FLOOD TIDAL DELTA SEDIMENTATION IN THE LATE CRETACEOUS MENEFEE FORMATION (MESAVERDE GROUP), SAN JUAN BASIN, NORTHWEST NEW MEXICO[1]

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ABSTRACT

Donselaar, M. E. 1984 Flood tidal delta sedimentation in the Late Cretaceous Menefee Formation (Mesaverde Group), San Juan Basin, northwest New Mexico – Geol. Mijnbouw 63: 323-331.

The Menefee Formation (Mesaverde Group, Late Cretaceous) in the San Juan Basin, northwestern New Mexico, consists largely of deltaic plain and paralic deposits. The deposits were formed along the west coast of the Cretaceous Seaway. The upper part of the Menefee sequence displays isolated sandstone bodies with a lobate geometry. The sandstone bodies are embedded in carbonaceous shales of coastal swamp/lagoonal origin. Sedimentary structures include inclined lamination, tabular and wedge-shaped cross-bedding in the lower parts of the sandstone bodies, and trough cross-bedding in the upper parts. The bipolar distribution of transport directions, as well as the presence of mud drapes on foresets and bottomsets, point to a tidal environment of deposition. The lobate sandstone bodies are thought to have been generated as flood tidal deltas.

Based on theoretical models for the stacking of tidal delta deposits, an indication is given of the relation between relative rise of sea level and behaviour of the flood tidal deltas and connected tidal inlets on the barrier coast of the Cretaceous Seaway.

INTRODUCTION

In Late Cretaceous time a NW-SE elongated epicontinental sea fringed the eastern part of the Cordilleran fold belt (Fig. 1). This sea, the Cretaceous Seaway of North America, maintained connections with both the Arctic Ocean to the north and the Gulf of Mexico to the south throughout most of the Late Cretaceous (WILLIAMS & STELCK, 1975).

The Seaway received clastic sediments from the Cordilleran fold belt. Sediment supply to the basin varied greatly in geologic time, owing to spasmodic uplift of the Cordillera. Stacking of eastward thrust slabs in the Cordilleran fold belt and the sediments deposited in the Cretaceous Seaway put a load on the continental lithosphere (Fig. 2) and this is seen as the primary cause of continuous subsidence of the sedimentary basin in Late Cretaceous time (JORDAN, 1981). The combination of variable sediment supply and continuous subsidence brought about large scale transgressive and regressive cycles within the sedimentary basin.

Eastward migration of the thrust fault zone in the Cordilleran fold belt tectonically deformed the deposits of the western margin of the Cretaceous Seaway (WOODWARD & CALLENDER, 1977) (Fig. 3). The saucer-shaped San Juan Basin in NW New Mexico was formed by these tectonic movements.

THE MESAVERDE GROUP IN THE SAN JUAN BASIN

Nomenclature for the Mesaverde Group in the San Juan Basin was first given by COLLIER (1919). Since then, numerous studies appeared on the stratigraphic framework of the basin (a.o. SEARS ET AL., 1941; PIKE, 1947; BEAUMONT ET AL., 1956; HOLLENSHEAD & PRITCHARD, 1961; BEAUMONT, 1971). The Mesaverde Group of Late Cretaceous (Santonian to Campanian) age is made up of the Point Lookout Sandstone, the Menefee Formation and the Cliff House Sandstone (Fig. 4).

It is generally accepted that the deposits of the Mesaverde Group in the San Juan Basin were formed along a fairly straight, NW-SE striking coast (HOLLENSHEAD & PRITCHARD, 1961) (see Fig. 1). Towards the NE, the coastal deposits (Point Lookout Sandstone and Cliff House Sandstone) interfinger with marine deposits that were laid down in a broad, shallow epicontinental sea (SEARS ET AL., 1941; HOLLENSHEAD & PRITCHARD, 1961). Towards the SW, the coastal deposits grade

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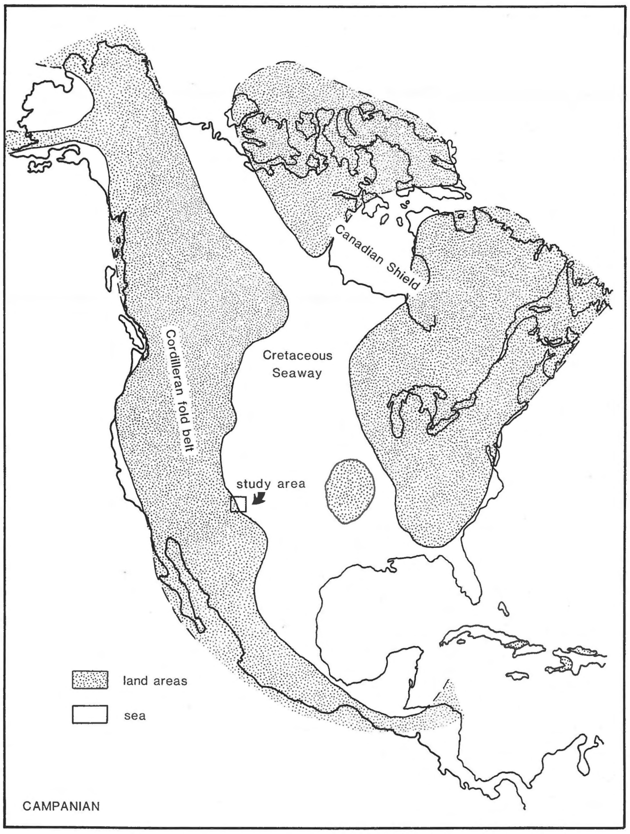

Fig. 1
Paleogeographic reconstruction of the Cretaceous Seaway of North America during the time of formation of the Mesaverde Group (Campanian). (Modified after Schuchert, 1955, and Williams & Stelck, 1975).

into coastal swamp and lagoonal sediments of the Menefee Formation. In time, the shore-parallel facies belts shifted in a seaward, and later in a landward direction (see Fig. 4).

While extensive work has been done to distinguish the successive transgressive and regressive stages of the epicontinental sea throughout the basin, few statements have been made on the tidal regime of this sea during Mesaverde times. SIEMERS & KING (1974) suggested the presence of tidal channels in the Cliff House Sandstone of Chaco Canyon, New Mexico, on the basis of faunal associations and the presence of bimodal cross-stratified sandstone. SLATER (1981), using a numerical model, calculated a microtidal range of the tides in an idealized Cretaceous Seaway.

THE MENEFEE FORMATION

Exposures of the Menefee Formation fringe the San Juan Basin (Fig. 5). It reaches a maximum thickness of 600 m in the southwestern part of the Basin; towards the northeast the Formation pinches out.

The sediments of the Menefee Formation consist of shales, carbonaceous shales, and low-sulphur coal in minable reserves. Carbonaceous shales and coal prevail in the lower and upper parts of the Menefee Formation (Fig. 6). In the middle part, the fine-grained sediments are interbedded with lenticular sandstones. Deposition took place in an alluvial plain to coastal swamp environment (MOLENAAR, 1977). Coal was formed under anaerobic conditions in a swamp directly behind the shoreline (BEAUMONT, 1971). From the presence of *Ophiomorpha* and *Uca-* like burrows at the base of the Menefee succession (SIEMERS ET AL., 1975) and from the direct lateral transition of carbonaceous shales into bioturbated coastal sandstones near the top, it is deduced that the lower and upper parts of the Menefee were deposited in a more open lagoonal/swamp environment. The interbedded sandstones and shales in the middle part of the succession represent deposits in distributary channels and interdistributary bays of the lower deltaic plain (SIEMERS ET AL., 1975). The Menefee coastal swamp/lagoonal area was protected from open sea by coastal barrier sandstones of the Point Lookout and Cliff House Sandstones. The coastal barriers of the Point Lookout Sandstone formed during a regressive stage in the

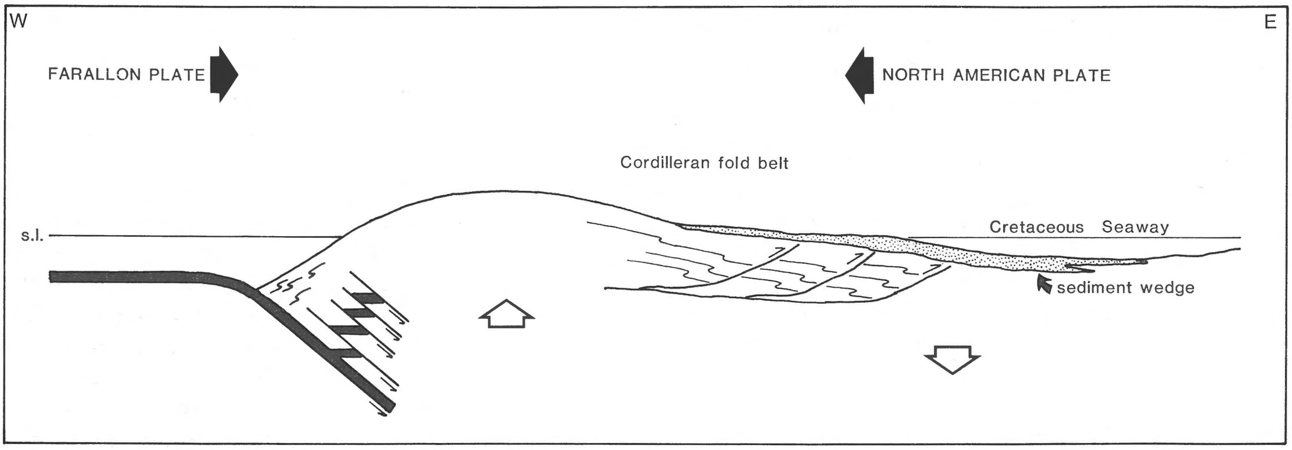

Fig. 2
Lithospheric loading of the crust by the stacking of thrust slabs in the Cordilleran fold belt, and by the sediment pile in the western part of the Cretaceous Seaway. The lithospheric loading resulted in continuous subsidence of the basin that fringed the Cordilleran fold belt to the east. (Based on discussion by Jordan, 1981. The plate nomenclature is according to McKenzie & Morgan, 1969).

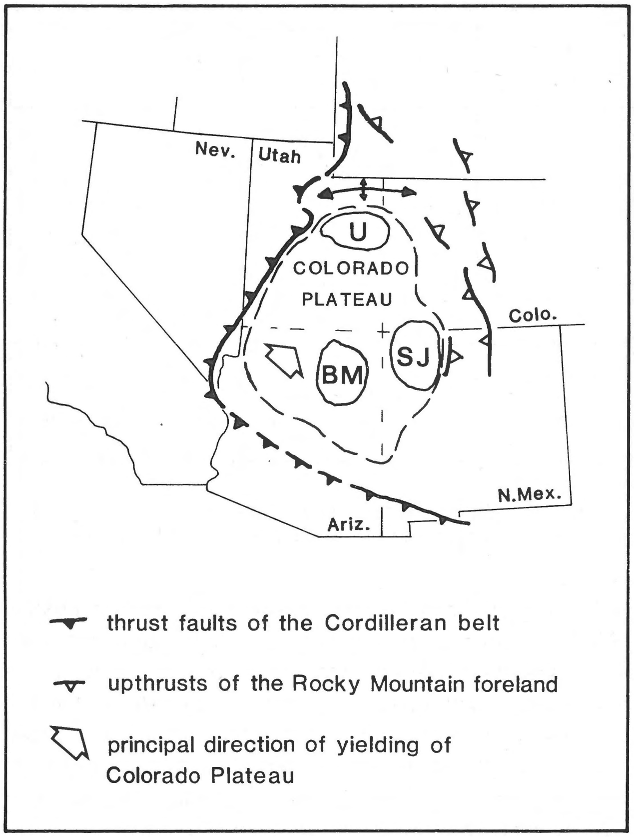

Fig. 3
Schematic tectonic map of the Four Corners area. The San Juan, Black Mesa, and Uinta Basins are saucershaped depressions, separated by anticlinal uplifts. The basins and uplifts were formed by the eastward prograding Cordilleran fold belt. (Modified after Woodward & Callender, 1977). SJ = San Juan Basin; BM = Black Mesa Basin; U = Uinta Basin.

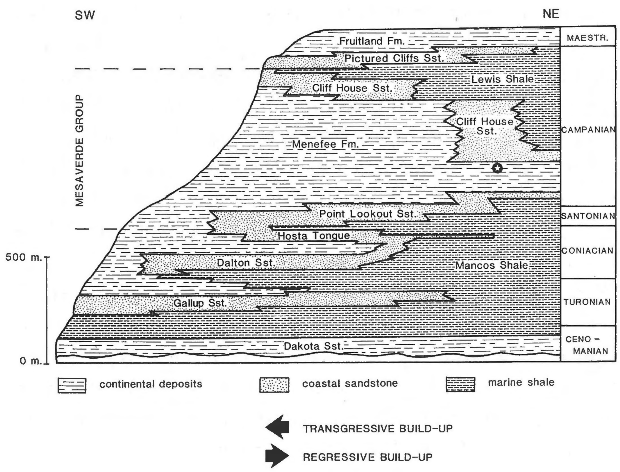

Fig. 4
Stratigraphic relationships of the Late Cretaceous deposits in the San Juan Basin in NW New Mexico. Asterisk indicates the stratigraphic position of the deposits discussed here. (Modified after Beaumont et al., 1956).

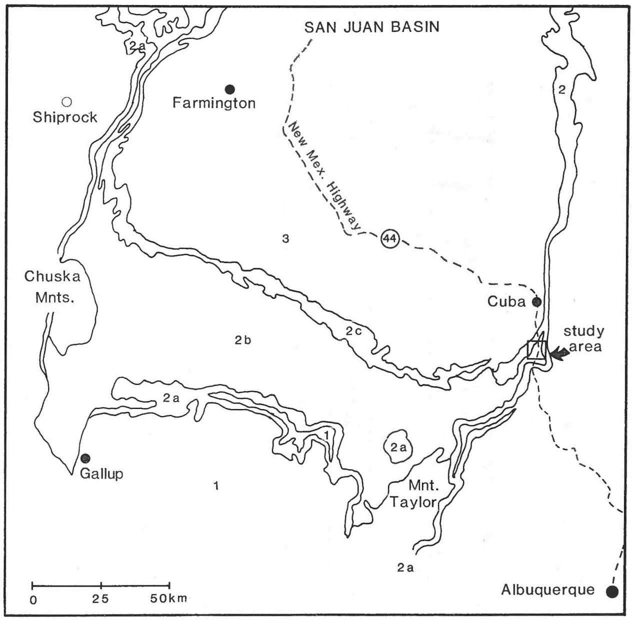

Fig. 5
Simplified geological map of the San Juan Basin in NW New Mexico (Modified after Beaumont et al., 1956). 1. Pre-Mesaverde deposits. 2. Mesaverde Group, consisting of (in ascending order): 2a. Point Lookout Sandstone. 2b. Menefee Formation. 2c. Cliff House Sandstone. 3. Lewis Shale and younger deposits.

Cretaceous Seaway. During the subsequent transgressive stage the deposits of the Cliff House Sandstone were formed. The coastal barriers consist mainly of extensive sheet sandstones.

STUDY AREA

The study area is situated in the eastern part of the San Juan Basin, 20 km south of Cuba along the old NM Highway 44 (Fig. 5). The Menefee Formation in this area has a thickness of 210 m and is overlain by coastal sandstones of the transgressive Cliff House Sandstone. The paleogeographic and stratigraphic framework of this area is well known by studies of HOLLENSHEAD & PRITCHARD (1961) and from detailed maps by WOODWARD ET AL. (1973). Sedimentologic work in this area has been carried out by SIEMERS ET AL. (1975), MANNHARD (1976) and SHETIWY (1978). From the NW-SE elongation of the coastal sandstones of the La Ventana Tongue of the Cliff House Sandstone (see HOLLENSHEAD & PRITCHARD, 1961), and the NE directed fluvial paleocurrent pattern, it can be concluded that the position of the coastline in this area agrees with the overall coastline elongation in the San Juan Basin.

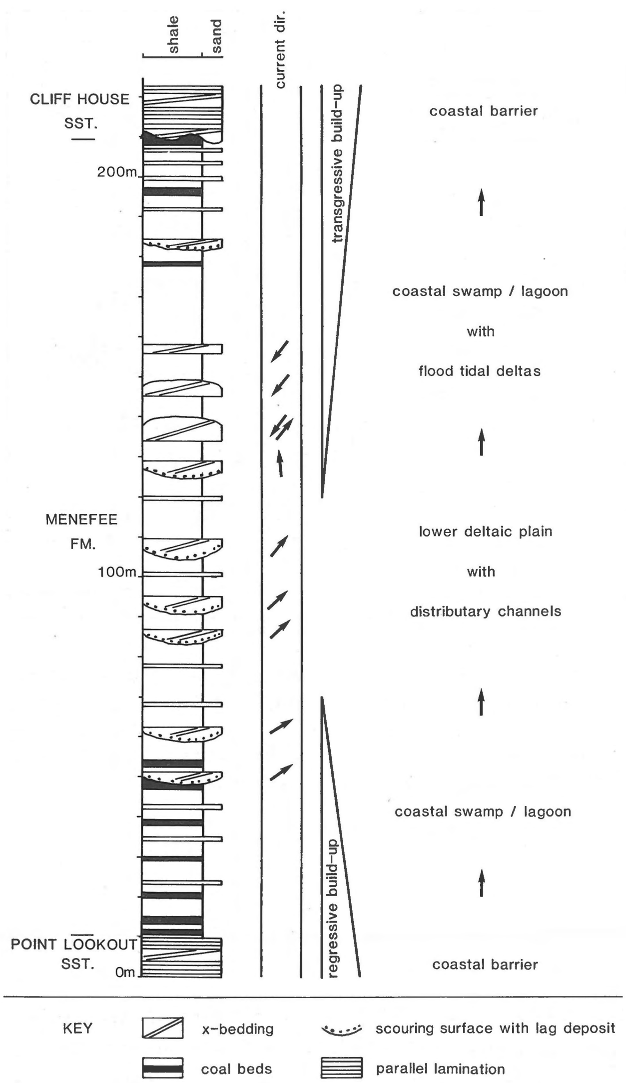

Fig. 6
Schematic log through the Menefee Formation in the La Ventana area. From the base of the Formation going up, the amount of coal decreases and the sand/shale ratio increases. Towards the top thin coal deposits reappear and the sand/shale ratio decreases again. The lobate sandstones discussed in this paper lie between 135-160 m. in the section.

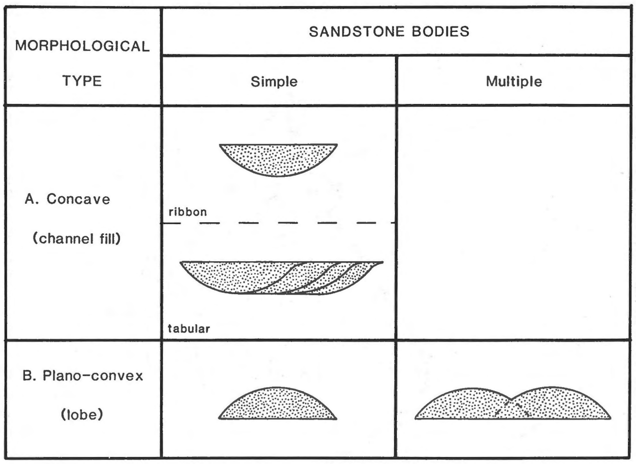

Fig. 7
Geometries of the most common sandstones of the Menefee Formation in the study area. (Modified after Nio & Hussain, 1984).

TIDAL DELTAS

Within the stratigraphic succession of the upper part of the Menefee Formation, two distinct types of sandstone geometry are encountered. The first type consists of lenticular to tabular sandstone bodies (Fig. 7, A). The sandstones have a concave to flat erosive lower surface, and a flat top. Cross-bedding in the sandstones shows a unidirectional NE transport direction. The sandstone bodies can be ascribed to fills of (laterally migrating) fluvial channels. The second type of sandstone bodies displays a lobate geometry (Fig. 7, B), with a flat, slightly erosive lower surface and a convex to undulating upper surface. Cross-bedding shows a bipolar (SW-NE) distribution. The second type of sandstone body will be described in detail. In this paper the terms concave and convex are used in the sense of concave-upwards and convex-upwards. In the study area four sandstones of both the simple and the multiple lobate type (see Fig. 7, B) are well exposed. The sandstones are loosely stacked and are embedded in carbonaceous shale of lagoonal origin (Fig. 8).

The sandstone bodies are made up of light-grey, fine-grained quartz sandstone. There are no vertical or lateral grain size variations within the sandstone body apart from shale clasts and plant fragments which are only present near the base of each body. The convex upper surface of the body is covered by a ferruginous cap; small-scale ripples are common on this surface. The upper surface has a slight (<2°) primary SW or landward dip.

Internally, each sandstone body is subdivided into two parts (Fig. 9). The lower part has a slightly erosive, flat base. The dominant structures are 10-95 cm high tabular to wedge-shaped sets and SW-inclined laminae (avalanche foresets). Reactivation surfaces are present (Fig. 10). The contact between the lower and upper part is partly gradual and partly erosive with local scours. Locally there is a thin shale break at the boundary. The upper part consists dominantly of 5-20 cm high trough-shaped sets.

Parallel to the foreset dip direction, reactivation surfaces and set boundaries in the lower part show a SW directed (i.e. landward) dip. The angle of inclination increases higher in the section (Figs. 9 and 10). The shale clasts at the base of each sandstone body decrease in size and eventually disappear up the foreset dip. Individual foreset laminae have a straight to sigmoidal shape. Mud drapes on the foresets are common (Fig. 11). Incomplete bundle sequences are present. Foresets pass into well-developed bottomsets, which contain regular intervals of double mud drapes, whereby each double mud drape consists of a mud lamina couplet separated by a thin

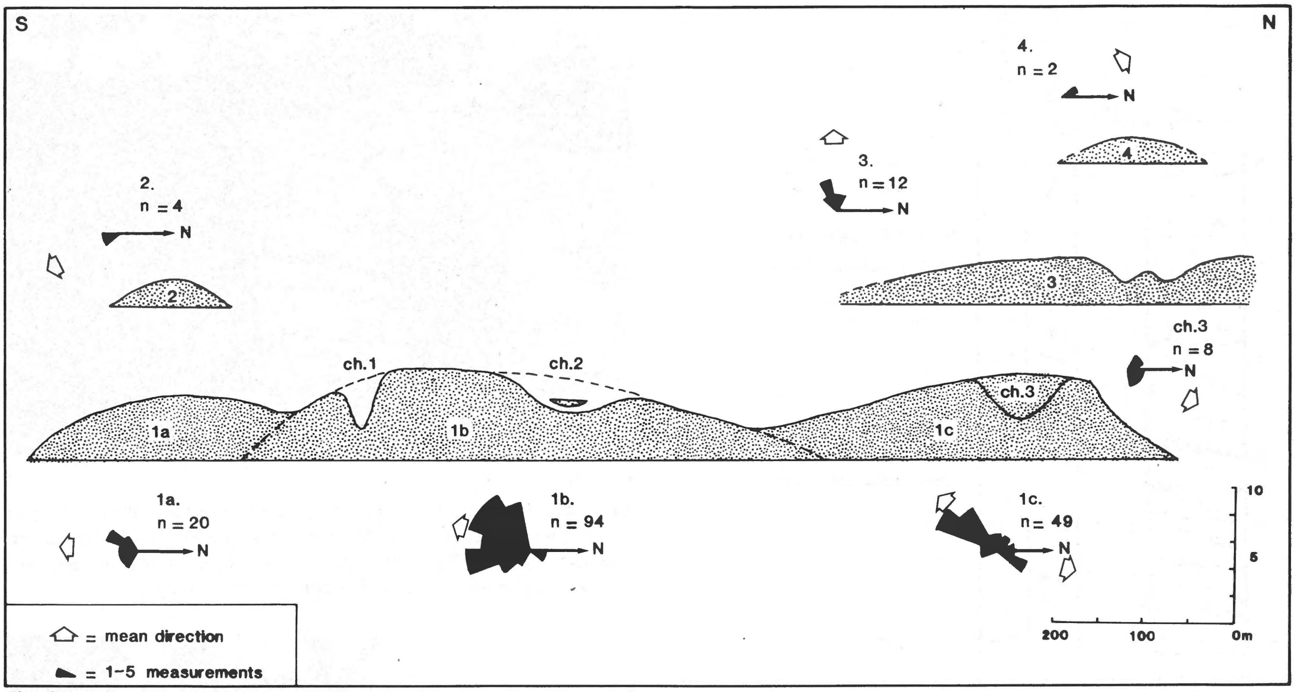

Fig. 8
Outcrop along old N.M. Highway 44 showing geometry and vertical stacking of the lobate sandstones, embedded in carbonaceous shale (shale forms white background). Upper part of the Menefee Formation in the study area. Sandstones nrs. 2 and 4 are of the simple lobate type, nrs. 1 and 3 are of the multiple lobate type. The rose diagrams show the distribution of the current directions in the sandstones. The current directions are measured from large-scale foresets.

sandy lamina. This suggests the preservation of daily tidal cycles as described by VISSER (1980), SIEGENTHALER (1982) and NIO ET AL., (1983). Bioturbation of the sandstones is limited, and confined to the upper part of each sandstone body. Foreset dips of the cross-sets show a bipolar distribution (Fig. 8) with a dominant SW component. In the lower part of sandstone body nr. 1 the subordinate NE direction is represented by a solitary train of small-scale ripples (ripple height 3 cm) that climbs the SW-directed larger foresets. The upper part of sandstone body nr. 1 contains several depressions (Fig. 8, ch.1-ch.3). The lower surface of these depressions is an erosive, scouring surface. Ch.1 and ch.2 are infilled with carbonaceous shales and 50-75 cm thick sandstone lenses. Ch.3 consists of a 3.3 m thick and 100 m wide sandstone lens. The foresets of the crossbedded sandstones dip to the NE. Adjacent to the sandstone lens the upper surface of sandstone body nr. 1 is covered by well preserved, straight-crested megaripples. Heights of the ripples are up to 30 cm, the transport direction is to the NE.

Sandstone body nr. 1 has a composite lobate geometry. Laterally, the sandstone body can be subdivided into three subunits (Fig. 8, nrs. 1a-1c) bounded by points of minimum thickness. At these points the extremity of one sandstone lobe drapes over the 'wing' of the adjacent one (Fig. 12). The separation of the two parts is accentuated by a major shale break. There are no erosive features at the contact. Mean foreset dip direction shifts from SSW to SW when going from 1a to 1c (Fig. 8). One kilometre to the N of the exposures described here, random measurements on similar sandstone bodies of the same stratigraphical level show a further shift of dip directions to the NW.

The sandstone bodies display certain characteristics that distinguish them from sandstone bodies of channel origin, which are also present in the upper part of the Menefee succession in the eastern part of the San Juan Basin.
The main distinctive features are:

1. the lobate geometry of the sandstone bodies;
2. the bipolar transport direction with a dominant SW. i.e. landward, component;
3. the arrangement of the internal structures. such as:
   - the uniform landward inclination of set boundaries and reactivation surfaces,
   - the flat lower surface that is only slightly erosive,
   - the dominance of smaller, trough-shaped sets in the upper part of the bodies, as opposed to higher, tabular to wedgeshaped sets and inclined laminae in the lower part,
   - the mud drapes on foresets and bottomsets.

From these characteristics we can interprete these sandstone bodies as flood tidal deltas, like those presently encountered in the lagoons on the North Atlantic coast of the USA (see e.g. BOOTHROYD & HUBBARD, 1975). The deltas develop at the distal part of a tidal inlet in response to flow expansion of the tidal current that passed through the inlet.

The flood tidal deltas in the Menefee lagoon expanded in the landward direction. The vertical sequence shown in Fig. 9

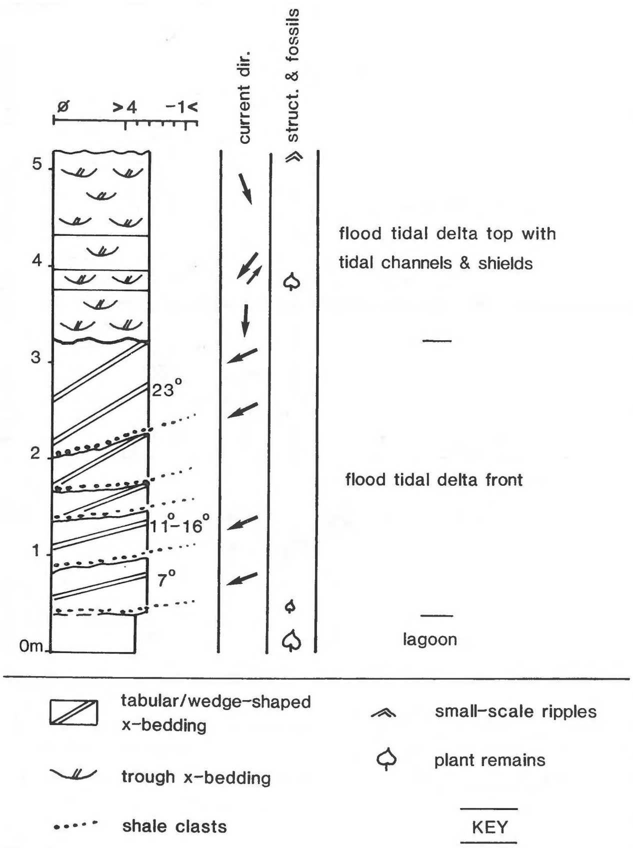

Fig. 9
Log through sandstone body nr. 1 of Fig. 8. Inclination of the foreset laminae increases upward from 7° near the base to 11°-16° and finally 23°. Section is measured at the site of Fig. 10.

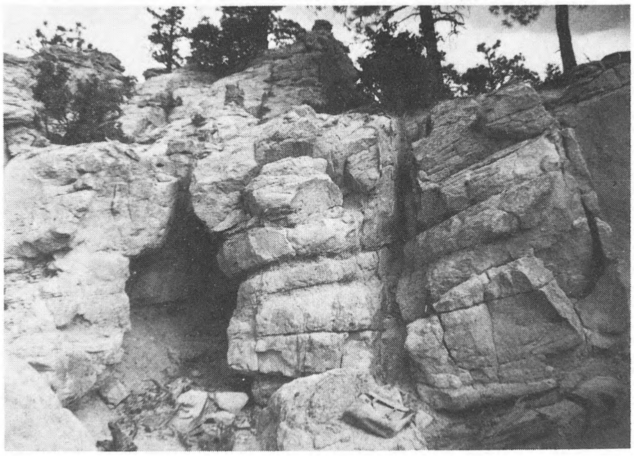

Fig. 10
Sandstone body nr. 1 (see Fig. 8) at the site of measured section in Fig. 9. Inclined reactivation surfaces dip to the SW (left). Inclination increases upward. The lower parts of the reactivation surfaces are accentuated by shale clasts. Hammer is 30 cm long.

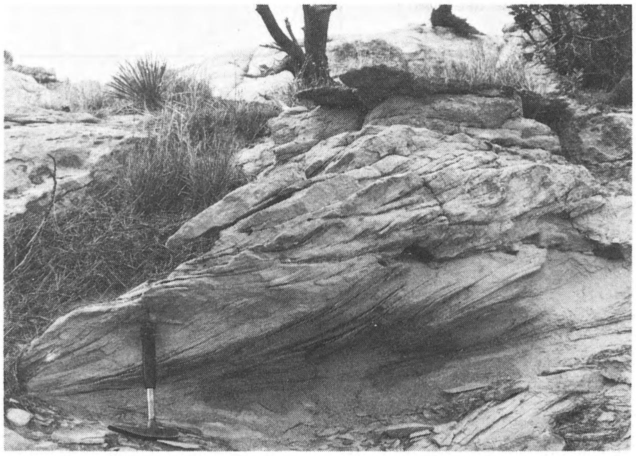

Fig. 11
Sandstone body nr. 1. SW-(left)-directed foresets pass into well developed bottomsets. The lower parts of the foresets and the bottomsets contain thin mud laminae. Hammer is 30 cm long.

represents the transition in time from delta front (lower part of the sequence) to delta top with flood directed distributary tidal channels (upper part of the sequence) (Fig. 13). The tabular and wedge-shaped sets in the lower parts are generated by straight-crested megaripples that migrated down the delta front. The steepening of the reactivation surfaces (Fig. 10) and of the set boundaries, as well as the presence of avalanche foresets on the steeper parts, reflect the transition in time from the lower (flatter) part of the delta front to the higher (steeper) part. The SW directed trough cross-sets were formed by migrating sinusoidal megaripples in the tidal channels and on the adjacent flood shields of the delta top.

The lens-shaped features in the upper part of sandstone body nr. 1 (Fig. 8, ch.1-ch.3) represent the distributary channels of the tidal delta. Ch.1 and ch.2 are abandoned channels that are subsequently infilled with fine-grained lagoonal sediment. Ch.3 is an infill of a major ebb channel within the flood tidal delta complex. The straight-crested, NE directed megaripples on the upper surface adjacent to the channel represent an ebb shield. The eccentric position of ebb channels within flood tidal delta complexes is common in modern equivalents (see e.g. BOOTHROYD & HUBBARD, 1975).

The regular thickness variations of sandstone bodies nrs. 1 and 2 (Fig. 8), as well as the divergence of transport directions from SE to NW, indicates that the tidal deltas consist of a series of coalescing lobes that debouch from a single tidal inlet.

The flood tidal delta sandstones in the upper part of the Menefee Formation can be considered to mark the start of the Cliff House transgression in this area.

PRESERVATION DEGREE

The described flood tidal delta deposits display a high degree of preservation. Both internal structural build-up as well as external plano-convex delta shape are preserved. Individual delta lobes drape the extremities of the adjacent lobe, without eroding the latter (Fig. 12). Erosive features are restricted to the scouring lower surfaces of the tidal channels on the delta

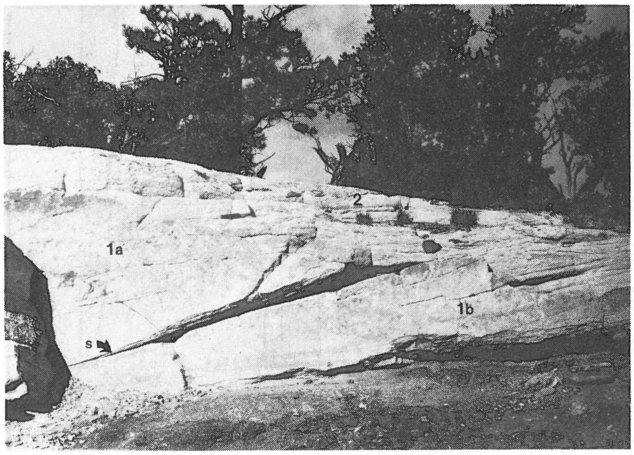

Fig. 12
Junction of two parts (1a and 1b; see Fig. 8) of the multiple lobate sandstone body nr. 1. Separation of the two parts is accentuated by a major shale brake (s) in the lower half of the sandstone. The upper half of the sandstone consists of a continuous trough cross-bedded sheet (2). The sandstone overlies a dark-grey carbonaceous shale. Hammer (30 cm long) for scale.

lobe. The high degree of preservation of the flood tidal delta deposits is largely due to the subsidence of the Cretaceous Seaway (Fig. 2) and also to the low position in the barrier sequence and the sheltered environment of formation, i.e. on the lagoonal side of a barrier island, protected from marine wave action.

TIDAL REGIME

The existence of tides is deduced from the presence of mud drapes on the foresets, of double mud drapes in the bottomsets, of incomplete bundle sequences, and from the bipolar distribution of transport directions.

The establishment of the kind of tidal regime on the barrier protected coast of the Cretaceous epicontinental sea, however, depends largely on indirect evidence. Barrier islands develop in micro- and meso-tidal environments and are absent on macro-tidal coasts (HAYES, 1975). In areas with a meso-tidal range and an active lateral inlet migration, such as the North Atlantic coast of the USA, the bulk of the preserved barrier deposits consists of tidal inlet sequences (KUMAR & SANDERS, 1974). Coastal deposits of the Mesaverde Group, however, are dominantly flatbedded sandstones with wave generated structures. Extensive tidal inlet sequences are lacking. A combination of these facts leads to the assumption of a micro-tidal regime for the Late Cretaceous Menefee-Point Lookout coast in the NW of New Mexico.

THEORETICAL MODELS

The high degree of preservation of the tidal deltas highlights the need for models for vertical stacking of such deposits. Vertical stacking can take place in an environment of relative rise of sea level, i.e. either on a subsiding coast and/or on a coast affected by sea level rise. When a coast is flooded in this way, a barrier island chain generally retreats landward (HEWARD, 1981). In this setting, flood tidal delta deposits either form a thin sheet, overlain by marine deposits, or are eroded by the tidal inlet related to the flood tidal deltas. However, depending on fluctuations in sea level and/or sediment supply, a barrier island can temporarily remain stationary and build upward (SWIFT, 1975) before resuming the landward migration. This setting is favourable for the formation of extensive superposed flood tidal delta deposits.

The main parameters that determine the arrangement of vertical stacking on a flooded coast are: the permanence or impermanence of the inlets (i.e. whether inlets stay open

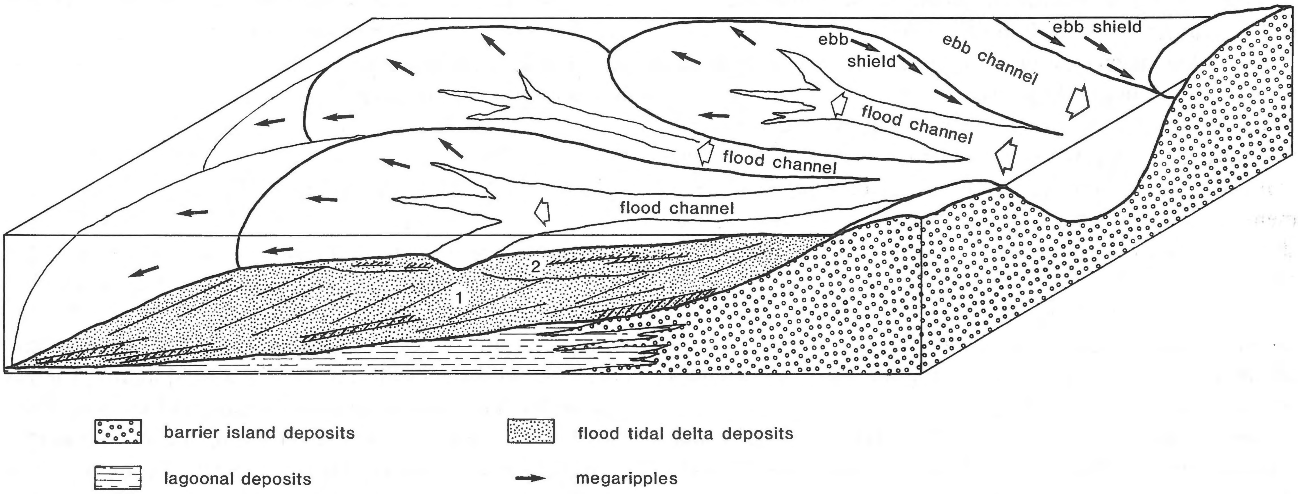

Fig. 13
Reconstruction of a landward expanding flood-tidal delta, based on the geometry of sandstone body nr. 1 of Fig. 8. Lower part (1) is made up of landward dipping megaripples and avalanche foresets, generated by sediment transport down the delta slope. Upper part (2) consists of megaripples and channel fills, formed on the ebb-shields and flood-shields, and by migration of the channels on the delta top.

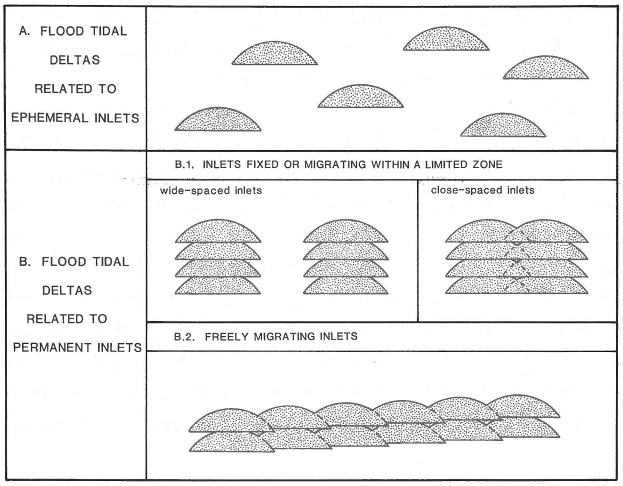

Fig. 14
Models for the vertical stacking of flood tidal deltas in an environment of relative rise of sea level. The delta deposits are schematically represented by plano-convex lenses. The use of the plano-convex shape is justified by the preserved geometries of the flood tidal delta deposits in the Menefee Formation.

A. Formation of flood tidal delta deposits connected to ephemeral inlets only takes place when the inlets are open. When the inlets are closed, the flood tidal delta deposits are covered with lagoonal fines. In time, this results in the formation of isolated sandstone lenses.

B. Permanent tidal inlets either are fixed, or migrate laterally. A fixed position of tidal inlets is generally related to pre-existing depressions in the substrate, such as flooded river valleys.

B1. Accumulation of flood tidal delta deposits connected to fixed inlets, or to inlets that migrate within a limited zone only, results in the formation of pillar-like sedimentary bodies. Close spacing of tidal inlets leads to the interconnection of the sedimentary bodies.

B2. Accumulation of flood tidal delta deposits adjacent to freely migrating permanent inlets results in the formation of extensive tidal delta belts.

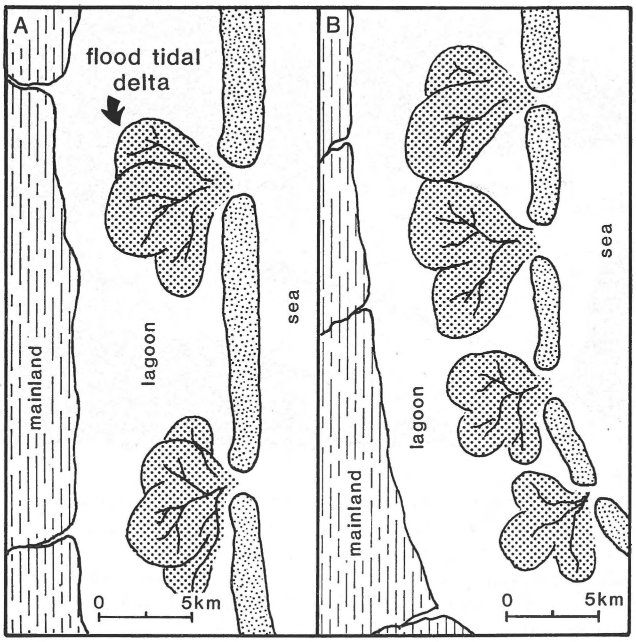

Fig. 15
The influence of inlet spacing on the interconnectedness ratio of tidal dellta deposits.

A. Isolated flood tidal delta bodies form on coasts with long barrier islands and few, wide-spaced tidal inlets. Long barrier islands typically form on coasts with a micro-tidal regime.

B. Coasts with short barrier islands and abundant, close-spaced tidal inlets are normal on meso-tidal coasts (Hayes, 1979). In this setting, flood tidal deltas can connect to form a continuous sheet.

permanently or for a few hours to several years (EL-ASHRY & WANLESS, 1968; ARMON & McCANN, 1979), the rate of relative rise in sea level, and the rate of lateral migration of the tidal inlet that is connected to the flood tidal delta.

The following models deal with a stationary barrier island position on an inundating coast:

In the case of ephemeral inlets, flood tidal deltas form intermittently. During periods when the inlet is closed the delta deposits are covered with fine-grained lagoonal sediments. The resultant deposits consist of isolated, lense-shaped sedimentary bodies with a random arrangement (Fig. 14, A).

In the case of permanent inlets, various types of vertical stacking depend upon the stability of the tidal inlet, i.e. whether the inlets are fixed, or migrate freely or within a limited zone (HEWARD, 1981).

Superposition of flood tidal deltas adjacent to fixed tidal inlets or to inlets that migrate within a limited zone, leads to the formation of narrow sedimentary bodies (Fig. 14, B1). The interconnectedness ratio of the sedimentary bodies depends on the spacing of the inlets on the barrier coast (Fig. 15).

Accumulation of flood tidal deltas related to freely migrating permanent inlets gives rise to the formation of extensive tidal delta belts (Fig. 14, B2).

The arrangement of the flood tidal delta deposits of the Menefee Formation, as shown in Fig. 8, is of the type of loosely stacked tidal deltas, embedded in lagoonal deposits. The closest theoretical approximation to this arrangement is a model of a barrier coast with ephemeral tidal inlets (Fig. 14, A) on an inundating coast.

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