GEOLOGIC REPORT ON UPPER CRETACEOUS COAL-BEARING ROCKS, RIO ESCONDIDO BASIN, COAHUILA, MEXICO*

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INTRODUCTION

In northern Mexico and adjacent parts of Texas, deposition of platform and basinal carbonate rocks of Early Cretaceous age was followed by the widespread deposition of terrigenous clastics during Late Cretaceous time (Weidie *et al.*, 1972). Detritus, derived chiefly from volcanic and shallow intrusive rocks exposed in the area of the present Sierra Madre Occidental, was transported by rivers several hundred kilometers eastward and deposited in marine, deltaic, and fluvial environments along the margin of the ancestral Gulf of Mexico. Deltaic deposits, some of which are coal bearing, were deposited over broad areas and are preserved today in areas (basins) that subsided more than adjacent regions or in areas that escaped erosion following Laramide folding and faulting (Fig. 1). Regional stratigraphic analyses show that deltas prograded in general from west to east, and that the main loci of deposition shifted eastward with time (Fig. 2).

Following a summary of the chief characteristics of the deltaic sequences of each basin, this report treats the stratigraphy of the coal-bearing and adjacent formations in the Rio Escondido Basin and presents recommendations to aid future coal exploration operations.

LATE CRETACEOUS BASINS, NORTHERN MEXICO AND VICINITY

Ojinaga Basin

The lithostratigraphy and biostratigraphy of the Ojinaga Basin have been described by Arenal (1964) and Wolleben (1965, 1967, 1968); a generalized stratigraphic section is given in Fig. 3. The Ojinaga Formation includes marine shelf and prodelta shale deposits; the San Carlos Formation in chiefly delta-front and distributary-channel sandstones and lower delta-plain deposits, including some coal beds; and the El Picacho Formation is delta plain and fluvial shale and sandstone, including some red beds. Non-marine fossils are present locally in the El Picacho Formation. The preserved stratigraphic sequence in the basin has a maximum thickness of 1600 m.

Big Bend Graben

Big Bend National Park and vicinity in Texas contains Late Cretaceous fluvial-deltaic rocks that are up to 650 m thick (Fig. 3); these rocks are preserved as erosional remnants in a large graben. The Pen Formation is sparsely fossiliferous gray shale, locally with septarian siderite concretions, of shelf and prodelta origin. The overlying Aguja Formation is sandstone, shale and rare coal

FRONTISPIECE A. Part of core GN-104 showing prodelta deposits of the Upson Formation. The following features are visible: intensely bioturbated muddy sandstone (a); weakly fissile shale in which burrowing has disrupted primary laminations (b); sandstone beds with scattered burrows (c). The sandstone beds are frontal splay deposits that increase in thickness and in number upward. The thinner sandstone beds have largely lost their identity because of intense bioturbation.
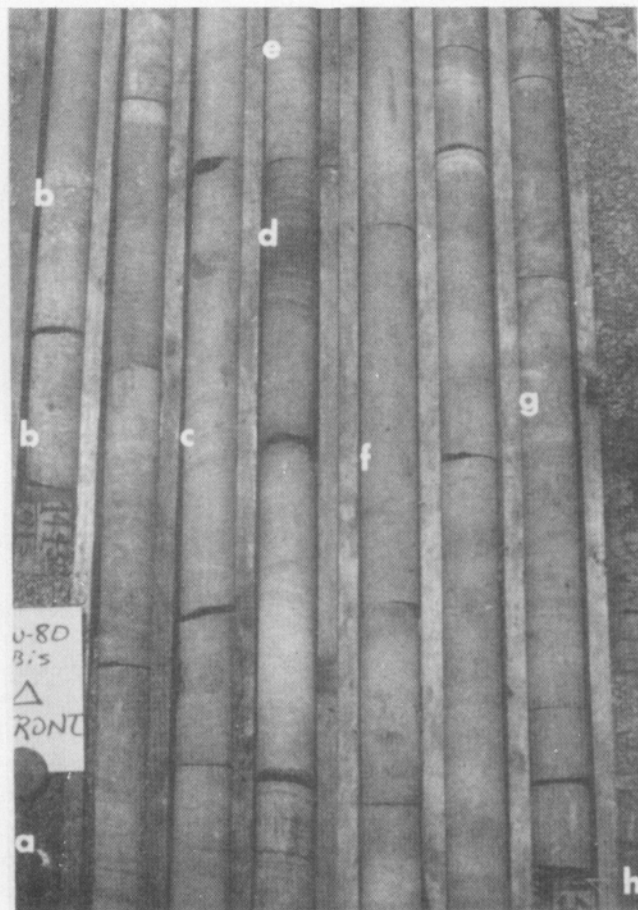
FRONTISPIECE B. Part of core GN-80 bis showing the following features: prodelta shale of Upson Fm. (a); shale clasts at base of distributary-channel sandstone (San Miguel Fm.,(b); foreset layers of trough cross-beds (c); laminated sandstone with abundant transported plant debris (d); current-ripple lamination (e); structureless sandstone (f); bioturbated sandstone (abandoned channel event, g) basal shale of the Olmos Fm. (h).

beds that formed as delta-front and lower delta-plain deposits. The succeeding Javelina Formation, representing fluvial and upper delta-plain deposits, is chiefly yellow, maroon, and green clays and local channel-fill sandstones. Dinosaur bones and petrified wood are present locally. Stratigraphic details of these formations are given by Hopkins (1965) and Maxwell *et al.* (1967).

Rio Escondido Basin

Stratigraphic units in the Rio Escondido basin (Fig. 3) are similar to those in the adjacent Sabinas basin, except that red beds have not been recognized in the Escondido Formation.

The stratigraphy of the basin is described in detail in the body of this reports.

Sabinas Basin

Roebeck *et al.* (1956) record about 1000 m of Upper Cretaceous terrigenous clastic rocks in the Sabinas basin (Fig. 3), where stratigraphic units were studied in outcrop and open pit coal mines. The marine shelf and pro-deltaic Upson Clay is overlain by the San Miguel Formation, chiefly delta-front and distributary channel sandstones. The overlying Olmos Formation, interbedded shale and sandstone, contains several meters of coal-bearing strata of delta-plain origin
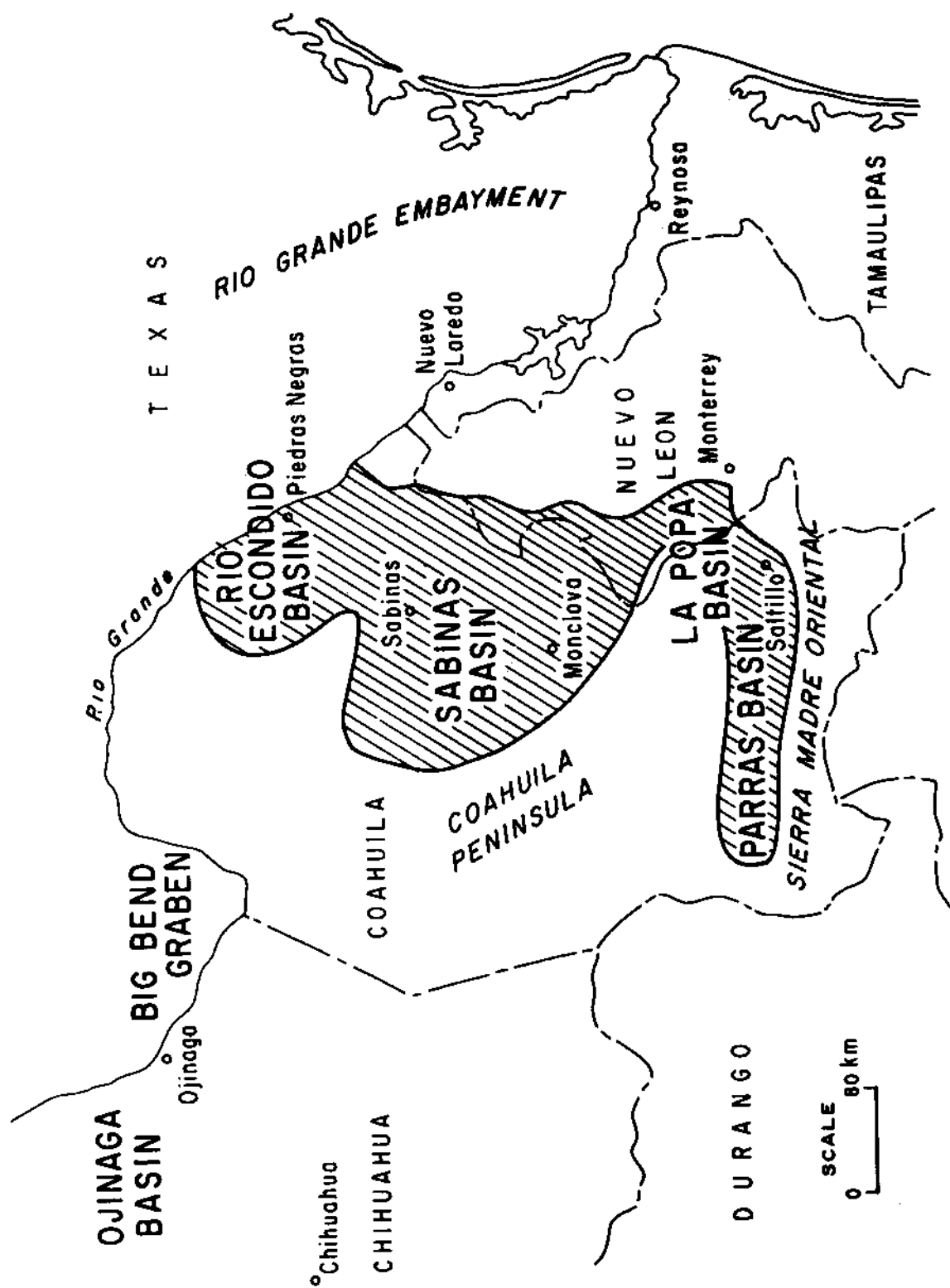
Fig. 1. Map of northern Mexico and adjacent part of Texas showing the location of preserved Late Cretaceous basins.
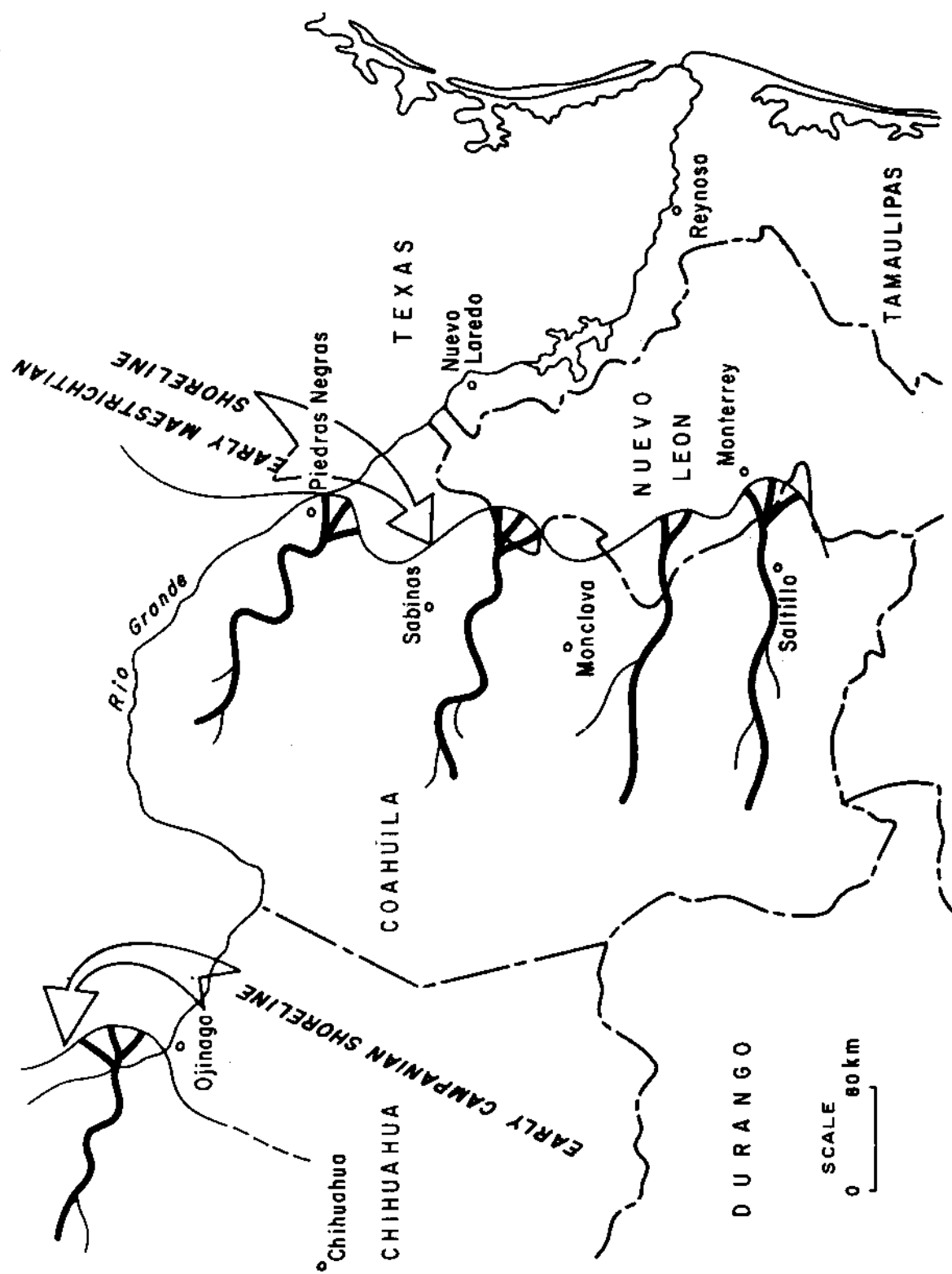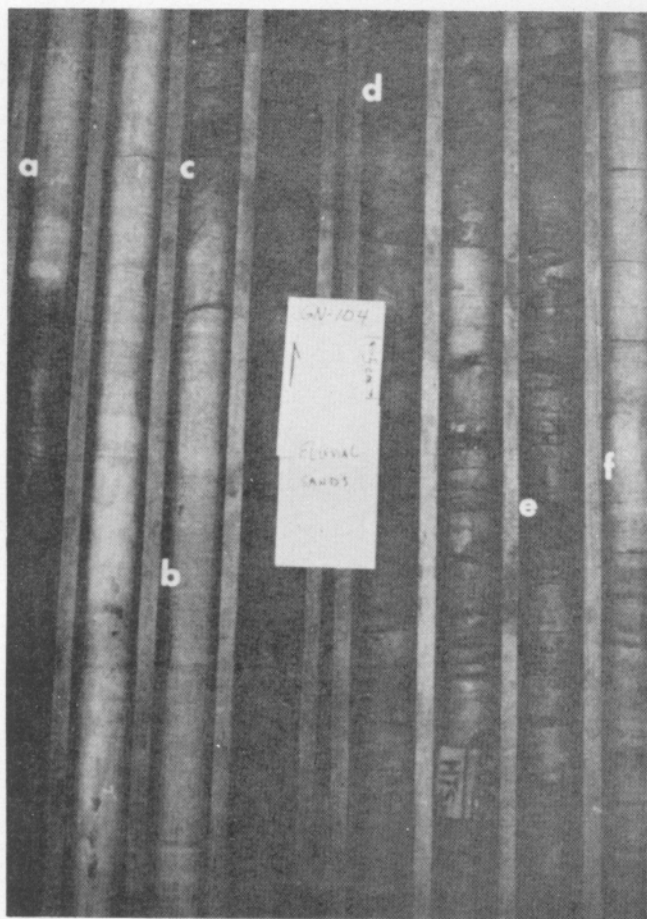
Fig. 2 Map showing the inferred shoreline position during Early Campanian and Early Maestrichtian time.

FRONTISPIECE C. Part of core GN-104 showing upper deltaplain deposits of the Olmos Formation. Features visible include: fluvial sandstone with granule-size lag deposit just above the base (a); parallel laminations (b); gradation from sandstone into overlying overbank shale (c); coaly shale of probable backswamp deposit (d); overbank shales (e); sandstone of probable lacustrine origin that grades both upward and downward into carbonaceous shale (f).

at its base. The succeeding Escondido Formation is composed mostly of marine shale and siltstone but includes some shallow marine or delta-front sandstone. The upper part of the Cretaceous sequence in the western part of the Sabinas basin is about 250 m of red claystone and siltstone of upper delta-plain facies. Roebech *et al.* (1956) placed the red beds in the Muzquiz Formation, but because the red strata interfinger with normal nonred rocks of Escondido type, the Muzquiz is best treated as a member or tongue of the Escondido Formation. The Muzquiz red beds resemble red beds in the Difunta Group to the south.

La Popa-Parras Basins

The Parras and La Popa basins differ from the other basins described here in several ways. They contain the thickest clastic sequence (6000 m of the Difunta Group, Fig. 3), they record four major cycles of delta progradation and marine transgression, they contain evaporites in the Jurassic sequence (Minas Viejas Fm.), they lack coal deposits, and they underwent the strongest degree of Laramide folding. Stratigraphic and sedimentologic data are given by McBride (1974) and McBride *et al.* (1974; 1975).

Deposits of the Parras and La Popa basins interfinger at their junction, but each basin was fed sediment from the west by separate rivers. Eastward progradation of deltas at least 200 km is recorded in the Parras basin. Prodelta and delta-plain facies in the Difunta Group are hundreds of meters thick (Fig. 3) because of the high rate of basin subsidence.

Delta-plain deposits are lenticular varicolored siltstone and claystone beds that include repetitious upward-coarsening and upward-fining lake deposits, locally including soil zones, that are interrupted by distributary-channel sandstone beds from 200 to 600 m wide and 3 to 10 m thick. Larger, multistory fluvial distributary sandstones are present only locally.

Delta-front sheet sar. ᴐne units, 3 to 15 m thick and up to 20 km wide, are characterized by parallel laminae and lesser trough crossbeds, *Ophiomorpha*, and transported oysters.

Delta-platform deposits are characterized by bioturbated clayey siltstone beds with marine molluscs that are intercalated with laminated sandstone beds introduced by flood discharge, many of which foundered to form ball-and-pillow structures. Some sand was carried down the prodelta slope as turbidity currents to produce flysch-like interbeds of turbidites and bioturbated background mudstone beds that contain foraminifers, *Exogyra*, and ammonites.

Delta-flank deposits include mudstone, oyster reefs, marine-mud and sand-falt deposits, and mixed terrigenous sand-oolite deposits.

Shelf-deposits include rare, thin glauconite beds, phosphatic limestone beds, and 9 lenticular biostromes. The latter are up to 300 m thick and 19 km long, and are red-algal packstones that
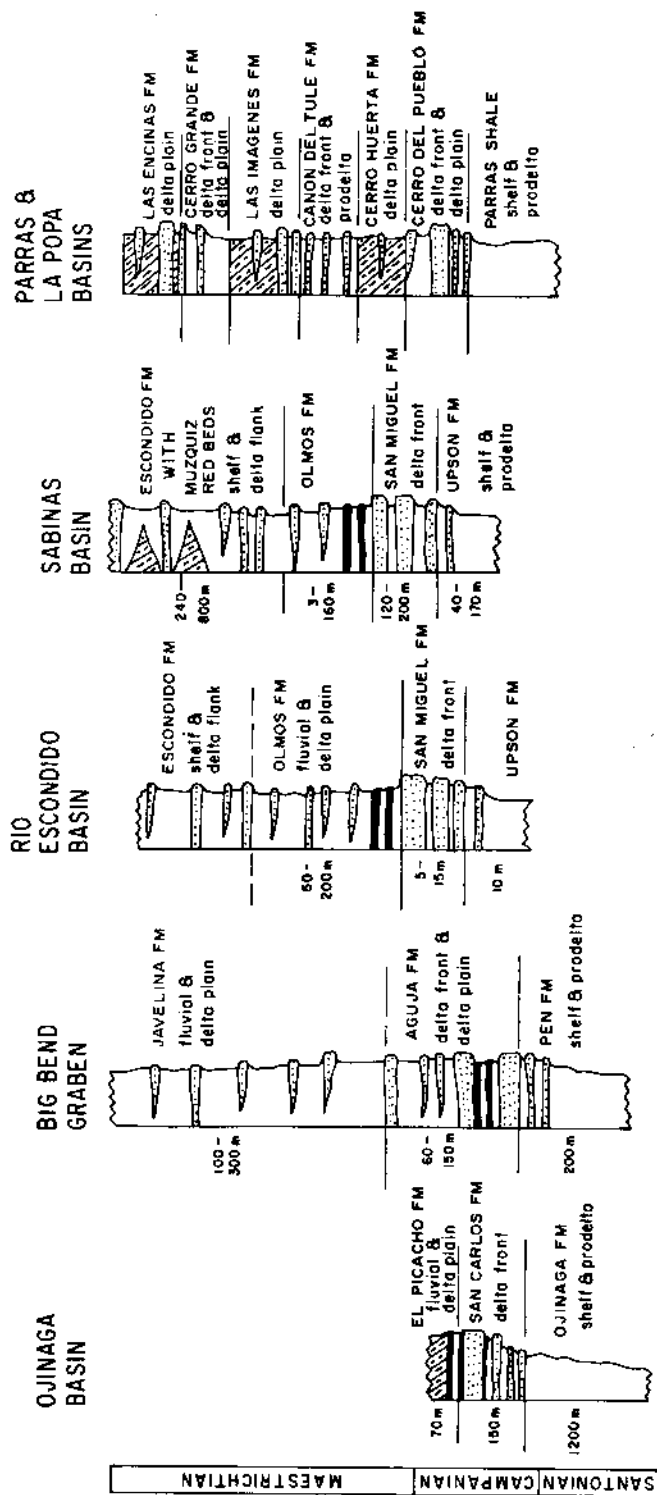
Fig. 3 Generalized stratigraphic sections of *Late Cretaceous* basins, northern Mexico and adjacent part of Texas. Diagonal lines indicate red beds; unpatterned areas are shale.

contain sparse rudists and other frame builders. Several biostromes are marginal to evaporite diapirs that may have been active during Late Cretaceous time.

EVIDENCE FOR DELTAIC DEPOSITION

The interpretation of a deltaic origin for the major part of the Upper Cretaceous clastic rocks discussed here is based on 1) a comparison of facies of the Cretaceous rocks with modern (Holocene) deltaic facies (eg., Fisher *et al.* 1969; Broussard, 1975), 2) a comparison of facies of the Cretaceous rocks with ancient rocks interpreted as deltaic in origin, and 3) the limitations of possible environmental interpretations that can explain the vertical succession of facies and formations in each basin.

The basic stratigraphic pattern that each basin has in common is that marine shale (e.g. Ojinaga, Pen, Upson, Parras Formations) is overlain by several meters or tens of meters of sandstone (e.g. San Carlos, Aguja, San Miguel, basal Cerro del Pueblo), which is succeeded by interbedded shale and sandstone (El Pichacho, Olmos, Javelina, upper Cerro del Pueblo Formations) that in places contains coal, non-marine fossils (land plants, dinosaurs), varigated strata including red beds, and lenticular sandstones. Such a regressive sequence can form only by progradation of a strand plain (non-barrier island coast), barrier-island coast, or deltaic coast. Detailed examination of the facies shows that only the progradation of a delta explains all the specific rock types and fossil types. Not all the facies of the Upper Cretaceous clastic rocks are strictly deltaic; some are marine-shelf deposits and some are fluvial deposits. However, the shelf facies generally grade upward into prodelta shale, and delta-plain deposits grade upward into fluvial sandstones and shale; both are the result of regression (basin-ward migration of the shoreline) and progradation (outbuilding of the shoreline).

The stratigraphic successions in the Ojinaga, Big Bend, Rio Escondido and Sabinas basins record only one major regressive sequence, whereas the Parras-La Popa basins record four major regressive (and intervening transgressive sequences). A greater rate of sediment supply to the Parras-La Popa basins and their faster rate of subsidence is a major reason for the different histories. The Ojinaga may have had more than one regression, but erosion has removed the evidence.

GENERAL STRATIGRAPHY OF UPPER CRETACEOUS ROCKS, RIO ESCONDIDO BASIN

General Relations

The Upper Cretaceous formations exposed in the Rio Escondido Basin are, from bottom to top, the Upson, San Miguel, Olmos, and Escondido. Lithic characters of the Upson, San Miguel and Olmos are known from cores taken by the C.F.E., but the Escondido Formation has not yet been cored except possibly in the far south. The Upson and Escondido formations have been dated as Santonian-Campanian and Maestrichtian respectively, but because the Upson-San Miguel-Olmos accumulated during regression, they all are diachronous units. In any location, such as a core hole, the Upson is older than the San Miguel, which in turn is older than the Olmos. However, because of diachroneity, the Olmos at the location of core 46 is *older* than the Upson at the location of core ED-80, although there is no fossil evidence to prove this interpretation. Because deltas prograded eastward, each formation is progressively younger in an eastward direction (Fig. 3A).

Environmental interpretation shows that the Upson Formation contains prodelta and probably shelf deposits, that the San Miguel contains delta-front and distributary channel deposits, and the Olmos contains delta-plain and alluvial plain deposits. Lithic characteristics of each formation are summarized in the following pages; stratigraphic details of the Upson, San Miguel and Olmos are shown on the stratigraphic cross sections that accompany the report. The environmental facies terms instead of the formation names have been used in the cross sections.

Upson Formation

The Upson Formation is composed chiefly of dark gray shale, locally slightly calcitic, that contains scattered blebs of pyrite. Lenticular beds of sandstone less than 1 m thick occur at scattered positions in the formation. These are frontal splay deposits that formed when sand spilled over distributary-mouth bars during flood episodes. Some of these sandstones can be correlated over distances of 2-3 km. The shale is poorly fissile because the original preferred orientation of clay minerals (illite and chlorite) was destroyed by bioturbation,

OLMOS FM.

MARSH

SEA LEVEL

SEAWARD ➡

DELTA FRONT SILTS & SD

SAN MIGUEL FM.

DEPOSITIONAL SURFACE

PRO-DELTA SILTY CLAY ➡

TIME
LINES

UPSON FM.

OFFSHORE CLAY ➡
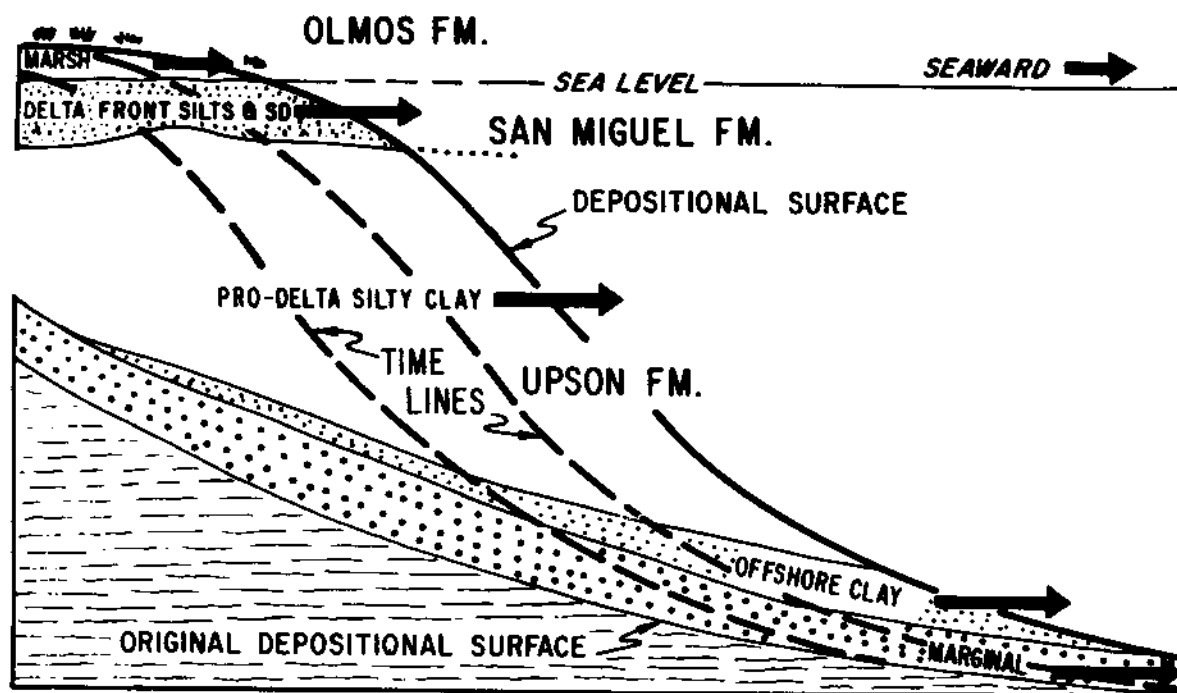
ORIGINAL DEPOSITIONAL SURFACE

MARGINAL

Fig. 3A. Seaward migration of depositional environments of a typical delta showing formation equivalents in the Rio Escondido basin.

EARLIER
DEPOSIT

POINT-BAR
DEPOSIT

CREVASSE SPLAY
DEPOSIT

CHANNEL-FILL
DEPOSIT

LEVEE
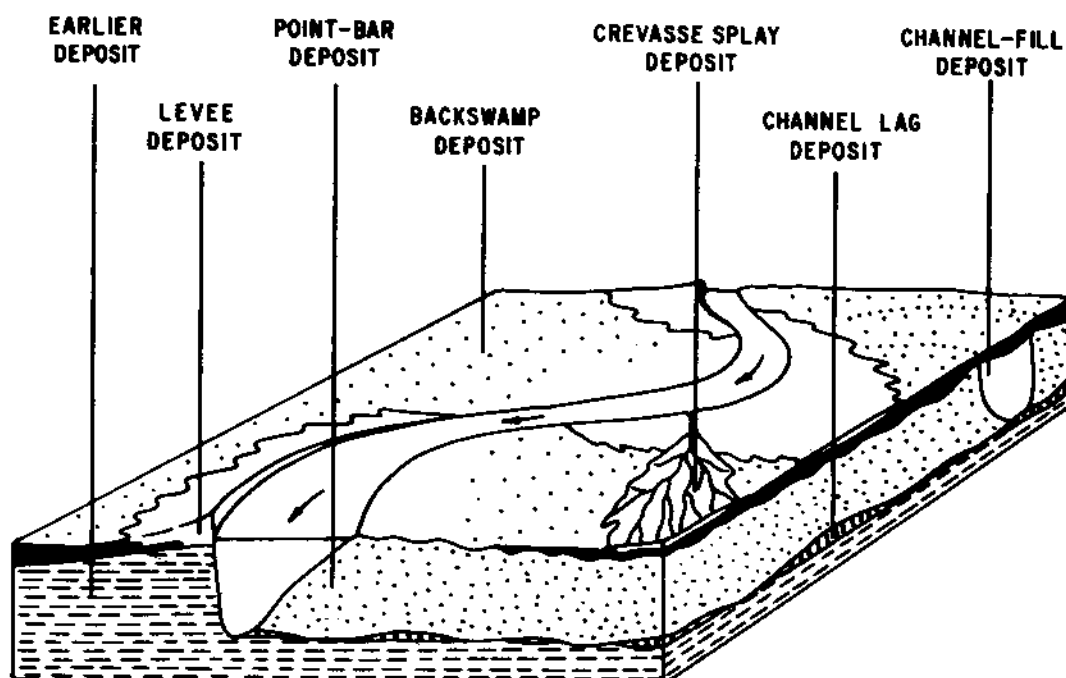DEPOSIT

BACKSWAMP
DEPOSIT

CHANNEL LAG
DEPOSIT

Fig. 3B. Block diagram of meandering-river flood-plain and channel deposits.

ie., by burrowing animals. Shale beds that escaped extensive bioturbation have good fissility.

The gray color of the shale is imparted by minute pieces of land plant debris, unresolvable organic matter, and pyrite. Terrigenous silt content in the shale ranges from 0 to 30 %; it probably was deposited during flood and storms events and was subsequently mixed with clay minerals during bioturbation. In addition to the nearly ubiquitous trace fossils, *Inoceramus* pla es (calcite prismatic layer only) and a sparse group of other molluscs are present locally. Shale was not examined for microfossils.

The complete thickness of the Upson was not penetrated in C.F.E. cores in the Rio Escondido Basin. The maximum thickness penetrated is about 70 m in the northern area, but the Upson probably is in excess of 200 m thick.

The Upson is overlain conformably by the San Miguel Formation. Siltstone and very-fine sandstone beds increase in abundance in the upper part of the Upson until a predominantly sandstone sequence of beds thicker than 1 m are encountered. In this generally gradational sequence the top of the Upson is arbitrarily placed at the base of the lowest sandstone bed thicker than 1 m where sandstone beds prevail over shale beds.

San Miguel Formation

The San Miguel Formation is chiefly fine to medium grained sandstone with some shale interbeds, but because it locally includes frontal-splay deposits, distributary-channel, and channel-mouth-bar deposits, it varies considerably in thickness and character. Interbeds of sandstone and shale a meter or so thick are common at the base and give way upwards to thicker sandstone beds with rare thin shale interbeds. In some cores shale beds are absent and 20 m of clean sandstone are present. Thus, the lower part of the formation is a sequence of beds that generally thicken upward and also coarsen upward; this sequence is typical of prograding regressive sand bodies. The upper part of the San Miguel is of variable character, but commonly shale interbeds interrrupt the sandstone layers, and the sandstone packages from 1 to 3 m thick tend to become finer grained upward. These upward-fining sequences were formed by deposition in distributary channels.

Burrows, including *Ophiomorpha,* occur in the lower part of the formation in some wells. Placers up to 20 cm thick of oyster shells and sandstone pebbles are present in a few cores; these are thin transgressive deposits that formed when active deltaic deposition had shifted temporarily to a different area. They have not been found in wells spaced only 1 km apart. *Ophiomorpha* burrows probably formed during short-term shut-downs of deltaic deposition. In Cretaceous rocks, *Ophiomorpha* were formed by a crustacean that lived in very shallow water in normal marine salinity. Beds a few decimeters thick that are intensely mottled by burrows 2-3 mm wide are present in a few cores; their significance is unknown.

Parallel lamination and structureless bedding are the most common stratification types in sandstones. Large-scale cross beds are present locally, but generally are impossible to identify in the small diameter cores that are available. Most sandstone beds have abrupt lower and upper contacts.

In the cores examined the San Miguel ranges in thickness from 3 to 30 m; it generally is from 8 to 15 m thick.

Sandstones that have not been bioturbated have framework (sand and coarse silt grains) compositions of 35 to 40 % quartz, 25 to 30 % feldspar and 30 to 35 % volcanic rock fragments and locally derived clay clasts. Most sandstones have secondary porosities of 15 to 25 % that was produced by removal by dissolution of calcite cement and some feldspars by acid subsurface waters. These sandstones now are weakly cemented by authigenic kaolinite and locally by authigenic chlorite. Clay clasts in some sandstones also have been chloritized and they now are green and resemble glauconite. Some sandstones retain all their previous calcite cement and have essentially no porosity.

Petrographic study of sandstone samples to establish diagenetic (post-depositional) events and their relation to coal beds in in progress.

Olmos Formation

The Olmos Formation is composed of dark gray, commonly carbonaceous shale with inter-

bedded sandstone beds from 1 to 5 m thick and local coal beds. The maximum thickness penetrated by C.F.E. cores is 63 m, but it probably exceeds 100 m total thickness. The lower part of the formation is composed of delta-plain, marsh, swamp, and bay deposits and thin distributary and fluvial channel deposits; the upper part is chiefly alluvial plain deposits of fluvial sandstones and overbank/backswamp shales (Fig. 3B).

Channel-fill sandstones commonly both decrease upward in grain size and in thickness of beds; also, many sandstones have a basal lag conglomerate layer a few centimeters thick of shale and coaly clasts, and pass upward from parallel or cross-lamination to current-ripple cross-lamination. Burrows are rare, but are present in a few beds. Sandstone is similar in composition to that in the San Miguel, except coal clasts and plant debris are more abundant in the Olmos sandstones.

Shale beds contain abundant minute plant fragments, local plant-root impressions, and, because of only moderate bioturbation, are moderately fissile.

Coal beds range in thickness from partings to about 2 m. Stratigraphic details of the coal beds are described later in the report.

The base of the Olmos Formation is placed at the top of the sandstone immediately below the lowest coal in the sequence, or at the top of the sandstone at the base of a predominantly shale sequence several meters. thick. The San Miguel-Olmos contact is a diachronous surface that corresponds with a facies change, i.e., seaward progradation of a delta-plain/delta-front interface (Fig. 3A).

Escondido Formation

The Escondido Formation, which overlies the Olmos Formation, is exposed along the Rio Bravo where it contains four mappable members (Fig. 4), and has a total thickness of 300 m (Cooper, 1970). The formation is chiefly fossiliferous shale, burrowed mudstone and siltstone, but contains numerous sandstone beds in the lower half. Glauconitic shale and impure limestone make up the

upper member, which is overlain at a bored surface by limestone of the Paleocene Midway Group. Prodelta shale and delta-front sandstone of a minor regressive event are present, in the lower part of the Escondido Formation, but interdeltaic and marine shelf deposits make up the bulk of the formation.

DETAILED STRATIGRAPHY OF UPPER CRETACEOUS ROCKS, RIO ESCONDIDO BASIN

Northern Area: Dip Sections

The zone of exploration situated near Piedras Negras covers an area running approximately 120 km north-south and 40 to 50 km east-west. Within this area, numerous wells have been drilled and cores taken for evaluation. For this study, data was obtained by examining the full diameter cores using a 10x hand lens and the unaided eye. Rock characteristics were recorded on a standardized logging form, and these were subsequently used to construct stratigraphic cross sections.*

The Rio Escondido Basin can be divided into two principal study areas. The northern part of the basin contains more control well and was studied in greater detail than the southern part of the basin.

Cores along three east-west transects were examined to provide stratigraphic control in a direction that is parallel with the present structural dip, and which coincides approximately with the paleoslope into the Cretaceous ocean basin.

Three different types of dip sections were constructed for each transect. The first type is a section showing the depth to the major coal beds found in the cores. This type of dip section shows that there are several major coal beds present in the northern area and that these coals offlap eastwards into the basin. Next, the dip sections were constructed to show the present structural attitude of the coals and the major facies recognized in the cores from each well location. The third type of dip section is a re-

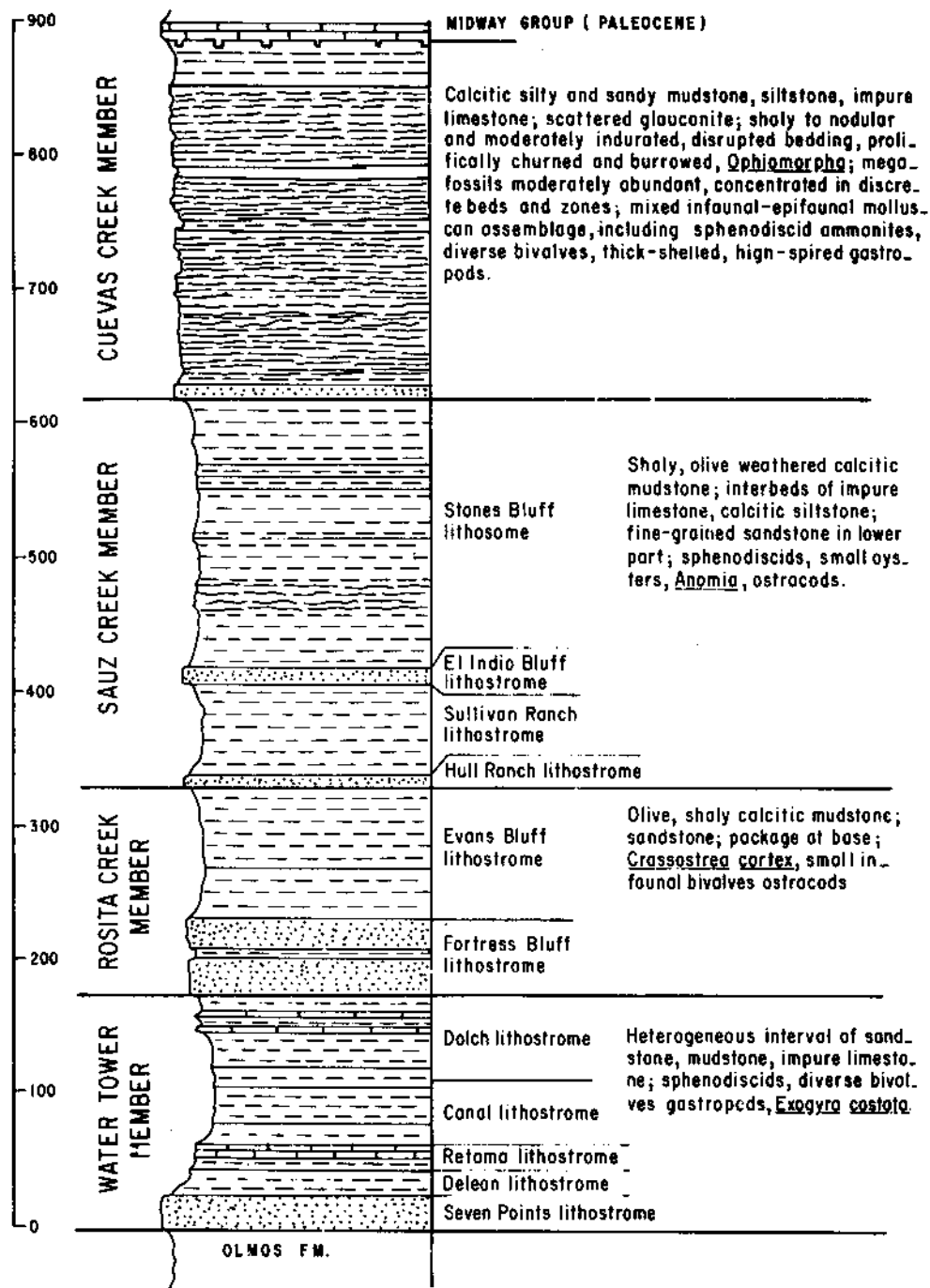* All log data are on file at C.F.E. office, Piedras Negras.

Fig. 4. Generalized composite columnar section of type Escondido Formation, Rio Grande Embayment.

MIDWAY GROUP (PALEOCENE)

CUEVAS CREEK MEMBER

Calcitic silty and sandy mudstone, siltstone, impure limestone; scattered glauconite; shaly to nodular and moderately indurated, disrupted bedding, prolifically churned and burrowed, Ophiomorpha; megafossils moderately abundant, concentrated in discrete beds and zones; mixed infaunal-epifaunal molluscan assemblage, including sphenodiscid ammonites, diverse bivalves, thick-shelled, high-spired gastropods.

SAUZ CREEK MEMBER

Stones Bluff lithosome

Sholy, olive weathered calcitic mudstone; interbeds of impure limestone, calcitic siltstone; fine-grained sandstone in lower part; sphenodiscids, small oysters, Anomia, ostracods.

El Indio Bluff lithostrome

Sullivan Ranch lithostrome

Hull Ranch lithostrome

ROSITA CREEK MEMBER

Evans Bluff lithostrome

Olive, sholy calcitic mudstone; sandstone; package at base; Crassostrea cortex, small infaunal bivalves ostracods

Fortress Bluff lithostrome

WATER TOWER MEMBER

Dolch lithostrome

Heterogeneous interval of sandstone, mudstone, impure limestone; sphenodiscids, diverse bivalves gastropods, Exogyra costata.

Canal lithostrome

Retama lithostrome

Deleon lithostrome

Seven Points lithostrome

OLMOS FM.

900
800
700
600
500
400
300
200
100
0

31

construction of the sedimentary facies and it shows probable correlations of sedimentary packages found in the basin.

Figure 5 shows dip section A-A' with the depth to the major coals plotted for each well location. In Zone "D" a coal bed 2 m thick can be correlated a distance of approximately 4 km. Overlying this are several other coals which offlap eastwards into the basin, i.e.: they are higher in the stratigraphic column in an eastward direction. Because of a lack of major structural elements (faults, folds) in the Rio Escondido Basin, the coals are progressively younger in an eastward direction. This correlation indicates that there are several distinct sedimentary packages along this transect, a conclusion supported by other dip-oriented cross sections.

The three major sedimentary depositional facies recognized in the cores are the shales and sandstones of the prodelta facies (Upson Fm.), the thick laminated and crossbedded sandstone of the delta-front facies (San Miguel Fm.), and the sandstones, shales, and coals of the delta plain and fluvial facies (Olmos Fm.) Note that the majority of the cores in this section do not penetrate through the delta-front facies into the prodelta facies. Therefore, the varying thickness of the delta-front sandstone is unknown. Because of the lack of this valuable information, a "net sand map" could not be constructed for the area. Such a map would have defined the loci of maximum sedimentation. Also note that cores from well ED-197 contains no coal because coring was begun in the delta-front facies rather than in the delta-plain facies (which contains the coal beds).

When the section is correlated on the coal beds, the basin fill can be seen to consist of several distinct packages. Each of these packages consists of the prodelta, delta-front and delta-plain facies. These packages offlap into the basin, with the most eastward package being found higher in the stratigraphic column than those packages found westward. The delta-plain facies of each package contains coal beds that can be correlated within that package, but the coal beds are separate and isolated from the coals found in the other packages.

Of the other two dip sections, B-B' is located 8 km north of A-A', and D-D' is located 4 km south of A-A'. These dip sections were chosen to illustrate lateral changes in the depositional facies of the northern area. The "depth to coal" dip sections of B-B' (Figure 6) and D-D' (Figure 7) show that the same pattern is present over the whole northern area. Large sedimentary packages, containing their corresponding coal beds, offlap eastwards into the basin. The "depth to coal" dip section D-D' (Figure 7) also shows the approximate location of the different depositional facies found in the cores for each sedimentary package. Parts of four and possibly five or more separate packages are recognized in this dip section.

The various dip sections show that the northern area is free of structural complications and that the basin fill consists of offlapping sedimentary packages. These packages each contain prodelta, delta-front and delta-plain facies. Within the delta-plain facies of each package are coal beds that are correlatable over varying distances within that package. The thickest coal is consistently found in the western part of the area. In the east, the sedimentary packages contain numerous coals that are thinner than their western counterparts.

Northern Area: Strike Sections

Two strike sections were constructed in the northern study area. Strike section S-S', which covers the full length of the northern area, is located 6 km east (basinward) of T-T'. For each strike section a "depth to top of delta-front facies" diagram was constructed. The top of the delta front (the top of the first thick sandstone below the oldest coal) can be used as a datum for further correlation. Cross sections were also constructed showing the facies recognized in each core and the lateral correlation of the facies using the top of the delta-front facies as a datum. These strike sections show that the basin is not structurally complicated and that a datum is present that can be used to make detailed correlations of the facies recognized in the cores. The sections also show that the thickest coals are found in the western part of the basin and that the correlation of coal beds in a strike direction is much more difficult to make. A possible explanation of this difficulty in correlation is that the distributary channels are dip-oriented, so that the distributary-channels sandstones interrut the lateral continuity of the delta-plain deposits.
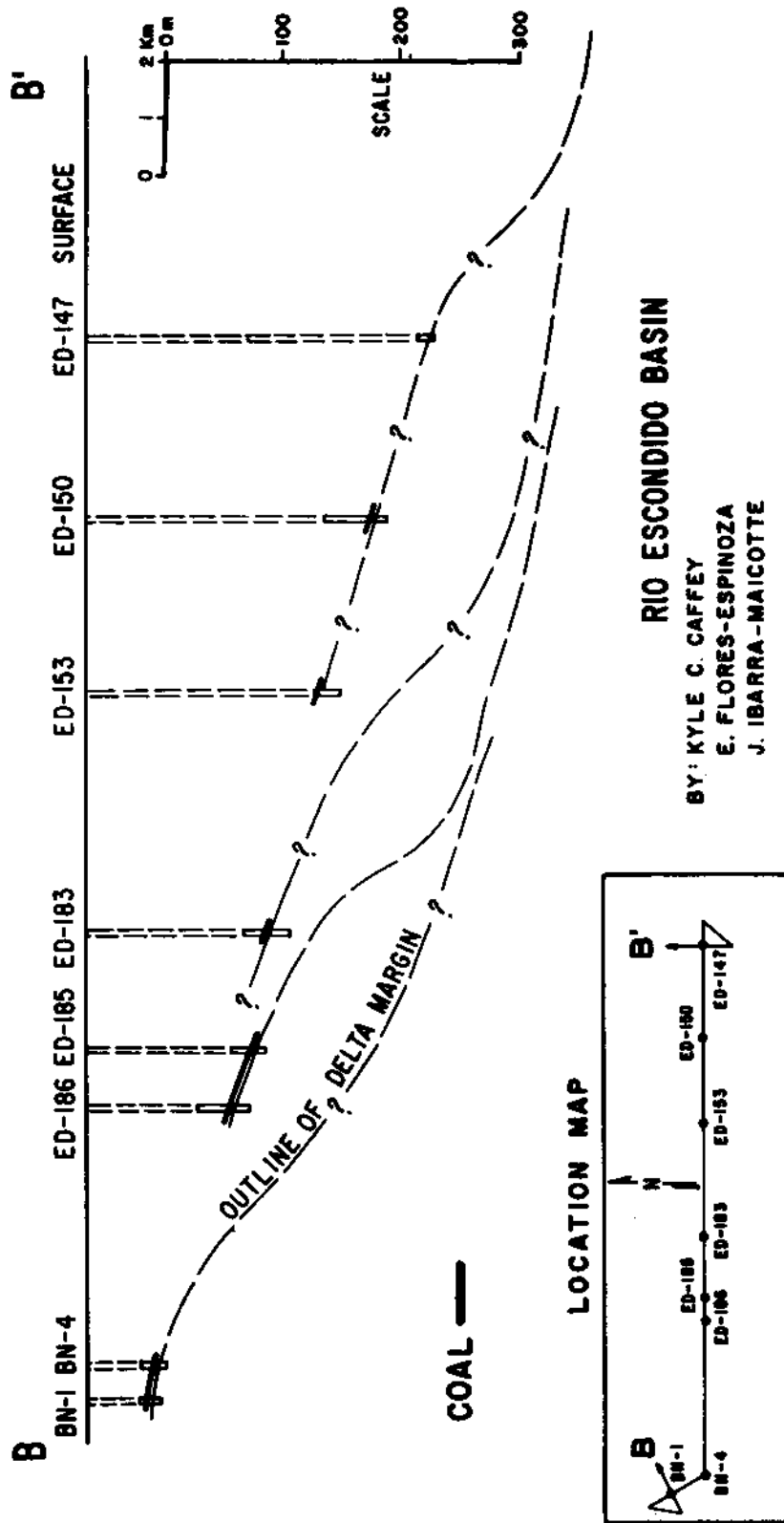
Fig. 5. Section A-A' showing depth to coal in strike section.

RIO ESCONDIDO BASIN

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MAY 1978

Fig. 6. Dip section B-B' showing depth to coal.

Fig. 7. Dip section D-D' showing depth to coal.

The variance in the depth to the top of the delta-front facies in each core is caused by the regional dip in the area and the particular location of the wells in the strike section. The top of the delta-front facies is essentially a horizontal surface now and therefore was a horizontal surface at sea level during Cretaceous time.

There is a lack of data on the lateral changes in thickness of the delta-front sandstone because the majority of the cores did not penetrate through the entire delta-front into the prodelta facies. However, in the wells that did penetrate into the prodelta, a complex pattern is hinted at by the presence of delta-front sandstones that are overlain by prodelta shales. Other wells (ED-44, ED-182, ED-183) show delta-front sandstones which have major shale beds which differ radically from adjacent wells (Ed-1, Ed-51, Ed-36) which have very thick delta-front sandstones with no shale beds. The areas of the delta front receiving large amounts of sediment built thick clean sandstone sequences, while marginal delta-front areas received intermittent pulses of sediment moved by current and wave transport. However, across the 17 km that the section extends, there are no interdistributary bay facies recognizable in the cores. In all cores the delta-front facies is present, but in varying thickness.

The lowermost coal beds present in strike section T-T' (wells ED-37 to ED-44) at first look as if they correlate. However, it is entirely possible that they are separate beds or beds that split into two beds (ED-6). Also note that the coals present in wells ED-21, Ed-16, and ED-11, are found slightly higher in the section than the coals in adjacent wells (ED-37, ED-6). The coals present 10 or more meters higher in the delta-plain facies are divided by distributary-channel facies and can be traced laterally, with confidence, only 1 or possibly 2 km (ED-16, ED-11, ED-6). The thickest and most laterally extensive coals present in the area are always found just above the delta-front facies (i.e., just above the San Miguel Fm.).

In Figure 8, which shows the "depth to the top of delta front" for strike section S-S', the depth to the delta front is a function of the well site and of the regional dip. The section extends more than 25 km and has delta-front facies present in every core that reached a depth that would penetrate it. Again, no interdistributary bay facies are recognized in the cores.

The delta-front facies ranges in thickness across the area as in T-T'. Again, the areas of the delta front near the mouths of distributary channels received large amounts of sediments and correspondingly the delta-front sandstones in these areas are thicker than on the marginal areas.

The coal beds in S-S' are laterally discontinuous and are correlatable only over a distance of 1 or 2 km because the coals are divided laterally by the distributary-channel facies (ED-110, ED-94, ED-91). The division of the coal beds laterally by the distributary channels is shown in map view in Figure 9. Because distributary channels are dip oriented, they tend to compartmentalize the coals. During lateral migration of distributary channels, and also during regressive progradation, they locally eroded coal beds and removed them from the site.

Note that the coal beds in transect S-S' are more numerous but thinner than the coal beds in transect T-T'. In the cores available for study, the delta-plain and fluvial facies is uninterrupted by transgressive sequences. As one moves upward in a core, once above the top of the delta-front facies no marine facies are encountered. Any transgressive deposits above the delta-front facies lie above the units sampled in the northern area. The only transgressive deposits found in the cores are in the delta-front facies. These transgressive units are usually less than 20 cm thick and consist of marine shells and burrows in a sandstone matrix. They represent lag material that accumulated during reworking of deltaic deposits by waves, and also the burrowing activity of marine organisms that occupied the area during times of no deltaic sedimentation.

Southern Area

The southern area of Rio Escondido Basin received less attention in this study because the wider spacing between wells gave less core control. The average spacing between wells in section R-R' is 2 1/2 km and the spacing in Z-Z' is approximately 5 km compared with an average spacing of 1 km between wells in the northern area. The two strike sections were constructed in order to study the depositional packages found in this part of the basin and to help reconstruct the depositional history of the entire basin.
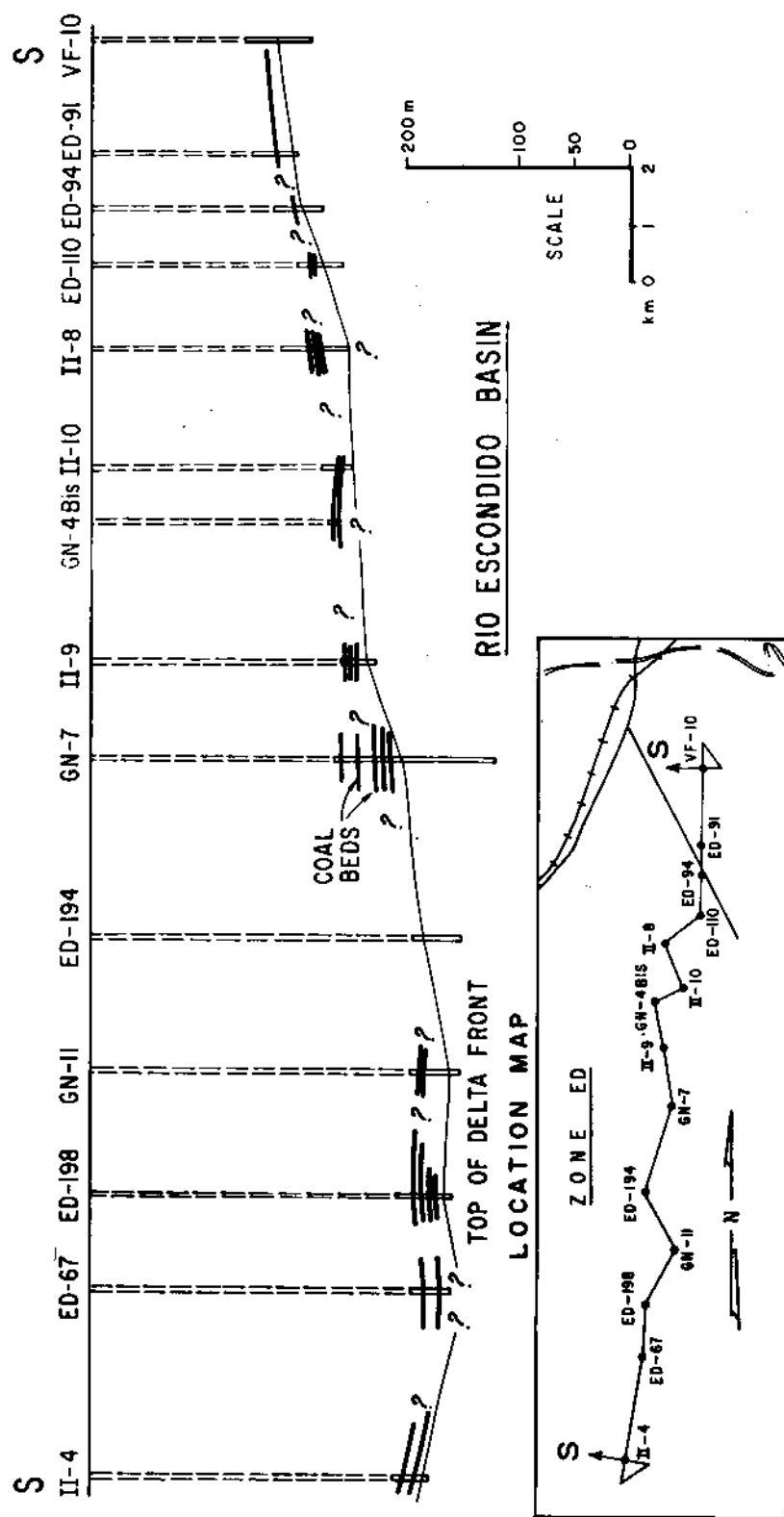
Fig. 8. Strike section S-S', datum on ground level.

Fig. 9. Facies of a lobate delta. Sand reaches the delta front through many small distributaries and is shaped by waves into a laterally continuous delta-front sand (facies C₁). Progradation of the sand produces a sheet or blanket sit.
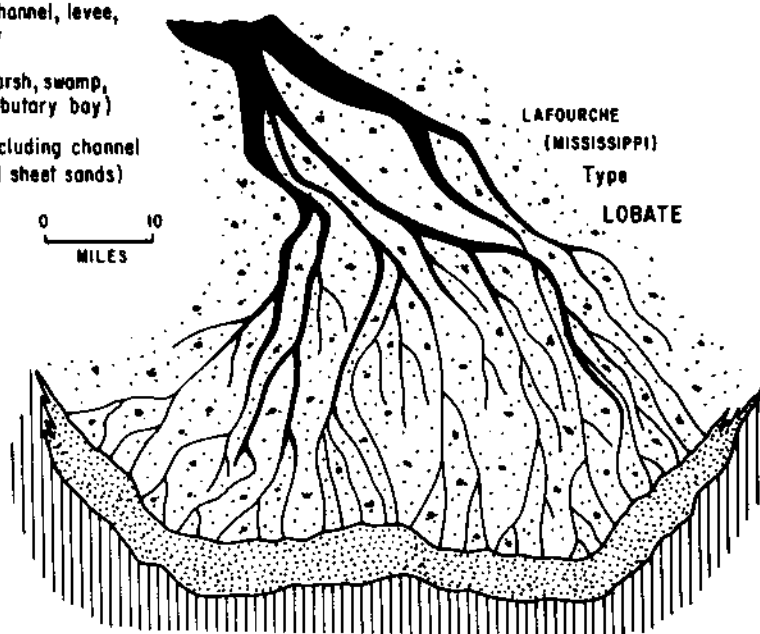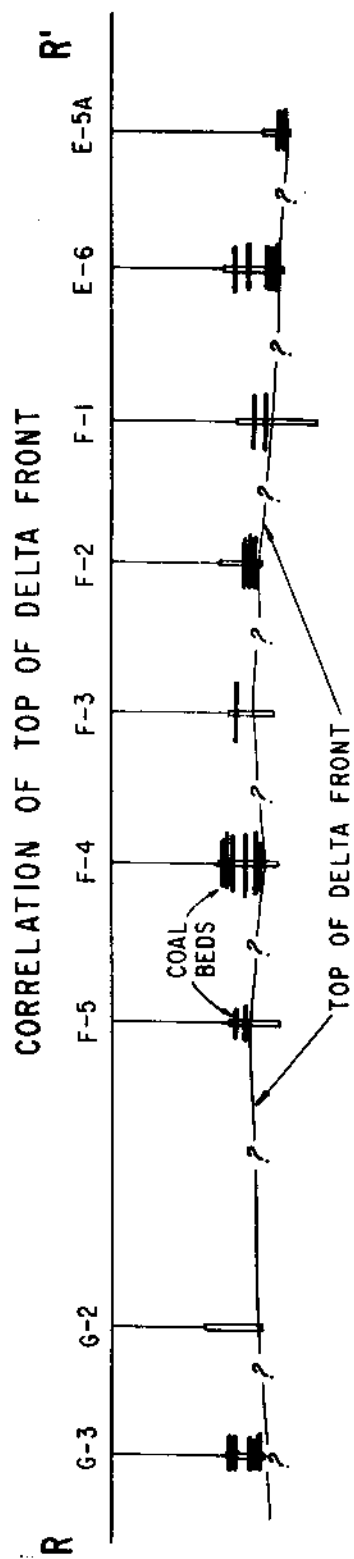
Figure 10, a cross section showing "depth to top of delta front" for R-R', shows that the top of the delta-front facies is essentially a horizontal surface and can be used as a datum for correlation of the facies found in the cores of the section. When this strike section is tied into the strike section T-T', the top of the delta-front facies is correlatable between the two sections. This correlation of the delta-front shows that the same deltaic packages continue from the northernmost well of T-T' (GN-5) to the southernmost well of R-R' (G-3), a distance of 45 km.

Too few wells penetrated completely through the delta-front facies into the prodelta facies to know the major loci of deposition, but the delta-front facies is present in all cores but one (G-3), in which coring stopped above the delta-front facies. Some vertical stacking of the delta-front

sandstone is recognized in wells F-5, F-4, and F-1. Minor transgressive units were deposited on top of the delta plain. Any major transgressive units in this area are above the cored intervals of this section.

There are numerous coal beds present in the delta-plain facies of this section. However, the wide spacing of the wells makes correlations of these coal beds unreliable. The thicker of these coal beds are in well F-2. These coal beds are not found 2 1/2 km away in the flanking cores. Also in this area, fluvial distributary channels divide the coal beds into "compartments". Control is not adequate to identify these compartments.

Laterally there is no continuous delta-front facies correlatable between the wells, and there

CORRELATION OF TOP OF DELTA FRONT

COAL BEDS

TOP OF DELTA FRONT

R   G-3   G-2   F-5   F-4   F-3   F-2   F-1   E-6   E-5A   R'

SCALE

0   2.5 km

0 m
100
200
250

LOCATION MAP

R'

N

R

G-3
G-2
F-5
F-4
F-3
F-2
F-1
E-6
E-5A
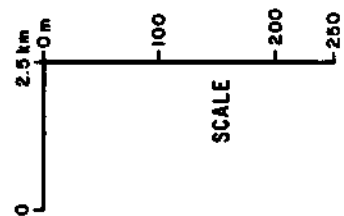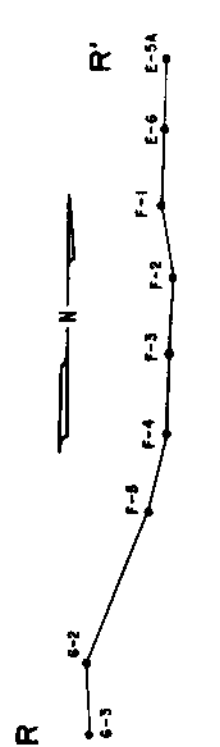
BY : KYLE C. CAFFEY
E. FLORES-ESPINOZA

Fig. 10. Strike section R-R' showing correlation of delta front; datum is ground level (in envelope).

is no delta-front facies present whatsoever in the two southernmost wells (GN-133 and G-126). Facies change laterally from prodelta to delta front and in some cores also to the delta-plain facies. Any coal beds found in the cores will also be discontinuous across the 5 km spacing between wells.

Vertically the changes are just as striking. Cyclic repetitive packages are recognized In all the other sections, only one cyclic package, consisting of prodelta, delta-front and delta-plain facies is present. In Z-Z' there are several of these packages stacked one upon another (GN-119). This vertical stacking of packages and the lateral discontinuity between facies strongly suggests that these deltaic packages are not part of the same deltaic sequence represented by the sections northward.

INTERPRETATION

General Comments

As stated in an earlier section, a deltaic interpretation for the Upson-San Miguel-Olmos vertical sequence is based on a comparison of facies in these formations with descriptions of Holocene and other Cretaceous deltaic deposits plus the environmental limitations imposed by the regressive sequence. Interpretations of major types of each formation are summarized in Table 1. Basically, the Upper Cretaceous deposits were formed during an eastward migration of a deltaic shoreline. Typical of deltaic deposits, most rock units are lenticular. Many rocks, including some coal beds, do not extend laterally far enough to be identified in cores only 1 km apart. The exception is the delta-front sandstone facies (San Miguel), which can be traced 45 km in a north-south direction. Most coal beds cannot be correlated more than 1 to 2 km (based on present core spacing), but coal-bearing intervals (several meters thick) can be correlated 3 to 8 km. Fluvial-channel sandstones in the Olmos are of no value for correlation beyond 1 or 2 km.

Deltas are bodies of sediment that accumulate where rivers enter oceans or lakes. Deltas can be classified by various criteria, but three basic types can be defined according to the chief process responsible for controlling the sand distribu-

tion and the main delta morphology. Thus, wave-dominated, river-dominated, and tide-dominated members are recognized as end members (or types) of a wide spectrum of delta types. Figure 11 shows how 23 different modern deltas are classified.

TABLE 1. INTERPRETATION OF MAIN ROCK TYPES

ESCONDIDO FORMATION

Marine shelf and distal prodelta deposits

OLMOS FORMATION

Sandstone: chiefly lenticular fluvial-channel deposits of fine-grained meander belts; minor overbank splays and interdistributary deposits.

Shale: chiefly floodplain deposits (sediment deposited from suspension when flood waters spilled over the flood plain); some swamp deposits and underclays; rare interdistributary muds at the base of the formation.

Coal: marsh and swamp deposits on the delta plain; possibly some backswamp (fluvial) deposits stratigraphically high in the formation.

UPSON FORMATION

Shale: prodelta and shelf mud deposited from suspension.

Sandstone: frontal splays (deposited when floods transport sand downslope from channel-mouth bars); thin storm or flood deposits.

Sandy shale and shaley sandstone: beds formed when animals mixed mud and sand together by burrowing activity.

SAN MIGUEL FORMATION

Sandstone: distributary-channel and channel-mouth-bar deposits; delta-front sand redistributed by waves; thin transgressive beds formed by wave-reworking during temporary abandonment of a delta lobe; frontal splays at the base of the formation.

Shale: thin beds formed during temporary abandonment of a delta lobe.

Fluvial facies (Dominantly sand)

Delta margin sand facies

Marsh/swamp and muddy overbank
sediment veneer

MISSISSIPPI

SEDIMENT INPUT

ELONGATE

ELONGATE

St Bernard
Lobo-Miss.

Po   FLUVIAL
DOMINATED

Danube
Latouche
Lobo-Miss.

LOBATE

Yukon ?
Mahakam

DANUBE

Ebro

MAHAKAM

Orinoco

Nile

Niger

WAVE DOMINATED

Mekong TIDE DOMINATED

CUSPATE

Rhone

Burdekin

Yalv

Colorado   Fly

ESTUARINE

Brazos
Sao Francisco

Copper

Ganges-
Brahmaputra

WAVE ENERGY FLUX
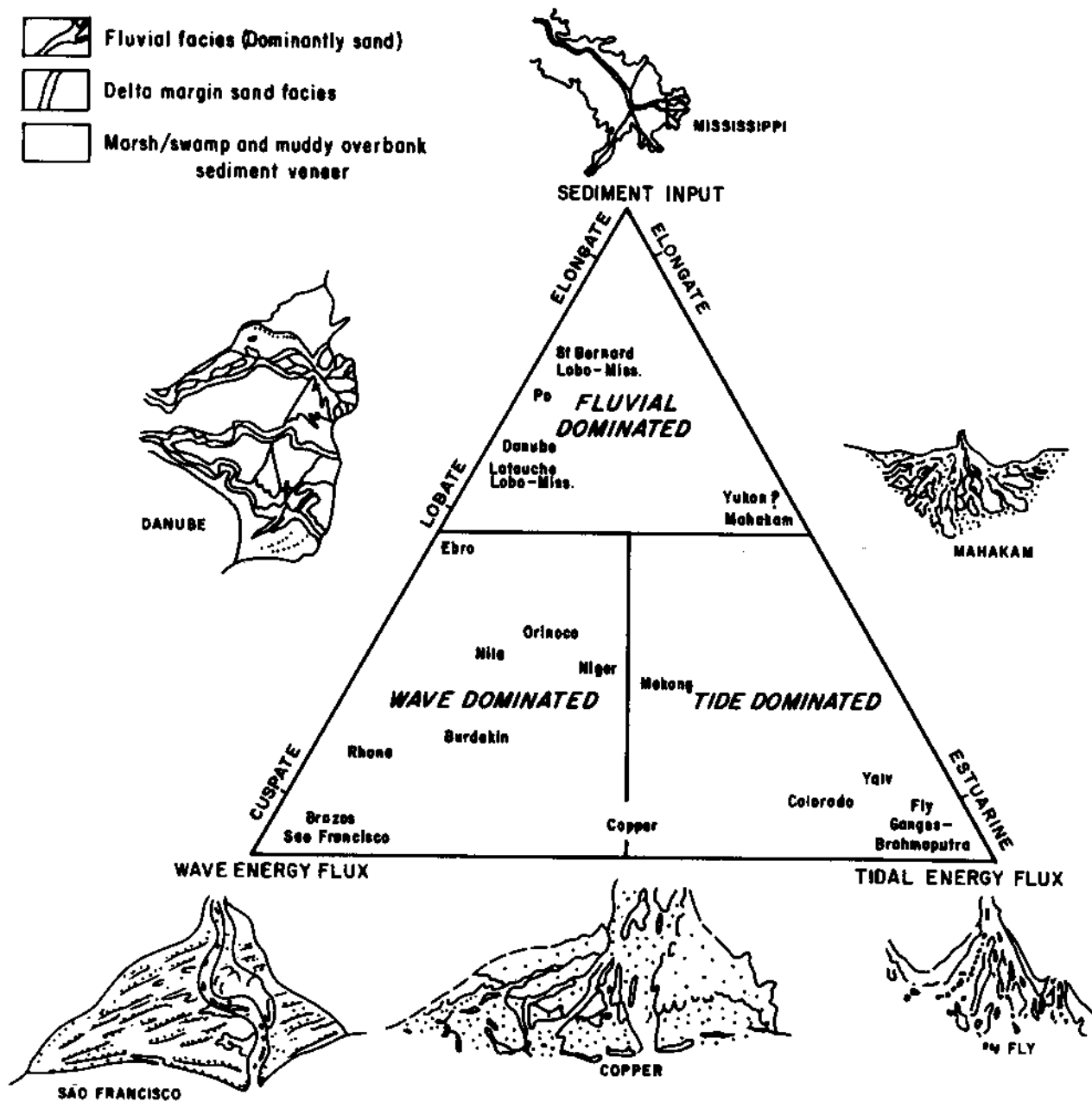
TIDAL ENERGY FLUX

SÃO FRANCISCO

COPPER

FLY

Fig. 11. Triangular classification of deltas.

41

Figures 12 and 13 show how the facies differ for some of the best studied deltas.

Cretaceous rocks in the northern part of the Rio Escondido basin have characteristics more like lobate wave-dominated deltas than other types. In wave-dominated deltas, much sand that reaches the front of deltas through distributary channels is reworked by wave action and distributed as broad shallow aprons of sand adjacent to channel-mouth-bars. As the delta builds out sand progrades, a sheet-like sand body is formed (i.e., the San Miguel Formation).

The strike cross-sections in the northern part of the Rio Escondido Basin show that the delta-front sandstone is continuous for 45 km in a north-south direction, that is, it is a sheet sandstone. Variations in thickness of the San Miguel sandstone reflects how close the core location is to a distributary channel, because distributary-channel deposits make up the top part of the sheet sandstone in places. The Cretaceous deltas had numerous small distributaries judging from the abundance of distributary-channel deposits found in the cores. No natural levee deposits were recognized in the cores, which suggests that distributaries had considerable mobility to shift laterally, to avulse to new locations, and to form many small channels during flood episodes.

The general thickness of the sheet sandstone depends on the rate of basin subsidence, rate of compactional subsidence of prodelta mud, wave strength, and rate of sand supply. These same factors influence the thickness and extent of organic coal deposits. Thick organic deposits are favored by slow outbuilding compared with rate of compaction; that is, rapid subsidence (because of compaction of prodelta mud) will favor thicker organic deposits. Coal beds in the Olmos are thickest where the San Miguel is thickest; compaction of prodelta mud was greatest where the mud was loaded by thick, heavy sand layers.

Although only one *major regressive event* is recorded in the northern part of the basin (in contrast with the Parras and La Popa basins), the rocks show that delta progradation was episodic and that minor transgressive events (recorded by lag conglomerates and *Ophiomorpha* burrows in the San Miguel) were frequent. Episodic outbuilding of deltas is a normal behavior as shown by

numerous studies of modern deltas (e.g. Scruton, 1960). The absence of marine tongues within the Olmos Formation indicates that there were no large-scale transgressions during deltaic deposition (the first major transgression is recorded in the Escondido Formation). Multiple minor episodes of delta growth are also recorded in the cores that have exceptionally thick San Miguel sandstones; here sandstones of successive minor progradational episodes are stacked vertically to make abnormal thicknesses.

In the southern part of the Rio Escondido basin the core spacing is too far apart to provide adequate information for a detailed environmental interpretation. Transect Z-Z' shows that the San Miguel is not present as a widespread sheet sandstone in this area. There seems to be a vertically stacked sequence of delta-plain and pro-delta-shelf facies. The alternation of regressive and transgressive facies suggests that the area was the site of deltaic deposition at widely spaced time intervals. Thus, there was less likelihood of developing extensive coal beds. However, if coal accumulated during each regressive event, the possibility exists for several coal beds to be present separated vertically by tens of meters. Additional coring is needed to establish the main facies in this area.

Summary of Stratigraphy and Geometry of Coal Beds in the Rio Escondido Basin

Previous work in other basins has shown that coal beds commonly split into several coal beds, pinch out, or are truncated by distributary channels. Because of these reasons, the correlations of coals made in this report should be considered probable but not proven interpretations. Positive correlation of individual coal beds cannot be made on 1 km spacing of test cores.

In the dip sections coals can be correlated a distance of approximately 5 km, whereas in strike sections the same coals can only be correlated, with confidence, a distance of 1 to 2 km. This reflects the compartmentalization of the coals by dip-oriented distributary-channel sandstone. Also, the coals tend to split from one thick (2 m) bed into several thinner (20 cm) beds in the proximity of the distributary sandstone. The splitting of coals near the channels is related to higher rates of sedi-
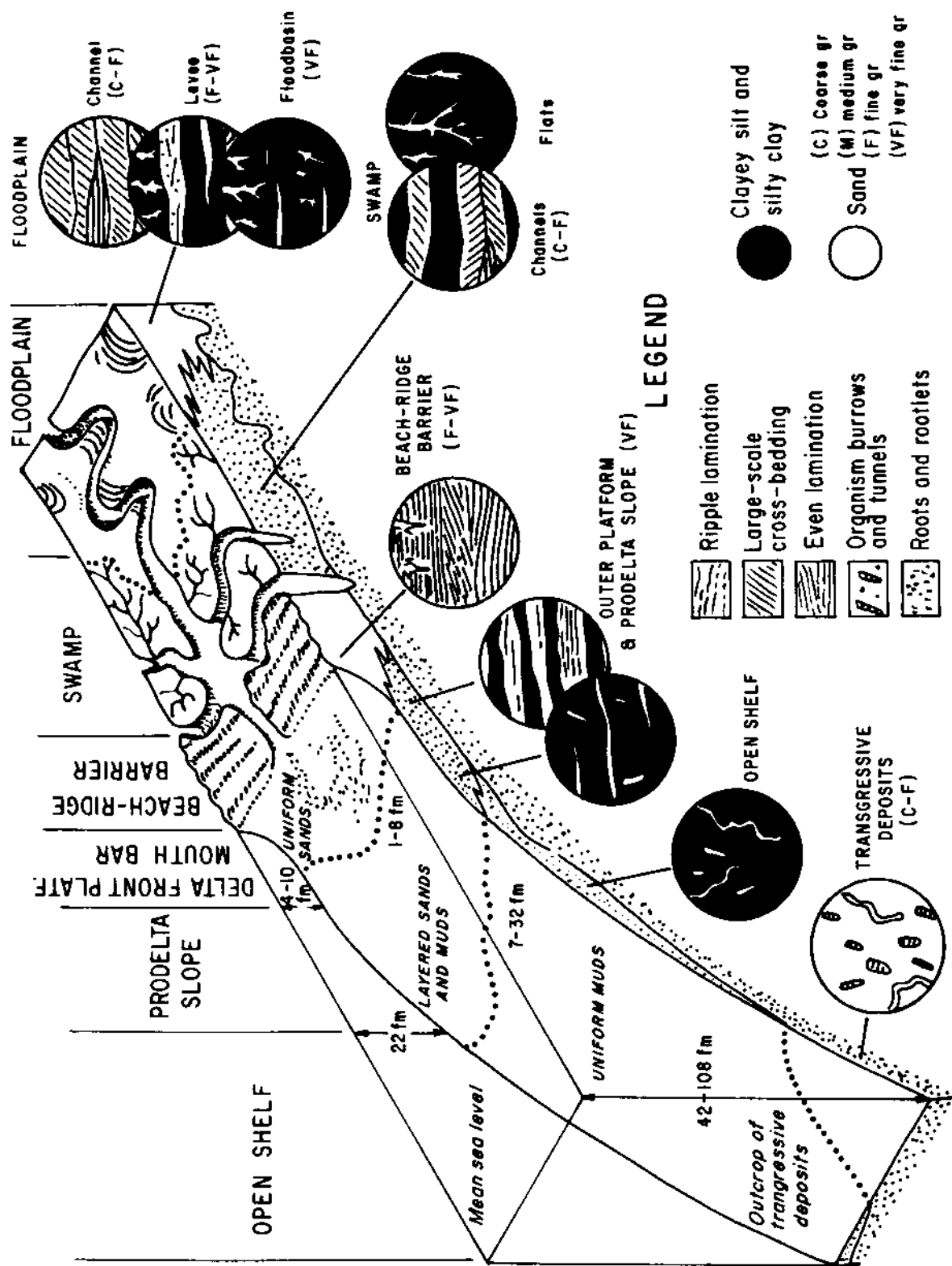
Fig. 12. Block diagram showing principal sedimentary facies of the Modern Niger Delta.

LEGEND

Clayey silt and silty clay

Sand

(C) Coarse gr
(M) medium gr
(F) fine gr
(VF) very fine gr

Ripple lamination

Large-scale cross-bedding

Even lamination

Organism burrows and tunnels

Roots and rootlets

FLOODPLAIN

Channel (C-F)

Levee (F-VF)

Floodbasin (VF)

SWAMP

Flats

Channels (C-F)

BEACH-RIDGE BARRIER (F-VF)

OUTER PLATFORM & PRODELTA SLOPE (VF)

OPEN SHELF

TRANSGRESSIVE DEPOSITS (C-F)

FLOODPLAIN

SWAMP

BEACH-RIDGE BARRIER

MOUTH BAR

DELTA FRONT PLATF.

PRODELTA SLOPE

OPEN SHELF

Mean sea level

22 fm

4-10 fm

UNIFORM SANDS

1-8 fm

LAYERED SANDS AND MUDS

7-32 fm

UNIFORM MUDS

42-108 fm

Outcrop of transgressive deposits

Fig. 13 Distribution of swamp and marsh environments on Mississippi deltaic plain.

LEGEND:
- NATURAL LEVEE
- FRESH MARSH
- BRACKISH MARSH
- SALINE MARSH
- SWAMP

UPLANDS

MISSISSIPPI
LOUISIANA

PRAIRIE TERRACE

Lake Pontchartrain

NEW ORLEANS

Mississippi River

Atchafalaya River

ATCHAFALAYA BAY

MARSH IS.

MISSISSIPPI SOUND

CHANDELEUR IS.

BIRDFOOT DELTA

600
300
180
60
30

MILES
KILOMETERS
0   50
0   80

N

mentation near the channels, that is, organic deposits are episodically covered by crevasse-splay deposits (Fig. 3b) and overbank muds that enter the swamps from the adjacent distributary channels. Farther from the channels these contaminant sediments do not interrupt the organic (coal) deposits.

In the Rio Escondido Basin the thickest coals are present in the western part of the study area, while more numerous but thin coal beds are present in the eastern part of the basin. The thickest coals are consistently found above the thickest accumulations of delta-front facies (San Miguel Fm.). Possibly higher rates of compaction (loading of the prodelta muds by thick accumulations of delta-front sands) in these areas allowed the swamps to subside and receive greater amounts of plant debris for longer periods of time. High rates of compaction would also allow a high-standing fresh water table to exist in the area, prohibiting the oxidation of the peat accumulations.

Coal beds occur at various stratigraphic positions in the Olmos Formation. However, the thickest and most extensive beds occur within 5 m above the base of the Olmos. These coal beds were formed in a delta-plain swamp not far behind the delta front (hence their position just above the delta-front sheet sandstone, i.e., San Miguel Fm.), where compactional subsidence permitted the thickest plant debris to accumulate. However, because the episodes of delta outbuilding alternated with short periods of transgression or nondeposition, there were several episodes of plant accumulation, and thus, several coal deposits in the lower part of the Olmos. Because the coals stratigraphically higher in the Olmos formed progressively (but not precisely) farther inland from the delta front, they tend to be thinner than the stratigraphically lowermost coal bed. Some coal beds, especially those more than 10 m above the base of the Olmos, may be fluvial backswamp deposits (Fig. 3b).

Within the Rio Escondido Basin several major packages (Fig. 7) of rock with coal beds are recognized. The coals in a dip transect can be seen to offlap from west to east into the basin. Each one of these major coals in found in the delta-plain facies of a prograding deltaic package. Within these separate packages, the coals can be correlated in strike and dip cross sections.

The thickest coals are found in the western part of the basin, while more numerous but thinner coals are found in the deltaic packages farther eastward in the basin. Additional exploration in the eastern part of the basin is needed to establish how far east the delta-plain facies extends.

The individual packages mentioned above are interpreted as separate delta lobes, where each lobe is the record of a major episode of delta growth (Fig. 14).

Recommendations for additional coring

1. The most useful information for coal *exploitation* will be gained by additional coring in the northern part of the Rio Escondido basin where commercial coal has been found. After coring has been completed on a 1-km spacing, additional cores could be useful at the center of each 1-km square area.

2. The most useful stratigraphic information for coal *exploration* will be gained by additional coring as follows:
   a. East of section R-R' to establish the extent of coal in this area.
   b. ED-191 offset and ED-217. Core the coal-bearing interval and continue through the San Miguel to about 5 m into the Upson to determine the thickness of the delta-front sandstone.
   c. Take several long stratigraphic test cores to determine the vertical range of coal beds and the precise stratigraphy of the region. These tests should be cored from about 5 m below the ground surface to 5 m into the Upson.
      5 km east of ED-147
      7 km east of ED-197
      ED-155 (not yet drilled)
   d. Deepen the following wells by coring 10 m into the Upson to determine the geometry of the delta-front (San Miguel) sandstone:

ED-67	ED-94	II-10
ED-198	ED-91	II-8
ED-110	II-4	GN-4 BIS

The cores in the southern part (south of section R-R') of the study area do not contain thick coals, and the area does not look like it will be a

I.- PROGRADATION

MARINE BASIN

COAL

Sea Level

ΔP

ΔF

PRO Δ

Δ P — DELTA PLAIN
ΔF — DELTA FRONT
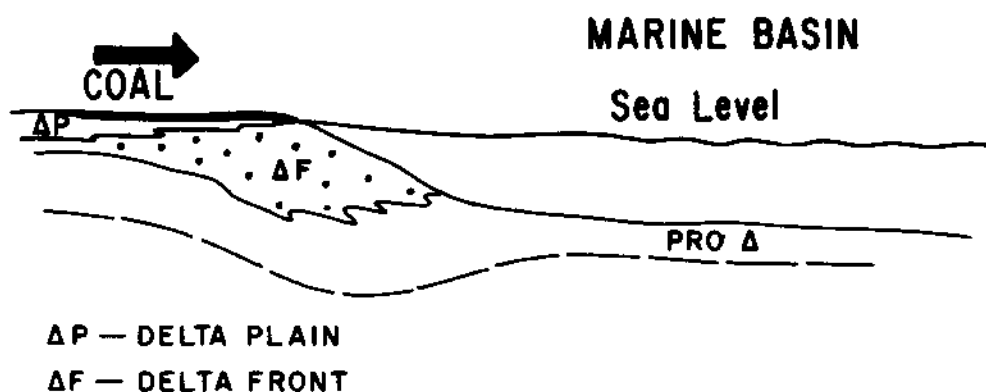
II.- LOCAL ABANDONMEN

**MINOR TRANSGRESSION
OF DELTA FRONT**

COAL

ΔP

Δ F

PRO Δ

III.- PROGRADATION

**NO VERTICAL STACKING OF
DELTAS, OFFLAPPING OF
COAL BEDS**

COAL
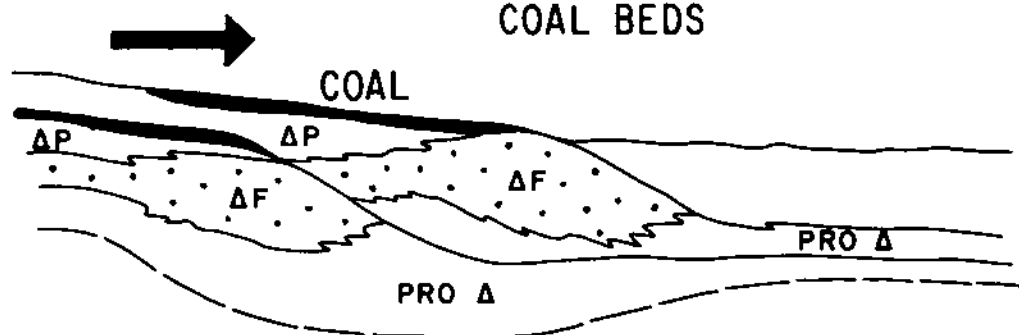
ΔP

ΔP

ΔF

ΔF

PRO Δ

PRO Δ

Fig. 14. Diagram showing the inferred origin of coal-bearing cyclic packages. Each cycle is the product of a major episode of deltaic deposition.

productive area. Nevertheless, additional cores, those originally planned for this area plus cores farther east and south, should be taken in order to enable the major deltaic facies to be determined. There are too few cores available at present to permit a proper interpretation of the facies and too few to evaluate the coal prospects.

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