Desmoinesian paleogeography of the Taos Trough and surrounding areas.

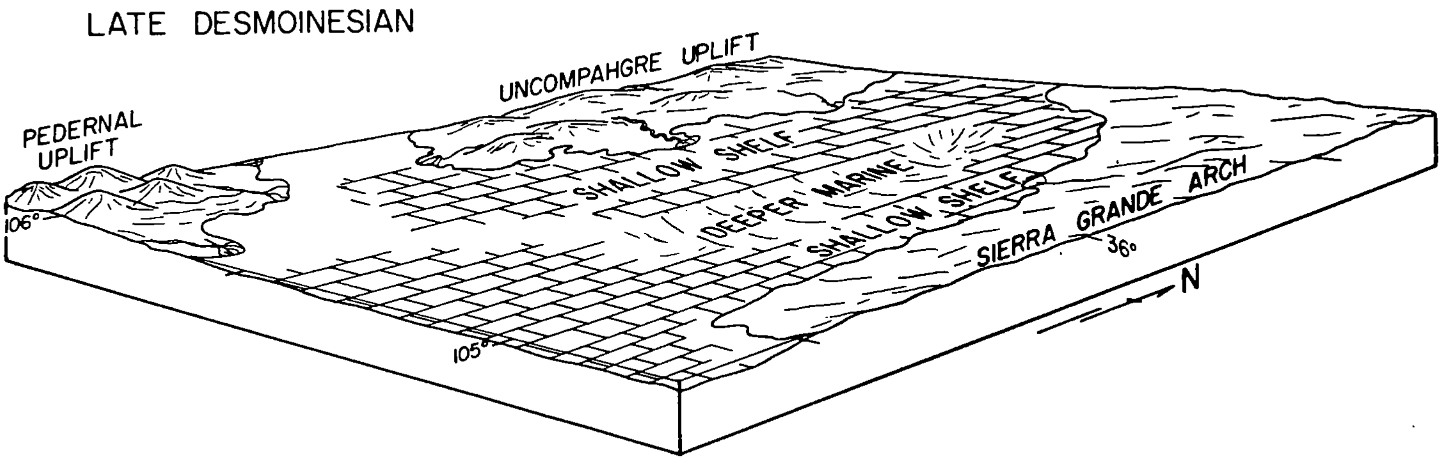

Figure 20. Late Desmoinesian paleogeography of the Taos Trough and surrounding areas.

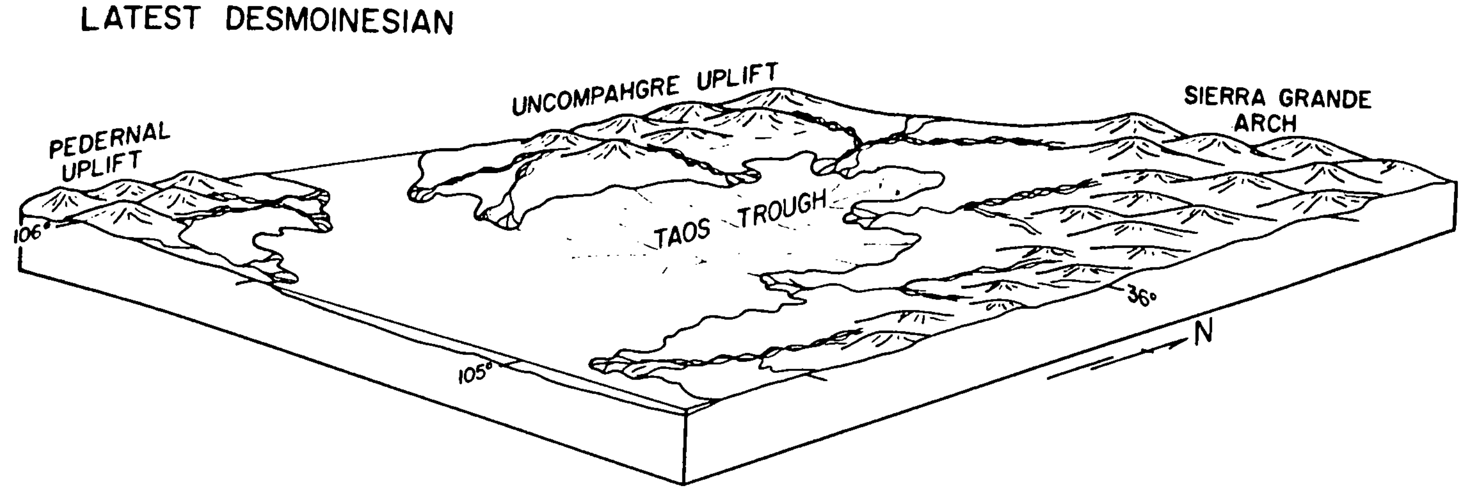

Figure 21. Latest Desmoinesian paleogeography of the Taos Trough and surrounding areas.

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