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SEQUENTIAL DEVELOPMENT OF AN ESTUARINE VALLEY FILL: THE TWOWELLS TONGUE OF THE DAKOTA SANDSTONE, ACOMA BASIN, NEW MEXICO

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ABSTRACT: **The late Cenomanian Twowells Tongue of the Dakota Sandstone in the Acoma Basin (northwest New Mexico, USA) is a basinwide sandbody, 30 m thick, deposited during a period of relative sea-level fall and subsequent rise. For most of its extent, the Twowells Tongue consists of two markedly different sandstone units: shoreface and estuarine, respectively. The shoreface sediments were deposited during a period of relative sea-level highstand. The shoreface profile is incomplete, having its uppermost part (upper shoreface and foreshore) removed during subaerial valley incision. In places, the lower shoreface deposits are overlain by paleosols. The erosional surface is of regional extent; it depicts a complex valley morphology, in places 30 m deep, and is locally overlain by pebbles and shell lags. The valley, created during a relative sea-level lowstand, was filled by the second sandbody, consisting of a thick package (20-35 m) of transgressive, cross-bedded medium sandstones probably deposited in a middle to outer estuarine setting. The transgressive deposits of the Twowells Tongue are capped by a horizon of *Pycnodonte* oysters underlying black offshore shales interpreted to represent abrupt marine deepening.**

The cross-bedded unit, sharply overlying offshore shales or lower shoreface sediments, resembles other sandbodies of the Cretaceous Western Interior Seaway, traditionally interpreted as "offshore ridges", or more recently as lowstand shorelines. However, the investigations in the Acoma Basin show that both the "shelf-ridge" and the lowstand shoreline models are inadequate explanations, because the cross-bedded lithosome of the Twowells Tongue has the internal characteristics of tidally dominated estuarine deposits.

INTRODUCTION

The Cenomanian Twowells Tongue of the Dakota Sandstone in west-central New Mexico (Figs. 1, 2), is a basin-wide sand tongue deposited during a major regressive-transgressive event (Cobban and Hook 1984). For most of its thickness it consists of two distinctive lithosomes: a lower lithosome consisting of prograding-shoreface deposits abruptly overlain by an upper lithosome of relatively coarse-grained, cross-bedded sand units elongated north-south (Beach and Thomas 1978; Lauth 1978), more or less parallel to the inferred shoreline. At first glance, and for most of its extent, the cross-bedded lithosome of the Twowells Tongue shows some similarity, in terms of geometry and facies associations, with shelf sand ridges (Stride 1982). The origin of the shelf ridges is controversial. Two major driving mechanisms are usually accepted: the shelf ridges originate (1) from obliquely oriented tidal currents and other shelf currents aided by bathymetric irregularities (Tillman and Martinsen 1985; Nummedal et al. 1986) or (2) plume-fed sediments (Coleman et al. 1981) derived from delta systems. These models have been widely used to explain the elongate and apparently shoreface-detached, coarse sandstone units of the Cretaceous Western Interior Seaway (Tillman and Martinsen 1984; Gaynor and Swift 1988 in Wyoming; Beaumont 1984; Pozzobon and Walker 1990 in Canada; Palmer and Scott 1984; Wolter 1987; Nummedal and Wright 1989 in New Mexico). These interpretations, however, are not widely applicable to all such partly (or completely) shale-encased, cross-bedded sandbodies. Recent work has suggested that some of the previously interpreted ridges are instead forced-regressive shorelines (Plint 1988; Plint and Norris 1991; Posamentier et al. 1992; Walker and Bergman 1993) or valley fills (Van Wagoner 1991; Jennette et al. 1991). In the latter case the discrepancies in interpretation (from a ridge to a valley morphology) may result from the wrong choice of horizontal datum. The presence of two volcanic ash beds in the offshore shales at the base of the study succession helped to reconstruct the correct depositional geometry of the Twowells sandbodies. The objectives of this study were to determine the processes responsible for the depositional facies, the architecture of the constituent sandbodies of the Twowells Tongue, and the relationships between the sandbody architecture and relative sea-level fluctuations.

GEOLOGICAL SETTING AND STRATIGRAPHIC FRAMEWORK

The Cretaceous strata along the southwestern margin of the Cretaceous epineic seaway were deposited in a subsiding foreland basin bounded to the west by the Sevier orogenic belt and to the south by the Mogollon Highlands (Fig. 1; Molenaar 1983; Eaton and Nations 1991). Thrusting along the north-northeast-trending Sevier orogenic belt occurred from the late Early Cretaceous (Armstrong 1968; Villien and Kligfield 1986) through the Late Paleocene (Villien and Kligfield 1986). The combination of these structural constraints and long-term, eustatic sea-level fluctuations resulted in complex depositional patterns reflecting the interactions of tectonics and eustasy (Molenaar 1983; Nummedal and Riley 1991). The western shoreline of the epicontinental seaway advanced and retreated across New Mexico many times, leaving a record of intertonguing marine and nonmarine sediments. The rock record documents five major transgressions and regressions of the western shoreline across New Mexico (Molenaar 1983; Hook 1983). The earliest of these cycles, the Greenhorn Cycle (Molenaar 1983; Hook 1983), lasted from middle Cenomanian time until middle Turonian (ca. 5 my). During the transgressive phase of this cycle (middle to late Cenomanian), the Dakota transgression, all of New Mexico was flooded by marine water. A conspicuous embayment, Seboyeta Bay, extended into west-central New Mexico, where the Dakota Sandstone was deposited (Hook et al. 1980; Hook 1983; Molenaar 1983; Gustason 1989). Rock units associated with higher-frequency cyclicity during this transgression include the various tongues and members of the Dakota Sandstone and Mancos Shale (Fig. 3; Landis et al. 1973; Molenaar 1983; Hook 1983). The middle to late Cenomanian Twowells Tongue (Dane et al. 1971; Hook et al. 1980), which can reach a thickness of 35 m in the Acoma Basin, is the most widespread of these tongues. The Twowells Tongue is underlain by the dark-gray Whitewater Arroyo Shale Tongue of the Mancos Shale and overlain by the Graneros Shale Member of the Mancos Shale (Fig. 3).

Previous researchers suggested that the Twowells Tongue was distributed across the shelf during a relative sea-level stillstand (Molenaar 1983) or during a minor regressive pulse (Peterson and Kirk 1977). Recently, in a detailed sedimentological and stratigraphic study, Wolter (1987) suggested that the Twowells Tongue was deposited in three stages: (1) a shoaling-upward shoreface stage (comprising the Whitewater Arroyo Shale Tongue and the lowermost unit of the Twowells Tongue), (2) a sharply overlying transgressive stage with cross-bedded deposits (second unit of the Twowells Tongue), and (3) a capping nondepositional stage with bioturbated sandstones and *Pycnodonte* oyster bed facies. The Twowells Tongue has been interpreted by Wolter (1987) to represent a combination of a

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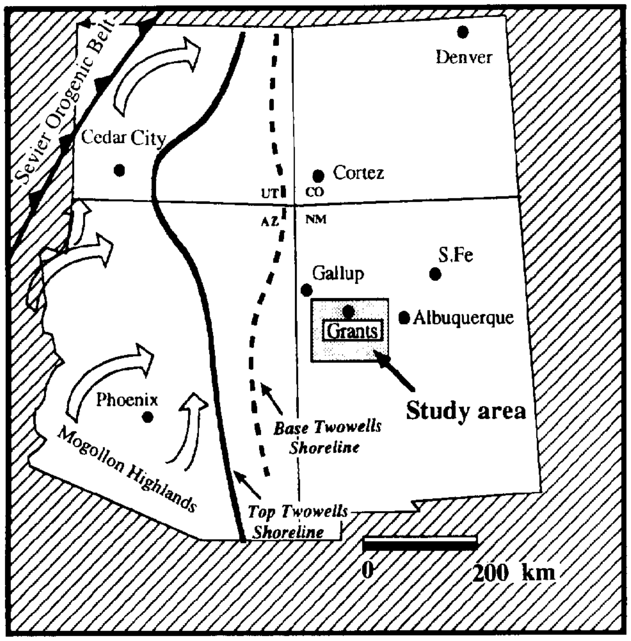

FIG. 1.—Location of study region with indication of transport direction of clastics that filled the Sevier foreland basin in southwestern Utah and northern Arizona–New Mexico (modified from Eaton and Nation 1990). The map indicates also the position of the shoreline at the base of the Twowells Tongue and the maximum transgression recorded at its top (from Molenaar 1983; Hook and Esterly 1985).

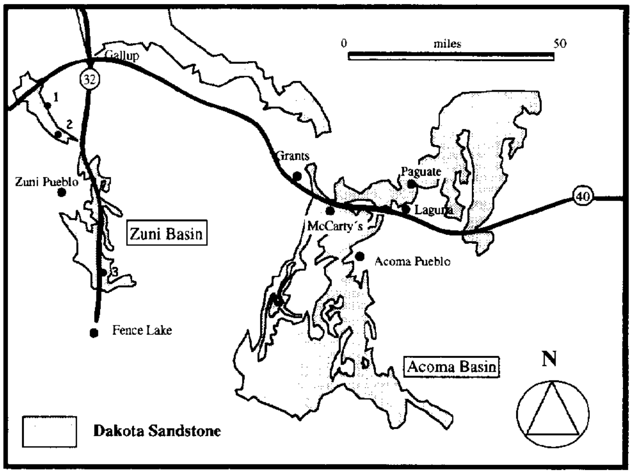

FIG. 2.—Schematic geologic map of the distribution of the Lower Cretaceous Dakota Sandstone in Acoma and Zuni Basins, northwest New Mexico. The investigations were carried out mainly in the Acoma Basin, within the Acoma Indian Reservation. Reconnaissance study was done also in the Zuni Basin in three localities: (1) Manuelito Canyon; (2) Twowells village; (3) Mesita de Yeso.

shoreface and an offshore shelf sand ridge detached southwards from a delta in the Four Corners area. In the Acoma Basin the cross-bedded facies forms a north-south-trending linear unit (the Acoma ridge) 32 km long, 10 km wide, and 35 m thick (Wolter 1987).

In the present work, I agree with the shoreface interpretation of the lower sandbody, but I argue that the upper sandbody accumulated as the transgressive infill of an incised valley.

METHODS

The Twowells Tongue of the Dakota Sandstone is exposed all around the Acoma Reservation, along Interstate 40 from McCarty's to Grants (Figs. 2, 4) and in few good outcrops in the Zuni Basin (Fig. 2). The outcrops within the Acoma Indian Reservation are easily accessible from minor roads crossing the Acoma land and from the exits of interstate I40. The sandbodies were studied by describing 16 sections and panoramic photomosaics. The measurements included recording sedimentary structures, grain size, paleoflow indicators, contacts, trace fossils, and body fossils. The thickness of the succession studied is about 40 m. Except for Section 16, which was measured within an off-limits area, and Section 11 (location in Fig. 4), the sections were spaced 500 m to 6 km apart, and incorporated into three cross sections (A–A′, B–B′, and C–C′, Figs. 8, 9, 13, shown later in the paper). Sections 16 and 11 were also incorporated into the three-dimensional fence diagram of Figure 14 (shown later). Two bentonite beds cropping out within the Whitewater Arroyo Shale were chosen as a datum for the measured sections. A reconnaissance study was carried out in the Zuni Basin in three principal localities (1, 2, 3) indicated in Figure 2.

FACIES ASSOCIATIONS

Two major facies associations were recognized within the Twowells Tongue: (1) a coarsening-upward sandy shoreface facies association, and (2) a cross-bedded sandstone facies association sharply overlying the shoreface deposits. The Twowells Tongue is capped by a horizon of *Pycnodonte* oysters that underlies organic-rich, fissile black shales.

Facies Association 1: Shoreface Sandbody

The shoreface sediments gradationally overlie the Whitewater Arroyo Shale Tongue of the Mancos Shale (Fig. 5). They constitute a coarsening-upward sequence of heterolithic units of shales and sandstones with planar-laminated to hummocky-cross-stratified facies (Fig. 6). The shoreface profile (maximum 15 m thick) is incomplete: most of the middle to upper shoreface is missing, having been eroded by a subaerial surface associated in places with paleosol horizons. In some areas (westward of McCarty's) the unconformity overlies the offshore Mancos Shale directly and the shoreface sandstones are completely missing. Five broad lithofacies were distinguished within the shoreface sandbody: (1) black, fissile shales; (2) siltstones with thin-bedded sandstone intercalations; (3) heterolithic units of sandstones and siltstones; (4) planar-stratified to hummocky-cross-stratified sandstones; and (5) sandstones with calcareous nodules (paleosols).

(1) Organic-Rich Black Shales

Description.—Lithofacies 1 consists of very dark to black, fissile, organic-rich, nonbioturbated mudstones forming intervals 6–10 m thick. The lithofacies underlies the Twowells Tongue and characterizes the Whitewater Arroyo Shale Tongue of the Mancos Shales. The shales contain two bentonite layers, each 4–15 cm thick, which form excellent marker horizons across the Acoma Basin.

Interpretation.—The prevalence of fissility and the lack of identifiable biogenic and sedimentological structures imply either oxygen-deficient, anaerobic conditions on the shelf bottom (Savrda et al. 1984; Davis and Byers 1989) or a substratum unfavorable for colonization by most benthic organisms (Driese et al. 1991). The shales are suggested to have been deposited in dysaerobic and anaerobic water probably by pelagic settling.

(2) Siltstones with Thin Sandstone Intercalations

Description.—Lithofacies 2, which overlies Lithofacies 1, is characterized by siltstones with thin layers of very fine sandstone, forming intervals up to 10 m thick. The sandstone-shale ratio ranges from 0.1 to 0.3. Sand-

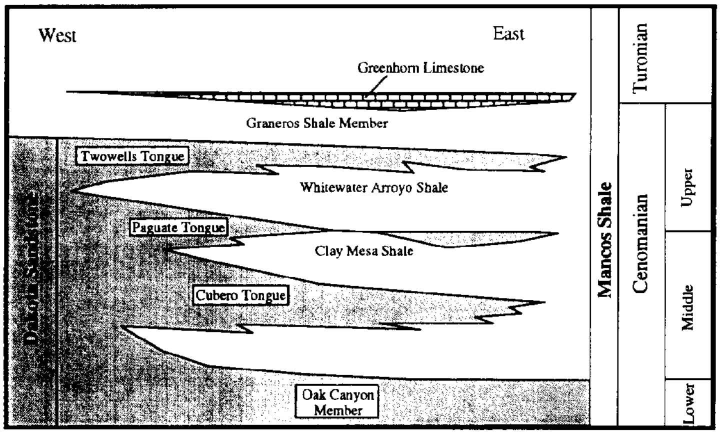

FIG. 3.—Schematic cross section of the intertonguing relationships of the Dakota Sandstone and the Mancos Shale along the southern flank of the San Juan Basin (modified from Cobban and Hook 1984). The Dakota Sandstone has not been successfully divided stratigraphically; the conventional stratigraphy is shown here.

stone layers are 2–5 cm thick and show planar to undulating geometry. Bed contacts may be diffuse or erosional with local scouring. The sandstones beds tend to become slightly thicker and more closely spaced upwards. Bioturbation is very intense with *Chondrites* and *Helminthoidea*. Current ripples and planar lamination are locally present in the thin sandstone beds.

Interpretation.—Lithofacies 2 is interpreted as representing deposition in a middle to outer shelf setting that was affected by episodic storms, probably in a transition zone of a prograding shoreface.

The contrast in lithology and bioturbation relative to the black shales of Lithofacies 1 suggests that these sediments were probably deposited in a shallower, generally better-oxygenated setting. The very fine-grained,

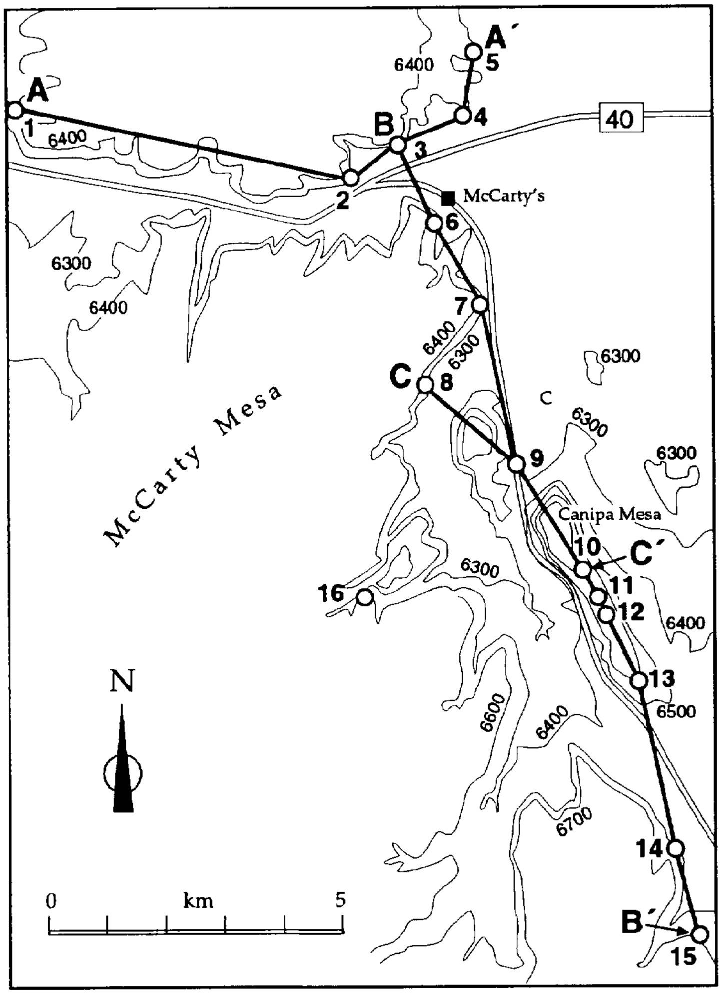

FIG. 4.—Location of the sections and cross sections in the Acoma Indian Reservation.

FIG. 5.—General view of the Twowells Tongue in Canipa Mesa with trace of Section 13 (see Figures 4 and 9 for location). The dissection of the mesa topography and the presence of a network of canyons provided a good three-dimensional control of facies and geometry. The Twowells Tongue forms the edge of the mesas and an easily recognizable prominent relief on the offshore Mancos Shales.

burrowed, faintly current-rippled sandstones, which dominate the uppermost part of the siltstone interval, are considered to be distal storm-current deposits on a shelf with a low rate of sedimentation.

(3) Heterolithic Units of Sandstones and Siltstones

Description.—Lithofacies 3 consists of poorly to moderately sorted, strongly bioturbated siltstones and very fine to lower-fine sandstones organized into discrete, coarsening-upward and thickening-upward units, each one 1–3 m thick. The lithofacies constitutes the lowermost part of the shoreface sandbody (Fig. 6) and can reach 10–15 m in thickness. It overlies Lithofacies 2 with a gradational contact and grades upward into lithofacies 4. Sandstone/siltstone ratio is 0.80–0.95. Weathering is typically blocky to semifissile (Fig. 6). Sandstone beds are 5–20 cm thick, with an average of 15 cm. Siltstone and shale interbeds are a few millimeters to 4 cm thick. Beds are tabular and can be followed for tens of meters. At their bases are usually thin zones of rip-up clasts 0.5–2 cm long.

The lithofacies is strongly bioturbated (90–100%) with *Paleophycus*, *Planolites*, *Chondrites*, and *Helminthoidea* traces. Only in the uppermost part were *Terebellina* and *Shaubcylindrichnus* observed. Because of intense bioturbation, contacts between sandstone beds and bounding strata tend to be diffuse and poorly defined. Sedimentary structures are almost completely obliterated, although discrete sharp-based beds, at the top of thickening-upward units, display clear parallel lamination, hummocky cross-stratification, and ripple lamination. Some of these beds contain shell debris, are cemented and form discontinuous concretions along the cliff face of the outcrops. Rare, discrete, fining-upward tabular strata were recognized in places.

Interpretation.—Lithofacies 3 is believed to have been deposited in the transition zone from an offshore to a lower-shoreface setting. The alternation of bioturbated and laminated sandstone reflects the alternation of fair-weather and storm-wave processes in a lower shoreface environment on a wave-dominated shoreline. Planar lamination in the thickest sandstone beds suggests conditions of upper-flow-regime plane-bed deposition (Dott and Bourgeois 1982; Hunter and Clifton 1982). The fining-upward beds can be interpreted to represent tempestites, the suspension fallout deposits of single, decelerating, sand-entraining currents (Aigner 1982).

(4) Planar-Stratified to Hummocky-Cross-Stratified Sandstones

Description.—Lithofacies 4, which gradationally overlies the heterolithic units of siltstones and sandstones, comprises clean, coarser-grained (lower fine) and planar-laminated to low-angle cross-laminated sandstones. Beds are 10–60 cm thick, with tabular to lenticular geometry. Bed bases are sharp and erosional over thin (a few millimeters to 1 cm thick) siltstone interbeds. Bed tops are commonly ripple cross-laminated, although commonly this lamination is destroyed by bioturbation. Bioturbation is slight in the sandstone beds, with *Thalassinoides* and rare *Ophiomorpha* traces, but is more intense in the interbeds. The degree of bioturbation and the percentage of siltstone interbeds decrease upwards. Escape burrows characterize the whole interval. In the uppermost part sandstone beds tend to become amalgamated, better laminated, and intercalated with lensoid shell beds. Shell beds (Fig. 7) are 3–15 cm thick and are composed of a wide variety and chaotic mixture of mainly articulated, benthic, molluscan shells (*Pinna*, *Inoceramus*, *Exogyra levis*, and *Exogyra trigeri*, among others; Cobban 1977). The overturned position of the shells suggests transport. In the uppermost part of the lithofacies amalgamated hummocky cross-stratification dominates the lithofacies assemblage.

FIG. 6.—Close-up view of the basal part of the shoreface lithosome of the Twowells Tongue (Facies Association 1). The blocky to semifissile sandstones and siltstones grade upward into the hummocky-cross-stratified sandstones (1.5 m Jacob's staff as scale).

Interpretation.—Lithofacies 4 is thought to have been deposited by decelerating, sand-entraining storm currents in a lower to middle shoreface environment. The clean, slightly burrowed, planar-laminated nature of the tabular-bedded sandstones suggests that the tempestites were deposited in a shallower environment than the heterolithic units of siltstones and sandstones, and that the rate of sedimentation had increased. Amalgamated, planar-laminated and hummocky-cross-stratified tabular sets, which characterize the uppermost part of the lithofacies assemblage, constitute

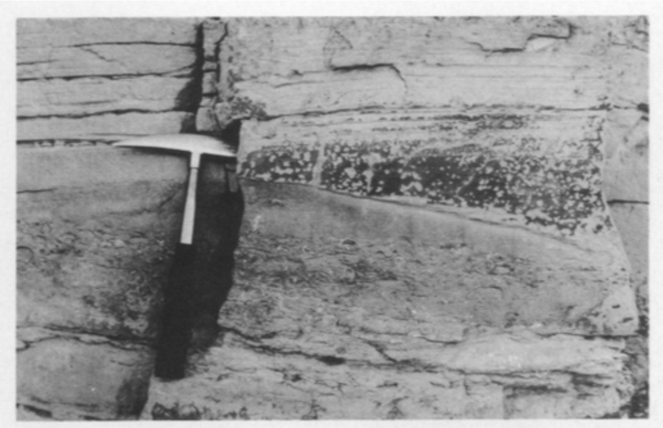

FIG. 7.—Amalgamated HCS sandstones. Note the storm layer with bivalve shells in overturned position.

a more proximal tempestite accumulation. Hummocky beds are interpreted to have been formed in a multidirectional flow regime as the result of combined, storm-wave oscillatory flow and unidirectional "steady" storm current (Harms et al. 1975; Dott and Bourgeois 1982; Swift et al. 1983; Greenwood and Sherman 1986; Southard et al. 1990). Hummocky-cross-stratified beds have sharp, erosional bases, suggesting that they accumulated during the waning phase of shelf storm currents. Physical structures indicate that the rate of sedimentation was high and that detrital feeders were not present. The lack of mud drapes and the predominance of *Ophiomorpha* burrows demonstrate that deposition was typified by agitated-water conditions in a shallow marine setting (Chamberlain 1978; Seilacher 1978; Pemberton 1992).

(5) Sandstones with Calcareous Nodules (Paleosols)

Description.—Lithofacies 5 is present only in few sections (1, 12, and 13 in Figures 8, 9, and 10), immediately below the major erosional surface that separates the shoreface deposits from the cross-bedded sandstones of the overlying lithosome. It consists of fine-grained, buff sandstone (the same as the shoreface), up to 1 m thick, with abundant carbonate nodules 1–4 cm long, and absence of sedimentary structures. No roots or mottling were observed.

Interpretation.—This lithofacies is interpreted as nodular caliche paleosol (Lehman 1989; Theriault and Desrochers 1993), as suggested by absence of primary sedimentary structures and the presence of caliche nodules. The absence of evidence of water-table oscillations, vertical roots, and generally organic material suggests that the water table was low, allowing almost complete drying and oxidation of the eventual organic debris deposited. Alternatively, the organic layer could have been removed by erosion. The paleosols record exposure of the shoreface and low rates of sediment supply.

Facies Association 2: Valley-Fill Deposits

The second facies association is easily recognizable in all Acoma and Zuni basins. It sharply overlies the first facies association (the shoreface) or the underlying offshore shales. Facies Association 2 consists of sets of cross-bedded medium to coarse sandstones with or without pebble and shell lags (Fig. 11). Its erosional basal surface has a complex topography with highs and lows that controlled the distribution and thickness of the cross-bedded sandstones. The strong difference in grain size and color between the underlying shoreface and the cross-bedded deposits make the two facies associations easily distinguishable in the field (Fig. 12).

(1) Pebble and Shell Accumulation

Description.—Pebble lags (Lithofacies 1), with very poor sorting and high matrix percentage, were recognized in several sections (1, 10, 12, 13; Figs. 8, 9, 10), abruptly overlying the middle and lower shoreface deposits or the paleosol beds (Fig. 10). The conglomerates, 3–13 cm thick, form laterally discontinuous lenses. Clasts are subrounded to rounded and can be as much as 5 cm in diameter. Their composition (quartz, chert, and sandstone) reflects an extrabasinal source. Matrix is fine to lower medium sandstone. Shell fragments, shark teeth, and rare bone fragments were found at the base of the pebble lag. Pebble layers are bioturbated, with large horizontal and vertical burrows penetrating the underlying deposits.

At the same stratigraphic level, and perhaps laterally equivalent, there are local lenses of shells (Fig. 11) up to 50 cm thick and laterally persistent for 30 m. They consist of transported accumulations of *Exogyra* in a matrix of medium sand. Pebbles are dispersed within these intervals and usually are concentrated at the top or, to a lesser extent, at the bases of the shell beds.

Interpretation.—The general characteristics of this interval suggest that the thin lensoid pebble layers and the shell accumulations represent condensed lags (Swift 1968; Nummedal and Swift 1987), probably produced during an initial rise of sea level across the underlying subaerial erosional surface. Their position, immediately overlying the paleosol horizons at the edge of the large valley, indicate that pebble lags were probably deposited over interfluve areas. Extrabasinal quartz and chert pebbles are interpreted to have been reworked from fluvial deposits by tidal currents, which contributed to the onshore transport of shark teeth and shells. The lensoid shell beds could also be interpreted as concentrates at the bases of channels infilled by cross-bedded sandstone units.

(2) Cross-Bedded Sandstones

Description.—This lithofacies consists of bidirectional, planar, trough to sigmoidal cross-bedded, slightly glauconitic, medium to coarse sandstone. It abruptly overlies the shale lithofacies, the fine-grained shoreface deposits, the paleosols, or the pebble lags (Figs. 10A, 11). The lithofacies is well developed in both Acoma and Zuni basins. Its thickness is quite variable, and ranges from 34 m in Sections 2 and 8 to 1 m in Section 14 (Figs. 8, 9, 13). As shown in the three-dimensional fence diagram (Fig. 14), it constitutes the infill of very broad scours, deeply incised into the underlying deposits. Although the morphology of the basal bounding surface is variable, the lithofacies shows always the same sedimentological characteristics, both within the valley as well as in the valley edges The cross-bedded lithofacies is made up almost entirely of sandstones (95–100%) and with a minor percentage of siltstones and mudstones. Planar cross-strata are 10–120 cm thick. Intervals of wedge-shaped planar cross-beds predominate, but tabular cross-strata are also present. Wedge cross-beds can be followed laterally for 15–20 m. Bases are sharp, with scours and in some places load structures. Cross-bed sets are composed of centimeter-thick, normally graded, steep planar foresets with abundant reactivation surfaces and pause planes. Commonly they are internally organized into bundled foresets in which thicker sandstones alternate with double-mud-draped, thin sandstone beds (Fig. 15A). Zones of rip-up clasts are common along the set boundaries and in the bottomsets. Bottomset laminae typically show tangential contacts with the lower bounding surface. Topset laminae were seldom observed, because they usually are sharply truncated and reworked by currents. Both wave ripples and interference ripples were observed. In places, cross-lamination grades upwards into strongly burrowed tops. Cross-strata pass laterally into thin-bedded rippled sandstones 3–15 cm thick. Cross-beds are separated by thin shale interbeds (a few millimeters to 10 cm thick), often with ripple lamination. However, primary structures are usually obliterated by the strong bioturbation. Her-

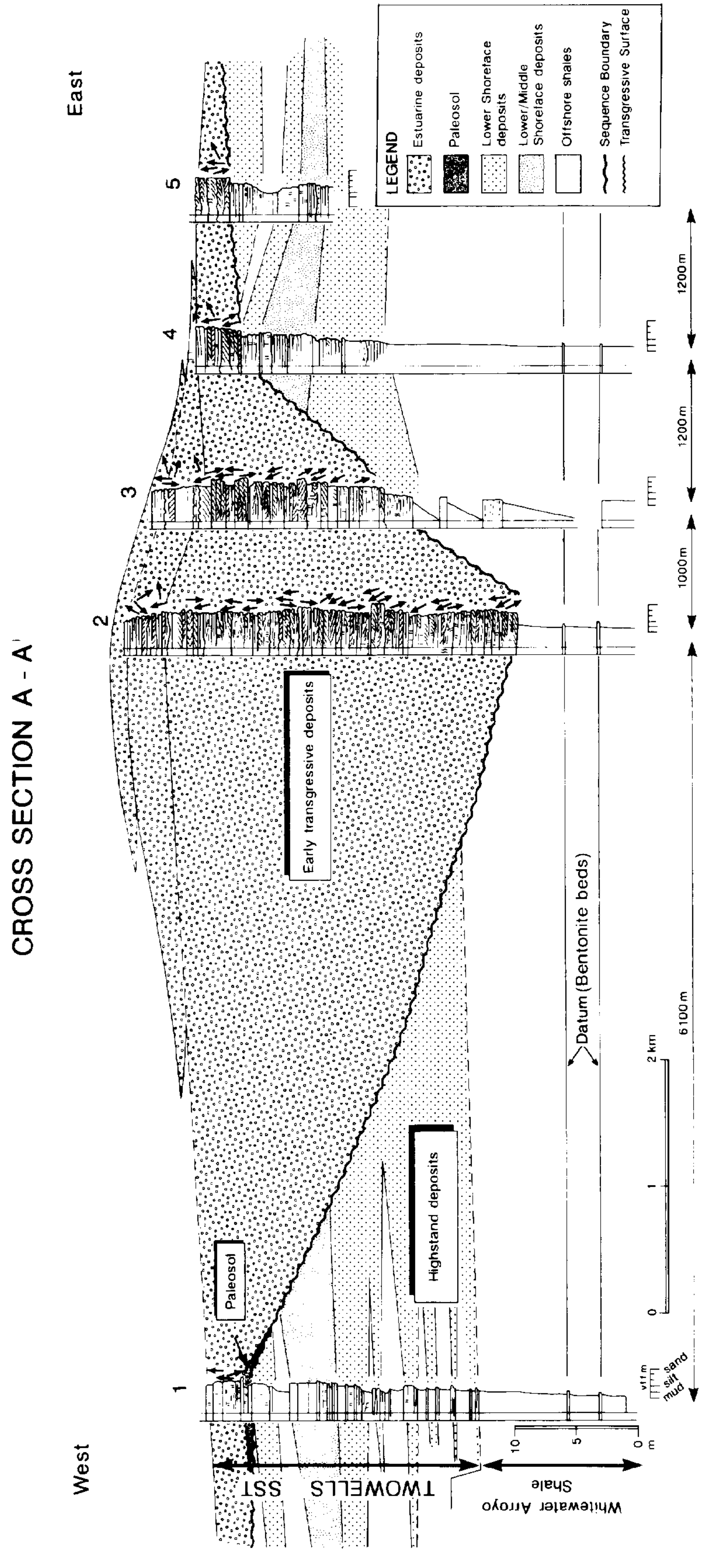

FIG. 8.—Cross Section A–A′ (location in Figure 4). Arrows indicate paleocurrent directions.

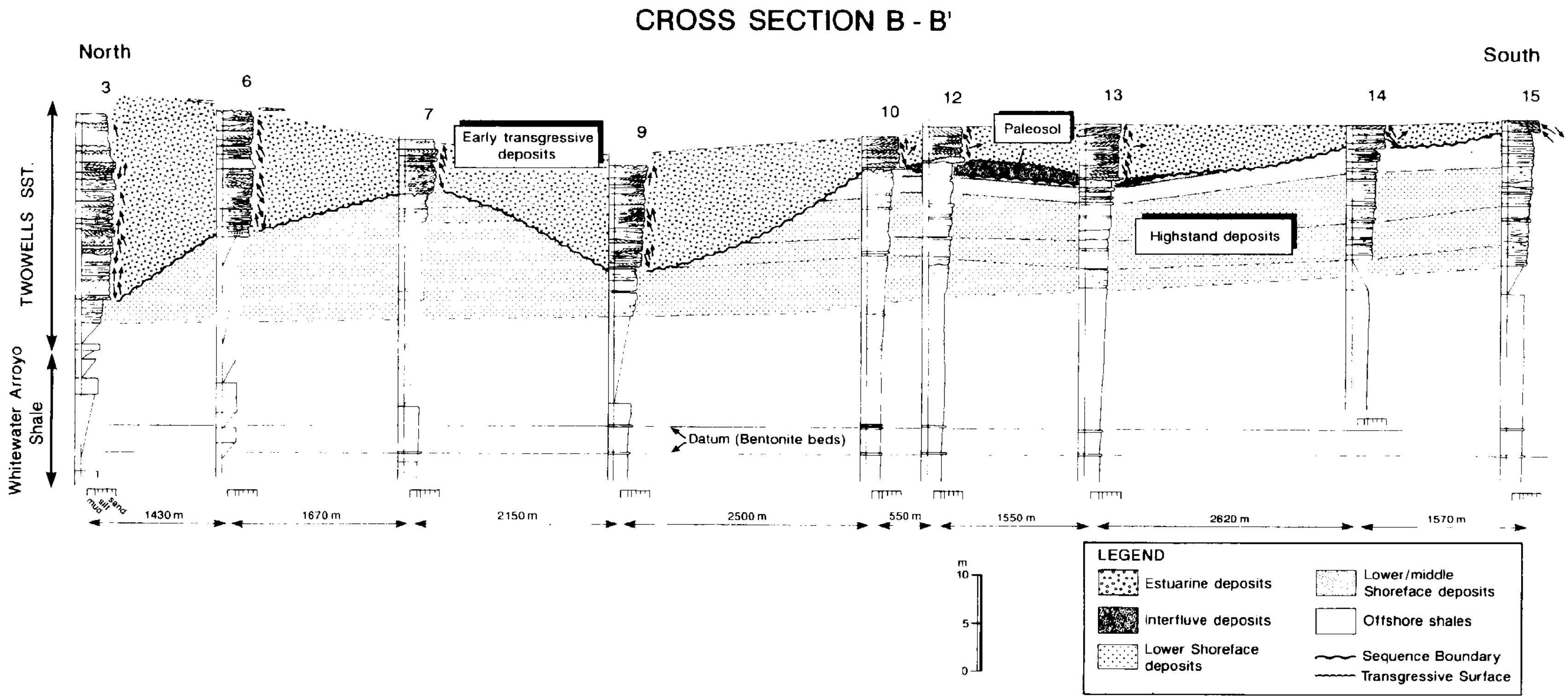

FIG. 9.—Cross Section B–B′ (location in Figure 4). Arrows indicate paleocurrent directions.

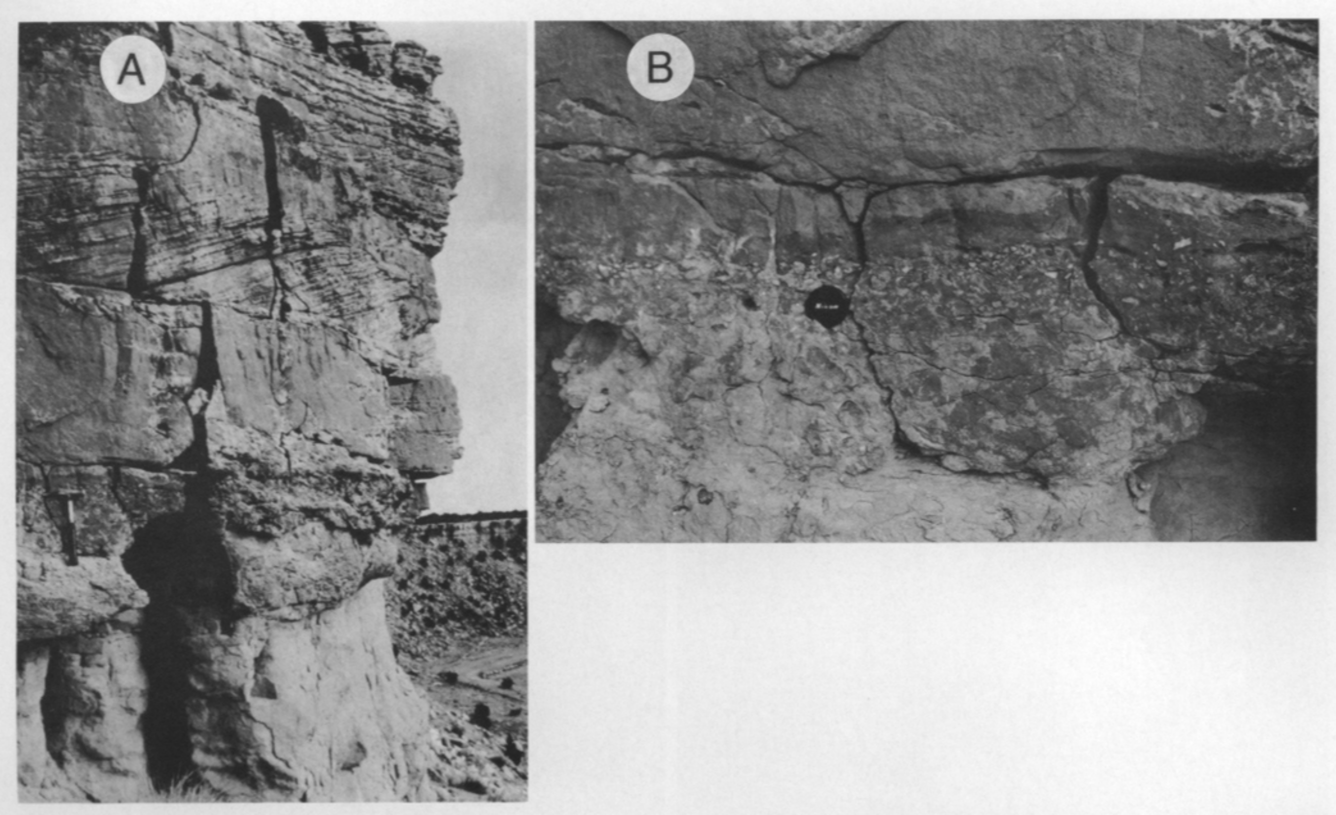

FIG. 10.—**A)** Outcrop view and **B)** detail of the boundary between the shoreface lithosome and the estuarine sandbody of the Twowells Tongue in Canipa Mesa (Profile 10 in Cross Section B–B′; Fig. 6). The top of the shoreface lithosome is marked by a paleosol horizon, directly overlain by the transgressive lag at the base of the cross-bedded estuarine sandstone. Note the clear contrast in both grain size and color.

ringbone current reversal patterns are common throughout the lithofacies (Figs. 10, 15B).

The lithofacies is vertically arranged into stacked coarsening- and thickening-upward to fining- and thinning-upward units 4–8 m thick and 300–600 m long. Within each unit (Fig. 16), the upward-coarsening component is 2.5–5 m thick, whereas the upward-fining part is usually thinner (1–4 m). Each unit gradationally overlies extensively burrowed siltstones and is composed of rippled-laminated sandstones grading vertically into cross-bedded sandstones. Trough cross-bedded very coarse-grained sandstone and microconglomerate (8–80 cm thick) form the bulk of the coarsening-upward parts. Normally, granules and small pebbles (maximum 0.5 cm in diameter) are concentrated along the trough bases. The uppermost upward-fining interval often contains a retrogradational stacking of bioturbated and cemented horizons laterally persistent for the whole length of the unit (Fig. 16). In the most distal part the units are strongly heterolithic and consist of rippled sandstone beds alternating with bioturbated shales.

The lithofacies is bioturbated and dominated by *Ophiomorpha* and *Asterosoma*, although *Aulichnites*, *Thalassinoides*, *Diplocraterion*, and *Skolithos* are also common (Fig. 17). Paleocurrents are bidirectional throughout the interval, and with only little dispersion are generally directed north (360–340°; dominant) and south (160–200°; subordinate direction).

Interpretation.—The cross-bedded sandstones are believed to have been deposited in an estuarine environment. Bipolar directions, herringbone cross-stratification, mud drapes, and reactivation surfaces are all characteristic of tidally influenced deposits (Visser 1980; Allen 1980; Clifton 1983; Allen and Homewood 1984; Mutti et al. 1985; Smith 1988; Wood and Hopkins 1989; Nio and Yang 1991; Dalrymple 1992). The double mudstone laminae along the cross-bedded foresets and paleocurrent directions provide evidence of bidirectional flow in a subtidal setting (de Raaf and Boersma 1971; Reineck and Singh 1973; Visser 1980; Boersma and Terwindt 1981; Allen 1980). The presence of very coarse sandstones and microconglomerates indicates that part of the deposits are fluvial but reworked by tidal currents. Most of the sandstones, however, are believed to have been reworked from the missing upper-shoreface deposits of the underlying sandbody. Dominant, landward-directed paleocurrents (to the northwest) suggest prevalent flood tidal currents. The deposits consist almost entirely of compound cross-beds, and probably can be assigned to Class VI sand waves of Allen (1980). They form discrete coarsening- to fining-upwards units migrating mainly in the axial part of the estuarine valley, similar to the tidal bars described by Mutti et al. (1985) in the Baronia formation of the Ager Basin (Southern Pyrenees) and to the tidal sand bars of Dalrymple et al. (1990) in the outer part of the Salmon River Estuary. The coarsening- to fining-upward motif and the lithofacies recognized suggest progradation and abandonment of the tidal bars in a subtidal setting.

The abundant but relatively low-diversity ichnofauna assemblage indicates a highly stressed environment and is consistent with an estuarine setting (Clifton 1983; Frey and Howard 1986; Smith 1988; Leckie and Singh 1991; Jennette et al. 1991; Pemberton 1992), where shifting substrate and fluctuations in salinity, temperature, and sedimentation rates are common.

UPPERMOST PART OF THE TWOWELLS TONGUE

Description.—The Twowells Tongue is capped by a strongly bioturbated, fossiliferous, fine sandstone layer 75 cm thick. The faunal assemblage

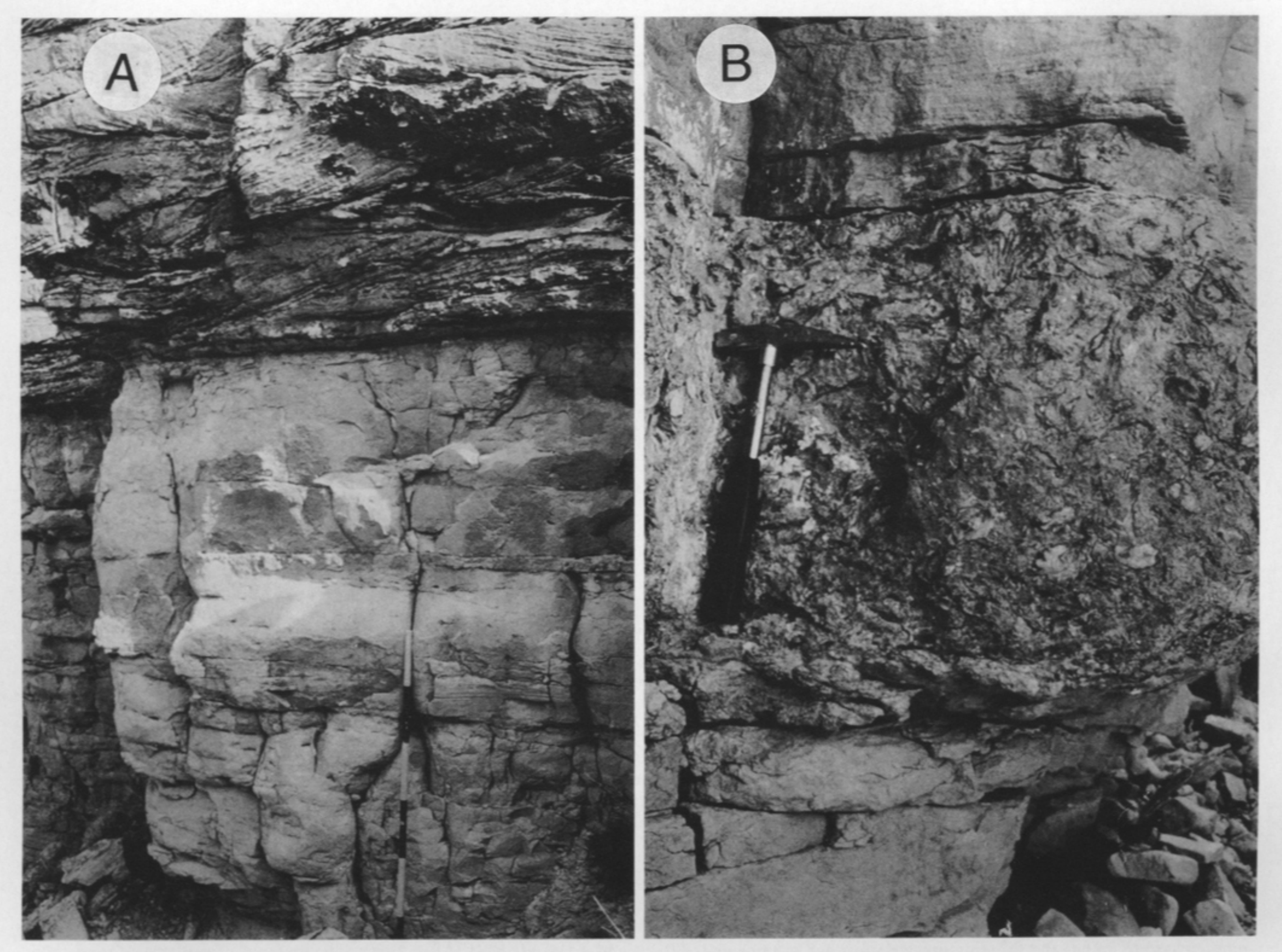

FIG. 11.—**A)** Unconformity surface between the lower shoreface deposits and the estuarine cross-bedded sandstones in Profile 12 (Cross Section B–B′; Fig. 9; 1.5 m Jacob's staff as scale). **B)** In places the sharp erosional surface is overlain by a concentration of shells that is laterally equivalent to the pebble-lag horizons.

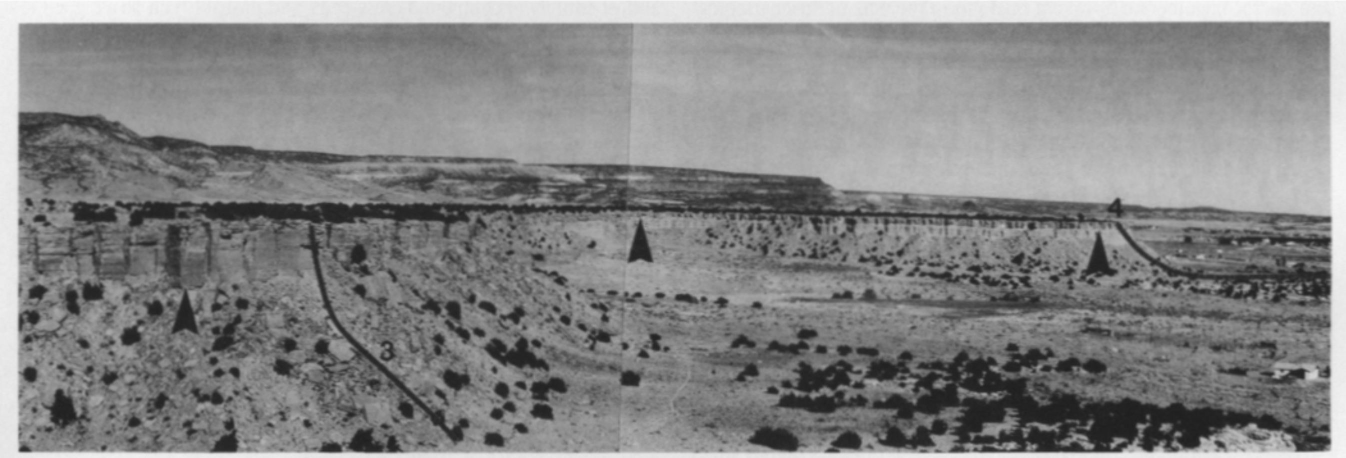

FIG. 12.—General view of the Twowells Tongue in the McCarty's area and trace of measured sections 3 and 4 (see Figures 4 and 8 for location). Note the erosional unconformity (marked by arrows) between the lower shoreface sandbody and the upper estuarine sandstones.

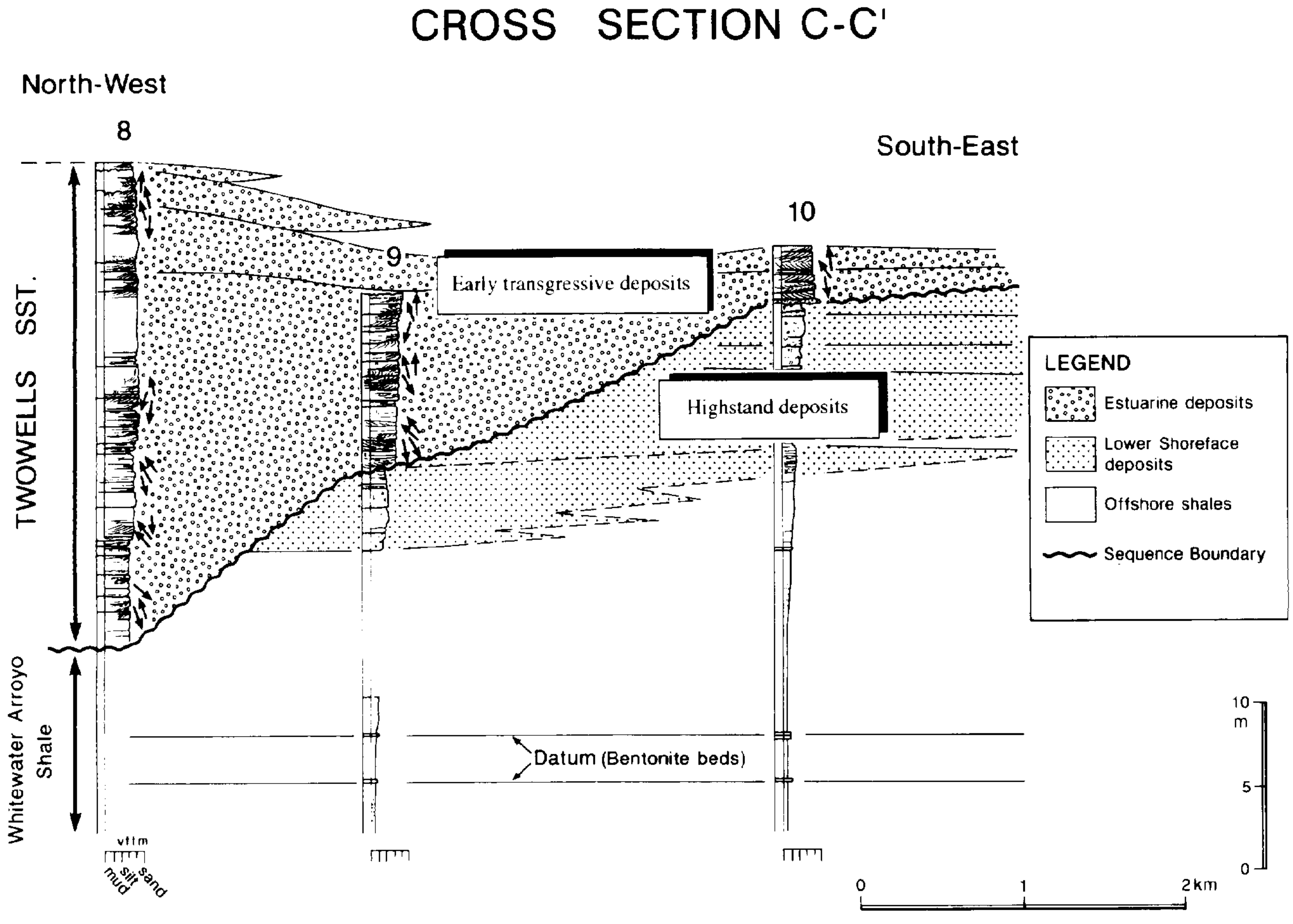

FIG. 13.—Cross Section C–C′ (location in Figure 4). Arrows indicate paleocurrent directions.

is of extremely low diversity, consisting exclusively of *Pycnodonte* oysters (Fig. 18). This layer is overlain by black, organic-rich shales within which nodular, fossiliferous limestones (two ammonites were found) and bentonite beds are intercalated. The shales, corresponding to the Graneros Shale Member of the Mancos Shale (Fig. 3), completely blanket the sandbody.

Interpretation.—The bioturbated sandstone lithofacies is inferred to indicate a nutrient-rich, sediment-starved, low-energy environment with low rate of sedimentation. This unit is interpreted to represent a marine deepening event that marks the top of the sandbody and the end of the sand supply.

SEQUENCE-STRATIGRAPHIC FRAMEWORK

The Twowells Tongue of the Dakota Sandstone encompasses two depositional sequences, albeit incomplete in terms of systems tracts (Van Wagoner et al. 1988, 1990): the first is associated with the Whitewater Arroyo Shale and the shoreface sediments, and the second includes the estuarine cross-bedded sandstone lithosome, the oyster beds, and the black shales that cap the Twowells Tongue.

Sequence 1: the Whitewater Arroyo Shale Tongue and the Lower Part of the Twowells Tongue

The Whitewater Arroyo Shale Tongue and the overlying shoreface deposits are interpreted to have accumulated on the shelf at highstand. Upward in the section, sandstones coarsen, mudstone percentage decreases, burrowing decreases, and hummocky cross-stratification becomes more common. This vertical trend reflects a gradual increase in wave and current energy on the shelf and is interpreted to have been caused by a decrease in the rate of creation of accommodation space. The overlying unconformity shows that this trend culminated in a relative sea-level fall.

This association can reach 15 m in thickness. It is muddier, finer grained, less glauconitic, and more burrowed and fossiliferous than the overlying valley-fill deposits. The texture and the vertical trends are characteristic of a storm-dominated shoreface. The upper-shoreface and foreshore (beach) deposits were either never deposited at the study location or were eroded during creation of the unconformity and, further, by the ravinement surface at the base of the cross-bedded facies association.

Sequence 2: the Upper Part of the Twowells Tongue

The second sequence is bounded at its base by a sharp surface of erosion (unconformity) that is onlapped by transgressive cross-bedded sandstone and shale.

Sequence Boundary

A main linear erosional low or paleovalley is cut into the Whitewater Arroyo Shale tongue and into the shoreface sandstones. Cross sections A–A′, B–B′, and C–C′ (Figs. 8, 9, 13) show its irregular surface across the Acoma Basin. The unconformity is of regional extent (Wolter 1987), is

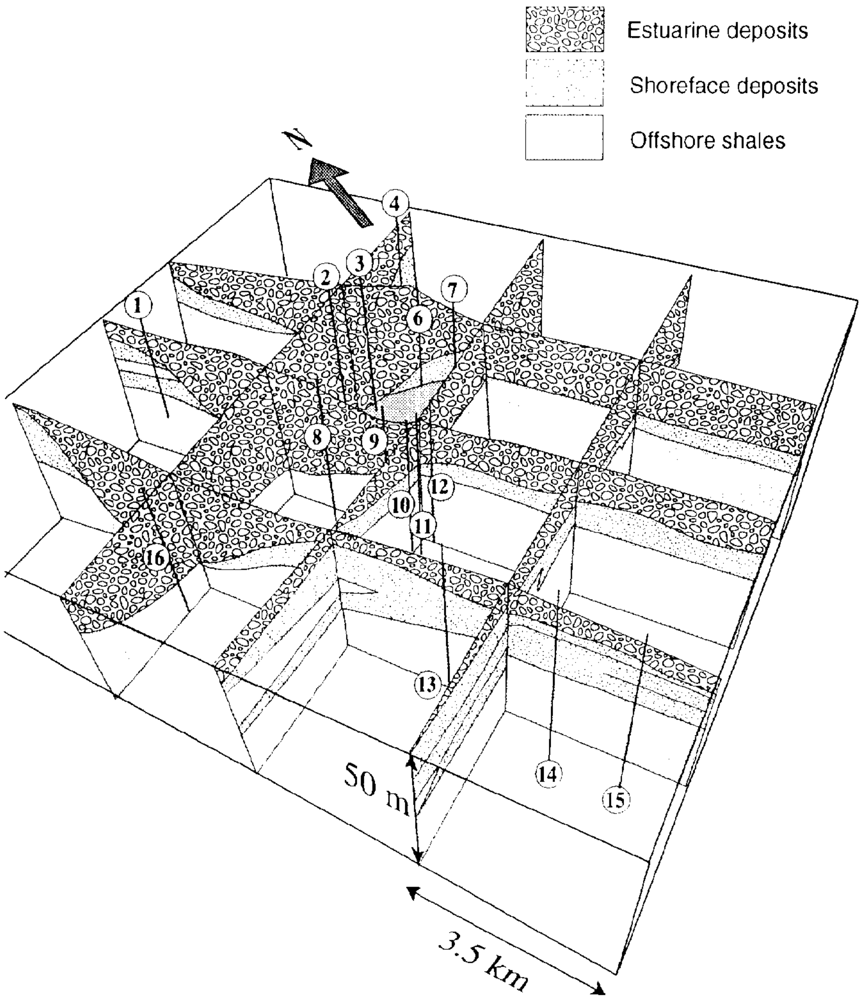

FIG. 14.—Tentative three-dimensional reconstruction of the Twowells Tongue in the Acoma Basin and projection of the logs measured. Note the deep valley infilled by estuarine cross-bedded sandstones cutting the underlying shoreface lithosome and the offshore mudstones.

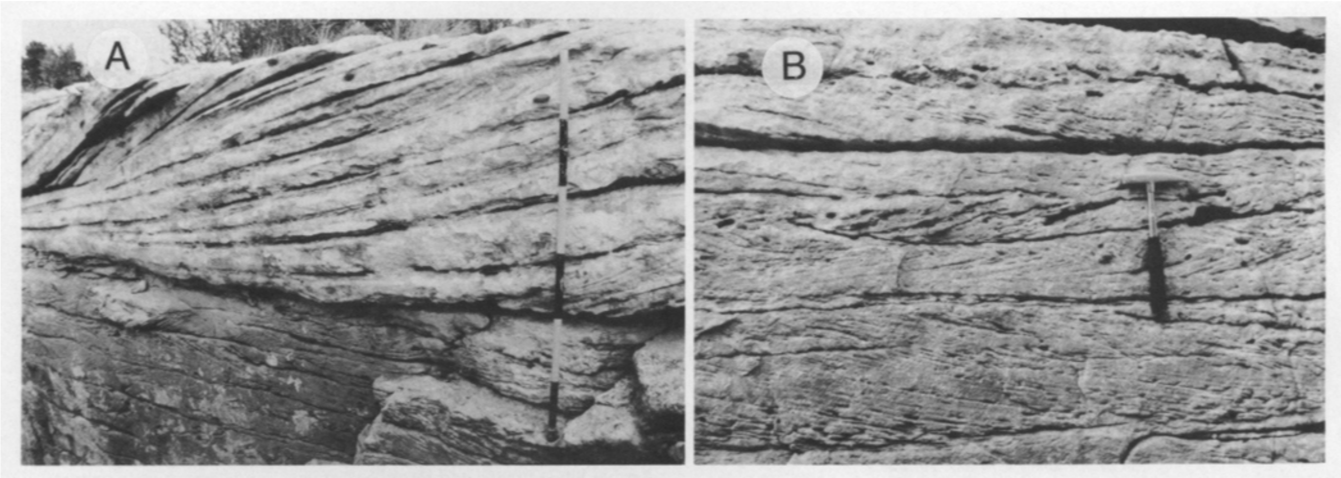

FIG. 15—Details of the estuarine cross-bedded sandstones: **A)** Bundled foresets in a composite bed form (15 m, Jacob's staff as scale). **B)** Erosional surfaces separate cross-bedded sets and herringbone laminated unit (center of figure).

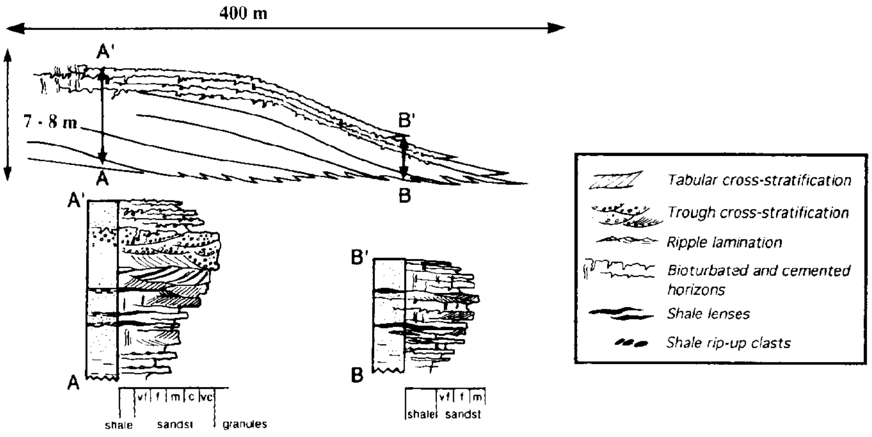

FIG. 16.—Sketch showing geometry, dimensions, and main facies characteristics of a coarsening- to fining-upward unit.

associated with subaerial erosional truncation, and represents a marked downward shift in facies as testified by the paleosols overlying the lower shoreface deposits, and is interpreted to represent a sequence boundary (Vail et al. 1977; Mitchum 1977; Van Wagoner et al. 1988). The paleovalley (Fig. 14) has its maximum erosional relief in the northwest sector of the study region, west of McCarty's (Cross Section A–A') and in McCarty's Mesa (Cross Section C–C'), where it cuts completely through the shoreface sandstone and part of the Whitewater Arroyo Shale Tongue. It has 22 m of incision into the underlying strata. In Cross Section A–A' the paleovalley has an asymmetric profile, with steeper slopes on the eastern edge. At McCarty's the sequence boundary overlies the black mudstones, only 3.5 m above the second bentonite bed, taken as a datum (Fig. 19).

Commonly, the sequence boundary is coincident with the base of the cross-bedded coarse sandstones of the upper part of the Twowells Tongue in the Acoma and Zuni Basins. The sequence boundary is traceable westward at least across the Zuni Basin, where a reconnaissance study showed the similarity in facies and facies associations. A brief overview in the Zuni Basin suggests that the sequence boundary defines several narrow erosional lows, as shown by frequent abrupt changes in thickness of the overlying cross-bedded sandstones.

Paleosol Development during Deposition of the Lowstand Systems Tract

Most of the measured sections in the Acoma and in the Zuni Basins lack deposits assignable to the lowstand systems tract, and the process at this time appears to have been erosion. As previously mentioned, up to 20 m of the underlying deposits were removed by erosion, believed here to be caused by both fluvial incision and subaerial exposure. A delta system is thought to have prograded from the Four Corners area into the Seboyeta Bay (Fig. 20) during lowstand. Interfluves are represented by incipient paleosols found at Canipa Mesa (Cross Section B–B'; Fig. 9) and section 1 (Cross Section A–A'; Fig. 8) immediately below the ravinement surface that marks the sharp contact with the cross-bedded, tidal facies. The paleosol here marks a hiatus in sedimentation associated with the sequence boundary and represents the product of subaerial exposure, preserved despite the subsequent sea-level rise (cf. analogous cases described by Van Wagoner et al. 1990 and Jennette et al. 1991). The time gap associated with the sequence boundary in the southern part of the Zuni Basin has been calculated to be about 1 my (Esterly 1985). Fluvial deposits were never recognized within the valley, although in the most complete estuarine succession, estuarine sediments overlie lowstand fluvial sediments (Dalrymple et al. 1992; Allen and Posamentier 1993). It is probable that the valley was a zone of fluvial bypass during fall in relative sea level as well as during the lowstand, or that the original fluvial incision was totally modified by the initial stages of marine transgression.

The Transgressive Systems Tract: Valley Fill and Valley Flooding

The Early Transgressive Systems Tract: Infill of the Valley.—In most of the measured sections, deposits of the early transgressive systems tract

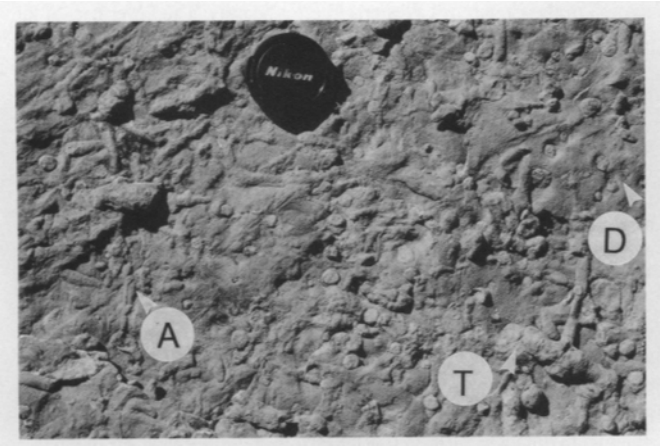

FIG. 17.—Typical ichnofauna of the cross-bedded sandbody of the Twowells Tongue. *Thalassinoides* (T), *Diplocraterion* (D), *Aulichnites* (A).

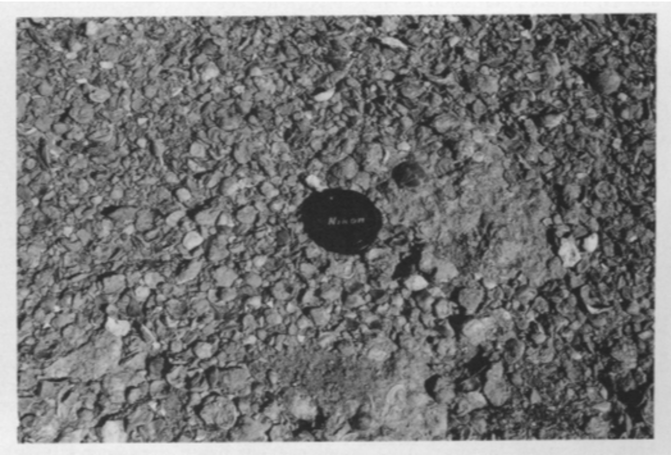

FIG. 18.—Concentration of *Pycnodonte* oysters at the top of the Twowells Tongue.

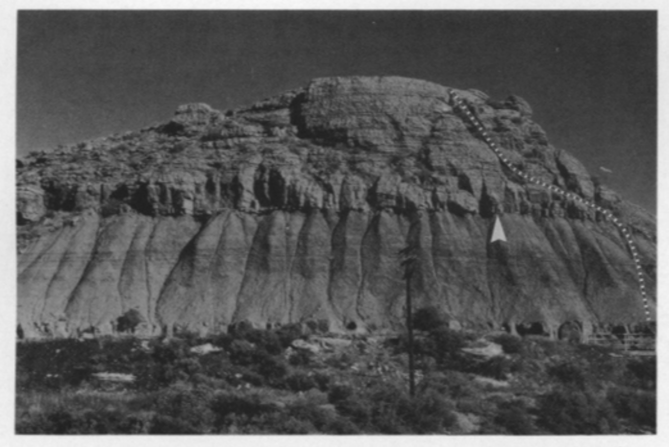

FIG. 19.—Twowells Tongue in McCarty's area and trace of Profile 3 (Cross Section A–A'; Fig. 8). The estuarine cross-bedded sandstones overlie the Whitewater Arroyo Shale with complete erosion of the shoreface deposits. The contact represents the sequence boundary of the Twowells sequence.

rest directly upon the sequence boundary. The transgressive surface coincides with the sequence boundary in almost all the outcrops (except in the interfluves, where it overlies the paleosol horizons), and with the tidal ravinement surface (*sensu* Allen and Posamentier 1993). In some places it is marked by a thin, lensoid conglomeratic layer (Fig. 10) or by a concentration of transported shells (Fig. 11B). The deposits are represented by the cross-bedded medium to coarse sandstones. As relative sea level rose, marine waters gradually flooded into the valleys and tidally influenced sedimentation prevailed (Fig. 20).

The cross-bedded sandstones that define the infill of the erosional valley within the Twowells Tongue are analogous to the Tocito valley fills (Jennette et al. 1991) and the Sego Sandstone (Van Wagoner 1991). The major aspect is the tide-dominated nature of the deposits, the stressed ichnofauna assemblage, the lack of open-marine processes, and probably the multistory infill. Unlike the tidal bars in the Sego, interpreted to be deposited by tidal deltas during sea-level lowstand, the cross-bedded sandstones of the Twowells Tongue are here interpreted as transgressive deposits. Initial deposition might have occurred during the late stage of the lowstand systems tract, when sediment supply was still exceeding the rate of sea-level rise (Hunt and Tucker 1992), but unfortunately present data are not sufficient to confirm such a hypothesis. The coarsening- to fining-upward units detected within the valley fill are traceable for a few hundred meters at most and are interpreted as the result of autocyclic processes rather than as sea-level-controlled parasequences (Van Wagoner et al. 1988). Further work should be done to address this issue.

The Late Transgressive Systems Tract: Valley-Flooding Phase.—Continued relative sea-level rise led to the transgressive flooding of the valleys. The cross-bedded sandstone that previously infilled narrow corridors were now deposited over the interfluve areas. No changes in facies were detected within the cross-bedded sandstones, except for a marked backstepping of parasequences in the uppermost part of the cross-bedded wedge in Cross Section A–A' (Fig. 8) and a wider dispersion in the paleocurrent directions. The paleocurrent dispersion and the lack of confinement suggest that the tidal bars were replaced by wider lobes (Fig. 20) or ridges in the seaward part of a tide-dominated estuary (see also Allen 1991; Leckie and Singh 1991; Dalrymple et al. 1990; Dalrymple 1992; Dalrymple et al. 1992). Estuarine sedimentation was replaced with fully marine conditions. The bounding surface has the form of a sharp flooding surface that marks the contact with the black shales and the limestone intercalations of the Greenhorn Limestone Member. This flooding event finally terminated tidal deposition and created conditions for shelf sedimentation.

OFFSHORE RIDGES VERSUS INCISED VALLEY FILL: DISCUSSION

The cross-bedded upper part of the Twowells Tongue was previously interpreted as plume-derived (Coleman et al. 1981) offshore ridges (Wolter 1987; Nummedal and Wright 1989), as suggested by its depositionally offshore position, up to 50 km offshore of the inferred shoreline, and in analogy with similar cross-bedded sandstones of the Western Interior Seaway (Tillman and Martinsen 1984; Palmer and Scott 1984; Gaynor and Swift 1988; Pozzobon and Walker 1990). As pointed out by Scheihing and Gaynor (1991) and Walker and Bergman (1993), the plume model seems to be an inadequate explanation for the deposition of poorly sorted, relatively coarse-grained sandstone in an apparently offshore position. The recognition of tidal influence in the cross-bedded lithosome of the Twowells Tongue and the lack of any wave-dominated structures (hummocky or swaly strata) as well as the ichnofabric (dominated by *Ophiomorpha*, *Asterosoma*, *Teichichnus*, and *Dipolocraterion*), strongly suggests a shallow nearshore environment rather than a shelf setting. The geometry of the cross-bedded lithosome here, moreover, indicates that the cross-bedded sandstones infill an incised valley. In accordance with the lithofacies recognized, a strong shift of the nearshore areas out for some 50 km beyond the earlier shoreface occurred, as a response to a drop in sea level. This was accompanied by a change in paleogeography from a wave-dominated environment during highstand to subaerial and fluvial erosion in the lowstand to a tidally dominated setting in the subsequent transgressive phase (Fig. 20). Only after the fluvial valleys were initially infilled by the transgression did the cross-bedded deposits flood onto the interfluve areas as transgressive, but still nearshore, ridges.

Recently, some of the so-called offshore ridges have been reinterpreted as lowstand shoreface deposits (Walker and Bergman 1993) formed when the shoreline was forced to prograde farther into the basin as a result of base-level fall (Plint 1988; Posamentier et al. 1992). The strong tidal signature of the deposits in the upper part of the Twowells Tongue and the contrast in both lithofacies and geometry with the underlying shoreface sediments argue strongly against a forced-regressive shoreface model (Plint 1988; Posamentier et al. 1992). A notable feature is indeed the apparent lack of forced-regressive shoreline at the base of the cross-bedded lithosome. As in the Sego Sandstone (Van Wagoner 1991), the forced-regressive shoreline could have been eroded during the lowstand or subsequent transgressive phase or could have been deposited farther seaward.

CONCLUSIONS

The Cenomanian Twowells Tongue of the Dakota Sandstone in west-central New Mexico was deposited during a time of major sea-level fluctuation in the Cretaceous Western Interior Seaway. The lower part of the Twowells Tongue consists of shoreface sediments gradationally overlying offshore shales, interpreted to have been deposited during sea-level highstand.

The upper part of the Twowells consists of transgressive cross-bedded estuarine sandstone sharply overlying the lower shoreface sediments. The bounding surface depicts a valley morphology, in places cutting down 20 m into the underlying highstand shoreface deposits, and is interpreted as a sequence boundary. Paleosol horizons, indicating periods of subaerial exposure, were found at two localities on the interfluves of the large valley. The valley records two different stages of infilling:

(1) During the initial phase of transgression, the valley was infilled by coarsening- to fining-upward medium-grained, cross-bedded estuarine tidal bars. Tidal deposits were never found to be associated with fluvial deposits. The lower bounding surface is interpreted to represent a transgressive surface coincident with the sequence boundary as well as with the tidal ravinement surface. It is marked by a transgressive lag of pebbles and shells.

(2) During a later stage of transgression, sedimentation occurred over

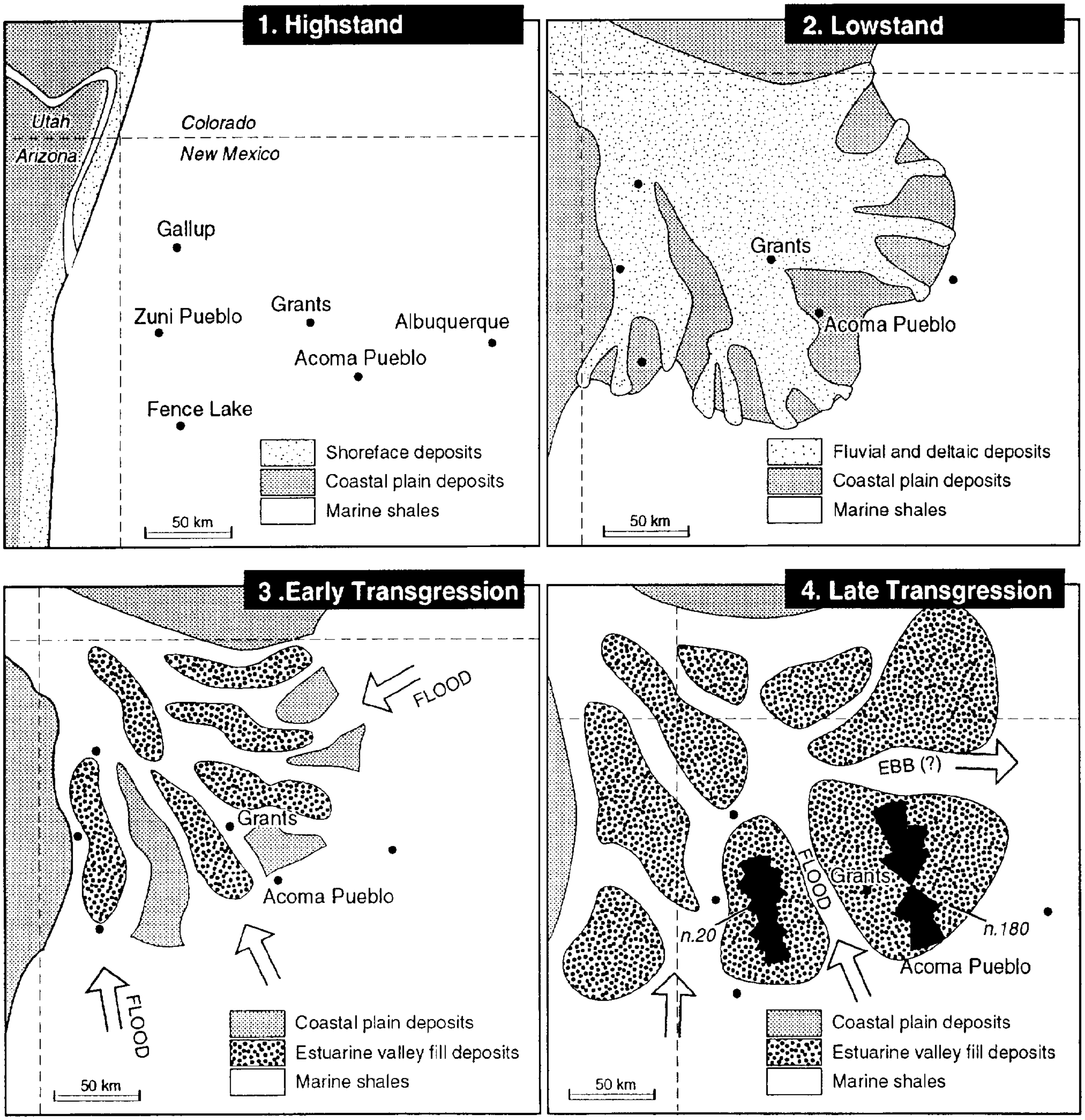

FIG. 20.—Hypothetical paleogeographic reconstruction of the Twowells Tongue during highstand, lowstand, and transgressive phases.

the interfluves. This was associated with a marked backstepping of parasequences and with wider paleocurrent dispersal. Estuarine sedimentation was then replaced with fully marine conditions.

The cross-bedded sandstones of the Twowells Tongue can be designated neither as "shelf ridge" deposits nor as forced-regressive shoreface deposits, because (1) they constitute the infill of a broad valley and (2) facies analysis and ichnofauna indicate a shallow estuarine setting rather than an offshore or wave-dominated environment. In addition, the cross-bedded sandbody in no way resembles the underlying shoreface sandbody.

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outcrops in the Acoma Reservation, if visited with permission, should be treated respectfully, because of their special significance to the Acoma People.

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