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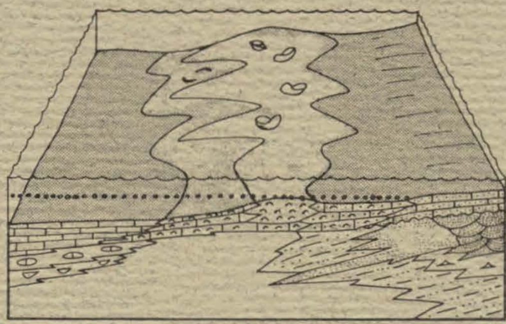
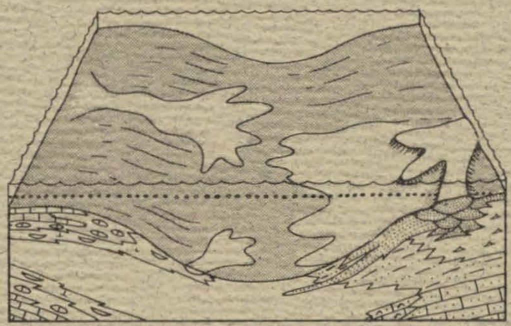
Epeiric Depositional Models for the Lower Cretaceous Washita Group

NORTH-CENTRAL TEXAS





By R. W. Scott, D. Fee, R. Magee, and Hooman Laali

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THE UNIVERSITY OF TEXAS AT AUSTIN • AUSTIN, TEXAS 78712

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ABSTRACT

The Washita Group in north-central Texas and southeastern Oklahoma consists of up to 114 m of intercalated shale, limestone, and sandstone that accumulated in the shallow, epicontinental sea of the East Texas basin. The Ouachita-Arbuckle Mountains to the north supplied terrigenous sediments, and the Central Texas platform to the south was a site of carbonate deposition leeward of the shelf margin of the Stuart City trend. Eleven lithofacies of the Washita were deposited within a repeatedly subsiding shelf basin that received an intermittent supply of terrigenous sediment. The deepest seaway formed after subsidence and was filled by a south-to-north progression of facies consisting of mollusk-echinoid wackestone on a shallow shelf, transitional packstone shale of deeper water, calcareous and sandy shales of the deepest water, thin-bedded sandstone of the shallower water shoreface, wavy lenticular sandstone and shale of the distal delta front, and deltaic-estuarine trough-crossbedded sandstone. Following basin filling, the carbonate shelf prograded northward, grading into nearshore sediments. This produced the south-to-north succession of mollusk-echinoid wackestone to either oyster packstone shale, oyster packstone and quartzitic-oyster packstone or quartzitic mollusk-echinoid packstone of the shoreface.

INTRODUCTION

The Washita Group is the uppermost sedimentary package of the Comanchean Series in north-central Texas. The Group represents the third and last depositional cycle of the Early Cretaceous transgression from the ancestral Gulf of Mexico. This third depositional event produced a widespread epicontinental seaway that extended into the Western Interior province and connected northward with the Canadian Arctic seaway.

Washita strata in north-central Texas were deposited in the East Texas basin, which was located south of the Ouachita Mountains and northeast of the Central Texas platform and Stuart City trend at the shelf margin. The paleogeographic setting has been reviewed by Hayward and Brown (1967) and Rose (1972) and is important because it places certain physical limits upon the interpretations of depositional environments in north-central Texas.

The early work on rocks now known as Comanchean was summarized thoroughly by Hill (1887). A complete summary of the Washita formations was given by Adkins (1933). Perkins (1961) reviewed the stratigraphic terminology of these units. A comprehensive bibliography to 1966 was prepared by Lokke (1967); and Young (1967a), Bishop (1967), Slocki (1967), Hayward and Brown (1967), Hendricks (1967), Brown (1971), and Rose (1972) reviewed Comanchean stratigraphy.

The objectives of this report are (1) to examine details of stratigraphic relations among the formations of the Washita Group, (2) to define lithofacies based on current petrographic methods, (3) to investigate lateral and vertical relations among these facies, and (4) to construct depositional models that incorporate data from Holocene studies. This study is intended to test previous hypotheses that interpreted Washita limestones to be either of shallow-water (Young, 1967a) or deep-water (Hill, 1894; Scott, 1940) origin and to review the relative roles that tectonic and climatic processes played in producing the cyclical deposits. Furthermore, similar facies are found in time-equivalent strata in Trans-Pecos Texas as well as in the underlying Fredericksburg and Trinity Groups in north-central Texas. Finally, this study provides insight into processes that formed lithosomes in epicontinental seas.

The study area extends from Fort Worth, Texas, northward to the Red River and southeastern Oklahoma (fig. 1), where the Washita Group exhibits its most complex and extreme facies changes. The transition between facies of the Central Texas platform and the East Texas basin occurs in the southern part of this area. The northern part is bounded by the Ouachita and Arbuckle Mountains. The study area is on the northwestern edge of the Gulf Coastal Plain.

Forty-six stratigraphic sections were measured and sampled (see Appendix for description of locations). Carbonate facies were studied by acetate peels, thin sections, and insoluble residues. Sandstones were thin sectioned and disaggregated, and grain-size analyses were performed by means of a visual-accumulation settling tube. The X-ray analyses of the clays were made with a Norelco diffractometer. Study techniques were described by Laali (1973), Fee (1974), and Magee (1974).

The Washita as a group is used in the sense employed by Hill in the original definition (1887a) and in subsequent restatements (1887b, 1890, 1891, 1894). In north-central Texas, the base of the group is a regional unconformity between the Goodland Limestone and the overlying dark-gray shale of the Kiamichi Formation. This lithic break can be traced and mapped throughout the region and within the subsurface of the East Texas basin. The Kiamichi is lithically similar to overlying Washita formations rather than the subjacent Fredericksburg formations (Perkins, 1961; Young, 1967a). The upper contact of the Washita Group on the outcrop is the top of the Buda Limestone or Grayson Shale, whichever occurs unconformably beneath the Woodbine Formation, a sandstone-shale sequence. Thus, the following formations compose the Washita Group in ascending order: Kiamichi, Duck Creek, Fort Worth, Denton, Weno, Pawpaw, Main Street, Grayson, and Buda.

The formations of the Washita Group are readily defined for mapping purposes, and most contacts are conformable and gradational by interbedding and by continuous change in clay or lime content. Because the detailed bed-for-bed correlation can affect the environmental interpretations, formational contacts will be described where we depart from the contacts picked by Slocki (1967) and other previous workers or where new observations are important.

The basal Kiamichi contact is the most distinctive contact in the Fredericksburg and Washita Groups. In Central Texas, it is unconformable as evidenced by prolific borings into the underlying Edwards Limestone that are filled with Kiamichi sediments (Bishop, 1967, p. 163). In addition, a corroded, pitted surface with marcasite, rounded chert, quartz, Edwards-like limestone pebbles, and glauconite mark this contact (Shelburne, 1959). Some workers believe that in north-central Texas the contact is conformable (Bishop, 1967). Durate (1968), however, interpreted the basal Kiamichi contact to be unconformable because burrows on the uppermost surface of the Goodland Formation in Choctaw County, Oklahoma, are filled with Kiamichi sediments. In the same county at Locality Ch1 (fig. 1), we have found rounded cobbles of Goodland Limestone dispersed in basal Kiamichi shales. *Thalassinoides*-type burrows filled with Kiamichi quartz silt and clay occur at Loc. Ch1 in Oklahoma and T3 near Fort Worth. Finally, channels up to 1.5 m across were scoured into the uppermost Goodland surface near Fort Towson, Oklahoma, and filled with Kiamichi gryphaeid packstones. Burrows and borings indicate that this unconformity was a submarine surface in most places.

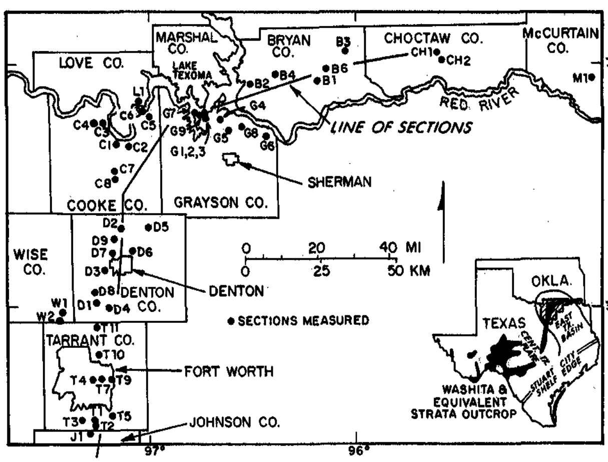


Figure 1. Location of measured sections of the Washita Group, north-central Texas and southeastern Oklahoma.

In the type area, Denton County, Texas, the top of the Denton Formation was placed at the base of the first Weno limestone bed above shale and shell beds (Taff and Leverett, 1893). However, in the Red River area, the basal Weno contains no limestone beds, and the contact generally is placed at the top of the highest shell bed (Hill, 1901). Throughout Tarrant and Denton Counties, gryphaeid packstones form a distinct zone approximately 1 m below the lowermost wackestones of the Weno Formation. Consequently, for stratigraphic purposes, the top of the Denton is placed at the top of the resistant shell packstone zone. In northeastern Bryan County, Oklahoma, well-indurated, shelly, crossbedded sandstone takes the place of shell packstones and wackestones at the top of the Denton. These beds are good markers which separate two dominantly shale intervals. At each locality the Denton-Weno contact is placed at the top of the distinct shelly marker bed. This placement does not prove unequivocally, however, that the sandstone beds are physically continuous and gradational southward with the shell packstone beds. Such a conclusion is a stratigraphic hypothesis that needs testing by the analysis of many closely spaced wells and outcrops. At all localities the Denton-Weno contact is either sharp or abruptly gradational and conformable.

The sharp Pawpaw - Main Street contact in north-central Texas is disconformable (Stephenson, 1918). In Tarrant County the contact is probably unconformable (B. Perkins, personal communication, 1975); large *Thalassinoides* burrows filled with limestone penetrate up to 10 cm into the underlying Pawpaw shales. Farther north, basal Main Street limestone beds become sandy, and in Oklahoma, basal limestone beds contain clay pebbles replaced by iron oxide, glauconite, phosphate grains, vertebrate fragments, and reworked Pawpaw fossils. At some localities, the basal 25 cm of Main Street is a fossiliferous, calcite-cemented sandstone. This disconformity may represent a ravinement erosional surface (Swift, 1968), which resulted from northward transgression of offshore facies across nearshore facies of the Pawpaw (Scott, 1976). South of the study area in Central Texas, the Pawpaw - Main Street contact is gradational and conformable (McGill, 1967).

Lithofacies of the Washita Group are genetically related lithic units having distinct stratigraphic and geographic distributions. They are defined primarily by grain size, sorting, carbonate content, and stratification type. Grain type and mineralogy are of secondary importance. Textural classification of carbonate rocks used herein follows Dunham (1962), and definition of carbonate grain types follows Folk (1974). Shale is defined as a fissile clay-rich rock; sandstone classification follows Folk (1974). Definition of stratification is after McKee and Weir (1953) and Reineck and Wunderlich (1968).

Lithofacies properties are summarized in table 1. Each lithofacies occurs in several formations (figs. 2, 3) and in predictable patterns of succession that are discussed later. Each stratigraphic occurrence of a facies is primarily composed of the distinctive rock types. However, more detailed sampling of some intervals reveals minor thicknesses of lithologies characteristic of other facies. This intermixing of lithologies is expected when facies are defined by the relative abundance of lithic components and need not weaken the definitions or interpretations. More detailed studies are needed to understand variations within facies and within beds of given localities. Although the facies are described as a north-south trend, we do not imply that they form simple east-west belts. Their distribution should conform to the outline of the basin and can be delineated by subsurface mapping.

Environmental interpretations are based on lithic features (composition, texture, and sedimentary structures), stratigraphic relations, and generalized fossil distributions. The paleogeographic setting of this area (landward of the Stuart City shelf margin) and comparisons with modern analogues have strongly influenced interpretations and have placed some environmental limitations upon the hypotheses. The coeval Georgetown Formation in Central Texas was deposited in an open-shelf environment (Brown, 1971; Rose, 1972). Complex interrelation between Washita carbonate and siliciclastic lithofacies supports the contention of Chave (1967) that carbonate sedimentation is influenced by the volume of siliciclastic sediment supplied to a depocenter. Hendricks (1967, p. 63) suggested that a changing sediment supply determined whether shale or limestone would be deposited in the Washita of the East Texas basin. The observed intertonguing of carbonate and siliciclastic lithofacies is best explained by the fluctuation of terrigenous supply. Either type of sediment in the same environment will be produced depending on the volume of quartz and clay being supplied at a given time. Where carbonate facies grade laterally into siliciclastic facies, contemporaneity of environments is indicated.

Shallow Shelf Wackestone

The broad, level-bottom, shallow shelf area is below the depth of normal wave base, which is determined by local hydrographic conditions. The shelf is beyond the influence of significant terrigenous sediment input. Medium-bedded and thin-bedded mollusk-echinoid wackestone facies of the Washita Group were deposited in a shallow-shelf environment (figs. 4A, B).

Medium-bedded, mollusk-echinoid wackestone consists of wavy beds 20 to 40 cm thick that are laterally persistent for several kilometers and possibly tens of kilometers (fig. 5A). Resistant, ledge-forming limestone beds are separated by thin laminae of calcareous shale 1 to 10 cm thick. This facies composes the basal part of the Duck Creek in the Trinity River area and forms one or two prominent beds in the lower part of the Duck Creek in the Red River valley. The medium-bedded, mollusk-echinoid wackestone also makes up the lower part of the Fort Worth Limestone and the lower part of the upper Weno and Main Street Limestones south of Denton.

Thin, wavy-bedded, mollusk-echinoid wackestone consists of strata 5 to 20 cm thick that normally are laterally discontinuous within about 250 m distance. Intervening shale strata are 5 to 25 cm thick and commonly contain limestone nodules, some of which are parts of *Thalassinoides* burrow fills from the overlying wackestone bed. This microfacies makes up the middle part of the Duck Creek throughout the study area, the basal Duck Creek in the northern part, and the upper part of the Fort Worth, Weno, and Main Street Formations. Thin-bedded, mollusk-echinoid wackestone either overlies or underlies the medium-bedded facies where present.

The main component of these two facies is carbonate silt and clay (60 to 85 percent); shell fragments normally compose 15 to 40 percent (fig. 5B). Rare pellet ghosts suggest that originally pellets may have been important constituents. The multiple origins of carbonate mud were summarized by Bishop (1972). This grain-size distribution is comparable to that in modern, low-energy areas such as Florida Bay. Diagenesis has destroyed most original mud grains, except for some coccoliths, so that the origins of the mud are unknown. Silt-sized dolomite rhombs are typically less than 5 percent of the matrix and are randomly dispersed or partly filled calcispheres and burrows. Small pyrite nodules are sparsely disseminated throughout, and most are oxidized to iron oxides or hydroxides.

The rarity of current accumulations, such as small-scale channel fills, suggests that sediments of this facies were deposited below wave base. Although thorough bioturbation destroyed most original structures, the widespread lateral extent of individual, parallel limestone beds supports low-energy deposition and the general absence of strong waves or currents. The local crossbedded carbonate sand lenses and megaripples indicate sporadic currents such as storms (figs. 5C, 5D). If the analogy of planktonic foraminiferal distribution on modern carbonate shelves is applicable here, depth would not have been much greater than 10 m, because pelagic foraminifers are rarely more than 1 to 3 percent. On the Florida shelf, pelagic foraminifers compose more than 1 percent of the sediment below 10 m (Rose, 1972). Thin, marly breaks between wavy-bedded limestone beds reflect periodic increases in terrigenous input; thin-bedded wackestone accumulated nearer to muddy waters or

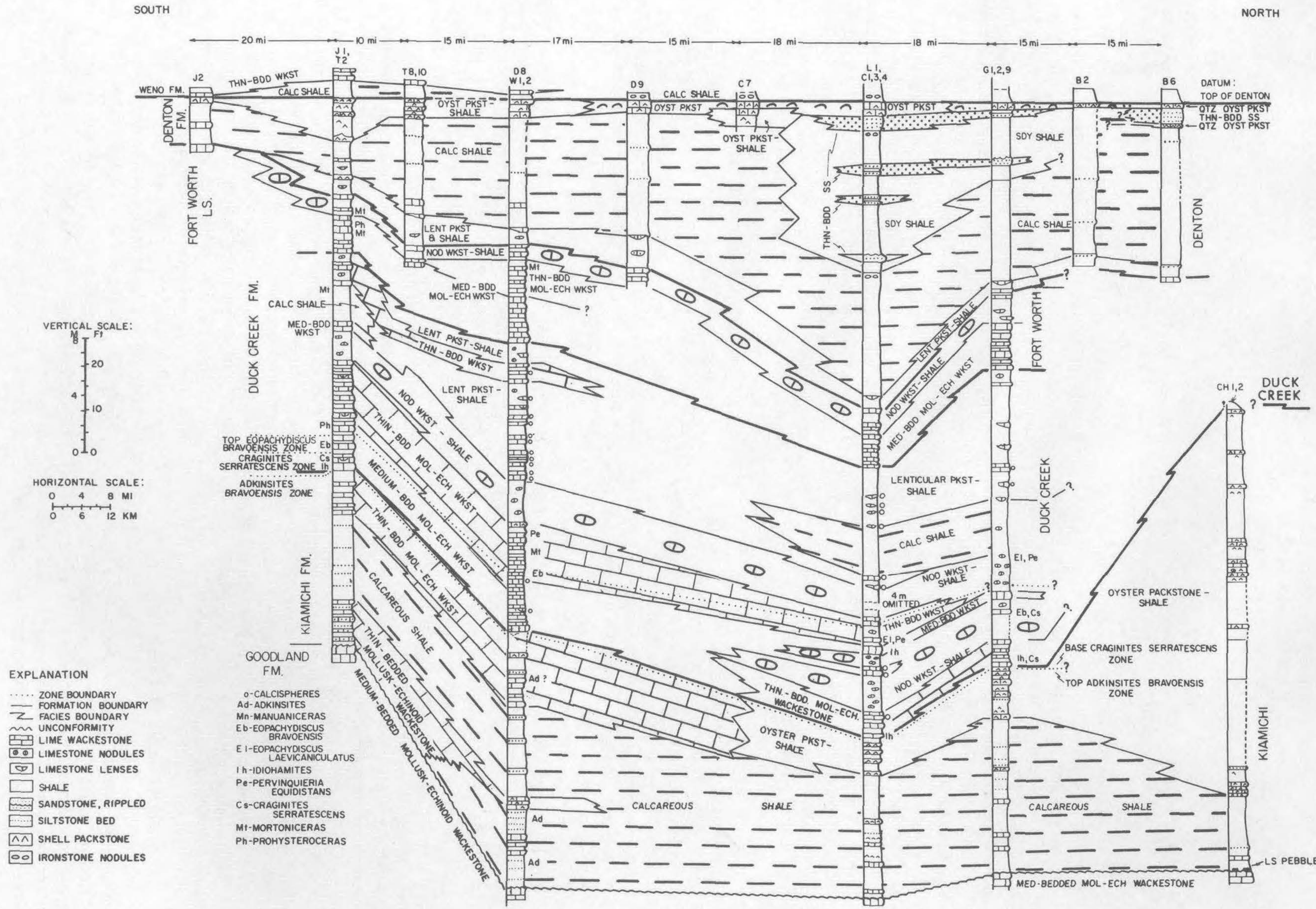

SOUTH
NORTH
20 mi
10 mi
15 mi
17 mi
15 mi
18 mi
18 mi
15 mi
15 mi
J2
J1, T2
T8,10
D8 W1,2
D9
C7
L1, C1,3,4
G1,2,9
B2
B6
CH1,2
DATUM: TOP OF DENTON
QTZ OYST PKST
THN-BDD SS
QTZ OYST PKST
WENO FM.
DENTON FM.
FORT WORTH LS.
DUCK CREEK FM.
KIAMICHI FM.
GOODLAND FM.
DENTON
FORT WORTH
DUCK CREEK
KIAMICHI
THN-BDD WKST
CALC SHALE
OYST PKST-SHALE
OYST PKST
SDY SHALE
THN-BDD SS
LENT PKST & SHALE
NOD WKST-SHALE
MED-BDD MOL-ECH WKST
THN-BDD MOL-ECH WKST
MED-BDD WKST
LENT PKST-SHALE
THN-BDD WKST
NOD WKST-SHALE
THIN-BDD MOL-ECH WKST
MEDIUM-BDD MOL-ECH WKST
THN-BDD MOL-ECH WKST
CALCAREOUS SHALE
THIN-BEDDED MOLLUSK-ECHINOID WACKESTONE
MEDIUM-BEDDED MOLLUSK-ECHINOID WACKESTONE
LENTICULAR PKST-SHALE
NOD WKST-SHALE
4 m OMITTED
MED-BDD WKST
THN-BDD. MOL-ECH. WACKESTONE
OYSTER PKST-SHALE
OYSTER PACKSTONE-SHALE
BASE CRAGINITES SERRATESCENS ZONE
TOP ADKINSITES BRAVOENSIS ZONE
TOP EOPACHYDISCUS BRAVOENSIS ZONE
CRAGINITES SERRATESCENS ZONE
ADKINSITES BRAVOENSIS ZONE
CALCAREOUS SHALE
MED-BEDDED MOL-ECH WACKESTONE
LS PEBBLES
VERTICAL SCALE:
M Ft
HORIZONTAL SCALE:
0 4 8 MI
0 6 12 KM
EXPLANATION
ZONE BOUNDARY
FORMATION BOUNDARY
FACIES BOUNDARY
UNCONFORMITY
LIME WACKESTONE
LIMESTONE NODULES
LIMESTONE LENSES
SHALE
SANDSTONE, RIPPLED
SILTSTONE BED
SHELL PACKSTONE
IRONSTONE NODULES
o-CALCISPHERES
Ad-ADKINSITES
Mn-MANUANICERAS
Eb-EOPACHYDISCUS BRAVOENSIS
El-EOPACHYDISCUS LAEVICANICULATUS
Ih-IDIOHAMITES
Pe-PERVINQUIERIA EQUIDISTANS
Cs-CRAGINITES SERRATESCENS
Mt-MORTONICERAS
Ph-PROHYSTEROCERAS

Figure 2.

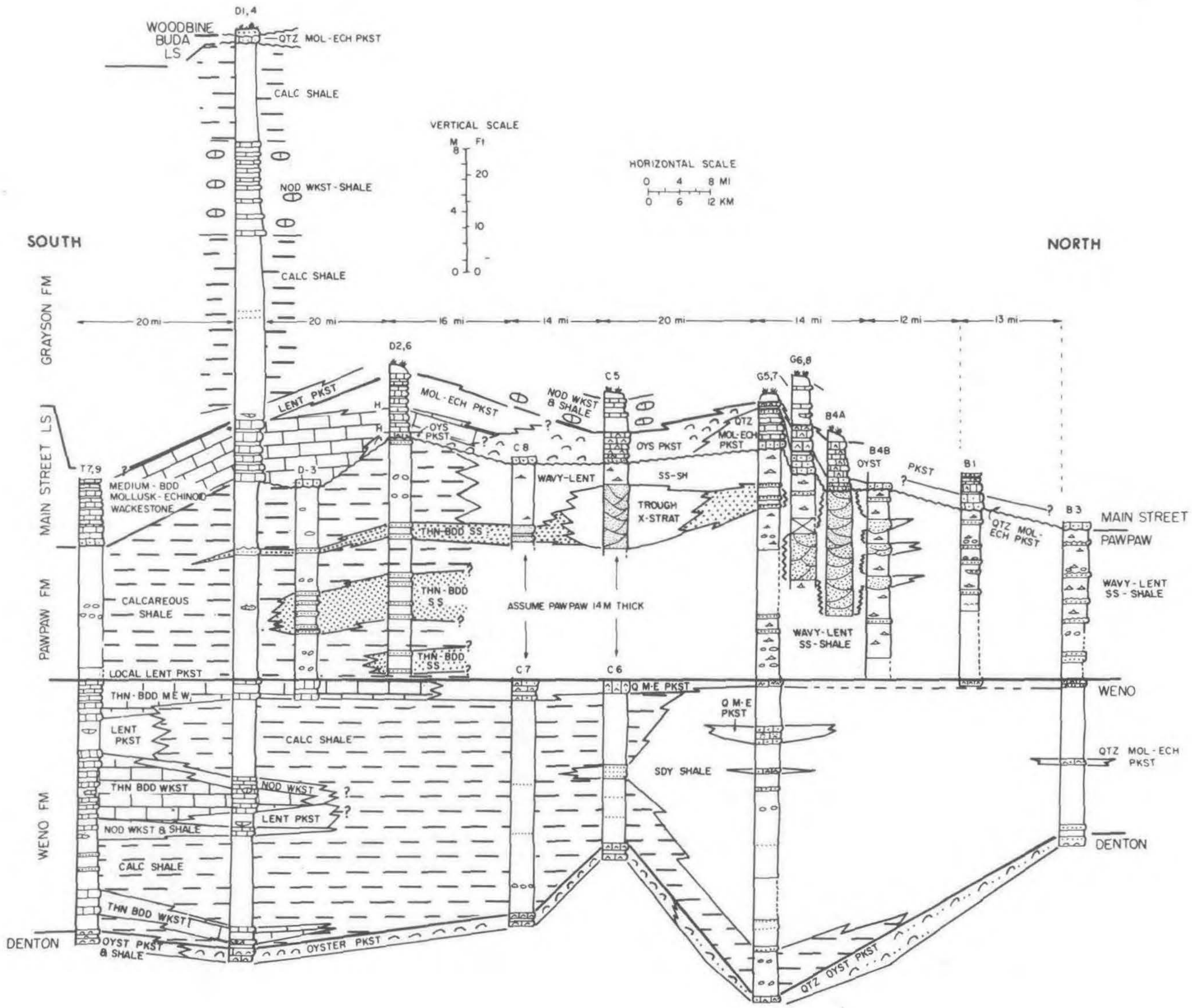


Figure 3.

Figure 2. Stratigraphic cross section of the lower Washita formations. Abbreviations of facies: thn-bdd mol-ech wkst = thin-bedded, mollusk-echinoid wackestone; med-bdd = medium bedded; nod wkst-sh = nodular wackestone-shale; lent pkst-sh = lenticular packstone-shale; calc = calcareous; oyst = oyster; ss = sandstone; sdy = sandy; qtz = quartz.

Figure 3. Stratigraphic cross section of the upper Washita formations. See figure 2 for explanation of abbreviations. Standard lithologic symbols used.

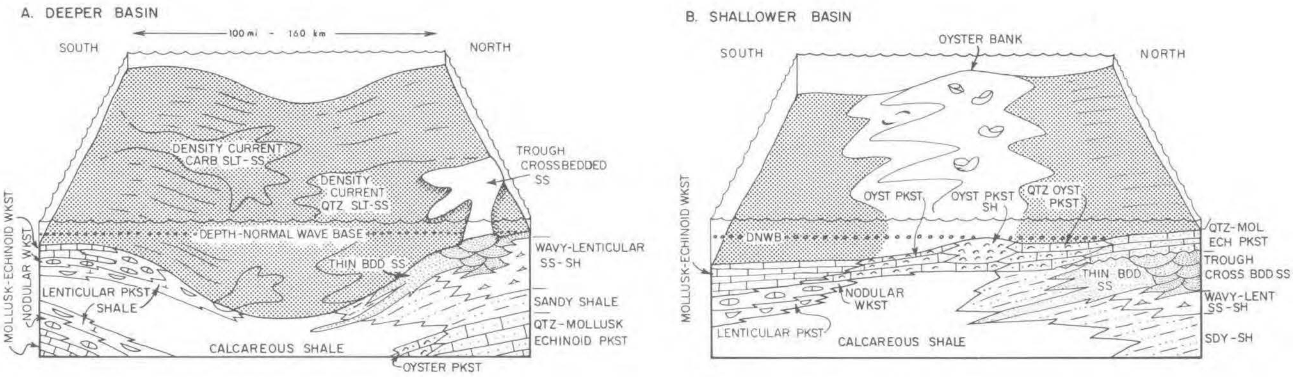


Figure 4. Alternate bathymetric models to explain vertical and lateral relations of Washita facies. Figure 4A shows the relationship of shallow shelf and transitional sediments to shelf basin muds and to nearshore facies northward. Figure 4B shows the relationship of shallow shelf carbonate on the south to nearshore carbonates on the north. See figure 2 for explanation of abbreviations.

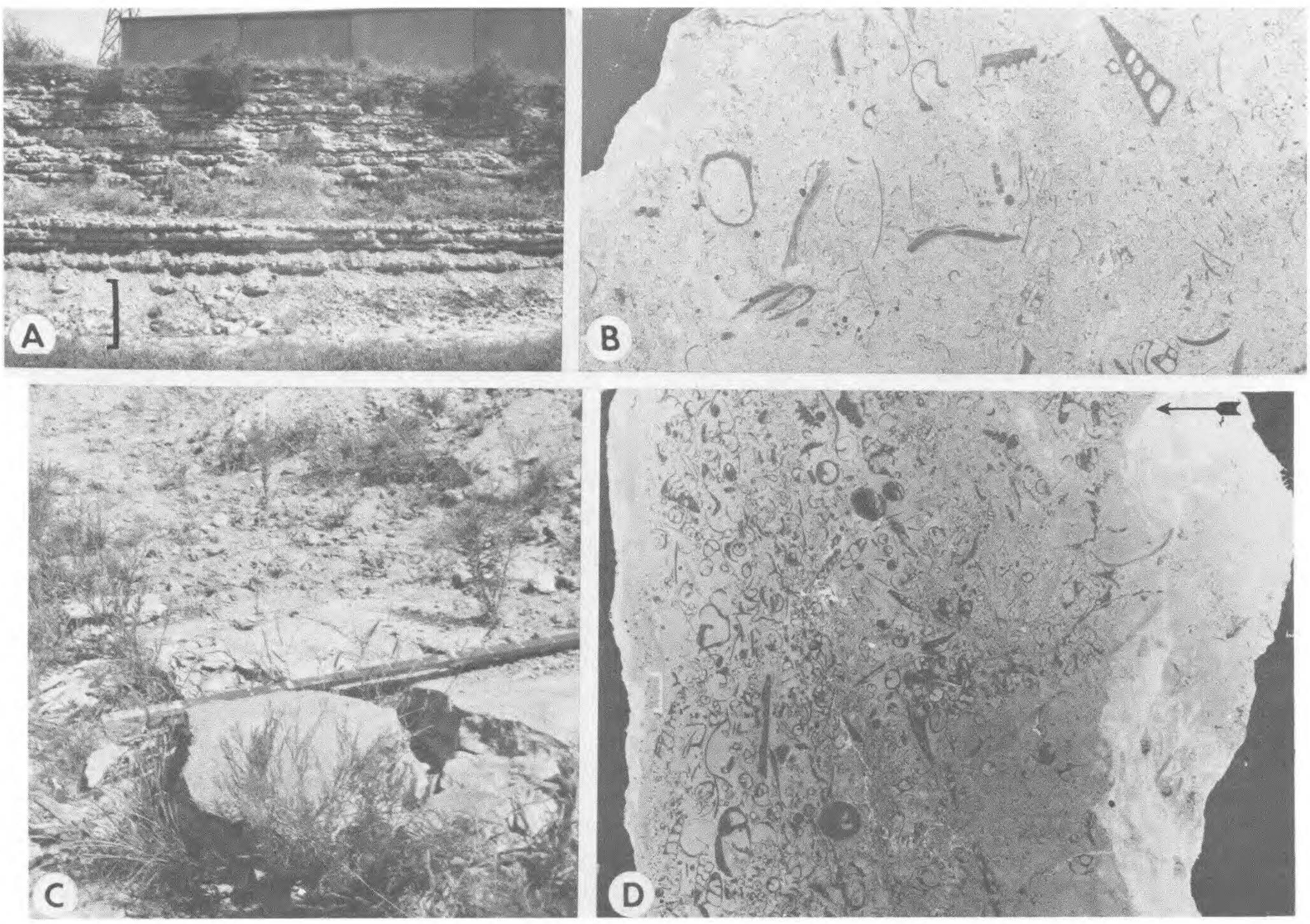


Figure 5. Mollusk-echinoid wackestone. A. Lower Duck Creek, Loc. T2; medium-bedded wackestone at base grading up into thin-bedded wackestone; bar = 2m B. Negative peel print of Fort Worth Ls., Loc. J1, × 2. C. Megaripple on top of Fort Worth, Loc. J1; rod = 1.4m. D. Negative peel print of megaripple packstone in C, × 0.5.

Table 1. Summary of properties defining Washita facies.

Lithofacies and Microfacies	Carb. Content (%)	Grain Size Range	Allochem (%)	Micrite (%)	Stratification	Dominant Grain Types and Fossil Grains	Dominant Mineral	Occurrence: Stratigraphic*	Occurrence: Geographic
Mollusk-Echinoid Wackestones:	>65	Clay-Gravel	10-40	60-90		Bivalves Echinoids Gastropods			
Medium bedded					Even, medium	Forams Calcispheres	Calcite	DC, FW WE, MS	N-S
Thin bedded					Irregular, wavy, thin		Calcite	DC, FW, WE MS	N-S
Nod.-lenticular and marl					Nodular to lenticular		Calcite - clay	KI, DC, FW, WE, MS, GY	N-S
Packstones:									
Oyster	70-90	Clay-Gravel	40-85	15-60	Lenticular to irregular, thin	Oyster	Calcite	KI, DE MS, GY	N-S
Quartzitic Oyster	As above but with > 10% quartz sand							DE	N
Lenticular Packstone-Shale	>65	Clay-Gravel	40-90	10-60	Even, thin; laminated lenses	Calcispheres Echinoids Mollusks Forams	Calcite and clay	DC, FW, DE WE, GY	N-S
Quartzitic Mollusk-Echinoid	20-80	Clay-Gravel	20-65 fossil >10 quartz	5-50	Even, thin	Bivalves Echinoids Forams	Calcite, quartz, clay	DE, WE, MS, BU	N
Oyster Packstone-Shale	90-40	Clay-Gravel	15-85	60-80	Thick to lenticular	Oysters	Calcite, clay	KI, DE	
Shales:									
Calcareous	10-25	Clay-Silt	5-15	5-15	Laminated-homogeneous		Clay	KI, DC, DE, WE, PP, GY	S
Sandy	>10	Clay-Silt	5-15		Laminated-mottled		Clay	DE, WE	N
Sandstones:									
Thin-bedded		Coarse siltstone-fine sandstone	>10		Thin bedded, even, thin-laminated wedge planar	Bivalves Echinoiderms Forams Ostracodes	Quartz, mica, feldspar	DE, WE, PP	N
Wavy-lenticular		Clay-very fine sand	0		Wavy, lenticular flaser	None	Quartz, mica	DE, WE, PP	N
Trough		Coarse siltstone-fine sandstone	0		Trough and wedge planar	None	Quartz, mica	DE, PP	N

* KI = Kiamichi; DC = Duck Creek; FW = Fort Worth: DE = Denton: WE = Weno, PP = Pawpaw; MS = Main Street; GY = Grayson; BU = Buda

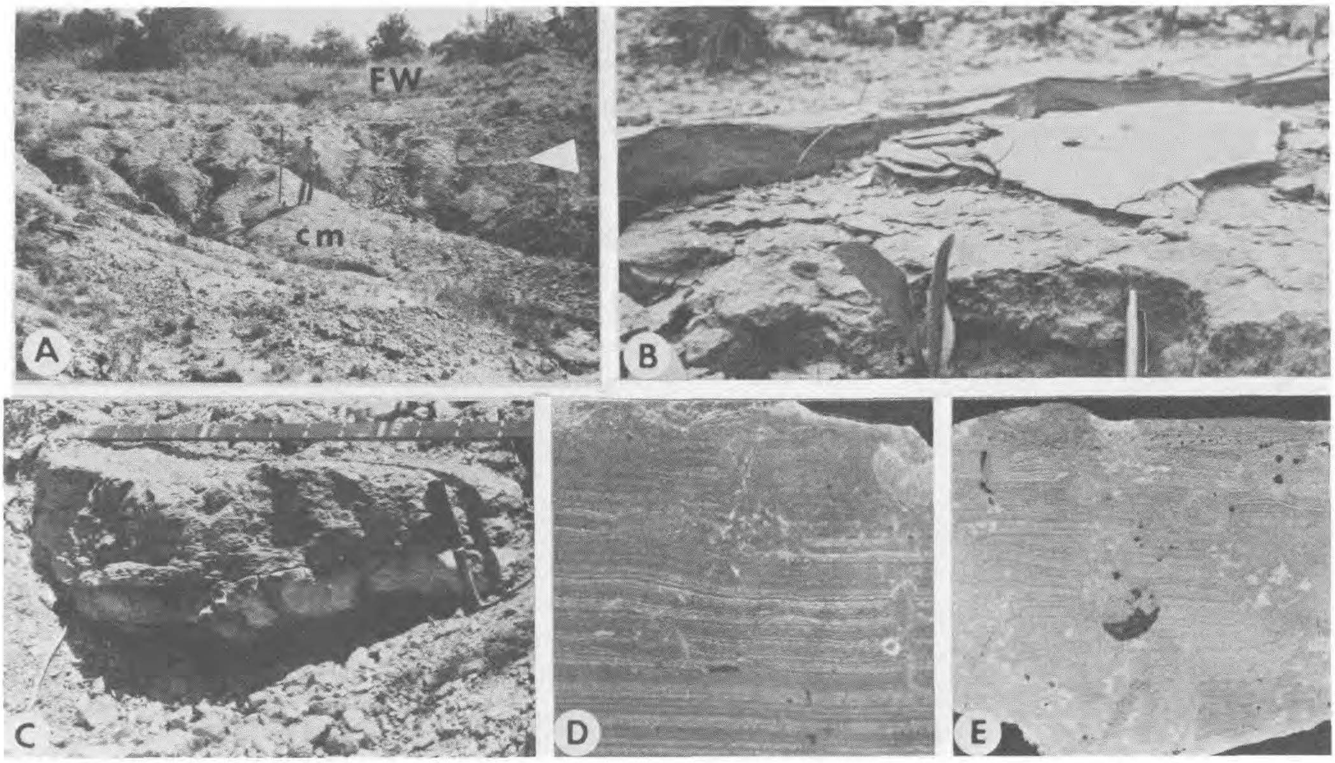


Figure 6. Lenticular packstone. A. Upper part of Duck Creek, Loc. G 2. FW = Ft. Worth Ls.; diamond points to lenticular packstone, cm = calcareous shale. B. Closeup of rippled top of packstone in A. C. Packstone lens with ammonite (a) at base; upper Duck Creek, Loc. T4. D. Negative peel print of calcisphere packstone, Upper Duck Creek, Loc. W2 (Laali's peel 34), × 1. E. Negative peel print of laminated carbonate mudstone lens in thin-bedded wackestone, lower Duck Creek, Loc. T1 (Laali's peel H3), × 1.

during periods of more frequent mud influx than did the medium-bedded limestones. Normal marine salinity is indicated by the varied fauna and flora of echinoids, ammonoids, bivalves, gastropods, benthic foraminifers, ostracodes, bryozoans, brachiopods, serpulids, calcispheres, and dasyclad algae. Common trace fossils are *Planolites, Chondrites,* and *Thalassinoides* (fig. 8A).

The shallow shelf, mollusk-echinoid wackestone facies is developed in the Duck Creek, Fort Worth, Weno, and Main Street Formations. This facies composes 35 percent of the Washita section in Tarrant County. It interfingers with or grades laterally northward into other facies. Southward, this facies progressively composes a greater part of the Washita section, represented by the Georgetown Limestone. Consequently, the shallow shelf persisted longer and more continuously south on the northeast slope of the Central Texas platform than in the North Texas basin.

Transitional Wackestone and Shale

This facies is transitional between the shallow shelf and the shelf basin (fig. 4A) and consists of nodular-bedded, mollusk-echinoid wackestone interbedded with thicker intervals of lenticular packstone-calcareous shale. Resistant wackestone beds consist of nodular zones generally less than 10 cm thick. These nodular zones may grade laterally into the shale or may persist across an outcrop. The intervening marly beds are from 10 to 50 cm thick and locally are somewhat thicker. This facies normally grades above or below into thin-bedded wackestone. The shale consists of 20- to 40-percent kaolinite, illite, and mixed-layer illite-smectite in subequal proportions.

This facies represents a transitional substrate that differed from the level-bottom, shallow shelf and sloped gently into the shelf basin. This substrate was the zone of interaction between carbonate and siliciclastic sedimentation. In the transitional zone, carbonate deposition was diluted by terrigenous clay, resulting in calcareous shale beds alternating with intervals of discontinuous wackestone nodules.

The gently sloping transition environment separated the deeper shelf basin from the shallow shelf. Direct evidence of the gradient is the common development of small-scale, carbonate channels in the lenticular packstone-shale facies of this environment (figs. 6A, 6B). Packstone lenses are 5 to 30 cm thick (fig. 6C) and are randomly distributed within intervals of calcareous shale; most lenses wedge out laterally into the surrounding shale. Intercalated shale beds range from 30 to more than 100 cm. The width of a lens ranges from 1 to several meters; local lenses may consist of a zone of connected lenses extending 30 m across the outcrop (see Duck Creek Formation at Loc. G2). Many lenses are evenly laminated or cross-laminated (fig. 6D). Grains are normally fine and well sorted; coarser grained lenses with gravel-sized shells are normally graded. Some display parallel, low-amplitude current ripples on the uppermost surface (fig. 6B). Most have sharp basal and upper contacts, and the base is concave down into underlying shale.

Channel-fill deposits consist of from 35- to 90-percent carbonate grains produced both on the shelf and in the transitional environments: intraclasts, glauconite, wood, mollusks, echinoids, foraminifers, calcispheres, and crinoids. Calcispheres compose 90 percent of some lenses in the Duck Creek. The micrite and clay-silt mud matrix demonstrates that winnowing played a minor role, whereas the concave-down base indicates scouring of the substrate. Parallel laminations indicate gravitational settling, and ripple laminations indicate the effects of bottom currents. The channel-fill sediments were deposited by a sediment-laden density current generated either locally or upon the shelf. The irregular vertical distribution of superjacent lenses indicates the action of a sporadic process such as storms rather than regular processes such as tides or waves. In modern carbonate lagoons, storms resuspend and winnow mud from the bottom, leaving pockets of lag gravel, or they scour pockets into which shells from elsewhere are deposited. Storms also transport debris from shallow water into deeper water. This latter process is comparable to the storm-generated sand beds described off the Texas coast by Hayes (1967).

Burrows are common in most lenses. The base of many lenses displays molds of large *Thalassinoides* networks. Nearly all lenses are pierced by *Chondrites* and, less commonly, by *Planolites* burrows. Some lenses are thoroughly bioturbated, but in most, relic lamination is preserved.

Small packstone lenses occur locally in the upper parts of individual beds of the mollusk-echinoid wackestone facies within the lower Duck Creek (fig. 6E), Fort Worth (fig. 5C, D), Weno, and Main Street. The lenses are generally less than 1 to 2 m wide and 10 to 20 cm thick. Most are thinly laminated and bioturbated. Composition of these lenses resembles the packstones within the calcareous shale. Because of the small scale, they are not recognized here as a separate microfacies.

The transitional facies of nodular wackestone-shale and lenticular packstone-shale are found in the Duck Creek, Fort Worth, basal Denton, Weno, basal Pawpaw, Main Street, and basal Grayson Formations in the southern area. These facies compose about 18 percent of the Washita section there and grade northward into basinal facies.

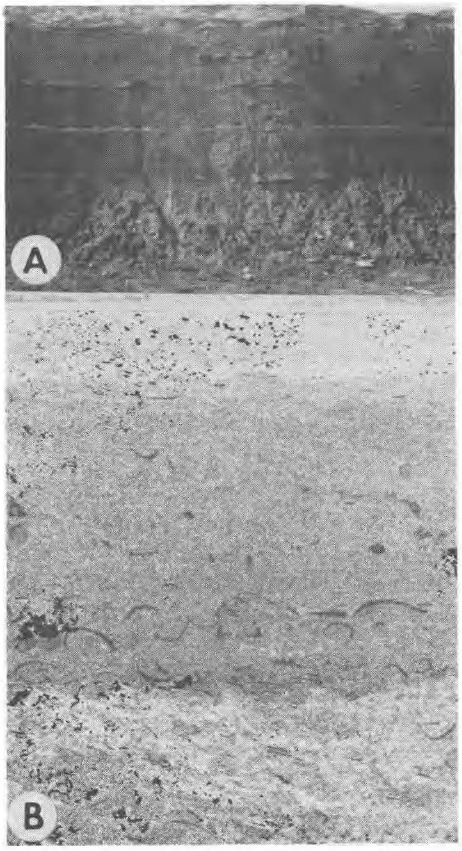


Figure 7. Calcareous shale. A. Loc. G4, lower part of Kiamichi Fm. 7 m thick with carbonate shale and shell packstone. B. Shell packstone interbed in calcareous shale, corner of Jacksboro Highway and State Highway 187, Fort Worth, Texas, × 2 (top is up).

Shelf-Basin Shale

The basinal calcareous shale facies represents the deepest environment in the Washita (fig. 4A). This medium- to dark-gray facies contains only 10- to 25-percent calcareous components. Kaolinite, illite, smectite, and mixed-layer illite-smectite clays compose 30 to 70 percent of the shale; quartz and muscovite silt are 25 to 65 percent, and quartz sand content is less than 5 percent. Pyrite and ironstone nodules up to 10 cm across and concentrated in local zones indicate that reducing conditions prevailed below the sediment-water interface. A diverse and locally abundant fauna represented by mollusk molds, *Chondrites* burrows, and indistinct mottles suggests that bottom waters were oxygenated.

In Tarrant County, calcareous shale units of the Denton contain laterally continuous, blocky, argillaceous limestone beds 15 to 20 cm thick occupying an interval less than 1 m thick. Insoluble clay and silt content is up to 60 percent, and fossils compose no more than 10 percent. Similar beds occur in dark-gray shale of the Kiamichi north of Tarrant County (fig. 7A). Sandy oyster packstone beds (fig. 7B), 5 to 10 cm thick, are rare in the Kiamichi Shale. These beds show graded bedding and ripple marks; they are separated from overlying oyster packstone facies by 3 m of calcareous shale.

In the northern part of the basin, mainly clay and silt were deposited, and in the south clay was diluted with carbonate grains. Occasionally density currents flowed into the basin from the north depositing distinctive flaggy siltstone beds 1 to 2 cm thick that are sparsely distributed within the fissile calcareous shale (Scott, Laali, and Fee, 1975). Basal and upper contacts are sharp, and flute casts, tool marks, and burrow casts mark the bases. Graded beds and climbing ripples are common; interference ripples are commonly well developed. Quartz sand and silt constitute 80 to 90 percent of the flagstones with minor amounts of feldspar, muscovite, glauconite, and clay. Density currents from the south flank of the basin transported in carbonate silt and sand with calcispheres and foraminifers. These density currents may have been generated by seasonal floods and storms.

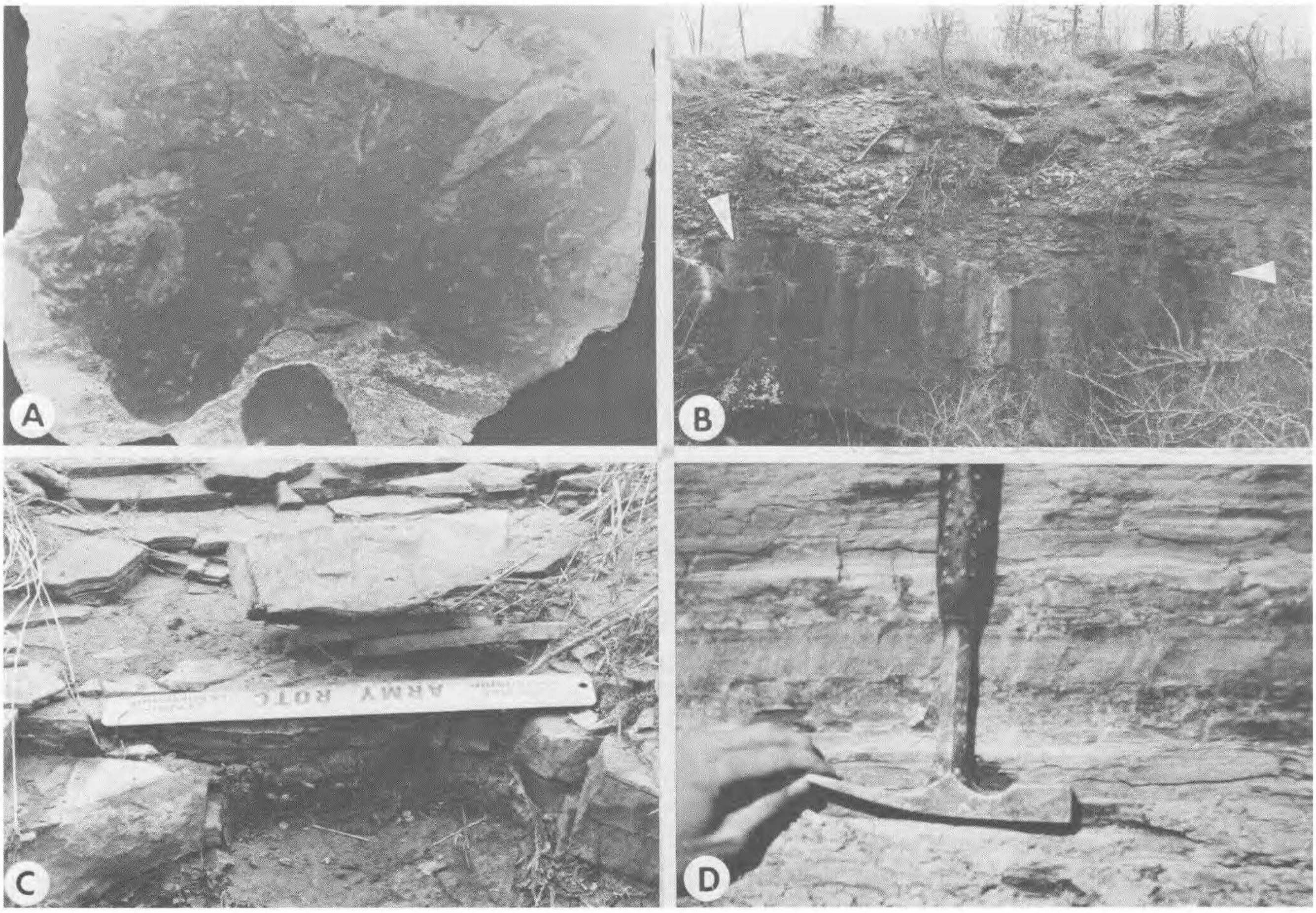


Figure 8. A. Bioturbated mollusk-echinoid wackestone, *Thalassinoides* burrow at base, *Planolites* burrows cut by *Chondrites* burrows, Fort Worth Ls., Loc. J1, × 0.8. B. Trough-crossbedded sandstone at Loc. B4A, Pawpaw channel sandstone disconformably overlain by Main Street quartzitic mollusk-echinoid packstone (arrow at contact). C. Closeup of thin-bedded sandstone in upper Pawpaw at Loc. D6; note flute at base of upturned bed. D. Wavy lenticular sandstone-shale, Pawpaw at Loc. B4B.

Although basin depth cannot be quantified, it was deeper than normal (nonstorm) wave base, which is generally less than about 10 m, and probably not deeper than average shelf depths of approximately 200 m. The nearshore area in southeastern Oklahoma was about 160 km from the shallow carbonate Central Texas platform; thus, the gentle slopes indicated by the fine-grained sediments suggest depths in the shallower part of the shelf range. Stratigraphic data show that the shoaling-upward succession from basin to shelf is generally 15 to 25 m thick. If stratigraphic thickness represents maximum subsidence without subsequent uplift and if shelf deposits were just below wave base, then an approximate maximum depth would be around 30 m. Such a depth is consistent with sedimentologic and paleoecologic data, but quantitative depth estimates are speculative.

The calcareous shale facies is most common in the southern outcrop area where it comprises the greatest thickness (4 to 10 m) of the Kiamichi, upper Duck Creek, Denton, Weno, Pawpaw, and lower Grayson Formations. This facies has its greatest northern extent in the Duck Creek Formation. In the Denton, Weno, and Pawpaw Formations, it grades northward into the sandy shale facies, and it is bounded above and below by mollusk-echinoid wackestones of the Fort Worth, Weno, and Main Street.

Distal Delta-Front-Shoreface Shale and Sandstone

The substrate of this environment sloped gently basinward from the northern nearshore environments (fig. 4A). It was at or just below normal wave base and was affected by storm waves, rip currents, and tidal currents. Dominant facies representing these environments are the thin-bedded sandstone and the sandy shale facies.

Sandy shale normally contains more than 10 percent quartz sand, 30 to 65 percent silt, and 30 to 65 percent mixed-layer illite-smectite, illite, smectite, and kaolinite. The calcareous content is generally less than 10 percent. The blocky, homogeneous to laminated rock is olive brown to dark gray. Silt- and sand-sized minerals are quartz, muscovite, glauconite, pyrite, magnetite, leucoxene, and hematite. Bioturbation is indicated by the common silt and sand mottles. Common interbeds are flaggy siltstone, described by Scott, Laali, and Fee (1975), and ironstone beds and concretion zones. Ironstone concretions are up to 50 cm across and locally contain up to 35 percent fossil echinoderms, bivalves, gastropods, ostracodes, and foraminifers. Partial replacement of fossils by iron oxide, as well as the fossil content, suggests that some ironstone replaced micritic limestone.

Sandy shale occurs in the northern outcrop belt in the Denton and Weno Formations, and it grades southwards into the calcareous shale facies. In the Weno, it is overlain and underlain by quartzitic mollusk-echinoid packstone. In the Denton, sandy shale is underlain by calcareous shale and overlain by thin-bedded sandstone. Sandy shale is the most prominent and persistent facies in the Denton north of Denton County where it composes more than half of the formation.

The thin-bedded sandstone facies exposed in northern Denton and Pawpaw outcrops consist of yellow-brown sandstone strata 10 to 50 cm thick, interbedded with dark-gray to olive-brown sandy shale (fig. 8C). Shale beds range in thickness from 10 to 100 cm and normally display the properties of the sandy shale facies or the wavy lenticular facies. Bivalves, echinoderms, foraminifers, and ostracodes make up to 3 percent of the thin-bedded sandstone facies. Characteristic structures of the sandstone beds are parallel stratification overlain by asymmetric ripple cross-strata. Parallel and interference ripples and flute marks (fig. 8C), tool marks, load clasts, and burrow casts mark the top and base of these sharply bounded graded beds. This suggests deposition of bedload by waning energy. The strike of parallel ripples in Denton and Pawpaw outcrops of the Red River area averages N. 67 W. The grain-size distributions of these sands are most comparable with modern offshore marine sands (compare fig. 9 with Visher, 1969 and Passega and others, 1967). General transport of sands in the northern area was from the northwest, as suggested by the orientation of tool marks and flute casts (Scott and others, 1975). The southward decrease in grain size and bedding thickness also supports a general south to southeast transport direction.

The provenance of submature Denton, Weno, and Pawpaw quartzarenites and subarkoses was primarily a terrane of older sedimentary rocks. Such a terrane is suggested by textural inversions, variations in quartz types, and a stable heavy mineral suite. Textural inversions in Weno and Pawpaw sands are poor sorting with a high degree of rounding in coarser sands and well-sorted, very fine-grained sand with a clay matrix. Common quartz is the dominant grain type, and feldspar, chert, metamorphic quartz, and undulose quartz are normally present. The heavy mineral suite is dominated by leucoxene and muscovite with lesser amounts of glauconite, biotite, tourmaline, rutile, zircon, magnetite-ilmenite, and garnet. Paleozoic sedimentary and low-grade metamorphic rocks in the Arbuckle and Ouachita Mountains are the closest terranes that could provide these grains. Heavy mineral suites in the Ordovician Simpson Group in the Arbuckles and in the Carboniferous Stanley and Blaylock Groups of the Ouachitas are dominated by ilmenite-leucoxene, rutile, tourmaline, and zircon (Honess, 1923; Ham, 1945). Ilmenite is also abundant in the Wichita Mountains to the west, which could have been an additional source if they were exposed at this time.

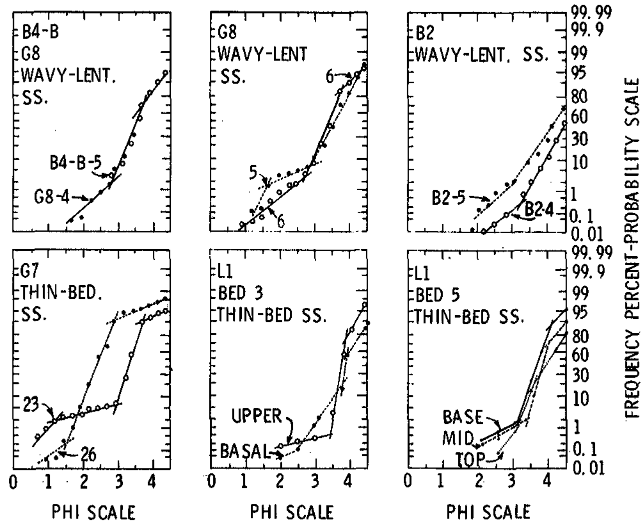


Figure 9. Cumulative probability grain-size distributions of the wavy lenticular sandstone-shale, and the thin-bedded sandstone facies. Locality number is in upper left corner. At Loc. B4B bed 5 is in lower part of section. The exact position of other samples is given by Magee (1974) and Fee (1974).

The thin-bedded sandstone facies of the Pawpaw interfingers southward with calcareous shale. Northward, sandstone beds in the Pawpaw become thicker and coarser grained. In the Red River area, this facies grades into the trough-crossbedded and wavy lenticular sandstone facies. Grain size is predominantly fine sand in Grayson County, very fine sand in Cooke County, and coarse silt in Denton County. These sandstones are similar in composition to laminated siltstones of the calcareous shale facies with which they apparently intergrade.

A problem remains regarding the precise agent that transported and deposited the thin-bedded sands. At least three seem possible: waves on the shoreface, other currents on the shoreface, or delta-front traction currents. Evidence such as grain-size distribution and fossils in the adjacent sandy mudstones suggests deposition by marine processes. However, thin-bedded sands also occur with the nearshore wavy lenticular sand-shale facies which is unfossiliferous. Deposition of the wavy lenticular facies, likewise, is not clear. Such sedimentary structures are found in tidal flats (Reineck, 1972), in subtidal deltas (Oertel, 1973), and in the lower shoreface and distal delta front, wherever currents transport waning supplies of sand. The absence of a shoreface fauna comparable to that in coeval rocks in the Western Interior (Scott, 1974) discourages that interpretation. Also, the presence of upper shoreface or beach sands would be expected in the Washita; however, their absence may be the result of post-Cretaceous erosion. A delta-related origin of these sands likewise suggests the development of a delta distributary system to the north. Again, erosion has removed much of the evidence.

Deltaic-Estuarine Sandstone and Shale

This nearshore environmental complex consisted of tide-influenced channels and subtidal shoals (fig. 4A). These environments are represented by the trough-crossbedded sandstone and the wavy lenticular sandstone-shale facies of the Pawpaw Formation in the northern part of the study area.

The trough-crossbedded sandstone facies is composed of elongate, convex-down sand bodies (fig. 8B) that trend about normal to the east-west strand. Channel fills range in thickness from 20 cm to 10 m, and the width ranges from 2 to more than 50 m. Larger channels cannot be traced for more than 1 km because outcrops are so widely spaced. Channel-fill sands are bounded laterally and vertically by the wavy-lenticular sandstone-shale facies. Axes of the component troughs of many channel bodies have a bimodal dip pattern that is approximately north-south. Elongate clay pebbles at the base of some channels are aligned north-south. These data suggest a north-south flowing tidal current system. Strong and slack currents are suggested by flaser bedding and clay drapes between sets.

These mature to immature, moderately well-sorted quartzarenites to subarkoses are fine to very fine grained (table 2). The heavy mineral assemblage contains glauconite and is similar to that of the other sandstone facies.

Although grain-size data (figs. 10 and 11) are not definitive, an upward decrease in current energy is suggested by basal lag pebbles overlain by trough-crossbedded sands and capped by the interbedded and rippled sands and clays of the wavy lenticular facies. Such a vertical succession of structures typifies channels on tidal flats, in estuaries and rivers (Klein, 1967), and distributary channels (L. F. Brown, Jr., personal communication, 1977). Because of the absence of shells in the basal gravel, which is characteristic of tidal channels, these channel-fill deposits probably were the product of estuarine or deltaic processes, which were further modified by tidal processes. Furthermore, grain-size distributions of the channel-sands are comparable to sands deposited in a wave-influenced deltaic environment (Visher, 1969). Plots of median size and the coarsest 1 percentile (fig. 12) suggest deposition from both traction and suspension load, which is typical of deltaic and estuarine channels.

The wavy lenticular sandstone-shale facies is characterized by interbedded silty sand and sandy shale intervals up to 4 m thick (fig. 8D). Bed thickness ranges from less than 1 to 8 cm. Wavy lenticular sandstone-shale is the dominant Pawpaw facies in the Red River area, and it interfingers southward with the thin-bedded sandstone facies. Lithologies of this type in the Denton are grouped with the thin-bedded sandstone facies because the units are less than 1 m thick and underlie persistent sandstone beds (Loc. L1).

Wavy sandstone beds display current ripples on uppermost surfaces; internal, small-scale cross-stratification consists either of small-scale cross-laminae or parallel laminae. Lenticular bedding is developed in shale containing sand lenses 5 to 15 cm long and 1 to 5 cm thick. Clay galls and indistinct bioturbation, as well as *Skolithos* burrows, are locally common. Hematitic ironstone laminae occur along bedding planes between sand and mud layers.

Composition of these sands resembles other sandstone facies. Shales consist of 40 to 50 percent **illite,** 25 to 30 percent expandable clay minerals, and 15 to 25 percent kaolinite. Grain size of the moderately to well-sorted sands in this facies ranges from very fine sand to coarse silt (table 2). Cumulative probability grain size plots (fig. 9) are comparable to those of nearshore sands in the shelf environment along the southern Atlantic and Gulf coasts (Visher, 1969). A plot of the median against the coarsest 1 percentile (fig. 12) suggests deposition by graded suspension as Passega and others (1967) found in the shelf environment off the Adriatic coast where the sediments seem to have been deposited since modern sea level.

A tidal flat origin for the wavy lenticular sandstone-shale does not seem likely for a number of reasons. This facies grades southward into marine basin facies rather than into lagoonal facies. The channel-fill sands lack basal shell lag gravels found in marine tidal channels. Associated tidal flat sediments, such as those of vegetated marshes, ponds, sand flats, or supratidal flats, are not evident.

An alternate hypothesis is that these facies accumulated in a deltaic environment. In this case, channel-fill sandstone would represent distributary channels. Wave- and tide-dominated, high-destructive deltas consist mainly of marine sediments, and the associated sand bodies are elongate or digitate tidal channels and bars normal to strand (Fisher and others, 1969). The marine portion of the delta may be up to 70 km wide and the zone of channel sands may extend more than 60 km landward. The areal extent of sand is comparable to that of the wavy-lenticular and trough-crossbedded facies in southeastern Oklahoma and northern Texas.

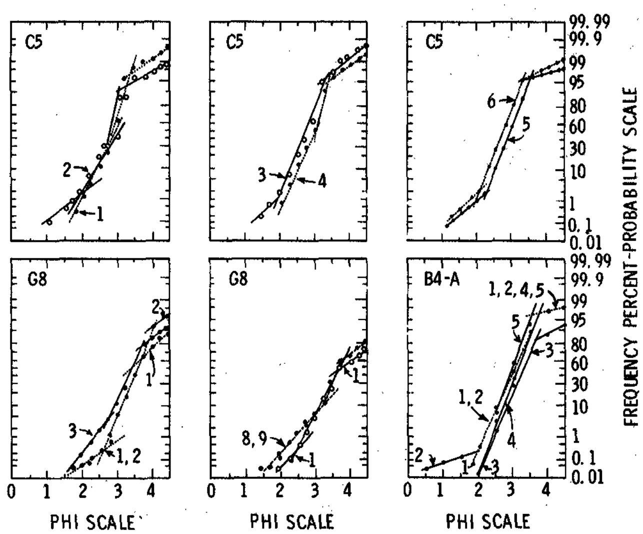
A third hypothesis is that these sediments were deposited in a tidal-dominated estuarine environment. In this setting, channel sands accumulate at the estuary **inlet,** as well as seaward and landward. Wavy lenticular sands and muds are deposited laterally and distaily to the channel sands. These distal facies then grade seaward into marine muds and landward into bay muds and deltaic sediments. A problem is that estuarine deposition seems to require an embayed coastline. Among Pawpaw outcrops, no coastline or beach facies are recognized. The present outcrop belt, however, may be seaward of the estuary mouth. In summary, trough-crossbedded facies may represent deltaic or estuarine channel inlet sands, and the wavy-lenticular facies may represent associated delta-front or channel-fringing facies.

Oyster Bed and Flank Packstone-Shale

The oyster packstone-shale facies represents *Texigryphaea* spp. or *Ilymatogyra arietina* biostromes flanked by or interrupted by wave-winnowed, storm-washover beds (fig. 4B). The 50 to 120 cm thick shales contain abundant oysters and are moderate gray, blocky to fissile, consisting of up to 60 percent insoluble clay. Articulated, juvenile to gerontic adult *Texigryphaea* shells dominate the fossil deposits with lesser numbers of *Rastellum* (*Arctostrea*) *carinata, Plicatula* sp., encrusting bryozoans, echinoids, ostracodes, and *Kingena wacoensis*. The clay matrix, age distribution, and absence of current structures all attest to the accumulation of the shells where they lived. Interspersed within the shale are oyster packstone beds 10 to 20 cm thick that normally are laterally persistent within an

Table 2. Summary of grain-size parameters in phi units of sandstone samples in the Denton and Pawpaw Formations.

Facies	Mean	Sorting	Skewness	Kurtosis
Trough Crossbedded:				
Mean of 16 samples	3.26	0.48	0.62	5.35
Range	2.64-3.83	0.37-0.67	0.07-1.12	1.87-8.52
Wavy Lenticular:				
Mean of 6 samples	3.84	0.48	-0.45	4.65
Range	3.43-4.41	0.40-0.59	-0.79-0.46	3.94-6.22
Thin Bedded:				
Mean of 11 samples	3.67	0.43	0.45	5.65
Range	2.55-4.23	0.30-0.61	-1.09-1.87	2.69-8.69



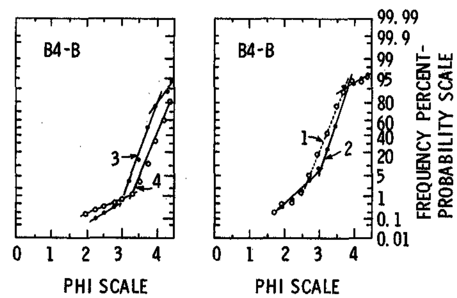


Figure 10. Cumulative probability grain-size distributions of the trough-crossbedded sandstone facies. Locality number is in upper left corner; sample numbers from Magee (1974) and Fee (1974).

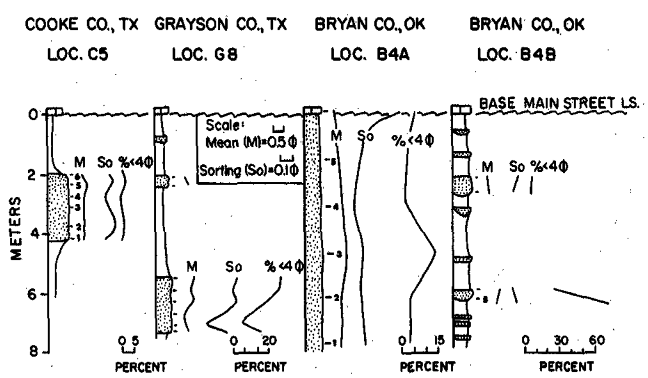


Figure 11. Vertical variations in grain-size parameters within several channel sand bodies of the Pawpaw.

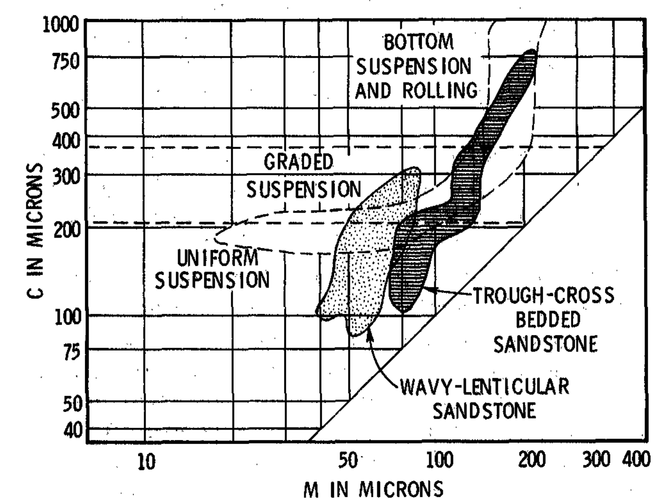
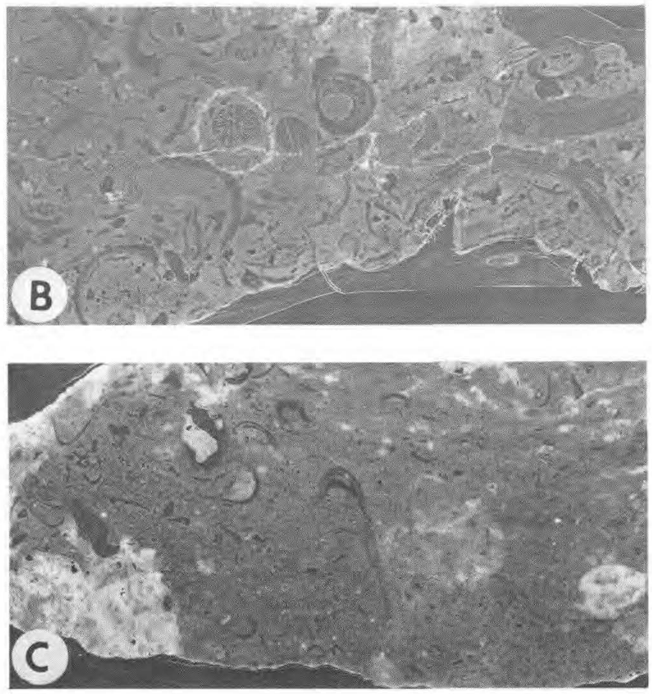


Figure 12. Passega diagram of the trough-crossbedded and wavy lenticular sandstone facies. C is coarsest 1 percentile and m is median grain size.

Figure 13. Oyster packstone. A. Loc. C5, Main Street packstones overlying wavy lenticular sandstone-shale and underlying Grayson nodular wackestones in roadcut. B. Negative peel print of *Ilymatogyra arietina* packstone from Loc. C5, × 1 (top up). C. Negative peel print of bioturbated *I. arietina* packstone, Main Street, Loc. D6, × 1 (top up).



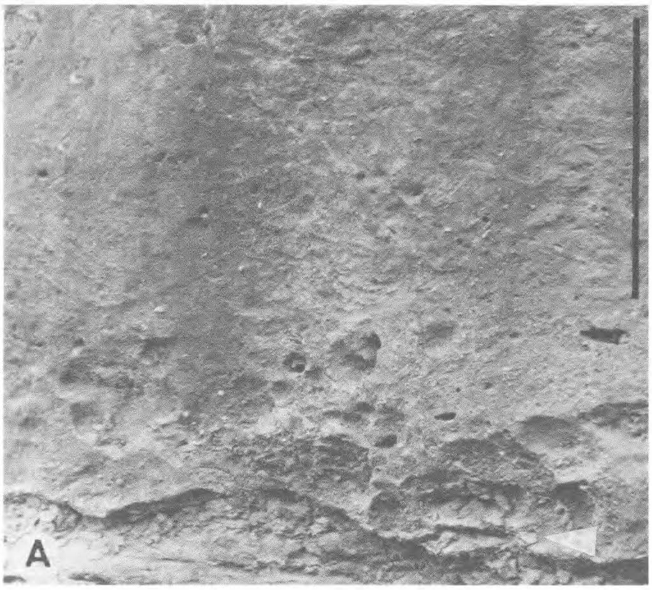
outcrop. Basal and upper contacts are sharp, and in places the strata are megarippled and cross-stratified. The basal surface commonly displays a dense network of *Thalassinoides* burrow casts indicating the presence of burrowers within the shale. *Texigryphaea washitaensis* is the dominant oyster and both whole valves and fragments compose 15 to 55 percent of the rock. Micrite matrix is 45 to 80 percent, and insoluble clay is 5 to 10 percent of the packstone beds. Locally, the packstone beds grade laterally into wackestone beds. The oyster packstone beds may be a winnowed, comminuted lag deposit or debris transported from the growth beds.

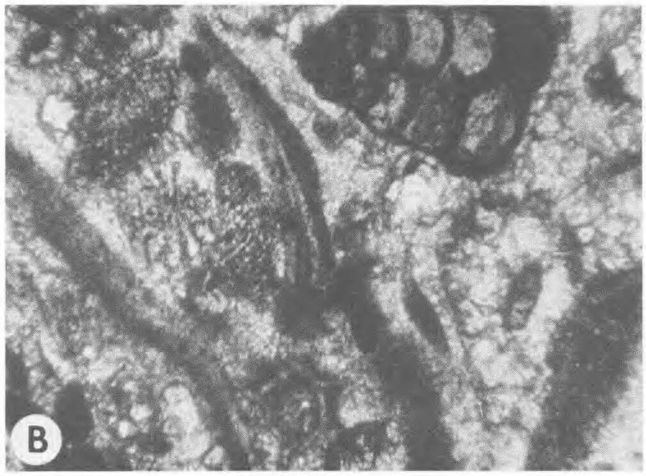
This facies occurs in the upper Kiamichi throughout the study area and in all parts of the Kiamichi in the north; it is also a part of the upper Denton in the south and the upper Main Street in the north (fig. 13A). Smaller clusters of *Texigryphaea roemeri* (Marcou) settled upon the muddy substrate of the upper Grayson in Tarrant County.

The oyster-bed-flank facies consist of thick beds of oyster packstone and quartzitic oyster packstone having a grain-supported matrix of 40 to 70-percent oysters. Quartzitic oyster packstone contains more than 10-percent quartz sand and silt. Locally, fossils may be as low as 30 percent, but the mixture of quartz and shells composes the grain-supported framework. Common oysters are *Texigryphaea washitaensis. Pastellum (Arctostrea) carinata, Lopha quadriplicata,* and *Ilymatogyra arietina.* Other fossils include ammonoids, trigonids, *Protocardia* sp., echinoid fragments, foraminifers, ostracodes, and bryozoans, as well as micrite intraclasts. These facies normally have 12- to 55-percent micritic and microsparry cements (fig. 13B, C). Strata are thin to medium bedded (15 to 40 cm) (fig. 13A) and locally contain megaripples and tabular-planar to small-scale trough cross-stratification. Megaripple amplitude is 2 cm, and wave length is 2 m; crests are evenly rounded. Shells are moderately sorted, subparallel, locally imbricated, and commonly graded. Thin interbeds, 10 to 20 cm thick, of medium-gray calcareous shale normally contain abundant *Texigryphaea washitaensis.*

Storm waves are likely agents for these irregularly distributed beds. This would suggest that the oyster beds grew in normal marine salinity below normal wave base, but within storm-wave base. This environment is analogous to the inferred origins of coeval shell beds deposited on the shoreface in the Western Interior (Scott, 1974). Comparable facies are also present in the Walnut Formation of north-central Texas (Flatt, 1976).

The quartzitic oyster packstone occurs mainly in northern outcrops of the Denton, Weno, and Main Street Formations. The facies grades southward into oyster packstone and shale facies and northward into quartzitic mollusk-echinoid packstone. Either calcareous shale or sandy shale overlies and underlies the oyster packstones and shales. This quartzitic facies lay closer to shore and a terrigenous source than other oyster facies.





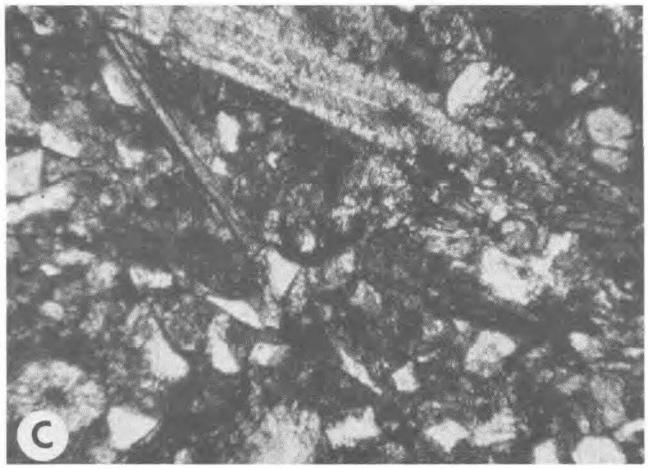


Figure 14. Mollusk-echinoid packstone. A. Main Street Limestone, Loc. B1; wavy basal contact with Pawpaw below; clay pebbles (arrow); faint, small-scale trough crossbedding above (bar = 15 cm). B. Photomicrograph of uppermost Weno quartzitic mollusk-echinoid packstone at Carpenter's Bluff north of Loc. G6, × 95. C. Photomicrograph of uppermost Weno quartzitic mollusk-echinoid packstone at Loc. G7, × 100.

Shoreface Packstones

This environment existed within the zone of normal wave action, generally shallower than 10 to 15 m and deeper than the depth of breaking waves, 3 to 4 m (fig. 4B). Facies deposited in this environment were the mollusk-echinoid and quartzitic mollusk-echinoid packstones of the Weno, Main Street, and Buda Formations from Denton County northward.

The grain-supported rock fabric is composed of 40 to 80 percent sand-sized fossil fragments and quartz (fig. 14A, B, C), but the matrix is a mixture of microspar, micrite, and clay. Where quartz and lesser amounts of feldspar together become more than 10 percent of the rock, mollusk-echinoid packstone grades into quartzitic packstone. Fossils consist of bivalves (including oysters), echinoids, foraminifers, gastropods, ostracodes, and bryozoans. Phosphate grains, glauconite, pellets, quartz, intraclasts altered to ironstone, and, rarely, wood are admixed. In some Weno outcrops, quartz content is so high that limestone is replaced by fossiliferous sandstone cemented by sparry calcite and micrite.

Sedimentary structures are indistinct. Thin to medium bedding predominates. Strata are relatively persistent from outcrop to outcrop. Only locally is small-scale trough cross-bedding (fig. 14A, Main Street, Loc. B1) or planar cross-bedding (Weno in Grayson County, Loc. G7) preserved. The transported shells, however, are subparallel to stratification, and, locally, grain size decreases upward in a bed.

Indistinct mottles suggest bioturbation, and locally distinct vertical to oblique burrows, up to 5 cm wide, are preserved. All of these features are characteristic of the shoreface model described by Davies and others (1971).

These clastic sediments grade southward either into oyster packstone in the Denton and Main Street, or into mollusk-echinoid wackestones in the Weno and Main Street. Where quartz increases to more than 80 percent and fossils are less than 20 percent, the facies grades into the thin-bedded sandstone-shale facies. The quartzitic mollusk-echinoid packstone is in vertical succession with sandy shale, but contacts are sharp. Local interbeds of sandy shale are 20 to 40 cm thick. The gradual decrease in quartz sand is reminiscent of the sediments in Card Sound between Miami and Florida Bay (Earley and Goodell, 1968).

Vertical succession of lithofacies within an exposure of Washita strata is relatively constant and predictable. In the southern part of the study area the succession differs from that in the northern part. Furthermore, the vertical succession partly resembles the lateral south-to-north facies changes. Northward thickening and increase in terrigenous elastics within the Washita has long been known (Hill, 1901; Adkins and Winton, 1920; Adkins, 1920; Slocki, 1967) (fig. 15). However, vertical successions have been described only in very general terms of limestone and shale units. An exception is the Main Street - Grayson sequence, for which the succession of foraminifer populations indicates a progressive deepening followed by shallowing (Albritton and others, 1954).

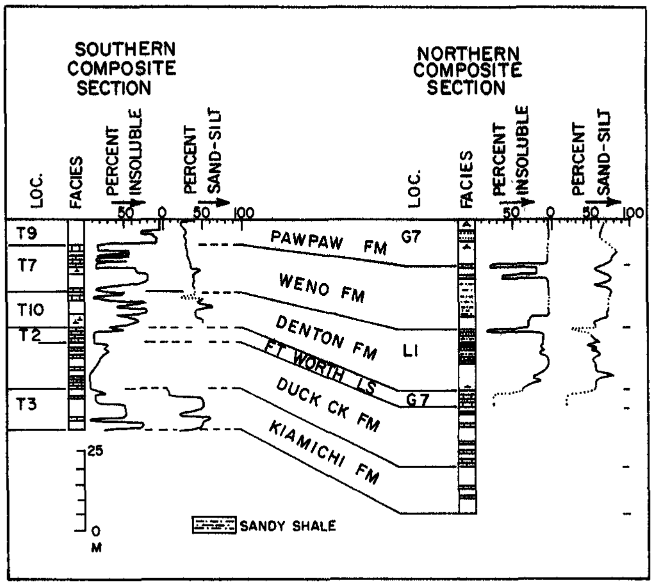


Figure 15. Regional variations within the pre-Main Street part of the Washita. Dotted lines indicate estimated amounts.

The vertical sequence of facies in the southern study area is cyclical. A typical carbonate cycle begins with medium-bedded, mollusk-echinoid wackestone, followed in ascending order by thin-bedded wackestones, nodular wackestone-shale, lenticular packstone-shale, and calcareous shale (fig. 2, Loc. J1, T2 and T8, 10). This depositional succession occurs in the Duck Creek, Fort Worth, Denton, Pawpaw, Main Street, and Grayson Formations. Locally, one or the other facies may be omitted or repeated at several horizons, as in the Duck Creek. The Weno section in Tarrant County consists of an inverted facies succession. In the Kiamichi, the thin-bedded wackestone facies is directly overlain by calcareous shale which, in turn, is overlain by thin-bedded wackestone or oyster packstones. In both the Kiamichi and Denton Formations, oyster packstone shale overlies and underlies calcareous shale. In the upper part of the Duck Creek, thin-bedded wackestone is intercalated within a thick interval of lenticular packstone shale without thick intervals of nodular wackestone. In the Grayson Formation, nodular and thin-bedded wackestones occur within calcareous shale without intervening lenticular packstone. These variations, however, do not invalidate the general predictable succession of facies.

In the northern or Red River region, the carbonate cycle is developed only in the Kiamichi, Duck Creek, Fort Worth, upper Main Street, and Grayson Formations (fig. 2, Loc. G1, 2, 9, CH1, 2; fig. 3, G6, 8). A siliciclastic cycle is developed in the Denton, Weno, Pawpaw, and lower Main Street Formations. In this cycle, calcareous shale underlies sandy shale that is interbedded with thin-bedded sandstone and is overlain by quartzitic mollusk-echinoid packstone or oyster and quartzitic oyster packstone (fig. 3, Loc. G5, 7). Sandy shale of the Denton appears to grade laterally and vertically into thin intervals of the wavy-lenticular sandstone-shale. But in the Pawpaw, calcareous shale grades directly into equivalent sandstone facies. Thin-bedded sandstone appears to grade laterally into trough-crossbedded sandstone. Consequently, a generalized, ideal cycle might consist in ascending order of calcareous shale, sandy shale, wavy-lenticular sandstone-shale, thin-bedded sandstone, trough-crossbedded sandstone, and quartzitic mollusk-echinoid packstone. Such an ideal sequence is not found in one section or a composite section. It simply summarizes the vertical and lateral relations among the siliciclastic facies in the Red River area.

Lateral intergradation of certain facies is likewise predictable. Medium-bedded wackestone commonly grades laterally into thin-bedded and nodular wackestone in the Duck Creek and Fort Worth Formations. Nodular wackestone and lenticular packstone-shale generally grade and intertongue northward with calcareous shale in the Duck Creek and Weno. In the Duck Creek and Kiamichi Formations, oyster packstone-shale typically replaces the calcareous shale facies northeastward. In the Denton, Weno, and Pawpaw, calcareous shale grades north into sandy shale; thin-bedded sandstone units are commonly interbedded and grade into units of trough-crossbedded sandstone.

In the upper Weno and Main Street limestones, thin-bedded wackestone grades north into quartzitic, mollusk-echinoid packstone and oyster packstone. In the Main Street Formation, oyster packstone and mollusk-echinoid packstone facies separate the wackestones in the south and quartzitic packstones in the north. In the northern outcrops of the Main Street, quartzitic mollusk-echinoid packstone is overlain by oyster packstone. The upper Denton beds in the south are oyster packstone-shale, and northward these grade into oyster packstone and quartzitic oyster packstone.

These vertical and lateral relations of the facies suggest that two models are needed to explain a deeper basin and a shallower basin in which shales and carbonates, respectively, grade northward into nearshore facies (fig. 4A, B).

REPETITIVE FACIES: TECTONIC OR CLIMATIC?

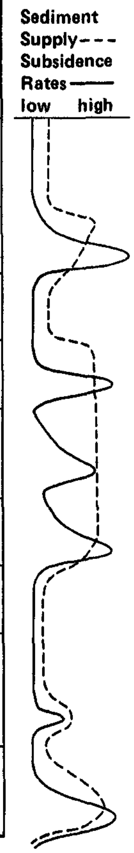
Since 1894 (Hill), the Washita Group has been considered to be a third transgressive-regressive cycle of what is now the Comanchean Series. Emphasis on unconformable boundaries between the three groups of sedimentary rocks led Lozo and Stricklin (1956) and Tucker (1968) to recommend that these groups be recognized as time-stratigraphic units of stage rank. Furthermore, subcycles of repetitive lithologies have been recognized within the Washita (table 3). These cycles have been interpreted to be the result of tectonic activity within the depositional basin or source area or to be the result of climatic cycles. The present environmental analysis may help to eliminate some hypotheses or to reformulate the question. First, however, let us review previous hypotheses.

The cyclical mode of Washita deposition was defined by Adkins (1933) as the alternation of the neritic environment represented by limestone, marl, clay, and shale, and the marginal environment represented by sand, silty clay, conglomerate, and gypsiferous sediments. Shell beds, like those in the Denton, were interpreted to be a reeflike environment. Adkins suggested that the alternation of deeper water neritic sediments with shallower marginal facies was the result of "oscillations of [sea] level or temperature" (1933, p. 278). Scott's (1940) depth zonation model, based upon ammonoid shell morphology, placed most limestones in deeper environments than most shales. This admittedly conjectural effort also incorporated a primitive oceanographic model that is no longer viable because of modern studies of Holocene carbonate environments.

Lozo and Stricklin (1956) revived the tectonic hypothesis of Hill (1894) to explain cyclical sand, clay, and lime sedimentary rocks preserved in the Trinity Group. They suggested that "episodic rejuvenation in the source area, resulting in an increased supply of clastics" produced the terrigenous facies and that carbonates indicate tectonic stability. Sedimentary structures and fossils indicate that the sandstones and carbonates were deposited in equally shallow, nearshore waters. Consequently, basin subsidence was not responsible for cyclic deposition. The sandstone wedges mark the beginning of a new transgressive cycle because the sands are underlain by unconformities and grade upward into shales and carbonates (Lozo and Stricklin, 1956, fig. 4). However, such relations are not

Table 3. Summary of concepts regarding the cyclic deposition, water depths, tectonic, and climatic factors influencing sediment supply and depositional rates.

FORMATIONS	Adkins 1932	Scott 1940	Hendricks 1967	Slocki 1967	McGill 1967	Young 1972	This Paper South	This Paper North
BUDA	Neritic	Infraneritic (120-600 ft)	Regression	Stable	Stable	Endemic Ammonoids	Shoreface	Shoreface
GRAYSON	Marginal	Infraneritic (120-600 ft)	Transgression (deeper)	Subsiding	Unstable	Cosmopolitan Ammonoids	Basin	Basin
MAIN STREET	Neritic	Infraneritic (120-600 ft)		Stable	Stable		Shelf	Shoreface
PAWPAW	Marginal	Infraneritic (120-600 ft)	Regression (shallower)	Subsiding	Unstable	Mixed to Endemic	Basin	Deltaic-Estuarine
WENO	Neritic	Infraneritic (120-600 ft)	Transgression	Stable	Stable		Shelf to Transition	Shoreface Basin
DENTON	Marginal	Epineritic Infraneritic	Regression	Subsiding	Unstable	------	Basin Transition	Shoreface Basin
FORT WORTH	Neritic	Epineritic Infraneritic	Transgression	Stable	Stable		Shelf	Shelf
DUCK CREEK U			Regression	Subsiding	Unstable	Cosmopolitan	Transition	
DUCK CREEK M L	Neritic	Epibathyal (> 600 ft)	Transgression	Stable Subsiding	Stable		Shelf	Basin Transition
KIAMICHI	Neritic	Epineritic (40-120 ft)	Regression		Unstable		Margin Transition	Shoreface Basin



evident in the Washita Group in north-central Texas. Other tectonic hypotheses have been proposed specifically for the Washita.

Hendricks (1967) divided the Comanchean into major transgressive-regressive cycles by using continuous, widespread datum surfaces such as disconformities or sharp lithic boundaries that are interpreted to be time significant. Alternation of terrigenous and carbonate Washita facies was interpreted to "reflect changes in sediment supply from source areas, more than oscillations in transgression and regression" (p. 63). Nevertheless, sand facies in the Red River area was thought to represent a minor regressive phase. Hendricks did not favor any one process to control the sediment supply, but he implied that rate of basinal subsidence would have been regular. Consequently, limestone would be deposited in deeper water than were shale, sandstone, and oyster beds.

Cyclical couplets composed of Washita elastics and carbonates were defined by Slocki (1967). He concurred with Hendricks that clastic deposits resulted from an increased sediment supply, and carbonates were deposited when the terrigenous supply was decreased. Slocki called on "tectonic and/or climatic activity at the source area" to control the supply. Furthermore, he concluded that limestone accumulated under slowly subsiding, stable conditions and that shale and sand filled rapidly subsiding basins. Thus, basin instability was accompanied by uplift and/or an increased runoff in the source area. McGill (1967) also thought that thick shale units reflect both uplift and rapid erosion in the source area and rapid subsidence in the depocenter. Because Washita strata south of Johnson County thin very little, the sea floor there was stable, and the hinge between the stable southern area and the unstable northern basin was in Johnson County. However, he concluded that calcareous shale partings in the Fort Worth Limestone indicate repetitive wet and dry climatic changes in the source area.

Young (1972) concluded that cosmopolitan ammonoid faunas represented times when the barrier reef complex was drowned and open circulation established. Endemic ammonoids evolved when the reef restricted circulation with the rest of the Tethyan realm. But a comparison of these faunal events shows that no direct correlation existed between the tectonic cycle in the East Texas basin and the Stuart City shelf edge. At the beginning of Washita deposition, open circulation coincided with basinal subsidence; however, at least two cycles of basinal filling and subsidence occurred in north Texas while a cosmopolitan ammonoid fauna evolved. Likewise, the mixed endemic fauna developed during several stages of subsidence and basinal filling. Grayson subsidence corresponded with breaching of the shelf edge barrier, and Buda reefs and stable shelf carbonates contain an endemic fauna.

The environmental interpretations given in earlier parts of this report suggest an alternate way to view the cyclic deposition within the Washita Group. Two sedimentologic relations can be isolated; each apparently has a different cause: carbonate-shale sequences suggest changing subsidence rates, and carbonate-sand sequences reflect both variable subsidence and supply rates. In the southern part of this area (Tarrant to Denton Counties), but north of the structural hinge in Johnson County, the alternation of calcareous shale with mollusk-echinoid wackestone represents alternating deeper and shallower environments in the North Texas basin. A simple tectonic pattern of alternately rapid and slow subsidence rates could produce a cyclic deepening of the basin followed by basinal filling that terminated with carbonate deposition. Thus, the carbonate-shale ratio in this shelf suggests fluctuating subsidence rates.

In the northern area (Cooke to Bryan Counties) near the Washita shoreline, the alternation of sandy shale with quartzitic, mollusk-echinoid packstone and sandstones may be explained by fluctuating subsidence rates. Carbonate packstones reflect both a decrease in terrigenous input and a decrease in subsidence rates resulting in shoreline progradation. Progradation resulted from basinal filling when carbonate-sediment production or terrigenous-sediment supply was greater than subsidence. Hence, associated sediments were sand and shale when the terrigenous supply was high and carbonate packstones when supply was low. Subsidence rates could be a local basinal phenomenon; it is difficult to correlate these rate changes with shelf-edge events or plate-tectonic events. The changing sediment supply may be a response to tectonic or climatic events in the source area, or locally to shifting deltas, which would be short-term events that probably would not affect the animal communities.

Perhaps studies of palynomorphs would provide evidence of climatic changes in the source area.

SUMMARY

Washita strata in north-central Texas and southeastern Oklahoma were deposited in a broad, shallow basin upon the Comanche shelf that lay north of the Stuart City shelf-edge complex. The positive Arbuckle-Ouachita Mountains lay north of the Washita shoreline. The Washita Group consists of up to 114 m (365 ft) of shale, limestone, and sandstone formations of late Albian and early Cenomanian age. This stratigraphic sequence is considered to be of group rank because it is a lithostratigraphic interval that can be distinguished from subjacent and superjacent units by lithic criteria. Most Washita formations have conformable contacts. The Kiamichi, however, rests disconformably on the Goodland throughout most of north Texas. No evidence for an unconformity exists between the Kiamichi and Duck Creek. The base of the Main Street and possibly the base of the Buda north of Denton, Texas, overlies a ravinement disconformity.

Eleven lithofacies provide the key for interpreting depositional environments and are enumerated in an idealized south-to-north progression. (1)Two microfacies of mollusk-echinoid wackestone were deposited on a relatively shallow shelf or platform. These grade basinward into (2) nodular mollusk-echinoid wackestone and lenticular packstone-shale of the sloping transitional zone. (3) The deeper shelf-basin sediments are calcareous and sandy shales that grade shoreward (northward) into (4) thin-bedded sandstone of the shoreface and (5) wavy-lenticular sandstone-shale of the distal deltaic environment. (6) Trough-crossbedded sandstones represent a deltaic or estuarine environment. (7) Oyster packstone-shale represents oyster biostromes between the carbonate shelf and shoreface. The biostromes are generally flanked by (8) washover beds of oyster and quartzitic oyster packstone. Landward, (9) quartzitic mollusk-echinoid packstones suggest a shoreface environment.

These facies exhibit a predictable stratigraphic (vertical) and geographic (lateral) distribution. This pattern is the result of several interacting processes: differential rates of basin subsidence, fluctuating volumes of sediment supply, and depth of wave base. The latter was controlled by basin filling and southward progradation of the northern shore and by a northward progradation of the carbonate shelf from the Central Texas platform. A cycle of rapid subsidence, followed by slower subsidence, resulted in deposition of basinal mud, followed upward by limestone prograding from a carbonate shelf to the south. On the north side of the shelf basin, coarse quartzose sediments mark the onset of shoreline progradation. Eventual shoaling of the basin caused the carbonates to grade into the quartz sands. The relative extent of carbonate and terrigenous sands was controlled by the volume of quartz supplied to the site of deposition.

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APPENDIX - LOCATION OF MEASURED SECTIONS

Texas

Johnson County:

J1 - (JCD-2, Magee, 1974) - Banks of small tributary east of Rock Creek, south of country road about 0.5 mi west FM 1932; Ft. Worth and Denton fms.

Tarrant County:

T1 - Readouts on FM 1187 at Rock Creek crossing west of Crowley; Kiamichi, Duck Creek and Ft. Worth fms.

T2- Banks of Rock Creek 0.25 mi south of FM 1187 at Loc. T1; Duck Creek Ls.

T3- Roadcuts on FM 1187 east of Mustang Creek crossing, 6 mi due west of Crowley; Kiamichi Fm.

T4 - Cuts behind buildings on southwest corner of Riverside and Lancaster, Ft. Worth; Duck Creek and Ft. Worth fms.

T5- Stream banks east of FM 734, 2.5 mi north of Crowley; Main Street Ls.

T7 - (T1-4, Fee, 1974) - Roadcuts on 1-20 between the Beach and Oakland exits; Ft. Worth, Denton, Weno, Pawpaw, and Main Street fms.

T9- (T5, Fee, 1974) - Cuts behind buildings on southeast corner of Brentwood Stair and Weiler roads; Pawpaw and Main Street fms.

T10- (TCD-1, Magee, 1974) - Bank of Big Fossil Creek about 0.25 mi north of I-820N and just north of Texas and Pacific R.R.; Denton Fm.

T11 - (TCD-2, Magee, 1974) - Badlands along Henrietta Creek 0.25 mi east of I-35W, 800ft south of Haslet Rd., 2.5 mi east of Haslet; Denton Fm.

Wise County:

W1 - Readout on U. S. Highway 287 under overpass of State Highway 114, Rhome; Kiamichi Fm.

W2 - Roadcut on U. S. Highway 287, 3.9 mi south of junction with State Highway 114, about 1 mi southeast of Rhome; Kiamichi and Duck Creek fms.

Denton County:

D1 - Composite from three nearby localities; stream banks along tributaries of Denton Creek north of State Highway 114 and west of U.S. Highway 377, northwest of Roanoke (see Fee, 1974, for map); Weno and Pawpaw fms.

D2 - (D4, Fee, 1974) - Roadcuts of State Highway 455 and east bank of Elm Fork Creek south of road about 5 mi east of Sanger; Pawpaw and Main Street fms.

D3- Artificial cut west of I-35W about 1 mi south of Bonnie Brae exit, Denton; Pawpaw and Main Street fms.

D4 - Roadcuts along abandoned road 0.5 mi south of FM 1171, northeast of Roanoke; Main Street and Grayson fms.

D5- Roadcuts along State Highway 455 5 mi east of Pilot Knob; Main Street Ls.

D6- Roadcuts along State Highway 10 on south bank of Clear Creek 3 mi northeast of Denton; Main Street Ls.

D7-(DC, Fee, 1974) - Roadcuts 0.25 mi east of Ganzer exit on I-35 about 1 mi north of Denton; Weno Fm.

D8- (DDC-1, Magee, 1974) - Composite section of stream banks off of tertiary road 0.5 mi south of FM 407 and on eastern bank of Denton Creek 4 mi east of Justin; Denton Fm.

D9- (DCD-2, Magee, 1974) - Composite section of stream banks west and east of I-35 on Clear Creek 7 mi north of Denton; Denton Fm.

Cooke County:

C1 - Railroad cuts on Gulf, Colorado and Santa Fe RR 0.2 mi south of the Red River; Kiamichi and Duck Creek fms.

C2 - Roadcut on east service road to I-35 0.1 mi south of the Red River bridge; Duck Creek Fm.

C3 - Abandoned quarry north of boat ramp on H. H. Moss Lake west of FM 1201 and 4.25 mi due north of its junction with FM 1202; Kiamichi Fm.

C4 - Drainage ditch a few hundred yards west of FM 1201 south of boat ramp of H. H. Moss Lake and 4.25 mi due north of its junction with FM 1202; Kiamichi Fm.

C5- (C2, Fee, 1974) - Road and stream cuts along gravel road 2.5 mi west northwest of Dexter; Pawpaw and Main Street fms.

C6 - (C1, Fee, 1974) - Roadcuts on same gravel road as C5 and just east of Rock Creek Crossing 3.5 mi northwest of Dexter; Weno Fm.

C7- (C3, Fee, 1974 & CCD-1, Magee, 1974) - Roadcuts on FM 372 and banks of Elm Fork of the Trinity 0.5 mi south of junction of FM 372 and FM 922, about 3 mi southeast of Gainesville; Denton, Weno and Pawpaw fms.

C8- (C4, Fee, 1974) - Roadcut on FM 372 and in creek bed 1.9 mi south of junction FM 372 and FM 922, 4.5 mi southeast of Gainesville; Pawpaw and Main Street fms.

Grayson County:

G1 - West-facing slope of Lake Texoma 0.3 mi west of State Highway 120, about 3.5 mi north of Fink; Kiamichi Fm.

G2 - Gullies crossing road to Loe's Highport about 1 mi west of State Highway 120, about 2 mi north of Fink; Duck Creek and Ft. Worth fms.

G3 - Exposures in drainage ditch on road to public boat ramp 1 mi north of Loe's Highport; Kiamichi and Duck Creek fms.

G4 - Quarry east of State Highway 84 and south of road connecting State Highways 84 & 1310, 2 mi west of Eisenhower State Park; Goodland & Kiamichi fms.

G5- Railroad cut 1.25 mi east of Pottsboro and 0.25 mi north of State Highway 120; Main Street Ls.

G6 - Gullies on south bank of Choctaw Creek east of road 1 mi north of Cherry Mound and FM 1753; Main Street Ls.

G7- (G1, Fee, 1974) - Roadcuts and shoreline in Russwood-on-the-Lake development, north-facing scarp on south side of Lake Texoma, 3.5 mi west of Fink; Denton, Weno, Pawpaw, and Main Street fms.

G8- (G2, Fee, 1974) - Stream banks and roadcuts at intersection of Owings and Lamar streets in Denison; Pawpaw and Main Street fms.

G9- (GCD-1, Magee, 1974) - Gully on south shore of Lake Texoma at Texoma Estates about 0.5 mi west of Loe's Highport and 3.2 mi west of Finks; Ft. Worth and Denton fms.

Oklahoma

Love County:

L1 - (LCD-1, Magee, 1974) - South-facing scarp on north bank of Red River at Horseshoe Bend on the Gilstrap Ranch about 5 mi south of Marietta; Ft. Worth, Denton, and Weno fms.

Bryan County:

B1 - (B2, Fee, 1974) - Roadcut on U.S. 70 about 10 mi east of Durant and 0.5 mi west of Blue on east bank of Blue River; Pawpaw and Main Street fms.

B2- (BCD-1, Magee, 1974) - Stream cuts east of gravel road 0.5 mi south of Cobb; Denton and Weno fms.

B3 - Southwest face of Sugar Loaf Mountain about 13.6 mi east of Caddo (turn off St. Highway 22 6.75 mi east of Caddo and go east 6.8 mi); Caddo, Denton, Weno, Pawpaw fms.

B4A - Stream bank east of N. Washington St, Durant; Pawpaw and Main Street fms.

B4B - (B1, Fee, 1974) - Roadcuts at intersection of State Highway 48 and U. S. 75 about 2 mi north of Durant; Pawpaw and Main Street fms.

B6 - (BCD-2, Magee, 1974) - Stream cuts 3 mi north of Bokchito and roadcuts 4.1 mi north Bokchito; Denton and Weno fms.

Choctaw County:

Ch1 - Roadcut on Indian Nation Turnpike 0.9 mi north of Loc. Ch 2; Goodland and Kiamichi fms.

Ch2- Roadcut on Indian Nation Turnpike 1.1 mi north of its junction with U. S. Highway 271 west of Hugo; Kiamichi and Caddo fms.

McCurtain County:

M1 - Idabel Stone Quarry on U. S. Highway 70 2.6 mi north of its junction with State Highway 3 and northeast of Idabel; Goodland and Kiamichi fms.