Don W. Lewis. PRELIMINARY STRATIGRAPHY OF THE PUNGO RIVER FORMATION OF THE ATLANTIC CONTINENTAL SHELF, ONSLOW BAY, NORTH CAROLINA. (Under the direction of Dr. Stanley R. Riggs) Department of Geology, July, 1981.

ABSTRACT


The distribution of an extensive sequence of Tertiary sediments has been delineated in the shallow subsurface across the continental shelf of Onslow Bay, North Carolina. Vibracoring and high resolution subbottom profiling (3.5 kHz, uniboom, and sparker) have revealed a broad belt of phosphatic sediments that extend southwestward for 125 km from the western Bogue Banks, across the shelf, to the outer portion of Frying Pan Shoals off Cape Fear.

The Tertiary section in Onslow Bay consists of Oligocene and/or Lower Miocene moldic, sandy limestones and fine quartz sands unconformably overlain by sediments of the Middle Miocene Pungo River Formation which are, in turn, unconformably overlain by either Pliocene and/or Pleistocene sediments. The Pungo River Formation consists of three sediment members with facies variations within each in northern Onslow Bay. These include 1) a quartz sand member; 2) a biorudite member; and 3) a phosphatic sand member. The other Pungo River facies are found in southern Onslow Bay near Frying Pan Shoals and consists of phosphorite sands, phosphorite quartz sands, phosphatic quartz sands, foram-rich muds, and clayey dolosilts. Preliminary analysis of the Onslow Bay sedimentary sequence and the associated foraminiferal faunas suggest that they are similar to that found in the Pungo River section of the mining district near Aurora.


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Phosphorite units in northern Onslow Bay contain mostly medium brown intraclastic and skeletal phosphate grains in concentrations which average 10 to 15% but occasionally reach 20-25% of the total sediment. Phosphorite units in the Frying Pan area contain dominantly dark brown pelletal phosphate grains which average 20 to 40% and occasionally constitute 50 to 65% of the total sediment.

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PRELIMINARY STRATIGRAPHY OF THE PUNGO RIVER FORMATION

OF THE ATLANTIC CONTINENTAL SHELF,

ONSLOW BAY, NORTH CAROLINA

By

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# PRELIMINARY STRATIGRAPHY OF THE PUNGO RIVER FORMATION OF THE ATLANTIC CONTINENTAL SHELF, ONSLOW BAY, NORTH CAROLINA

A THESIS

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BY

DON W. LEWIS

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# INTRODUCTION

The Middle Miocene Pungo River Formation is a major sedimentary phosphorite unit which underlies the north-central Coastal Plain of North Carolina. Many workers have studied the Pungo River Formation since Brown (1958) first described phosphatic sediments from the subsurface of Beaufort County, N.C. The major works include Kimrey (1964,1965), Gibson (1967), Leutze (1968), Miller (1971), Potluri (1971), Brown et al. (1972), Riggs et al. (in press), Scarborough et al. (in press), Katrosh (1981), Katrosh and Snyder (in press) and Snyder et al. (in press). These workers have focused on the Pungo River Formation in or near the mining district of Aurora and the Aurora Embayment on the North Carolina Coastal Plain. Steele (1980) found Pungo River sediments unconformably underlying the Quaterary sands of Bogue Banks with a lateral subcrop extent of approximately 4.1 km. Meisburger (1979) found Miocene phosphatic sands just south of Bogue Banks while conducting a near shore vibracoring reconnaissance for sand suitable for beach replenishment. Snyder et al. (in press) present seismic data that provides further evidence for the presence of the Pungo River formation on the continental shelf in Onslow Bay. Portions of this seismic data are incorporated into this thesis.

Supported by a National Science Foundation grant, Dr. Stanley R. Riggs of East Carolina University and Dr. Albert C. Hine, University of South Florida, have directed two research cruises in order to determine the extent and distribution of the Pungo River Formation in Onslow Bay. A broad belt of phosphatic sediments was delineated by extensive vibracoring and high resolution seismic profiling during May and October, 1980,

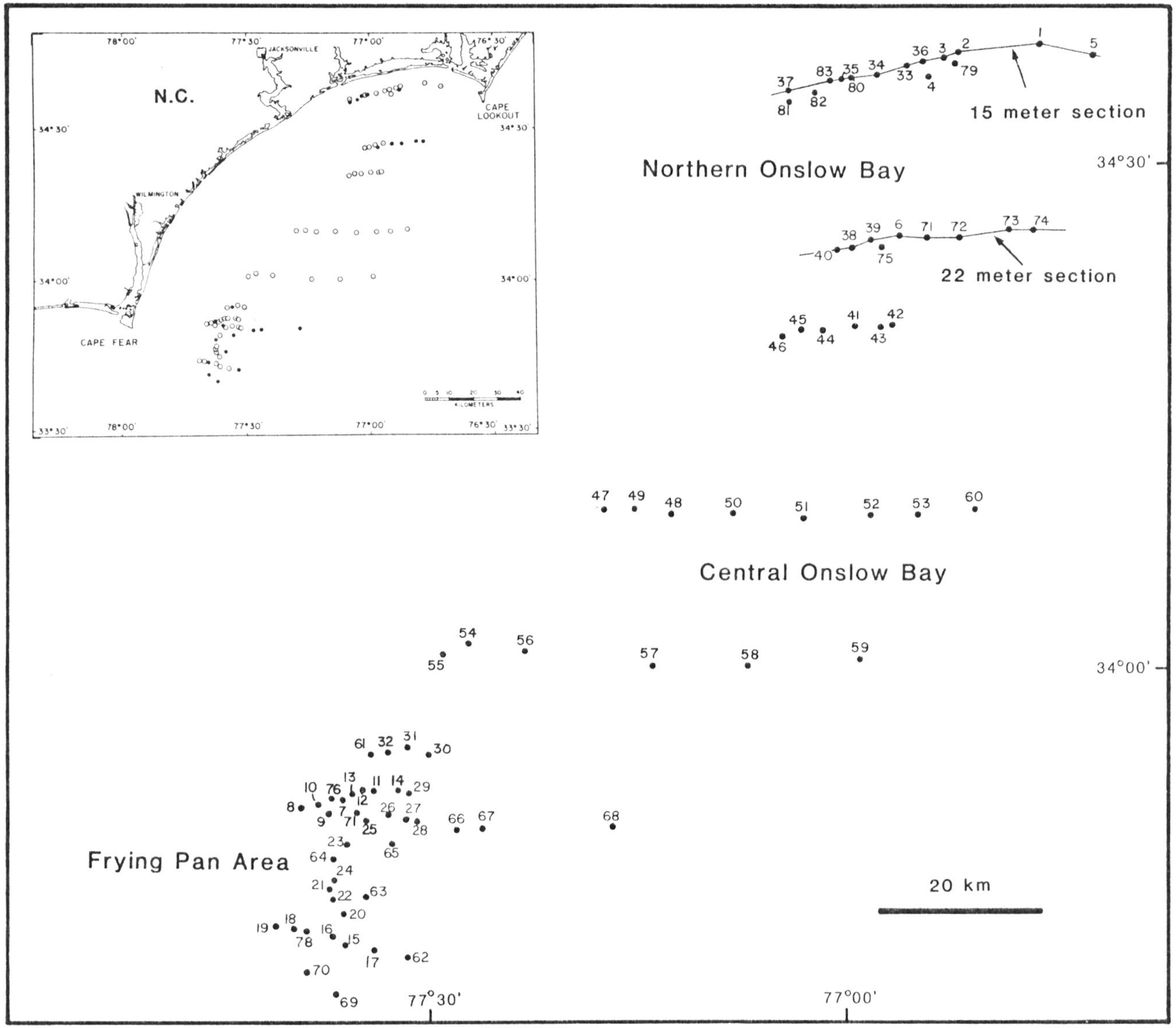



Figure 1. Location map showing vibracore sites and the two seismic profiles of Snyder et al. (in press).

from the R/V EASTWARD and R/V ENDEAVOR, respectively (Fig. 1). This phosphatic belt has been traced southwestward for 125 km from western Bogue Banks, across the shelf, to the outher portion of Frying Pan Shoals off Cape Fear, N.C.

The objectives of my study were to 1) describe and characterize the lithofacies of the Pungo River Formation and the stratigraphically adjacent formations and 2) to delineate the distribution and geometry of the Pungo River in Onslow Bay.

## GEOLOGIC SETTING

The emerged North Carolina Coastal Plain is underlain by Cretaceous to Quaternary sediments and sedimentary rocks that extend from a featheredge along the Fall Line to a maximum thickness greater than 3 km at Cape Hatteras. The area represents an oceanward thickening wedge of southeast dipping strata that unconformably overlie an oceanward dipping pre-Cretaceous basement. Figure 2 shows the stratigraphic framework for the Coastal Plain of North Carolina as presented by Baum _et_ _al_. (1978).

The Middle Miocene Pungo River Formation occurs in the north-central Coastal Plain where Miller (1971) recognized that the updip limit for the formation was structurally controlled as it occurs along a north-south hinge zone where the eastward dip of the underlying strata suddenly increases. Hine _et_ _al_. (1979) recognized a north-south trending subbottom scarp in seismic sections from northern Onslow Bay and Bogue Sound. They interpreted this scarp, termed the White Oak Lineament, to be a southern extension of Miller's hinge zone (Fig. 3). Snyder _et_ _al_. (in press), using seismic stratigraphy, correlated Pungo River sediments from Bogue

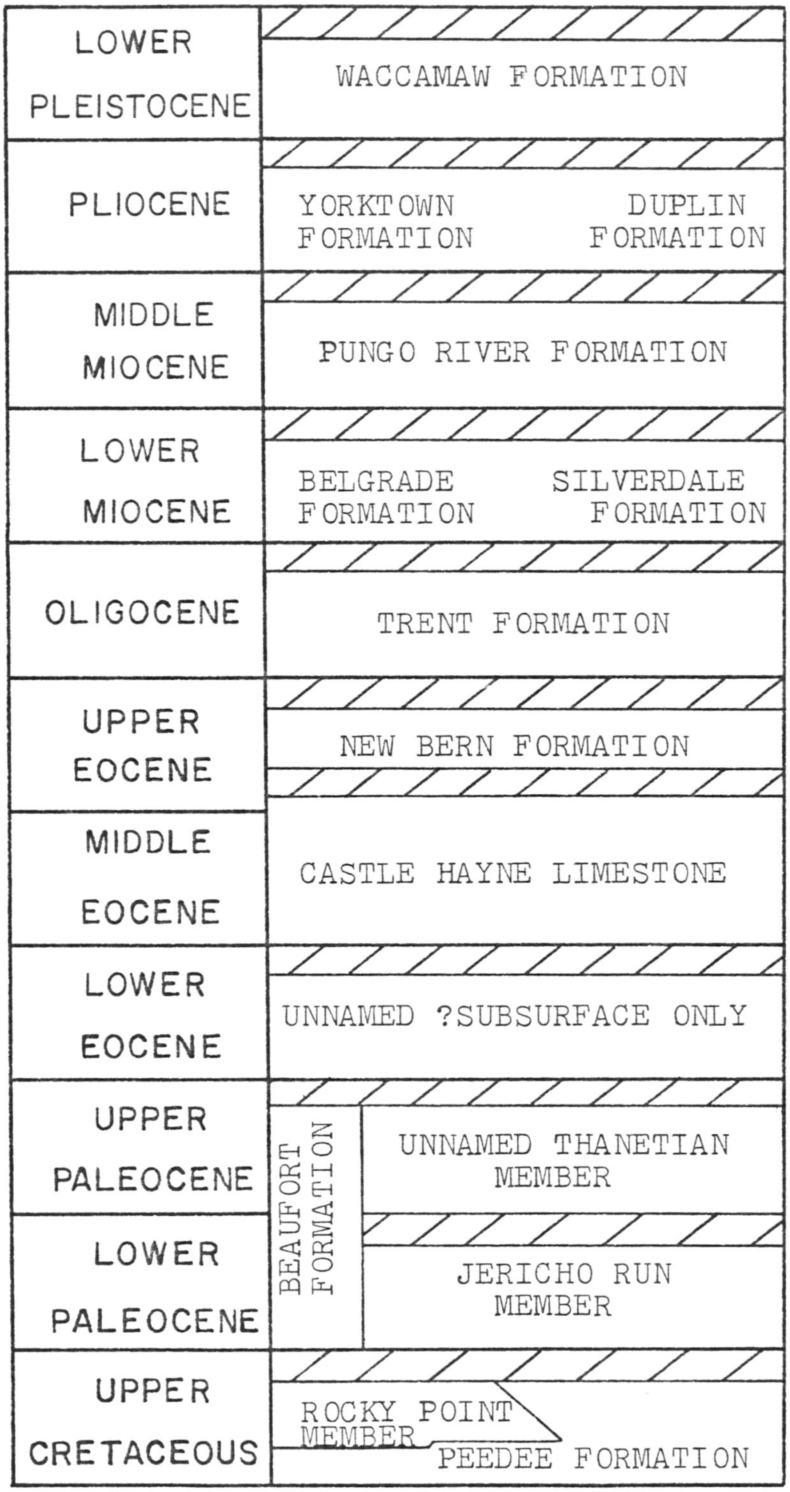



Figure 2. Stratigraphic framework for the upper Cretaceous to lower Pleistocene strata of the Coastal Plain of North Carolina (from Baum *et al.*, 1978).

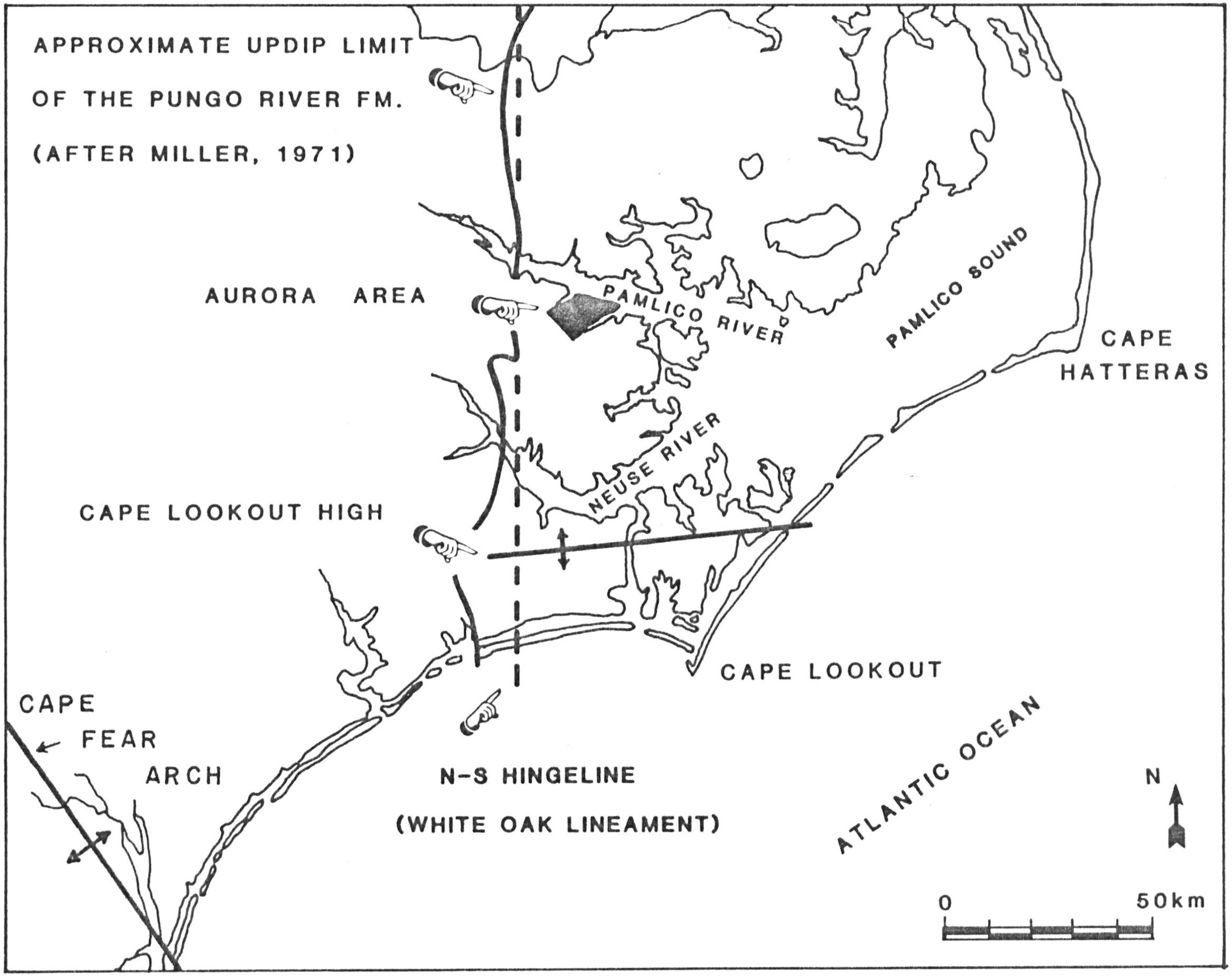



Figure 3. Map showing the north-south hingeline of Miller (1971) and the White Oak Lineament of Snyder et al. (in press). Also shown are the Cape Lookout High and the Cape Fear Arch which define the Onslow Bay basin into which Pungo River sediments were deposited.

Banks (Steele, 1980) with seismic reflectors from northern Onslow Bay. They postulated Pungo River sediments east of the White Oak Lineament and pre-Pungo River sediment to the west.

Structurally the sediments in Onslow Bay lie between the Cape Lookout High to the north (Snyder, in press) and the Cape Fear Arch to the south (Fig. 3). The Cape Lookout High is a positive east-west feature located south of the Neuse River and separates the Pungo River Formation of the Aurora Embayment from the Pungo River sediments in Onslow Bay. Only a thin section of Pungo River sediments are found over the Cape Lookout High.

The Cape Fear Arch is a major northwest-southeast trending positive feature that enters Onslow Bay in the Carolina Beach area just north of Cape Fear. This Arch is a pre-Tertiary basement structure that has controlled Tertiary deposition in southeastern North Carolina. The Pungo River Formation, in Onslow Bay, was deposited around the nose of the Cape Fear Arch and preserved on the present day continental shelf.

# PROCEDURES

## Field Phase

### Coring

Cores were obtained using the 9 m (30 ft.) vibracoring equipment from Ocean/Seismic/Survey. This system consists of a quadruped frame that sits on the sea floor, a 680 kg (1500 lb.) vibrator head that runs on compressed air and rides up and down a 9 m aluminum H beam, and a 14.2 cm (4 in.) diameter iron core barrel containing a plastic liner, core catcher, and cutterhead. Figure 4 shows the vibracorer in working position. The vibracoring rig was fitted with a penetrometer to determine and record the depth and rate of penetration.

The initial objective of the May, 1980 cruise was to define the lithostratigraphy in northern Onslow Bay. This was done by replicating the 15 and 22 meter seismic sections of Hine _et al_. (1979) and Snyder _et al_. (in press) and vibracoring each of the seismic units (Fig. 1). With the 3.5 kHz seismic system operating, the ship steamed along the course of the 15 or 22 meter profile. In most cases potential core sites were located so that seismic reflectors approaching the surface would be penetrated thus insuring that the sediments above and below the reflector would be sampled. Once the core site was located the ship returned to that location and anchored. Each core, when retrieved aboard ship, was processed as follows. The plastic liners were extruded, sawed into 1.5 m sections, labeled, and stored in an upright position. Cursory examination of core samples, taken at each 1.5 m section, and construction of preliminary logs were accomplished onboard ship. The location of

Figure 4. The Ocean/Seismic/Survey vibracore rig shown in operating position with a 6 m (20 ft.) core barrel. A 9 m (30 ft.) core barrel was used in Onslow Bay.

subsequent vibracores along each profile depended upon the contents of the core. Seismic reflectors were assumed to represent distinct lithologic units, an assumption which proved to be true in most cases. More than one core per seismic unit was attempted where adjacent seismic reflectors were widely separated. This was done to determine facies relationships between reflectors.

Once the Pungo River Formation was delineated in northern Onslow Bay the coring operations progressed southward across the shelf where there was no previous seismic information. Core-hole locations were based upon preliminary seismic traces and the surfacing seismic reflectors in combination with the contents of previous cores.

Sixty cores representing approximately 518 m (1700 ft.) were taken in May, 1980, from the R/V EASTWARD. All of these cores were used in this study and constitute the main data base for the stratigraphic conclusions presented in this work (Appendix I). Several cores from the October, 1980 cruise were used to supplement the May data, although these were not analyzed in as much detail as the previous cores.

## Seismic Profiling

The 3.5 kHz system, hull-mounted in each ship, was run continously while the ships were under way. High-resolution seismic profiling was done utilizing a uniboom and sparker system and obtained penetration up to 50 m and 100 m, respectively. Figure 5 shows the uniboom seismic tracts obtained in Onslow Bay. S.W.P. Snyder of the University of South Florida reduced the seismic data and produced the finished reductions used in this study. The siesmic profiles used herein serve only as aids to lithostratigraphic interpretation and correlation. The siesmic interpretations

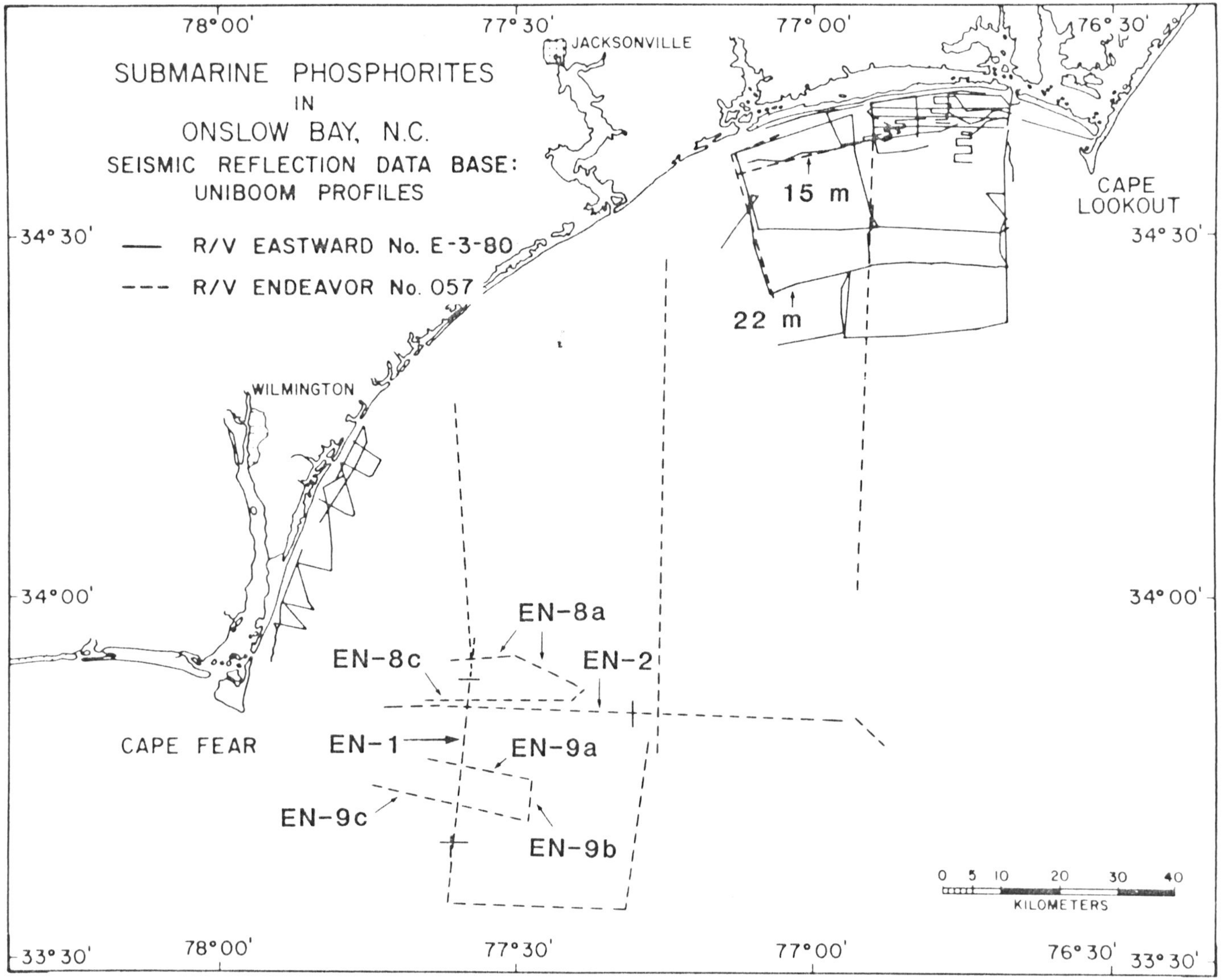



Figure 5. Uniboom seismic profiles in Onslow Bay, the ones refered to in the text are labeled.

are those of Snyder and I have not attempted to modify them.

## Laboratory Phase

The 1.5 m core sections were sawed open longitudinally into sections representing 1/3 and 2/3 portions of the core. The 2/3 portions were bagged in plastic sleeves and stored for future studies. The 1/3 sections were then described in detail and photographed. Subsamples were taken of each lithology and/or every 1.5 m for textural analysis and allowed to air dry.

Textural analysis consisted of weighing the air dried sample, wet sieving through a $4\phi$ (230 mesh) screen, then drying and weighing the $>4\phi$ fraction to determine the amount of mud in each sample. The $>4\phi$ fraction was then Ro-tapped using a $0.5\phi$ screen interval. Each size fraction was weighed and the percentage of the total sediment sample for each fraction was calculated. Every size fraction was then described using a binocular microscope in order to determine the mineralogic composition and estimate the volumetric concentration of each. Estimations are accurate to within ±10%. The degree of accuracy was determined by periodically comparing estimated values to several 200-grain point counts. This procedure was carried out for each lithology.

The textural and mineralogic data for 118 subsamples (1300 size fractions) were compiled by the ECU B-6800 computer using SPSS (Statistical Package for the Social Sciences). Lithologic data were used in conjunction with seismic data to recognize and define the stratigraphic units within individual core holes. These strata were then correlated among the cores.

# LITHOLOGIES

Several distinct stratigraphic units, which range in age from Oligocene and/or Lower Miocene to Holocene, are now recognized in Onslow Bay. Only the lithologies of the Tertiary section will be considered in this thesis. A generalized stratigraphic section for the Tertiary sediments found in Onslow Bay is shown in figure 6. Lithologies from different localities are listed opposite each other in order to facilitate graphic presentation. This should not be interpreted as a proposed correlation because stratigraphic relationships between areas have not yet been determined.

## Northern and Central Onslow Bay

### Pre-Pungo River Sediments

Sediments which underlie the Pungo River Formation in northern and central Onslow Bay are of two lithologies. In hole OB-37, at the western end of the 15 meter section (Fig. 1), a grayish green, slightly fossiliferous, muddy (18%), fine quartz (78%) sand was found. Fossil content varies throughout the core and averages less than 10% but approaches 40% in two 1/2 to 3/4 m shell beds (Fig. 7). Bivalve fragments predominate but foraminifera and ostracods are present also. Bedding structures are absent, however, abundant small (<1 cm) clay clasts occur throughout the core.

The other pre-Pungo River lithology was found in holes OB-54, OB-55, and OB-56 located at the western end of profile 5 (the fifth east-west core transect south of Bogue Banks). This pre-Pungo River unit consists

| AGE | FORMATION | NORTHERN ONSLOW BAY | | | FRYING PAN AREA | |
|---|---|---|---|---|---|---|
| | | member | facies | lithology | facies | lithology |
| Pliocene | Yorktown | | SHELLY CALCAREOS QUARTZ SAND | | | |
| Miocene | Pungo | | VERY FINE QUARTZ SAND | | | |
| | | PHOSPHATIC SAND | PHOSPHATIC QUARTZ SAND | P | | |
| | | | PHOSPHORITE QUARTZ SAND | P P | MUD | |
| | | BIORUDITE | TIGHT BIOCLASTIC DOLOSILT | | SANDY MUD | |
| | | | BARNACLE BIORUDITE | | PHOSPHORITE QUARTZ SAND | P |
| | River | QUARTZ SAND | CHERTY QUARTZ DOLOSILT | | QUARTZ PHOSPHORITE SAND | P P |
| | | | DOLOSILTY QUARTZ SAND | | PHOSPHORITE SAND | P P P |
| Lower Miocene ? | Silverdale/ Belgrade ? | | FINE LIGHT GREEN QUARTZ SAND | | FINE LIGHT GREEN QUARTZ SAND | |
| | | | | | MOLDIC LIMESTONES & CALCARENITES | |

Figure 6. Generalized lithologic section for the Onslow Bay sediments described in the text.

Figure 7. A. Core OB-37, pre-Pungo River sands from northern Onslow Bay.

B. Close-up of pre-Pungo River calcarenite from hole OB-56.

C. Core OB-55, interbedded limestones and calcarenite sands.

D. Close-up of moldic limestones from hole OB-55.

Figure 8a. A. Core OB-35, an example of the cherty quartz dolosilt member of the Pungo River Formation in north-central Onslow Bay.

B. Close-up of sandy mottle in dolosilt.

C. Angular chert nodule in dolosilt.

Figure 8b. A. Core OB-58, an example of the dolosilty quartz sand member of the Pungo River Formation in north-central Onslow Bay. Dolosilt laminae can be seen in the quartz sand.

B. Close-up of dolosilt laminae.

**Fig. 7**

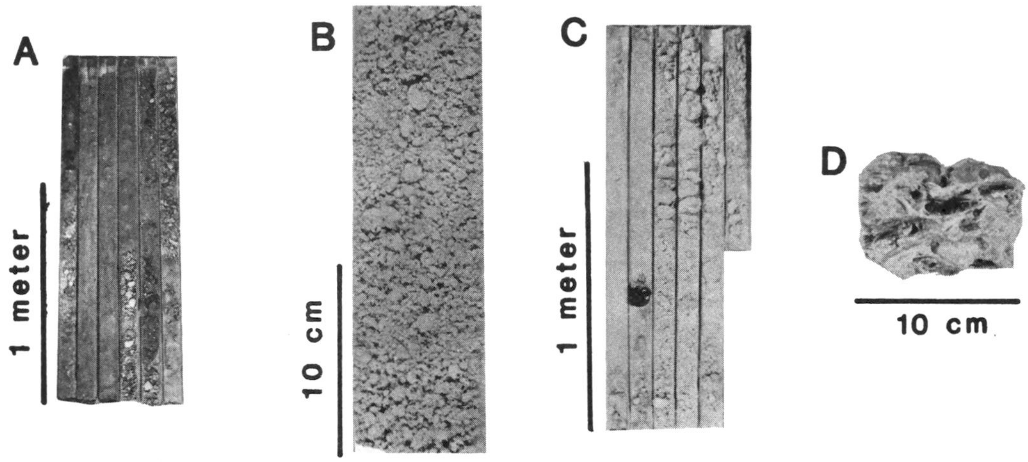



**Fig. 8a**

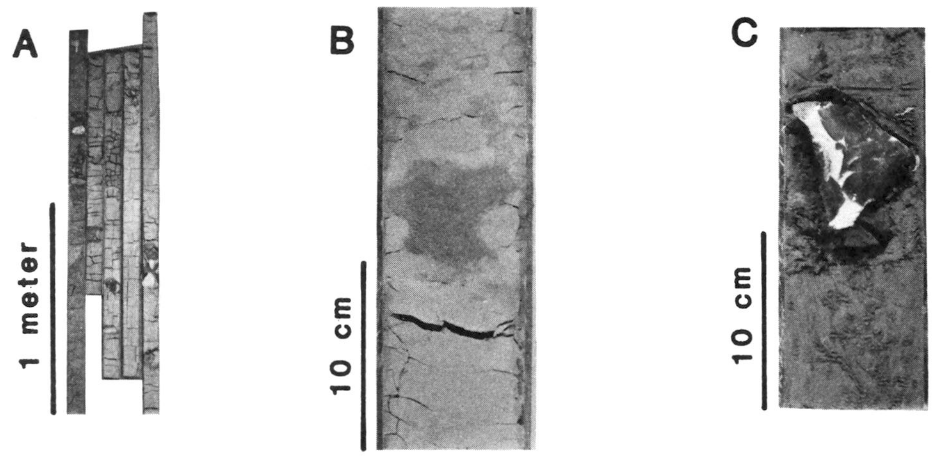
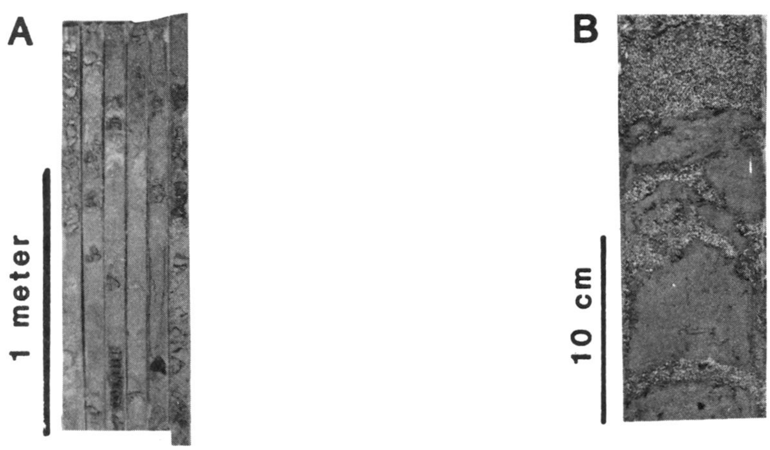



**Fig. 8b**



of interbedded loose calcarenites, indurated calcarenites, and gray moldic limestones (Fig. 7). Barnacle and bivalve fragments dominate the calcarenite sands with some echinoid, gastropod, and worm tube fragments present.

Pungo River Sediments

Seven distinct lithologies have been recognized within the Pungo River Formation. Several of these exhibit lithologic similarities which permit grouping of lithologies into three separate informal members, a quartz sand member, a biorudite member, and a phosphatic sand member (Fig. 6).

Quartz Sand Member. The quartz sand member occupies the lowest stratigraphic position of the Pungo River Formation. It is, in general terms, a light olive green to brown, slightly phosphatic (5%), fossiliferous (13%), muddy (40%), fine to medium angular quartz (42%) sand. A microscopic examination of the silt-size material shows that approximately 90% of the mud is made up of euhedral dolomite rhombs and clay while the remainder is very angular quartz grains and minor glauconite. The majority of phosphate grains are the intraclastic type and medium brown in color. The faunal assemblage consists dominantly of barnacle fragments, foraminifera and ostracods. Glauconite is present, but averages less than 1%.

The quartz sand member can be divided into two alternating and interbedded lithofacies. A cherty quartz dolosilt facies contains abundant large ($\geq$10 cm), angular, dolosilt coated, dark olive-green chert nodules (Fig. 8a). Dolosilt and clay comprises up to 95% of the sediment in places but averages about 70%. This facies is usually characterized by clean brown sandy mottles in a light olive-green dolosilty clay (Fig. 8a). Fossils, mostly barnacle fragments, constitute less than 5% of the sediment in this facies.

Interbedded with the cherty quartz dolosilt is a dolosilty quartz sand facies. This lithology is characterized by a light brown clean quartz sand with abundant olive-green dolosilty clay laminae or beds (Fig. 8b). The dolosilty clay ranges in thickness from 1 cm to 0.5 m. Barnacle plates and foraminifera constitute up to 75% of the sediment in small (≤5 cm thick) shell beds but average 13% of the total sediment. Phosphate concentrations within both facies average less than 5% and consist mostly of black to very dark brown intraclastic grains (95%) with pelletal and skeletal phosphate making up the remaining 5%.

Biorudite Member. The biorudite member lies stratigraphically above the quartz sand member and is composed of two carbonate facies. The lowermost lithofacies, found in hole OB-33 (Figs. 1 and 9), is an olive-green to gray, muddy (30%), barnacle biorudite. The mud is dominated by dolomite at the base and grades upward to calcium carbonate toward the top. Barnacle fragments constitute an average of 63% of the entire sediment and as much as 97% of the sand fraction. Minor amounts of pectinid and coral fragments are also present. Phosphate content is negligible and quartz is present in concentrations of less than 5%. Glauconite (<1%) is found throughout the core. This sediment is mostly unconsolidated but indurated laminae and beds (1 to 5 cm) occur scattered throughout the micritic section.

Overlying the barnacle biorudite is a dry bioclastic dolosilt. This facies is a yellowish-green, barnacle-rich (22%), dolosilt. Barnacles

Figure 9. A. Core OB-33, an example of the barnacle hash facies of the biorudite member of the Pungo River Formation in northern Onslow Bay. The darker section in the bottom of the core has a dolomitic mud matrix but the lighter upper portion is micritic calcium carbonate.

B. Close up of biorudite member showing the barnacle hash facies.

C. Core 36, tight bioclastic dolosilt in contact with the overlying phosphatic sand member.

D. Close-up of contact between the biorudite and phosphatic sand member of the Pungo River Formation in northern Onslow Bay.

Figure 10a. A. Core OB-3, phosphatic sand member in contact with the underlying biorudite member.

B. Close-up of above contact showing phosphate and quartz pebbles at the contact and sharks tooth below.

C. Close-up of phosphatic sand showing clay mottles.

D. Close-up of phosphatic sand from hole OB-53 showing mottled appearance.

Figure 10b. A. Core OB-5, the uppermost lithology of the Pungo River sediments found in northern Onslow Bay.

Fig. 9

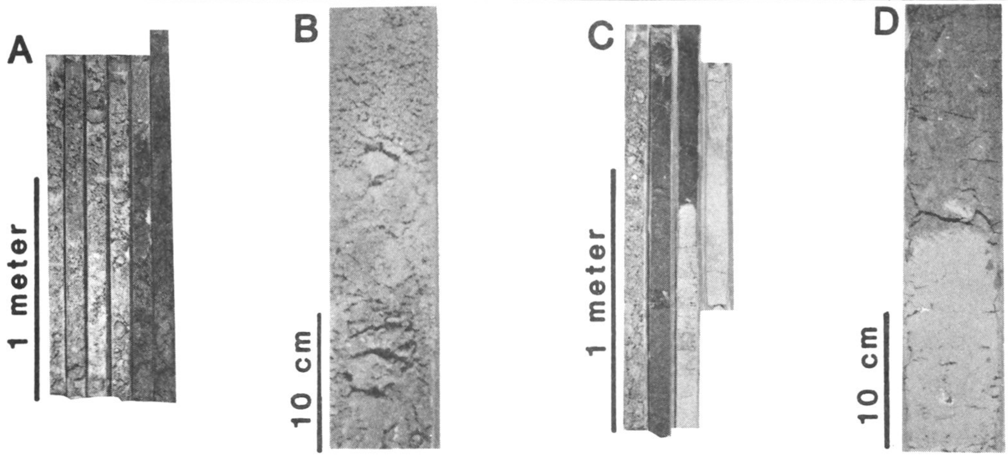



Fig. 10a

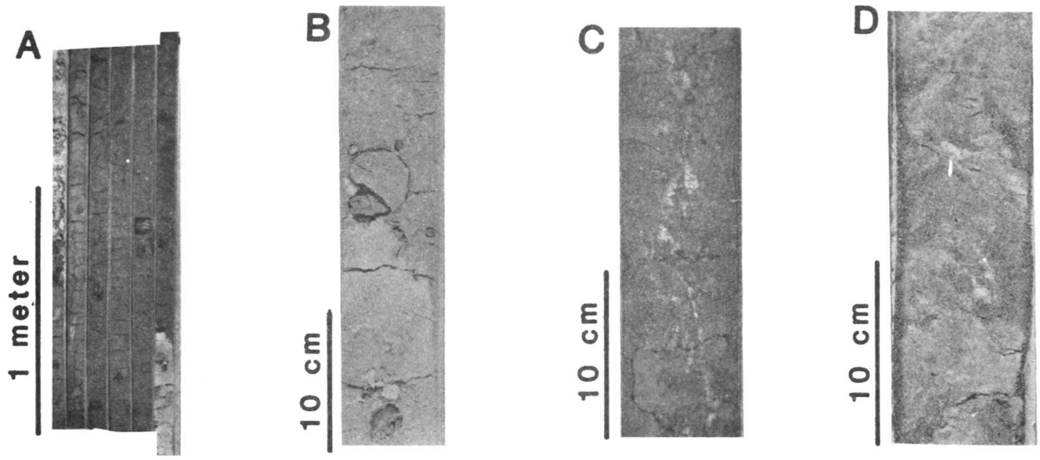
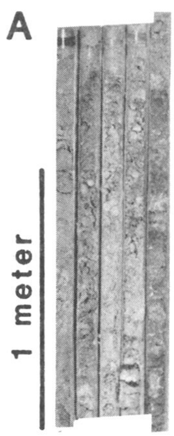



Fig. 10b



are commonly poorly preserved and coated with tiny rhombs of dolomite. Dolosilt mud constitutes 74% of the entire sediment making this facies very dry and difficult to core. Very sharp contacts with the overlying strata were found in holes OB-3 and OB-36 (Figs. 9 and 10a). Sharks teeth and quartz pebbles were found 10 cm below this contact in hole OB-3 (Figs. 9 and 10a). No sedimentary structures were found as this facies is very uniform throughout.

Phosphatic Sand Member. The phosphatic sand member of the Pungo River Formation consists of sediments that vary in mineral composition both laterally and vertically. Three lithofacies are recognized and separated on the percentage of mud and phosphate within the sediment.

The phosphorite quartz sand facies is an olive-green, muddy (25%), slightly fossiliferous (5%), fine to medium phosphorite (17%) and angular quartz (50%) sand. Fossils include bivalves, barnacles, echinoids, and foraminifera. A preliminary examination of the foraminifera revealed two species diagnostic of the Pungo River Formation, Virgulinella miocenica (Cushman and Ponton) and Uvigerina calvertensis Cushman (S.W. Snyder and V. Waters, pers. comm.). The vast majority of the phosphate grains are intraclastic, the remainder are mostly skeletal with a minor amount of pelletal phosphate. Minor amounts of dolosilt and glauconite are present in the very fine sand and silt fraction.

The phosphatic quartz sand facies is an olive-green, muddy (30%), slightly fossiliferous (5%), phosphatic (6%), fine to medium angular quartz sand. The fossil assemblage is the same as found in the phosphorite quartz sand facies. The foraminiferal species Globigerina woodi woodi Jenkins, which is diagnostic of the Middle Miocene Pungo

River sediments, occurs in the phosphatic quartz sand facies (Snyder and Waters, pers. comm.).

Both of the facies described above have a characteristic mottled appearance (Fig. 10a). Clay clasts are common in places. If other primary sedimentary structures such as bedding, burrows, etc. were present in these facies the coring process must have destroyed them. This is not an unreasonable assumption as these sediments underwent a tremendous amount of expansion during vibracoring. It was common for the core barrel to penetrate 6 m (as measured by the penetrometer) and recover 9 m of sediment. The reason for such expansion is not fully understood.

The uppermost lithology of the Pungo River Formation in northern Onslow Bay is a green, muddy (15%), fossiliferous (35%), fine to medium angular quartz sand. Only hole OB-5 on the easternmost edge of the Pungo River outcrop zone encountered this sediment (Figs. 1 and 10b). Indurated calcareous quartz sand fragments, which usually measure less than 10 cm thick, are common from 4.5 m to 6.3 m within this core. Fossils include ostracods, barnacles, echinoids, bivalves, and foraminifera. Within the last 1.5 m the fossils are poorly preserved and soft to the touch. Three foraminiferal species indicative of the Pungo River Formation are found in this sediment: Globigerinoides altiaperturus Bolli, Globigerina woodi woodi Jenkins, and Virgulinella miocenica (Cushman and Ponton) (Snyder and Waters, pers. comm.).

## Frying Pan Area

### Pre-Pungo River Sediments

In the Frying Pan area of southern Onslow Bay the Pungo River sediments overlie a grayish-green, muddy (35%), fossiliferous (15%), very fine quartz sand. The amount of mud varies vertically and laterally throughout this area ranging from 15% to 65%, however, no apparent trends are recognized. Fossils consist of broken bivalve fragments, barnacles, and moderately to poorly preserved foraminifera. Fossils constitute an average of 15% of the total sediment but range from absent to nearly 40% in thin (≤10 cm thick) fossil rich beds in holes OB-10 and OB-24. In one core (OB-8) a moldic biomicrudite with interbedded calcarenites was found in sharp contact with the overlying quartz sand (Fig. 11).

### Pungo River Sediments

Five Pungo River lithofacies are recognized in the Frying Pan area of southern Onslow Bay. Each lithology will be discussed in this section in order of decreasing phosphate content, which does not necessarily represent the stratigraphic sequence. The stratigraphic relationships between lithologies will be discussed in detail in a later section.

Phosphorite Sand Facies. The lithology with the highest phosphate content is an olive-green, muddy (12%), foraminiferal (5%), quartz bearing (<5%), phosphorite (80%) sand. Phosphate grains, which compose about 90% of the sands, are dominantly the dark brown, fine grained pelletal type. A further breakdown of the phosphate grain types is shown in Table 1.

Figure 11. A. Core OB-10, pre-Pungo River quartz sands of the Frying Pan area of southern Onslow Bay.

B. Close-up of above sands.

C. Core OB-8, pre-Pungo River sand in contact with an underlying limestone and calcarenite sands.

D. Close-up of lithified calcarenite sand.

Figure 12. A. Core OB-24, phosphorite sand facies in sharp contact with the underlying pre-Pungo River sands and the overlying surficial sands.

B. Close-up of phosphate pebble at the above contact with the pre-Pungo River sands.

C. Close-up of dark olive-green phosphorite sands.

D. Close-up showing pelletal phosphate filled burrow.

Figure 13. A. Core OB-14, sharp contact of pre-Pungo River sands and quartz phosphorite sand facies. Notice the vertical color change in the Pungo River portion of the core, this represents the vertical gradation from the quartz phosphorite sand facies to the overlying phosphatic facies.

B. Close-up of contact showing a phosphate pebble.

C. Bone fragment in the quartz phosphorite sand facies.

D. Clay clasts in the quartz phosphorite sand facies.

**Fig. 11**

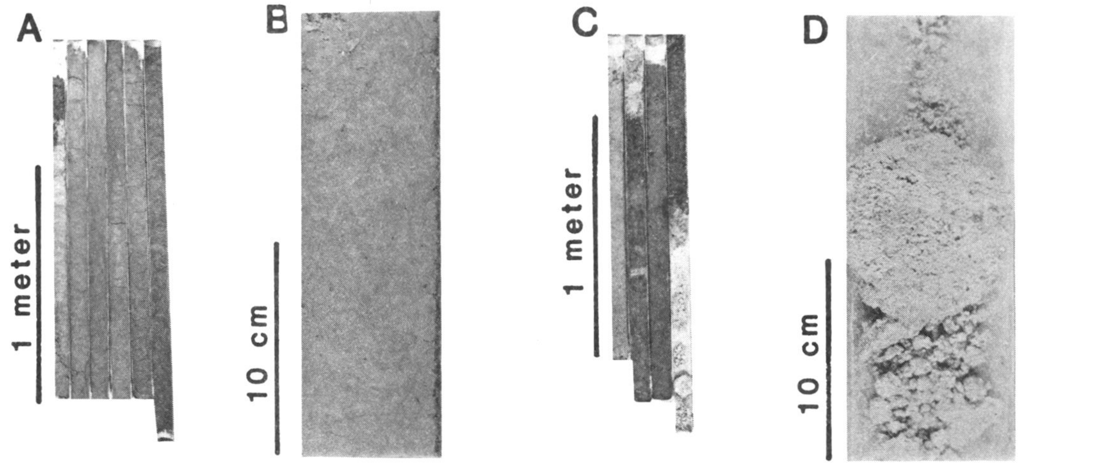



**Fig. 12**

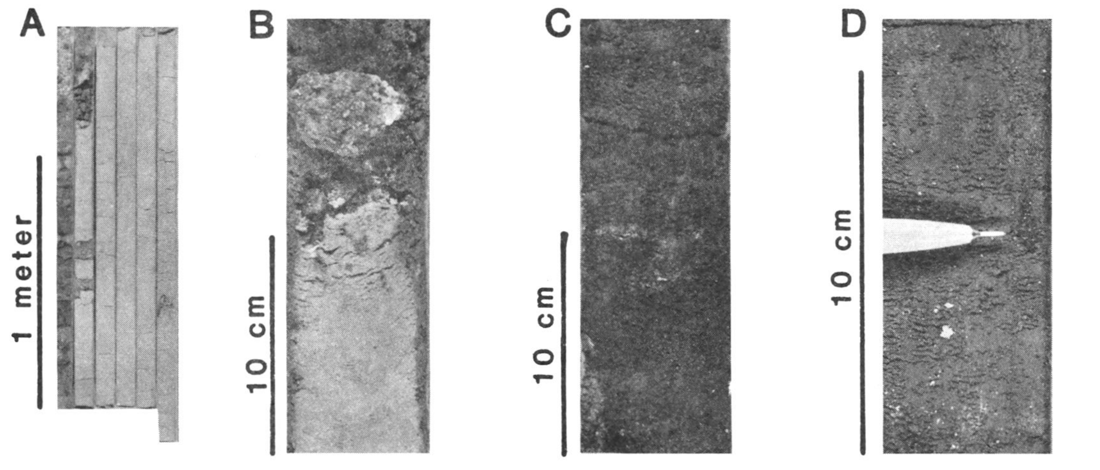
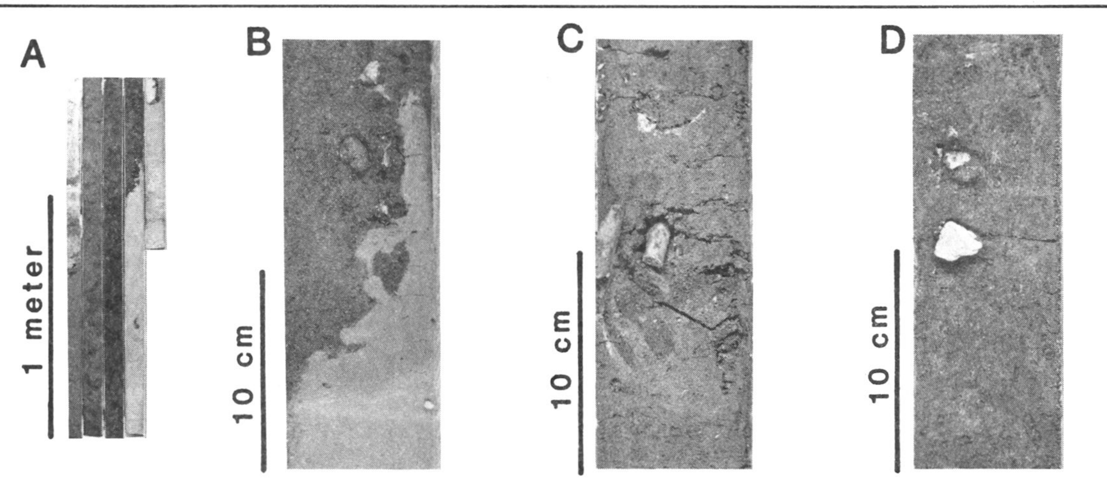



**Fig. 13**



In a preliminary examination of the microfauna, Siphogenerina lamellata Cushman was the only foraminiferal species recognized that is diagnostic of the Pungo River Formation (Snyder and Waters, pers. comm.). Recognizable sedimentary structures are few and are present only as small (few centimeters) pelletal phosphate-filled burrows which gives the sediment a mottled appearance (Fig. 12). The contact between the phosphorite sand and the underlying pre-Pungo River quartz sand is very sharp and is marked by abundant phosphate pebbles and broken microsphorite pieces as large as 4 cm in diameter in OB-24 (Fig. 12). Core OB-64 bottomed in a very sandy, moldic limestone. It is uncertain whether this represents the contact at the base of the Pungo River or only an interbedded carbonate unit. The phosphorite sand facies occurs only in holes OB-24 and OB-64 and in both cases the unit is overlain by a thin (<0.5 m) Holocene sand (Fig. 12). The thickest section of this facies sampled to date measures 3 m in core OB-64.

Table 1. Phosphate grain types for each phosphatic lithofacies in Onslow Bay.

| Lithofacies | Total Phosphate | Skel. | Intra. | Pell. | Crack. |
|---|---|---|---|---|---|
| Phosphatic Sand Member | 11% | 14% | 77% | 3% | 6% |
| Phosphorite Sand Facies | 80% | 5% | 35% | 60% | - |
| Qtz-Phos Sand Facies | 48% | 6% | 18% | 66% | 10% |
| Phos-Qtz Sand Facies | 19% | 7% | 12% | 59% | 22% |
| Sandy Mud Facies | 4% | 31% | 47% | 20% | 2% |

Skel. = Skeletal phosphate grains
Intra. = Intraclastic phosphate grains
Pell. = Pelletal phosphate grains
Crack. = Crackled phosphate grains

Quartz Phosphorite Sand Facies. This facies is an olive-green, muddy (25%), foraminiferal (5%), quartz (20%), phosphorite (50%) sand which occurs in holes OB-11, 14, 25, 26, and 30 (Figs. 1 and 13). Phosphate grains constitute an average of 48% of the whole sediment and 65% of the sand fraction. Pelletal grains predominate while intraclastic, skeletal and crackled phosphate grains make up the remainder of the phosphate fraction (Table 1). Crackled phosphate is a newly recognized grain type which are usually round to subround, light brown in color and have a rough surface texture, unlike the other phosphate grain types which have smooth and polished surfaces (Fig. 14). Pelletal phosphate is found concentrated as burrow fillings as in the phosphorite sand facies. Small (≤2 cm) rounded clay clasts are present in the quartz phosphorite sand facies (Fig. 13) as well as small bone fragments. This facies occurs in sharp contact with the underlying pre-Pungo River quartz sand, but grades upward into the overlying facies. This gradation consists of a decrease in phosphate concentration, an increase in mud and microfauna, and a general lightening in color (Fig. 13).

Phosphorite Quartz Sand Facies. A grayish-green, muddy (35%), foraminiferal (23%), phosphorite (19%), very fine angular quartz (23%) sand is the only other phosphorite lithofacies found to date in the Frying Pan area. This lithology exhibits more textural and compositional variation than the lithologies already described. The amount of mud varies from about 5% to as much as 55%. Phosphate grains average 19-20% but range from 10% to 30%. Pelletal grains still dominate the phosphate fraction constituting about 60% of all phosphate grains. Crackled grains make up approximately 20-22% of the phosphate component while the remainder

Figure 14a. A. Close-up of skeletal phosphate grains from the Pungo River sediments of Onslow Bay.

B. Intraclastic phosphate grains from the Pungo River Formation. Note the irregular grain shape.

C. Pelletal phosphate grains from the phosphorite sand facies of the Frying Pan area. Note the smooth near uniform grain shape and size.

D. Crackled phosphate grains. Very irregular shape and contains fragments of quartz and foraminifera. Lacks the smooth surface exhibited by other phosphate grain types.

E. Pelletal phosphate grains from the surficial sands of southern Onslow Bay. Lighter in color than the pellets from the Pungo River facies.

Figure 14b. A. Thin section of skeletal phosphate grains.

B. Thin section of intraclastic phosphate grain, note the many inclusions within the grain.

C. Pelletal phosphate grains in thin section. The highly polished surface can be seen as well as black microscopic material.

D. Thin section of a phosphate replaced foraminifera.

E. Thin section of some surficial pelletal phosphate grains of the Frying Pan area.

**Fig. 14a**

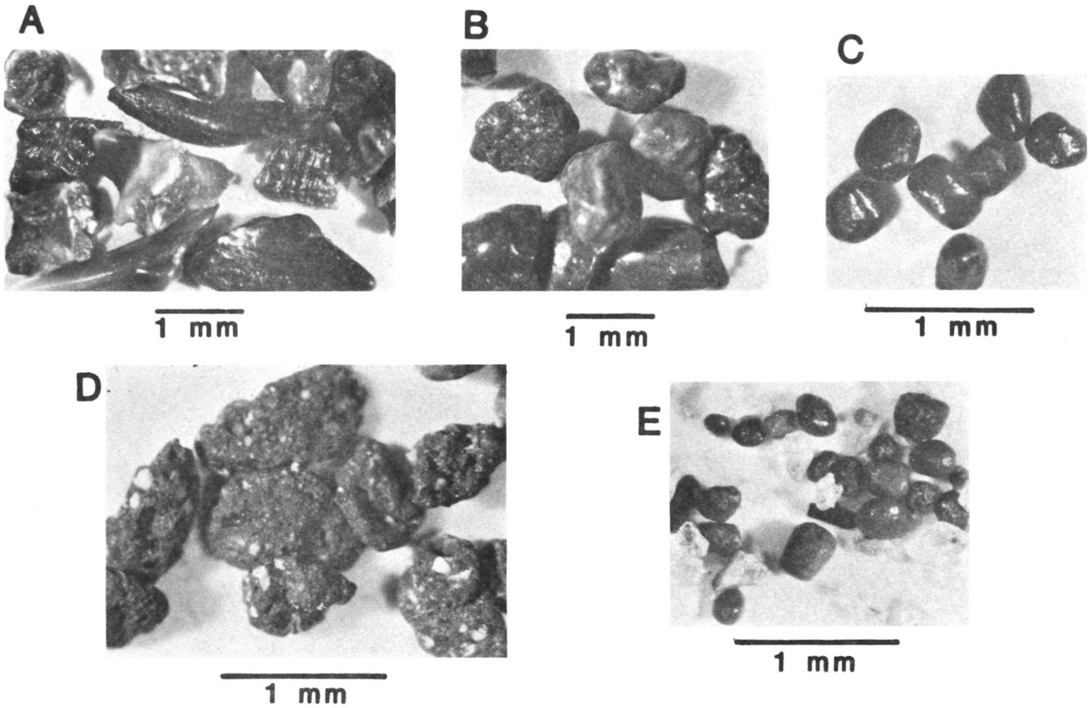
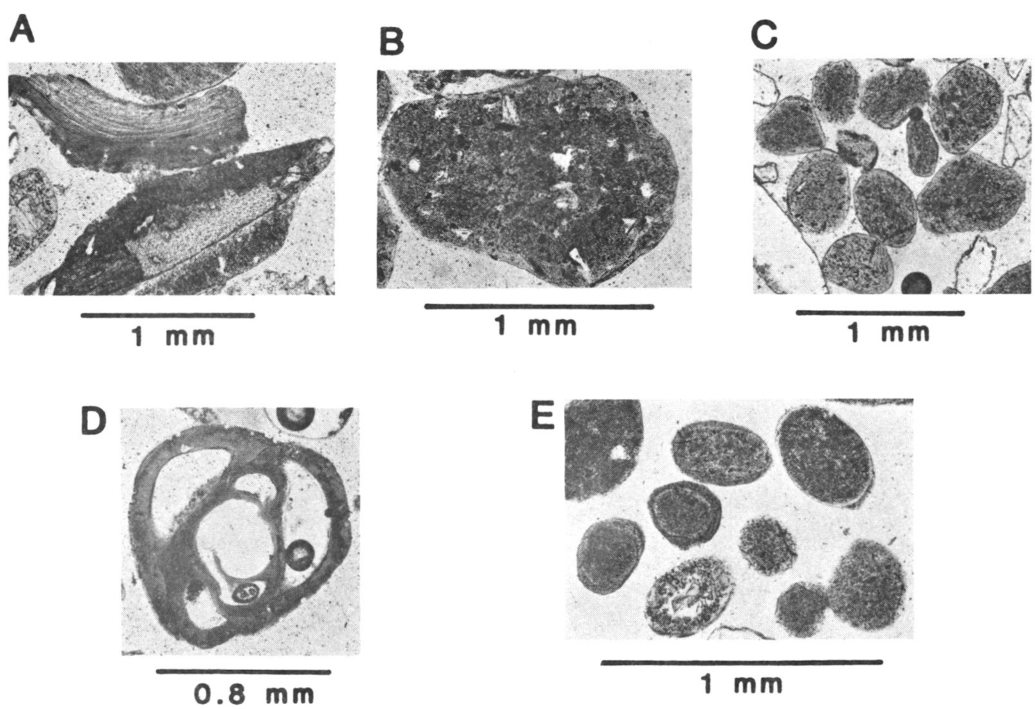



**Fig. 14b**



is composed of intraclastic and skeletal grains (Table 1). This lithofacies occurs in holes OB-14, 20, 22, 23, 26, and 29 (Figs. 1 and 15). Characteristic of each core in this lithology is a mottled appearance speckled with abundant white foraminifera (Fig. 15). This unit grades downward into the underlying quartz phosphorite sand facies and upward into the sandy mud facies as found in holes OB-20 and OB-29 (Fig. 15).

Sandy Mud Facies. This lithofacies is a greenish-gray, slightly phosphatic (<5%), foraminiferal (15%), quartzose (25%), mud. The mud is composed mostly of terrigenous silts and clays with minor amounts of dolosilt. Quartz grains are very angular and very fine grained. Phosphate averages only 3-4% in the sandy mud facies and is dominated by intraclasts with almost equal amounts of skeletal and pelletal grains. This lithology occurs in hole OB-9, 20, 27, and 29 and contains abundant clayey mottles and bone fragments (Fig. 16). The lower contact is gradational into the underlying phosphorite quartz sand facies. In hole OB-27 the upper contact is gradational into a dolomitic clay of the mud facies. Elsewhere the sandy mud facies occurs in sharp contact with the clean surficial sands that are present throughout the Frying Pan area.

Mud Facies. The least phosphatic Pungo River lithology found in the Frying Pan area is a cream colored to very light green, slightly quartzose (5%), slightly fossiliferous (9%), dolosilt to dolomitic clay. There is only a trace amount of phosphate in this lithofacies. Fossils include barnacle fragments but consist mostly of foraminifera. This lithofacies occurs in holes OB-15, 17, 21, 27, and 28, is very uniform, and exhibits no recognizable sedimentary structures (Fig. 17). The thickest sections recovered measure 3.8 m and 3.7 m in holes OB-17 and

Figure 15. A. Core OB-20, phosphorite quartz sand facies in southern Onslow Bay.

B. Close-up showing characteristic white foraminiferal speckled appearance and clay mottles.

Figure 16. A. Core OB-27, phosphorite quartz sand facies grading upward into the sandy mud facies with 0.5 m of surficial sands.

B. Close-up of sandy mud facies showing no sedimentary structures.

Figure 17. A. Core OB-28, mud facies in the Frying Pan area.

B. Close-up showing uniform appearance of the mud facies.

**Fig. 15**

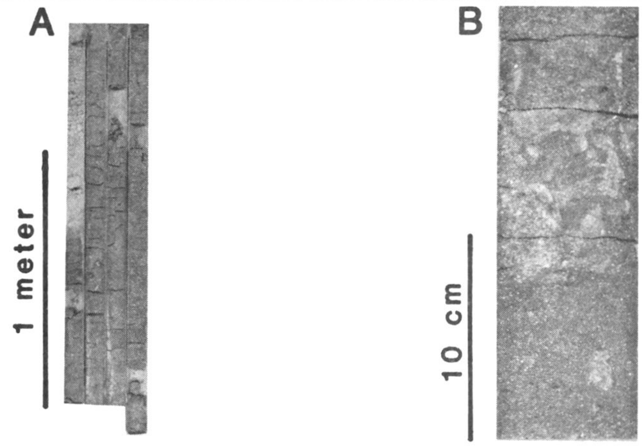



**Fig. 16**

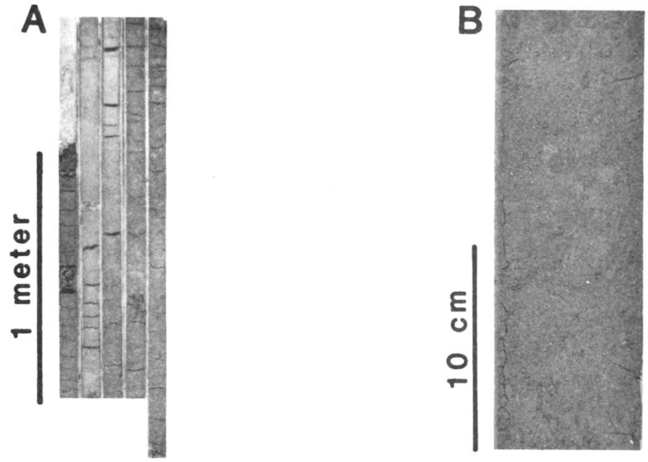
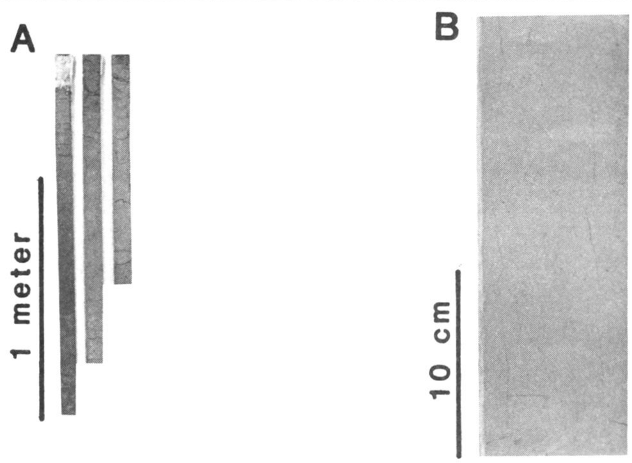



**Fig. 17**



and OB-28, respectively. The mud facies in hole OB-27 grades downward into the sandy mud facies; the other four cores bottomed in the mud facies.

# STRATIGRAPHY

## Northern and Central Onslow Bay

### Pungo River Sediments

One of the objectives of the May, 1980 cruise was to define the lithostratigraphy in northern Onslow Bay by replicating the 15 and 22 meter seismic sections of Snyder et al. (in press) and vibracoring each of the seismic units (Fig. 1). Utilizing the vibracores, the lithostratigraphy was defined, confirming the assumption that the Pungo River Formation extends southward onto the continental shelf. Three lithic members, described in the previous section, constitutes the Pungo River Formation in northern Onslow Bay.

In the 15 meter section, the members occur in an apparent offlap sequence, with each cropping out on the seafloor or present below a thin Pleistocene sediment cover (Fig. 18). In contrast, the 22 meter section shows an apparent offlap relationship between the quartz sand member and the unsampled seismic sequences (also present in the 15 meter section). These are overlapped by the biorudite and phosphatic sand members. Note that the biorudite member does not crop out in the 22 meter section as it does in the 15 meter section (Fig. 18). The different stratigraphic patterns of the two profiles can be explained by examining the depositional and erosional history of the Pungo River sediments in this area.

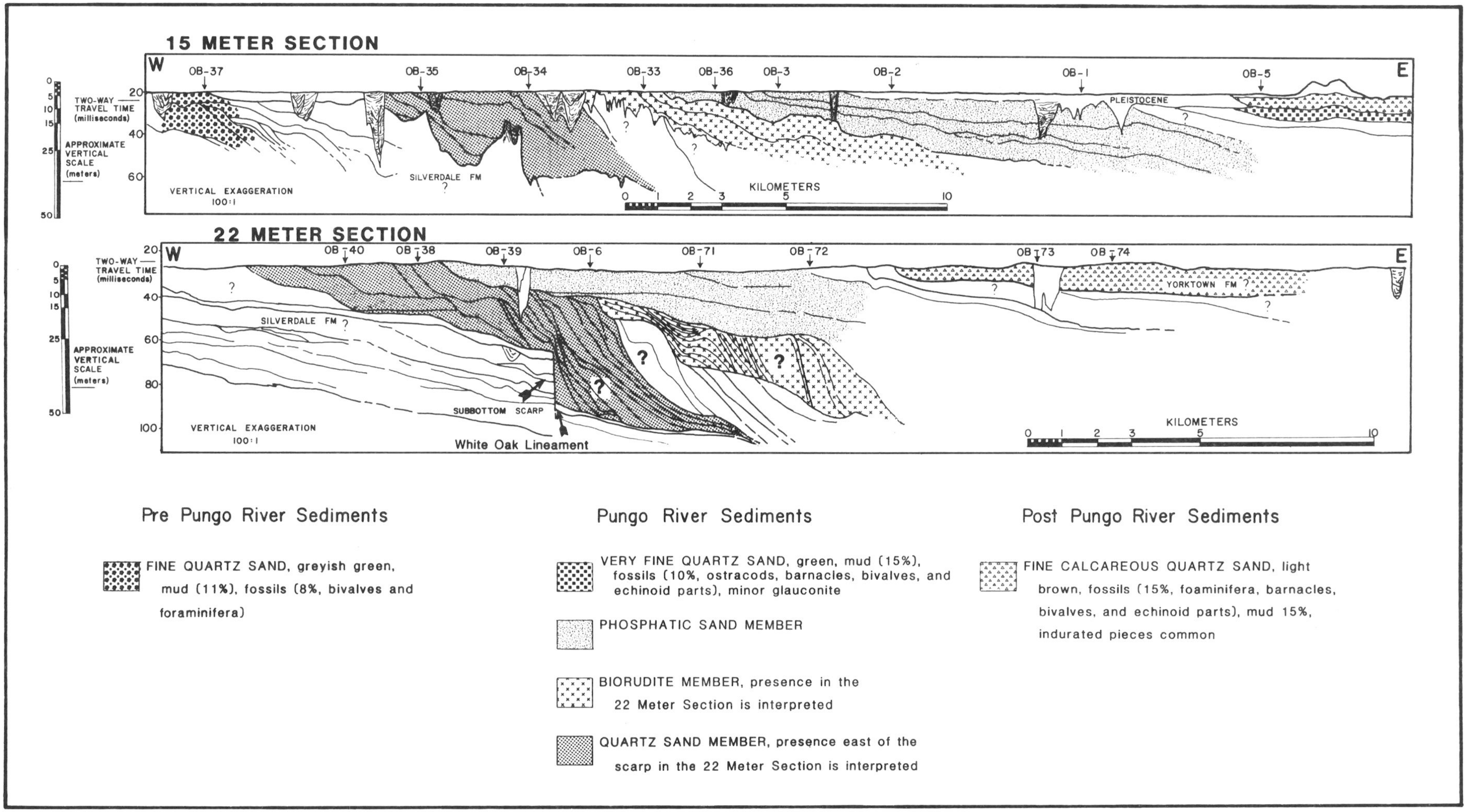



**Figure 18. East-west seismic sections in northern Onslow Bay showing vibracore locations and sediment lithologies.**

The depositional basin shallowed northward from the 22 meter profile toward the 15 meter section and on to the Cape Lookout High. Irregular topography, associated with the N-S trending White Oak Lineament (Snyder _et al._,in press), produced the subbottom scarp as shown in the 22 meter section of figure 18. Marine sediments of the quartz sand member were deposited in the basin as a major transgressive sequence. The detailed seismic reflectors within this member in the 22 meter section suggest that a series of minor sea-level oscillations occurred within the transgressive sequence. These sediments succeeded in burying the scarp of the White Oak Lineament. Following the deposition of the quartz sand member the unsampled seismic sequence was deposited and subsequently truncated by erosion. The biorudite member was then deposited, followed by massive erosion producing the apparent offlap geometry. Because the biorudite member occurs deeper in the section in the 22 meter profile than in the 15 meter profile, suggests that the depositional basin was deeper in the area of the 22 meter section and shallowed northward toward the 15 meter section, and/or compaction and subsidence accompanied deposition of the Pungo River sediments east of the White Oak Lineament in the 22 meter section.

Another transgressing sea deposited the overlapping phosphatic sand member on top of the biorudite member in the 22 meter section. Although these two members appear conformable in the 15 meter section, the contact is very sharp and the basal pebble lag in the phosphatic sand member (Fig. 10) represents an unconformable contact. Another erosional episode, which includes present day erosion, truncated the entire formation producing the present outcrop distribution in northern Onslow Bay as shown in figures 18 and 19.

The stratigraphic sequence described for the 22 meter section persists southward into the central portion of Onslow Bay. The facies of the quartz sand member exhibit some variations to the south, however, these changes are relatively minor and the diagnostic characteristics are still recognizable. The quartz content increases to about 55% from about 42% in northern Onslow Bay; phosphate is dominately intraclastic grains and increases from 2% in the north to about 5% in the Central Bay area; and dolosilt is restricted to thin, well defined laminae as opposed to being disseminated throughout quartz sands as in the north.

Within the phosphatic sand member, the average phosphate concentrations increase from 11% in the north to as much as 24% in hole OB-53 located toward the eastern end of profile 4 (Fig. 1). The two facies of this member recognized in northern Onslow Bay, were not recognized in hole OB-53. Rather, the mud content changed continuously throughout the core as did phosphate concentrations which ranged from 7% to 24%.

A preliminary reduction of a N-S seismic profile running from northern Onslow Bay to the central portion of the Bay shows the reflectors of the phosphatic sand member to be relatively flat with little to no apparent dip. This indicates an eastward dipping sequence as the seismic profile approximates the strike direction. A map outlining the distribution of Pungo River sediments in northern and central Onslow Bay is shown in figure 19.

The facies relationships are not fully understood due to poor lateral data control, but it can be said with a certain degree of confidence that the lithologies found in northern Onslow Bay, with the

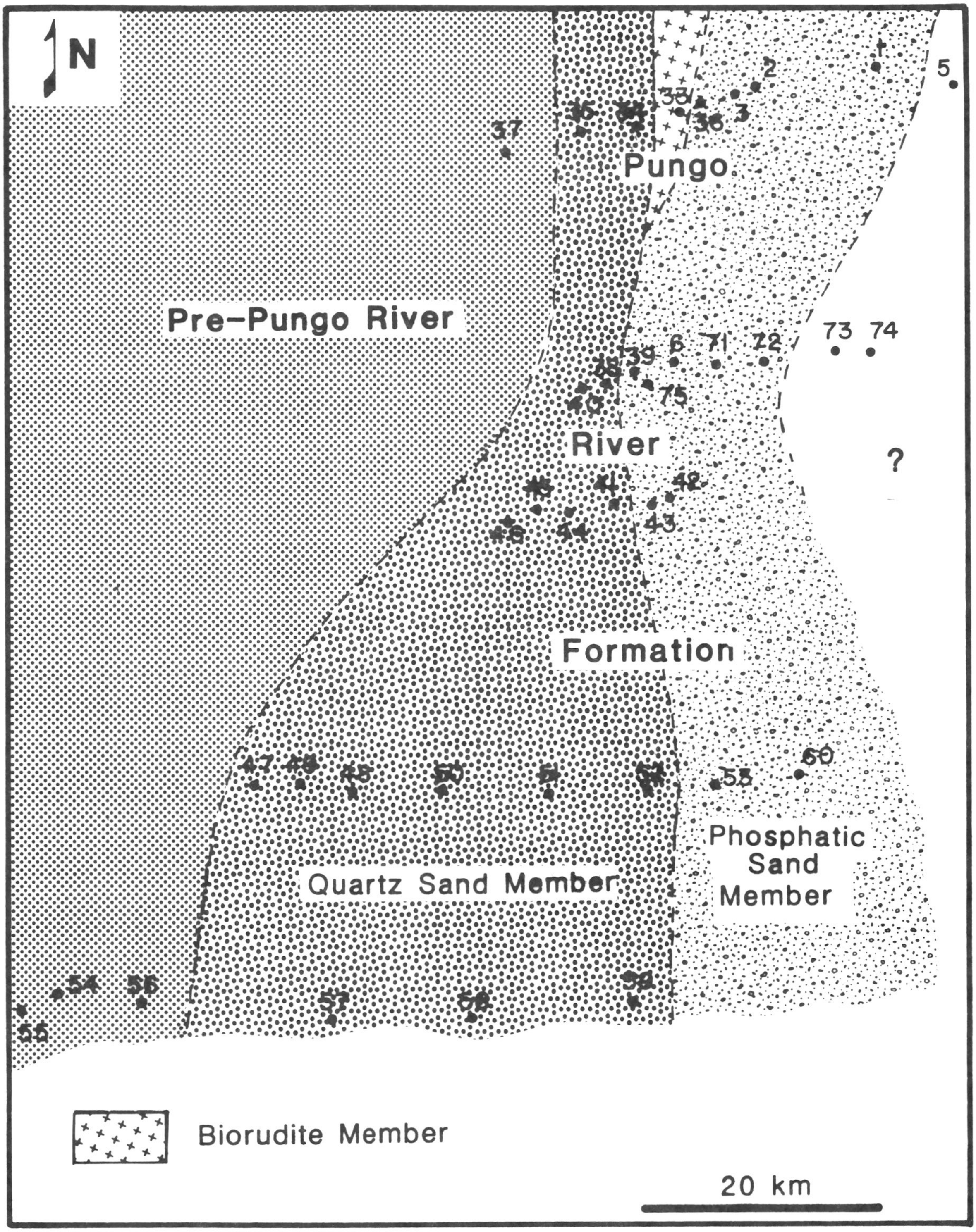



Figure 19. Geologic map of the pre-Pleistocene sediments in north-central Onslow Bay showing core locations.

exception of the biorudite member, do extend southward to the central portion of the Bay. Thus, the sedimentologic and stratigraphic information from the core holes in conjunction with the seismic data, suggest the following sequence of events for the depositional history of the Pungo River Formation in northern and central Onslow Bay.

1) The erosional topography associated with the White Oak Lineament controlled the deposition of a thick sequence of Pungo River sediments east of the Lineament.
2) The Pungo River sediments were deposited as three lithic members which are composed of at least six distinct lithofacies.
3) Each lithic member is characterized by distinct lithologic associates, and is separated by an erosional surface, which in some places is a distinctive angular unconformity.
4) Erosion following the deposition of the phosphatic sand member produced the different stratigraphic geometries that are found in the 15 and 22 meter profiles.

## Frying Pan Area

Luternauer (1966), Pilkey and Luternauer (1966, 1967), Freas and Riggs (1966), and Riggs and Freas (1967) described surficial sands rich in phosphate from a section of Onslow Bay just north of Frying Pan Shoals near Cape Fear, N.C. These sands, which contained anomalously high concentrations of phosphate, were assumed by these workers to represent surface sands eroded from nearby seafloor outcrops of the phosphatic sediments of the Pungo River Formation. In order to test this theory, the May, 1981 cruise extensively vibracored the subsurface units and sampled the surface sediments (using a shipek grab sampler) within the zone of high phosphate concentration. The area of enriched surface sands is shown in figure 1 by the numerous vibracore sites due east of Cape Fear. These surface sands will be discussed later.

Numerous seismic profiles were run through the Frying Pan area. Most have been reduced and are included in the following sections as the framework upon which lithologies are superimposed (Figs. 5, 20, 21, and 22).

Pre-Pungo River Sediments

The pre-Pungo River sediments in the Frying Pan area are light green, fine quartz sands and occasional calcarenites which underlie the phosphatic sediments of the Pungo River Formation throughout the Frying Pan area (Figs. 12 and 13). The contact between pre-Pungo and Pungo River sediments is usually very sharp and is marked in many places by a quartz and phosphate pebble lag deposit and/or a burrowed and bored pre-Pungo River surface (Figs. 12 and 13).

The initial stratigraphic interpretation is that the pre-Pungo River sands may be correlative with the Lower Miocene Belgrade or Silverdale Formations of Baum et al. (1978). They described the Belgrade and Silverdale Formations from the type section on the North Carolina Coastal Plain, as pelecypod-mold biomicrudites with interbedded unconsolidated quartz arenites. These lithologies are similar to the sediments found in hole OB-8 (Fig. 11). They further describe the Belgrade as an inshore facies of the Silverdale Formation. A Lower Miocene age for the

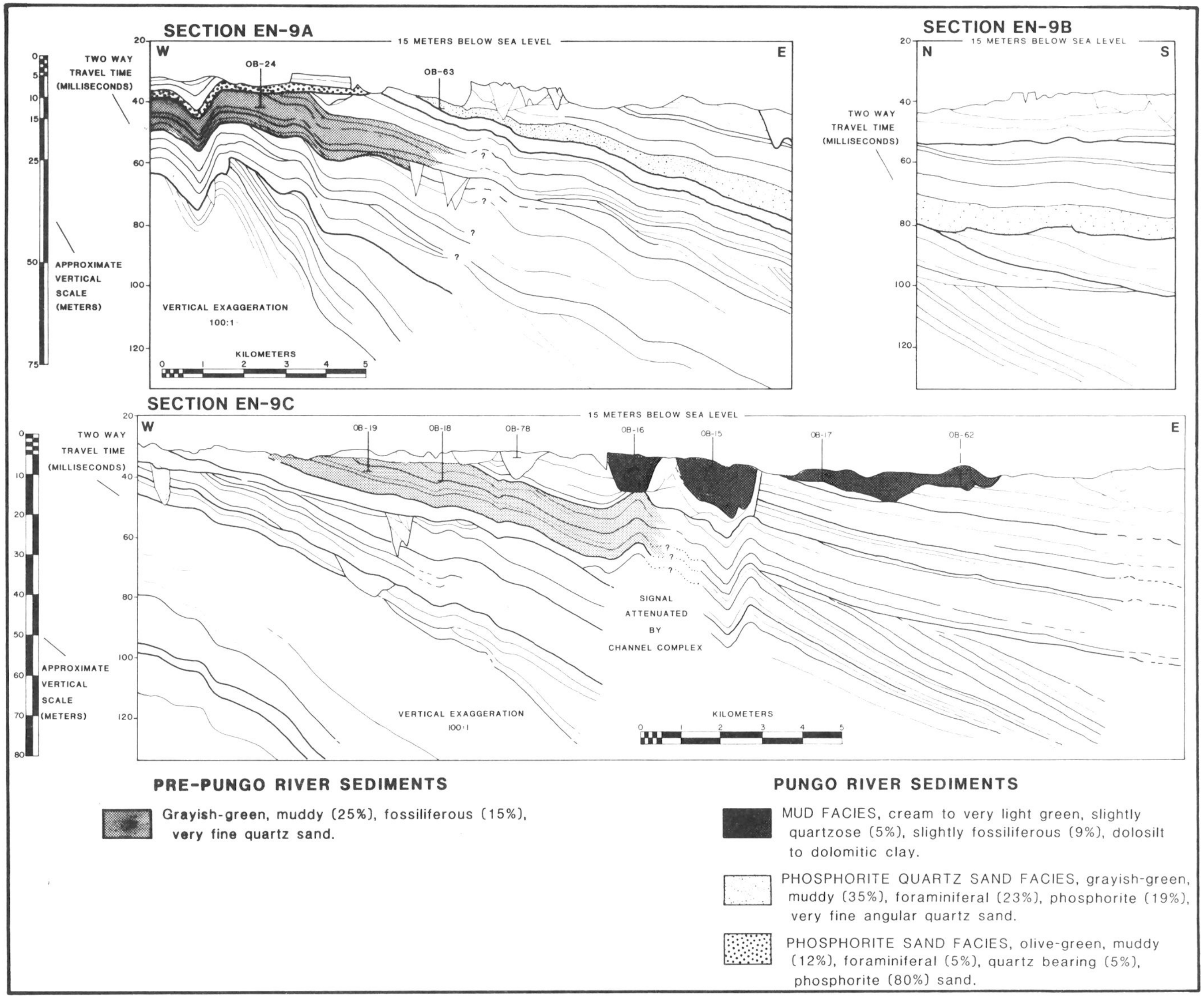



**Figure 20. East-west seismic sections in the Frying Pan Area of southern Onslow Bay with the vibracore locations and sediment lithologies superimposed.**

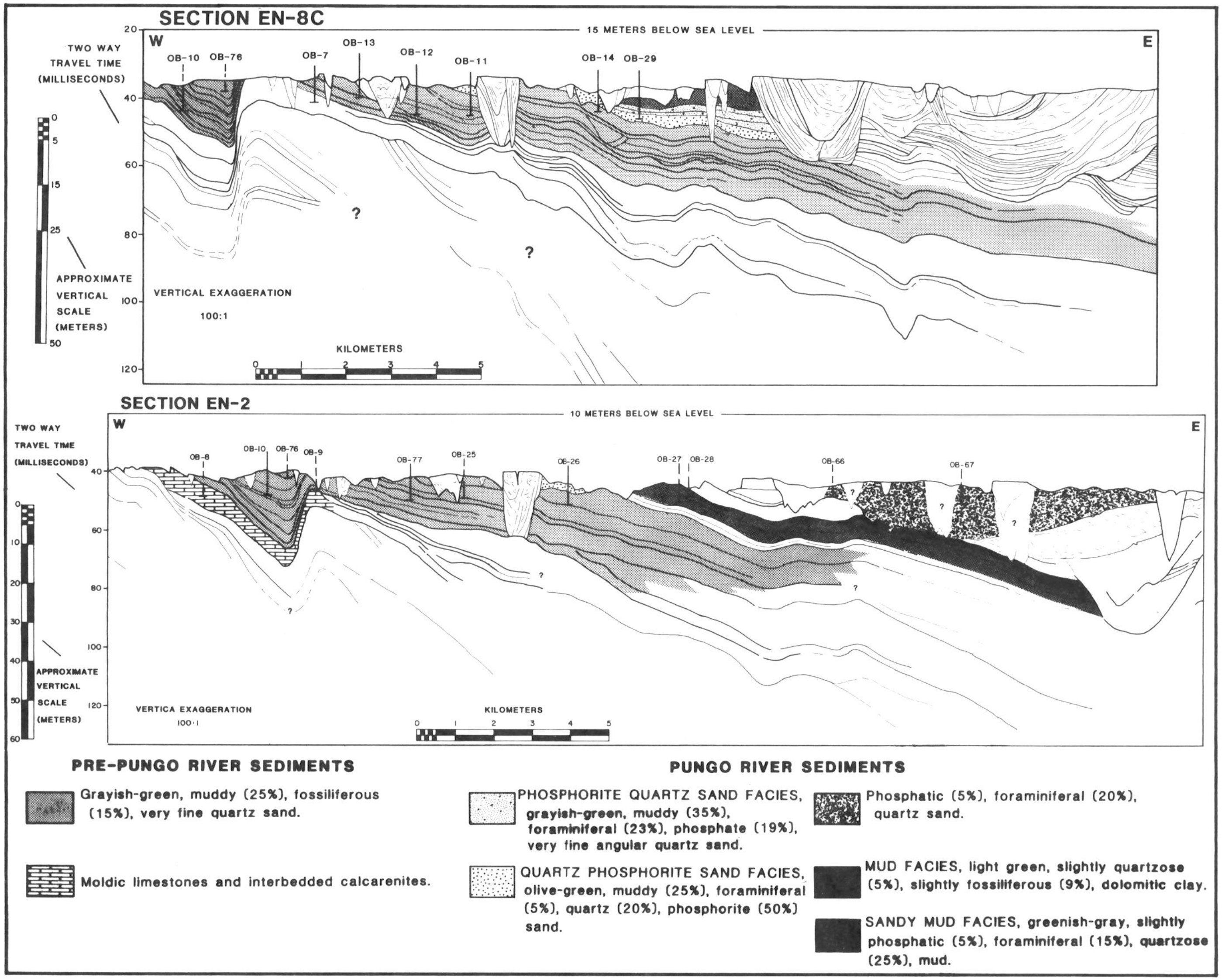
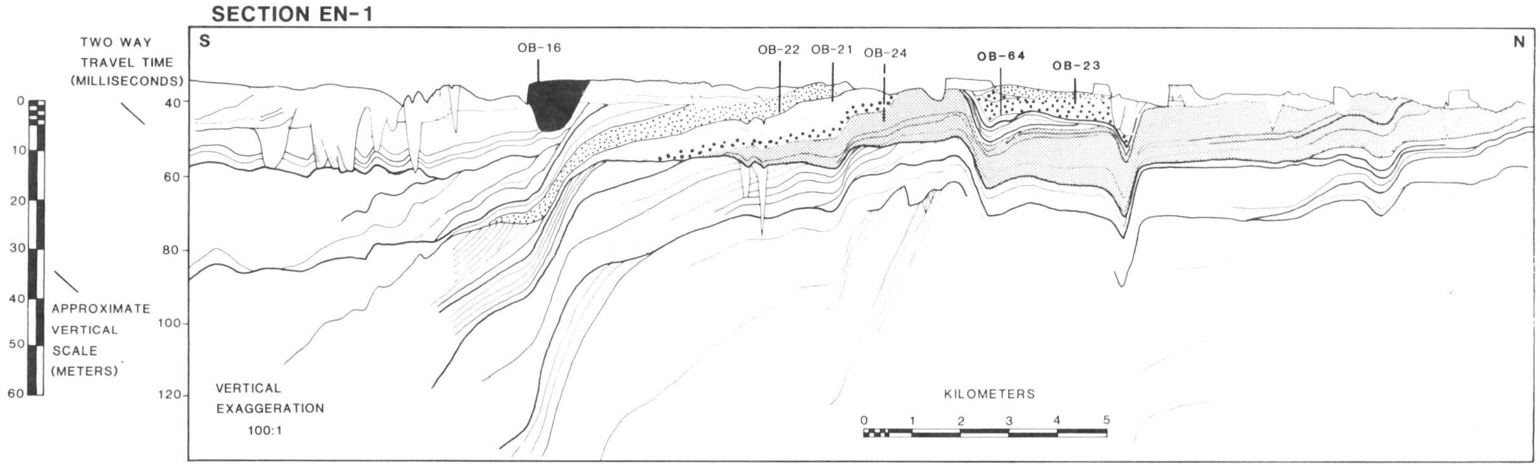



**Figure 21. East-west seismic sections through the Frying Pan Area showing vibracore locations and sediment lithologies.**




**PRE-PUNGO RIVER SEDIMENTS**

Grayish-green, muddy (25%), fossiliferous (15%), very fine quartz sand.

**PUNGO RIVER SEDIMENTS**

MUD FACIES, light green, slightly quartzose (5%), slightly fossiliferous (9%), dolomitic clay.

QUARTZ PHOSPHORITE SAND FACIES, olive-green, muddy (25%), foraminiferal (5%), quartz (20%), phosphorite (50%) sand.

PHOSPHORITE SAND FACIES, olive-green, muddy (12%), foraminiferal (5%), quartz bearing (5%), phosphorite (80%) sand.

**Figure 22. North-south seismic section in the Frying Pan Area of southern Onslow Bay showing vibracore locations and sediment lithologies.**

Silverdale Formation has been documented by Kellum (1925, 1926), Richards (1948), and Vokes (1967, 1970).

Another interpretation is that the light green fine sands are actually non-phosphatic units of the Pungo River Formation. Lithologically these sediments cannot be correlated with any known Pungo River sediments. However, there is some evidence that suggests that these sands may be interbedded with the typical phosphatic sands of the Pungo River Formation in the Frying Pan area. At the point where sections EN-1 and EN-9C intersect, fine light green quartz sands which are extrapolated eastward along EN-9C from holes OB-18 and OB-19, are found to overlie sediments of the quartz phosphorite sand facies of the Pungo River. Another piece of evidence to support this interpretation is that Pungo River phosphatic sediments were found in hole OB-9 along section EN-2. This hole is located at a point along the eastern edge of a flexure basin where the older sediment units in the basin approach the surface (Fig. 21). Holes OB-10 and OB-76, as well as hole OB-77 encountered the fine green sands. If OB-9 represents Pungo River phosphatic sediments that are in place, they are stratigraphically lower than the fine green sands and thus, would represent interbedded Pungo River sediments. Two possible sources of error may cause the latter interpretation to be incorrect. The interpretation of the seismic data and the location of the point of intersection between profiles may not be exact and could result in misinterpretation. Also, hole OB-9 has been extrapolated to the nearby seismic profiles as indicated by the dashed line showing the core depth. It may be that OB-9 is located within a small shallow erosional outlier of the Pungo River Formation which was not encountered in section EN-2.

Another possible interpretation must be considered for the fine green sands. These sediments may not be correlative with any known units on the Coastal Plain.

Pungo River Sediments

The phosphatic Pungo River sediments in the Frying Pan area occur as two and possibly three distinct depositional and stratigraphic sequences. First, is the older sequence of east and southeast dipping phosphatic facies which exhibit a vertical gradation in sediment components. The lithologies of this sequence exhibit an upward decrease in phosphate and increase in clay and foraminiferal content. This vertical facies relationship occurs in holes OB-14 and OB-29 in section EN-8C (Fig. 21) and in holes OB-27 and OB-28 in section EN-2 (Fig. 21) and is illustrated by the photographs in figure 13. The phosphorite sand facies is found only along sections EN-9A and EN-1 (Figs. 20 and 22). Hole OB-64 contained phosphorite sands located in a flexure basin approximately 3.5 km wide. Down-warping of this basin occured after deposition of the Pungo River sands, as evidenced by the lack of unit thickening in the flexure. The phosphorite units found in holes OB-64 and OB-23 (Fig. 22) were deposited as updip extensions of the units cored in hole OB-24 and OB-22 (Fig. 22) and are preserved as erosional outliers due to down-warping of the flexure basin.

The second sequence, the sandy mud and the mud facies, are found conformably overlying the phosphatic facies of the Pungo River Formation in holes OB-27, OB-28 and OB-29 as shown in figure 21. However, south of sections EN-8C and EN-2, along section EN-9C (Fig. 20), the same sediments occur within shallow cut and fill basins. These sediments are slightly sandy dolosilty clayey and slightly clayey dolosilts. Beacuse of their stratigraphic position and the presence of dolosilt sediments, the conclusion is that these facies represent the middle Pungo River sequence in the Frying Pan area. The different depositional setting may only reflect the topography at the time of deposition.

The third and youngest Pungo River sequence found in the Frying Pan area is a phosphatic, foraminiferal-rich quartz sand which was deposited in topographic channels cut into the older Pungo River sequences. Holes OB-66 and OB-67 are the only holes to penetrate this sequence (Fig. 21). These sediments fill a major north-south trending channel that measures over 12 km wide and extends completely across the Frying Pan area (Fig. 23). This feature can be recognized on the eastern side of all the east-west seismic sections (Figs. 20 and 21). The extent of this channel structure to the north and south of the Frying Pan area is not known. The formation of the channel shaped basin was probably fluvial as it is an elongate linear feature that downcut into the older sequences of Pungo River sediments. Since it is filled with marine Miocene Pungo River sediments (preliminary examination of the foraminiferal assemblage indicates a Pungo River fauna), the river system must have been Miocene in age. Following channel formation the area was inundated by a transgressing sea which allowed infilling by the upper sequence of marine phosphatic sediments.

Picking stratigraphic tops and bottoms of the Pungo River sequences in the Frying Pan area is, in most cases, impossible due to the limited vibracore distribution. Thus, the stratigraphic interpretations in this study are only preliminary and will undoubtedly be refined as new data are collected.

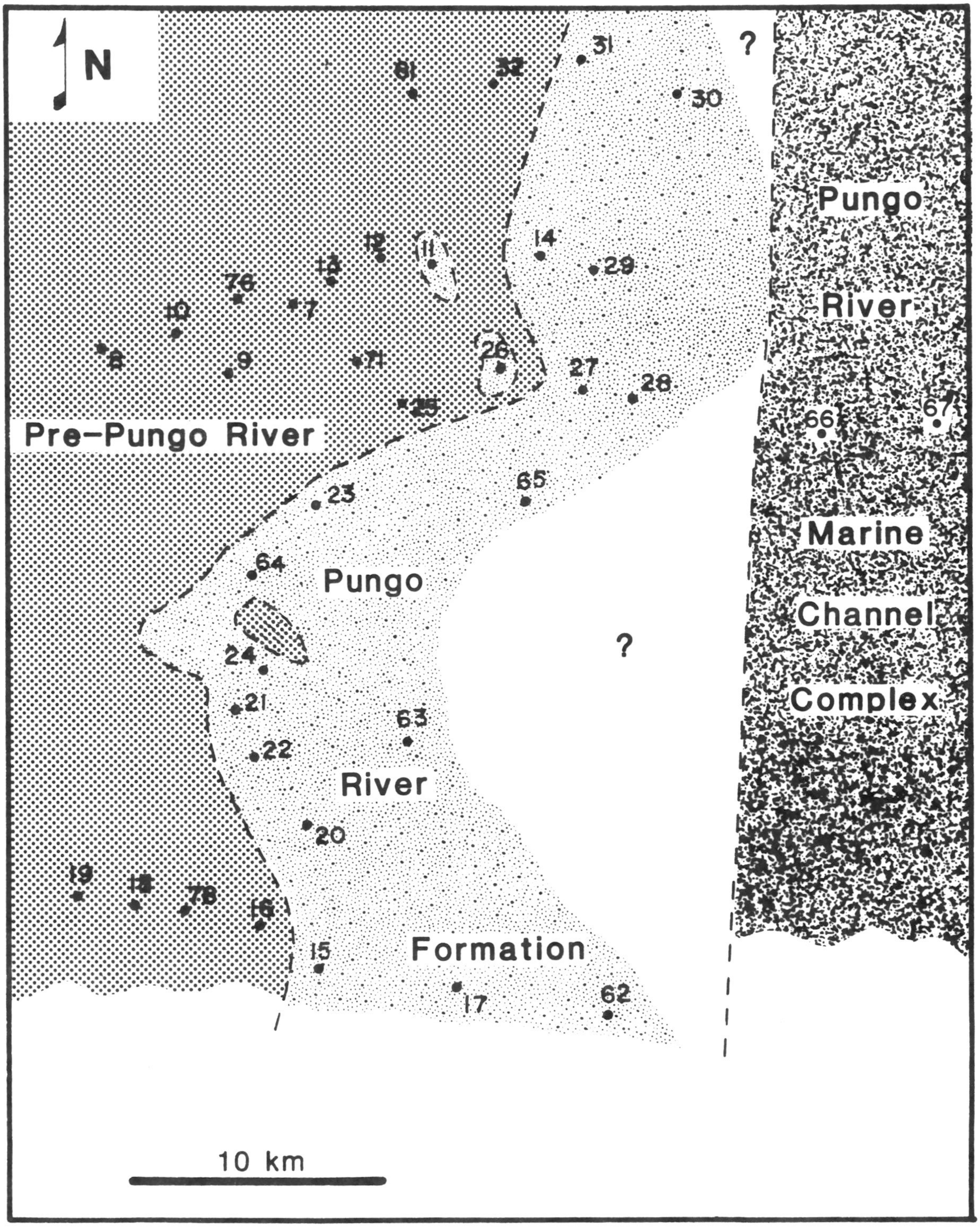



Figure 23. Geologic map of the pre-Pleistocene sediments in the Frying Pan area of southern Onslow Bay.

### Surficial Phosphatic Sands

The phosphate enriched surficial sands of the Frying Pan area first described by Luternauer (1966) were found to have a sporadic distribution. They ranged from absent up to 1 m thick. Within the Frying Pan area, the phosphate concentrations average 20% and occasionally reach 90% of the total sediment. Three distinct phosphate grain types are present in these sands. One type is black to very dark brown and looks very similar to the phosphate in the underlying Pungo River sediments. The other two types are light brown to caramel colored; one is very fine grained, semi-translucent pellets and the other is fine to medium grained intraclasts. The phosphate in the Holocene sands north of the Frying Pan Shoals are predominantly the caramel colored, fine grained pellets (Fig. 14).

## PHOSPHATE CONCENTRATIONS

Bulk rock analyses of representative samples from each lithology found in Onslow Bay are presented in Appendix II and are summarized by stratigraphic unit in Table 2. Phosphatic units were sampled more extensively than nearly barren units. The surficial sands in the Frying Pan area varied in $P_2O_5$ concentrations more than any other sediment, with a range of 0% to 18.1% $P_2O_5$. All other sediment units analyzed had a narrower range of $P_2O_5$ values.

In northern Onslow Bay, the quartz sand and biorudite members of the Pungo River Formation average less than 2% $P_2O_5$, whereas the phosphatic sand member averages 4.0% $P_2O_5$. As this latter member is traced southward into central Onslow Bay the $P_2O_5$ values increase to 9.8%.

## BULK ROCK ANALYSES FOR ONSLOW BAY SEDIMENTS

| | Lithologies | Samples | $P_2O_5$ | MgO | CaO | $Al_2O_3$ | $Fe_2O_3$ | Insols |
|---|---|---|---|---|---|---|---|---|
| Northern Onslow Bay | PHOSPHATIC SAND MEMBER | 19 | 4.3% | 0.9% | 7.8% | 1.2% | 0.8% | 73.4% |
| | BIORUDITE MEMBER | 2 | 0.9% | 5.1% | 36.0% | 1.0% | 0.8% | 16.9% |
| | QUARTZ SAND MEMBER | 12 | 1.6% | 0.9% | 5.3% | 0.5% | 0.4% | 79.3% |
| Frying Pan Area | SURFICIAL SANDS | 7 | 7.6% | 0.7% | 22.0% | 0.3% | 1.0% | 51.5% |
| | FORAM-RICH QUARTZ SAND | 2 | 1.8% | 0.6% | 14.8% | 0.5% | 0.6% | 65.1% |
| | MUD FACIES | 3 | 1.7% | 2.4% | 12.2% | 1.3% | 1.1% | 61.6% |
| | SANDY MUD FACIES | 4 | 3.1% | 1.1% | 13.1% | 1.2% | 0.6% | 63.3% |
| | PHOSPHORITE QUARTZ SAND FACIES | 7 | 6.5% | 1.3% | 21.9% | 1.2% | 0.7% | 47.0% |
| | QUARTZ PHOSPHORITE SAND FACIES | 13 | 12.7% | 1.0% | 27.1% | 1.0% | 0.6% | 38.5% |
| | PHOSPHORITE SAND FACIES | 1 | 21.7% | 0.9% | 39.5% | 0.8% | 0.5% | 14.3% |
| | PRE PUNGO RIVER SANDS | 2 | 0.8% | 2.2% | 24.5% | 0.5% | 0.5% | 45.8% |

Table 2. Bulk rock chemical analyses for the sediments of Onslow Bay.

In the Frying Pan area, $P_2O_5$ values decrease up-section and have an inverse relationship to mud content. The lowermost phosphorite sand facies, which averages 80% phosphate and 12% mud, yields $P_2O_5$ values from 15.2% to 21.7%. The middle quartz phosphorite sand facies, which averages 48% phosphate and 25% mud, has a mean value of 12.0% $P_2O_5$. The upper phosphorite quartz sand facies averages 19-20% phosphate and 35% mud and has a mean $P_2O_5$ value of 7.9%. The upper mud facies of the Pungo River Formation in the Frying Pan area averages less than 5% $P_2O_5$.

## CONCLUSIONS

1. The continental shelf in Onslow Bay is composed of an extensive area of outcropping Miocene phosphatic sediments, the documented limits of which measure approximately 20 by 130 km (Figs. 19 and 23).
2. These Miocene sediments belong to the Pungo River Formation and consist of three members in northern and central Onslow Bay: 1) quartz sand member, 2) biorudite member, and 3) phosphatic sand member. Each member is composed of several lithic facies with distinct sediment characteristics. In the Frying Pan area there are three Pungo River phosphorite to phosphatic sequences which to date have not been correlated with any sediments in northern Onslow Bay.
3. The Pungo River sediments have a regional east to southeast dip east of the White Oak Lineament and occur within flexure basins,

erosional outlier basins, and channel fill basins west of the lineament.

4. Significant phosphate concentrations occur in the phosphatic sand member of the Pungo River Formation in northern and central Onslow Bay, while the major phosphorites occur in the lower sequence of the Pungo River Formation in the Frying Pan area of southern Onslow Bay. A minor economic potential also exists in the Holocene sands of the Frying Pan area.

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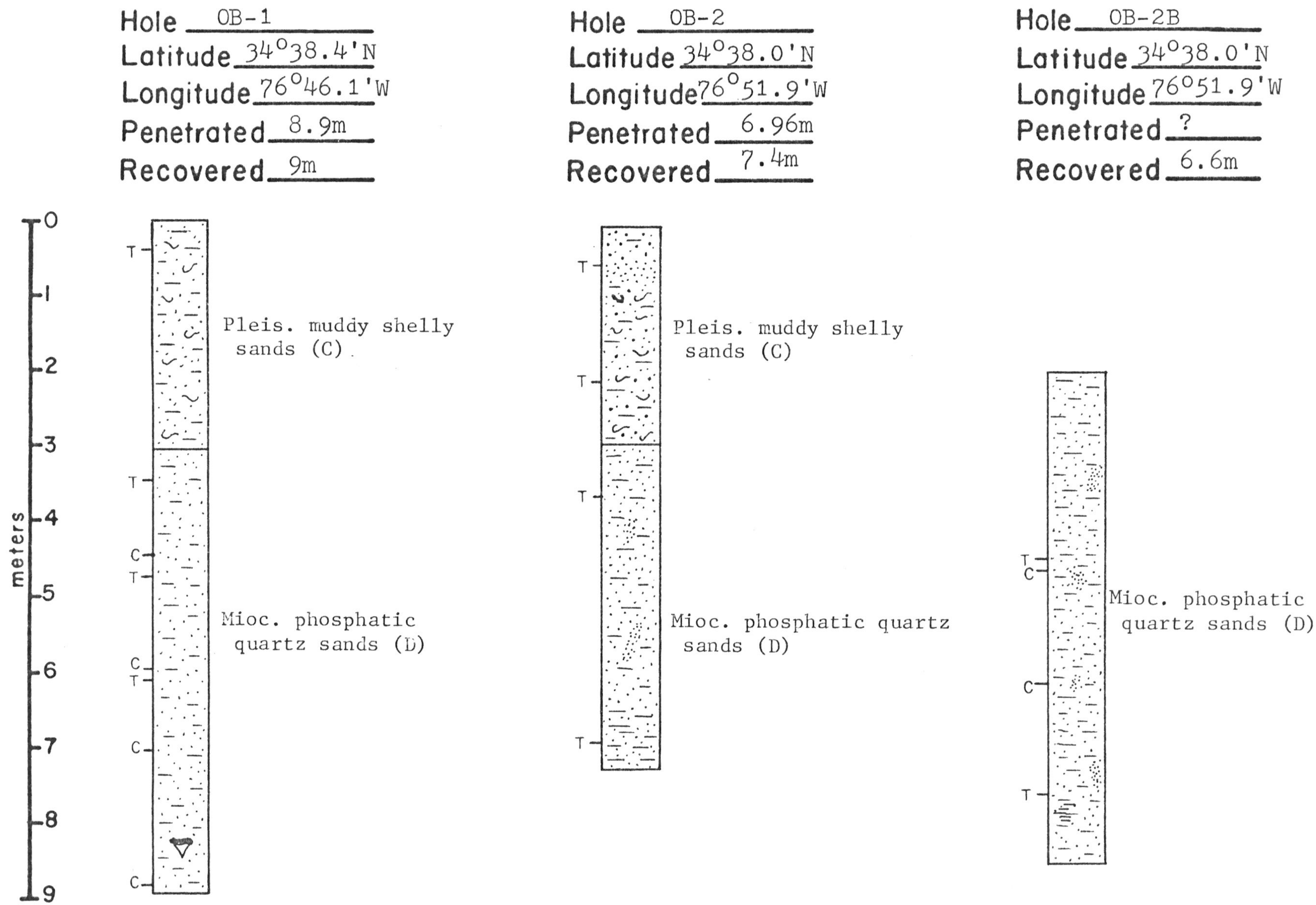
# APPENDIX I: CORE HOLE DATA

# Legend for Appendix I

| Letter Code | Lithologic unit discussed in the text |
|---|---|
| A | Surficial sands |
| B | Pleistocene calcarenites and limestones |
| C | Pleistocene muddy shelly quartz sands |
| D | Phosphatic sand member of the Pungo River Formation in northern Onslow Bay |
| E | Biorudite member of the Pungo River Formation in northern Onslow Bay |
| F | Quartz sand member of the Pungo River Formation in northern Onslow Bay |
| G | Mud facies of the Frying Pan area |
| H | Sandy mud facies of the Frying Pan area |
| I | Phosphorite quartz sand facies of the Frying Pan area |
| J | Quartz phosphorite sand facies of the Frying Pan area |
| K | Phosphorite sand facies of the Frying Pan area |
| L | Pre-Pungo River quartz sands |
| M | Pre-Pungo River calcarenites and/or limestones |

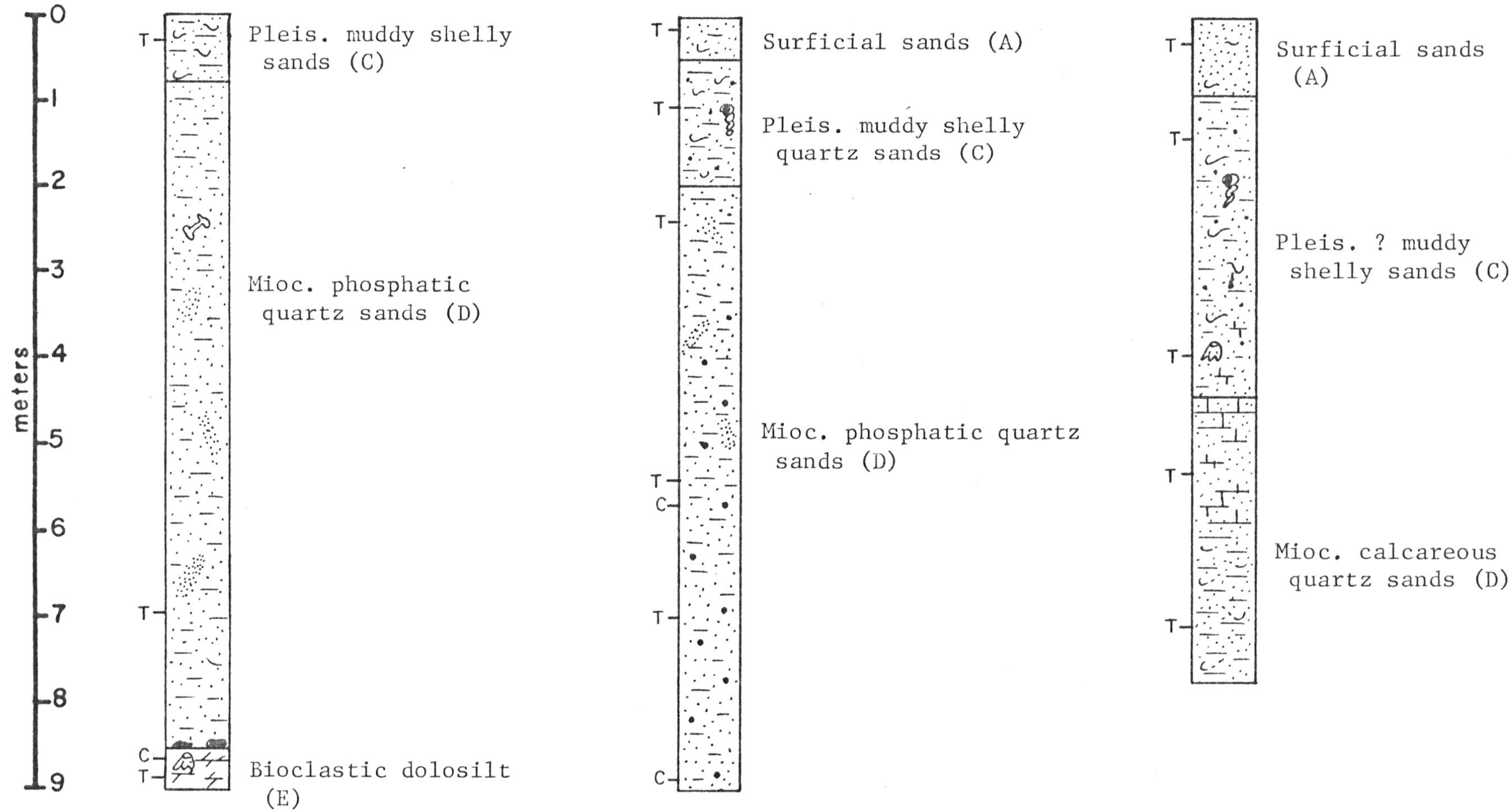
| Symbols | Meaning |
|---|---|
| T | Location in the core where a sample was taken for textural analyses |
| C | Location in the core where a sample was taken for bulk rock chemical analyses |

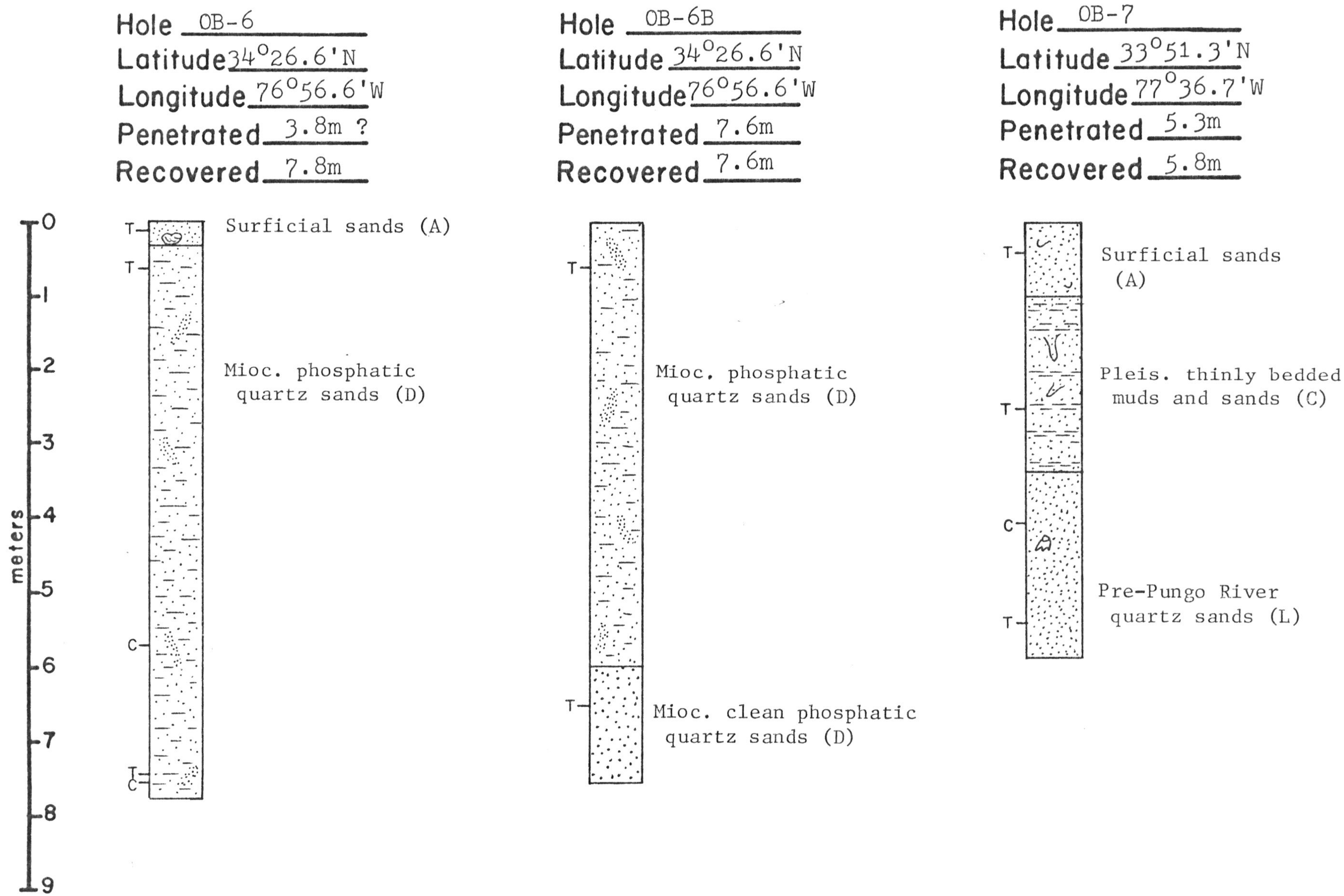

Hole OB-1
Latitude 34°38.4'N
Longitude 76°46.1'W
Penetrated 8.9m
Recovered 9m
Hole OB-2
Latitude 34°38.0'N
Longitude 76°51.9'W
Penetrated 6.96m
Recovered 7.4m
Hole OB-2B
Latitude 34°38.0'N
Longitude 76°51.9'W
Penetrated ?
Recovered 6.6m
meters
0
1
2
3
4
5
6
7
8
9
Pleis. muddy shelly sands (C)
Mioc. phosphatic quartz sands (D)
Pleis. muddy shelly sands (C)
Mioc. phosphatic quartz sands (D)
Mioc. phosphatic quartz sands (D)
T
C

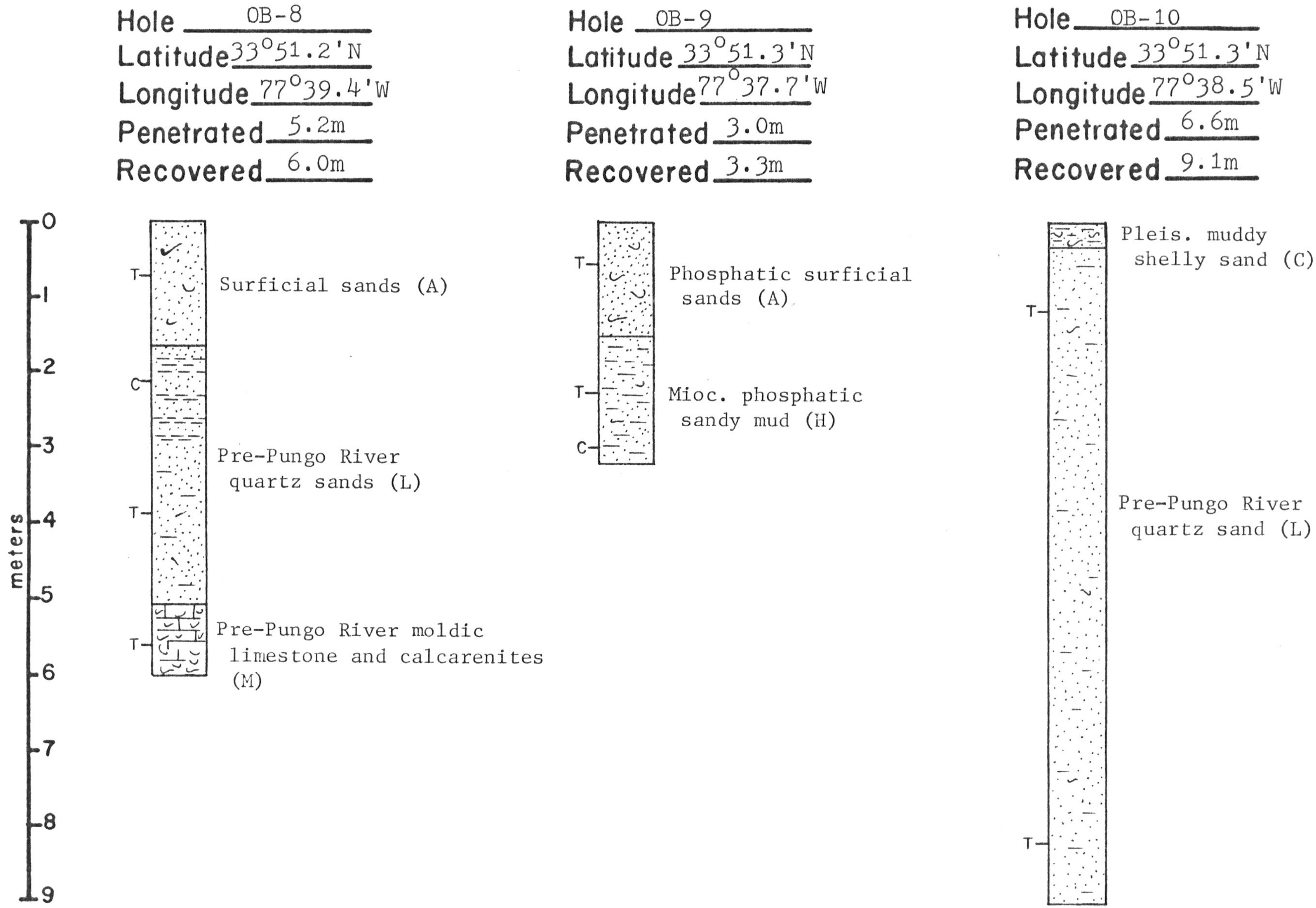
Hole OB-3
Latitude 34°37.7'N
Longitude 76°53.4'W
Penetrated 6.7m
Recovered 9.1m

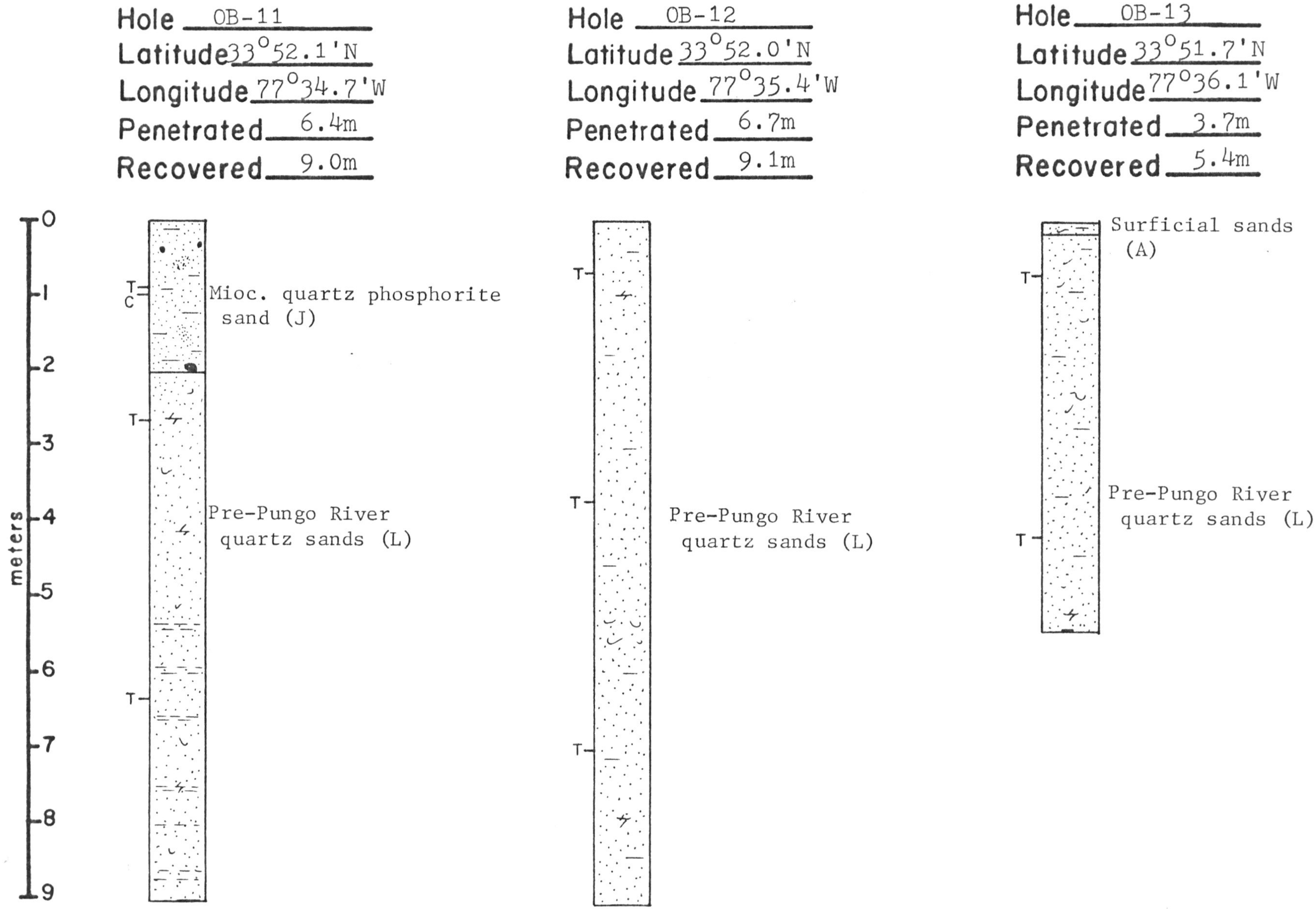
Hole OB-4
Latitude 34°36.5'N
Longitude 76°54.8'W
Penetrated 7.3m
Recovered 9.1m

Hole OB-5
Latitude 34°38.2'N
Longitude 76°42.5'W
Penetrated 5.8m
Recovered 7.8m

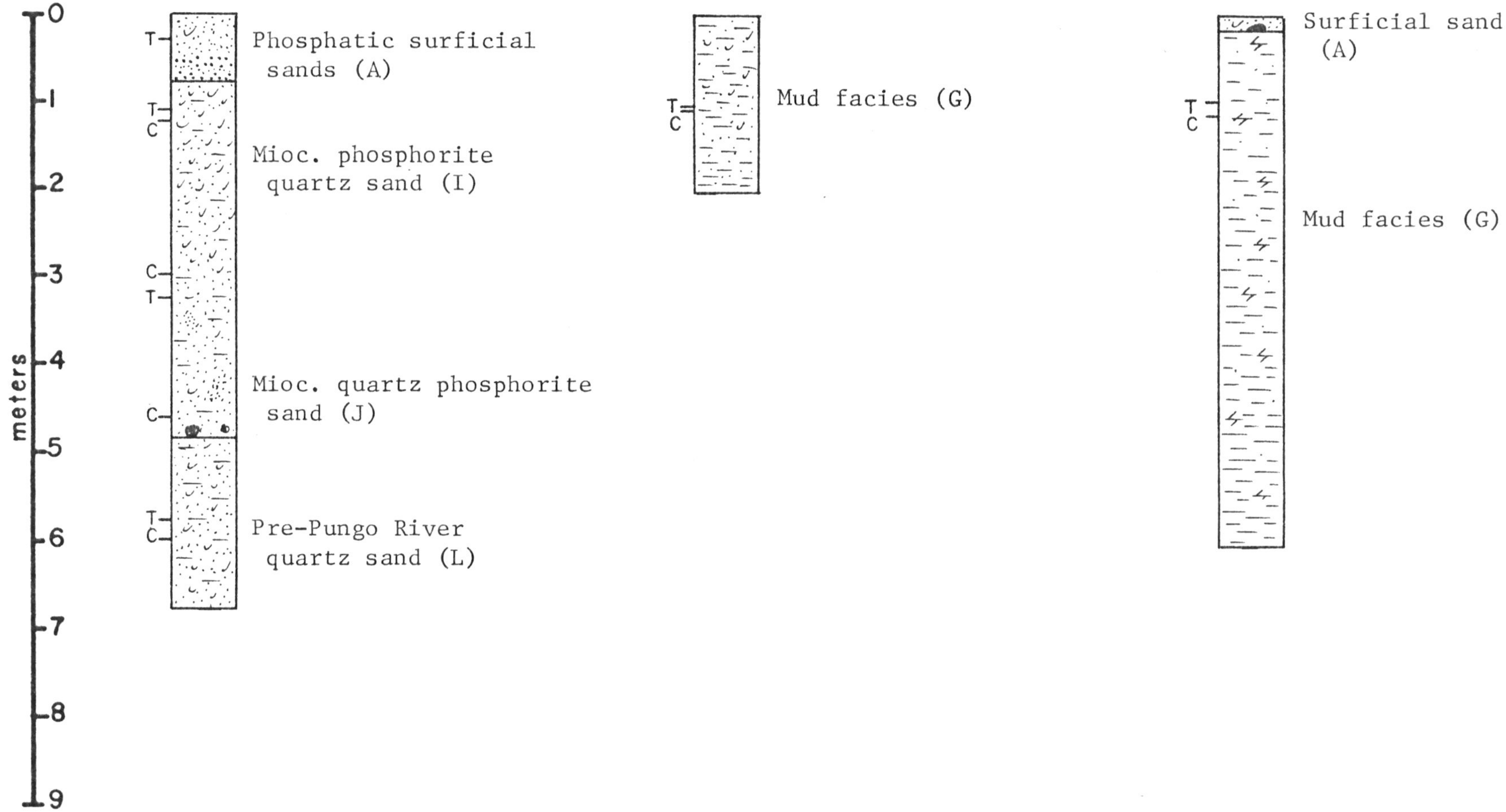


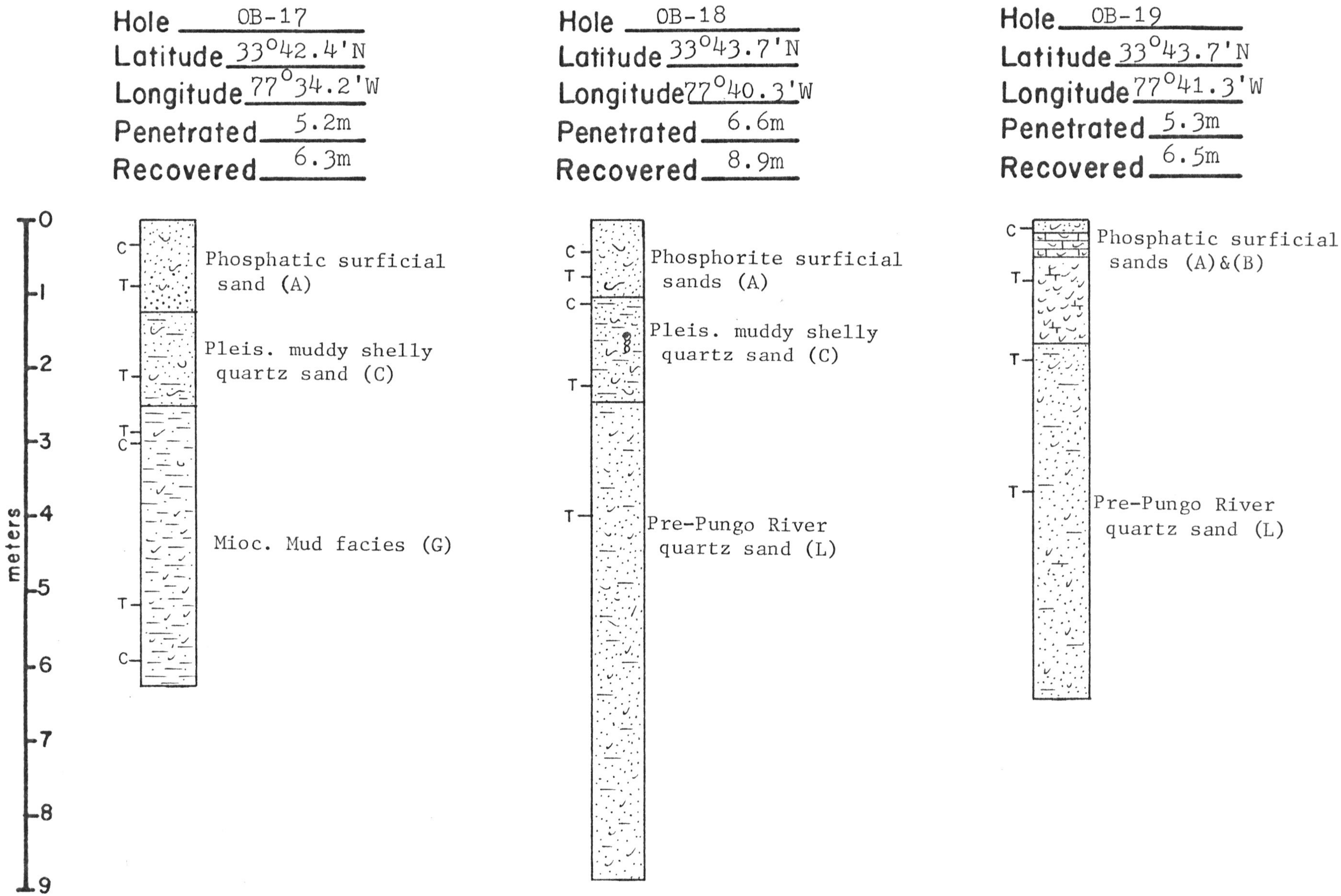

Hole OB-6
Latitude 34°26.6'N
Longitude 76°56.6'W
Penetrated 3.8m ?
Recovered 7.8m
Surficial sands (A)
Mioc. phosphatic quartz sands (D)
Hole OB-6B
Latitude 34°26.6'N
Longitude 76°56.6'W
Penetrated 7.6m
Recovered 7.6m
Mioc. phosphatic quartz sands (D)
Mioc. clean phosphatic quartz sands (D)
Hole OB-7
Latitude 33°51.3'N
Longitude 77°36.7'W
Penetrated 5.3m
Recovered 5.8m
Surficial sands (A)
Pleis. thinly bedded muds and sands (C)
Pre-Pungo River quartz sands (L)
meters
0
1
2
3
4
5
6
7
8
9
T
C


Hole OB-8
Latitude 33°51.2'N
Longitude 77°39.4'W
Penetrated 5.2m
Recovered 6.0m
Hole OB-9
Latitude 33°51.3'N
Longitude 77°37.7'W
Penetrated 3.0m
Recovered 3.3m
Hole OB-10
Latitude 33°51.3'N
Longitude 77°38.5'W
Penetrated 6.6m
Recovered 9.1m
meters
0
1
2
3
4
5
6
7
8
9
T
C
Surficial sands (A)
Pre-Pungo River quartz sands (L)
Pre-Pungo River moldic limestone and calcarenites (M)
Phosphatic surficial sands (A)
Mioc. phosphatic sandy mud (H)
Pleis. muddy shelly sand (C)
Pre-Pungo River quartz sand (L)

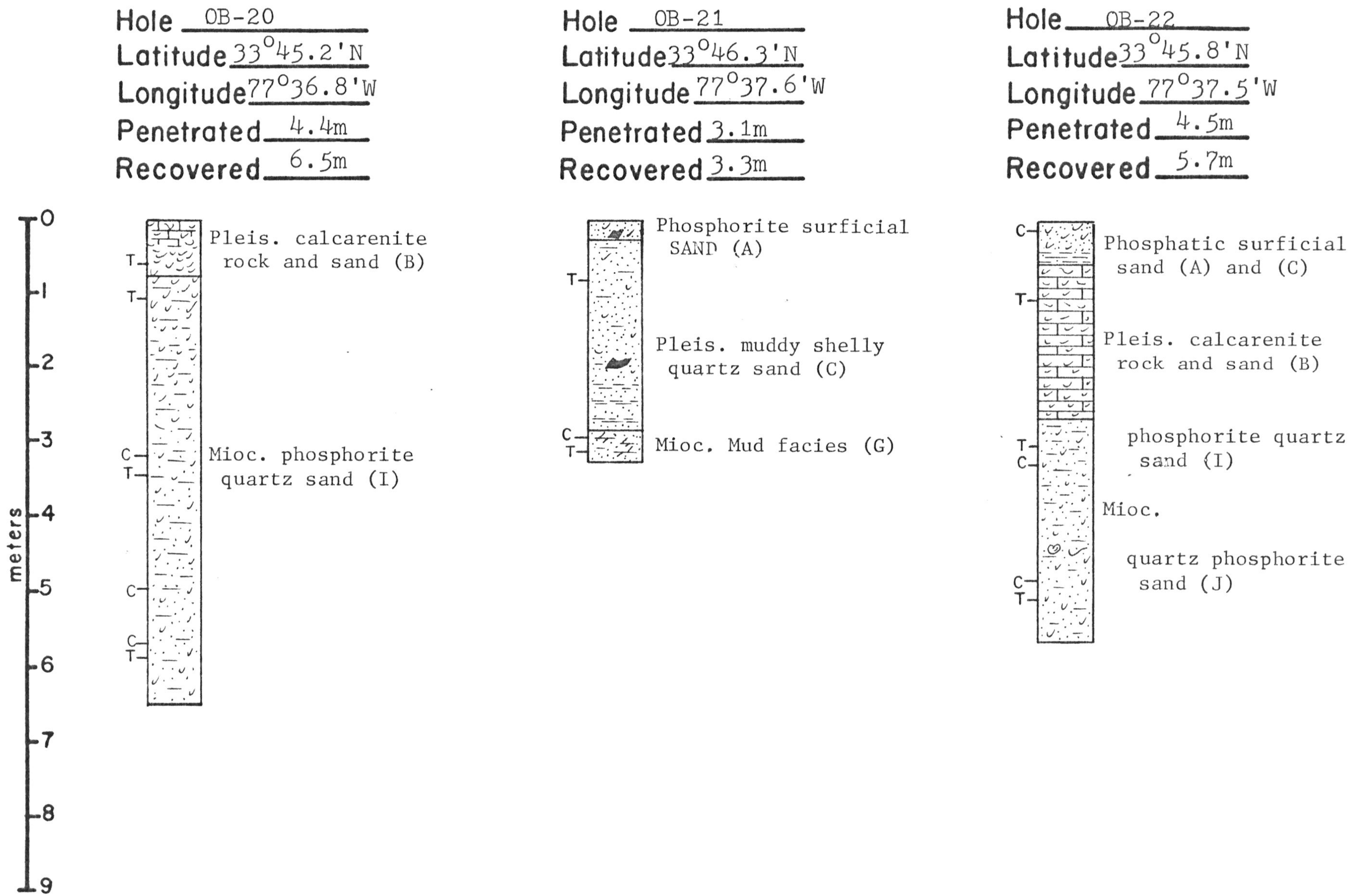

Hole OB-11
Latitude 33°52.1'N
Longitude 77°34.7'W
Penetrated 6.4m
Recovered 9.0m
Hole OB-12
Latitude 33°52.0'N
Longitude 77°35.4'W
Penetrated 6.7m
Recovered 9.1m
Hole OB-13
Latitude 33°51.7'N
Longitude 77°36.1'W
Penetrated 3.7m
Recovered 5.4m
meters
0
1
2
3
4
5
6
7
8
9
T
C
Mioc. quartz phosphorite sand (J)
Pre-Pungo River quartz sands (L)
Pre-Pungo River quartz sands (L)
Surficial sands (A)
Pre-Pungo River quartz sands (L)

| | | | |
|---|---|---|---|
| Hole | OB-14 | OB-15 | OB-16 |
| Latitude | 33°51.7'N | 33°42.8'N | 33°41.1'N |
| Longitude | 77°33.9'W | 77°36.2'W | 77°37.4'W |
| Penetrated | 4.6m | 1.8m | 3.4m |
| Recovered | 6.8m | 2.1m | 6.1m |

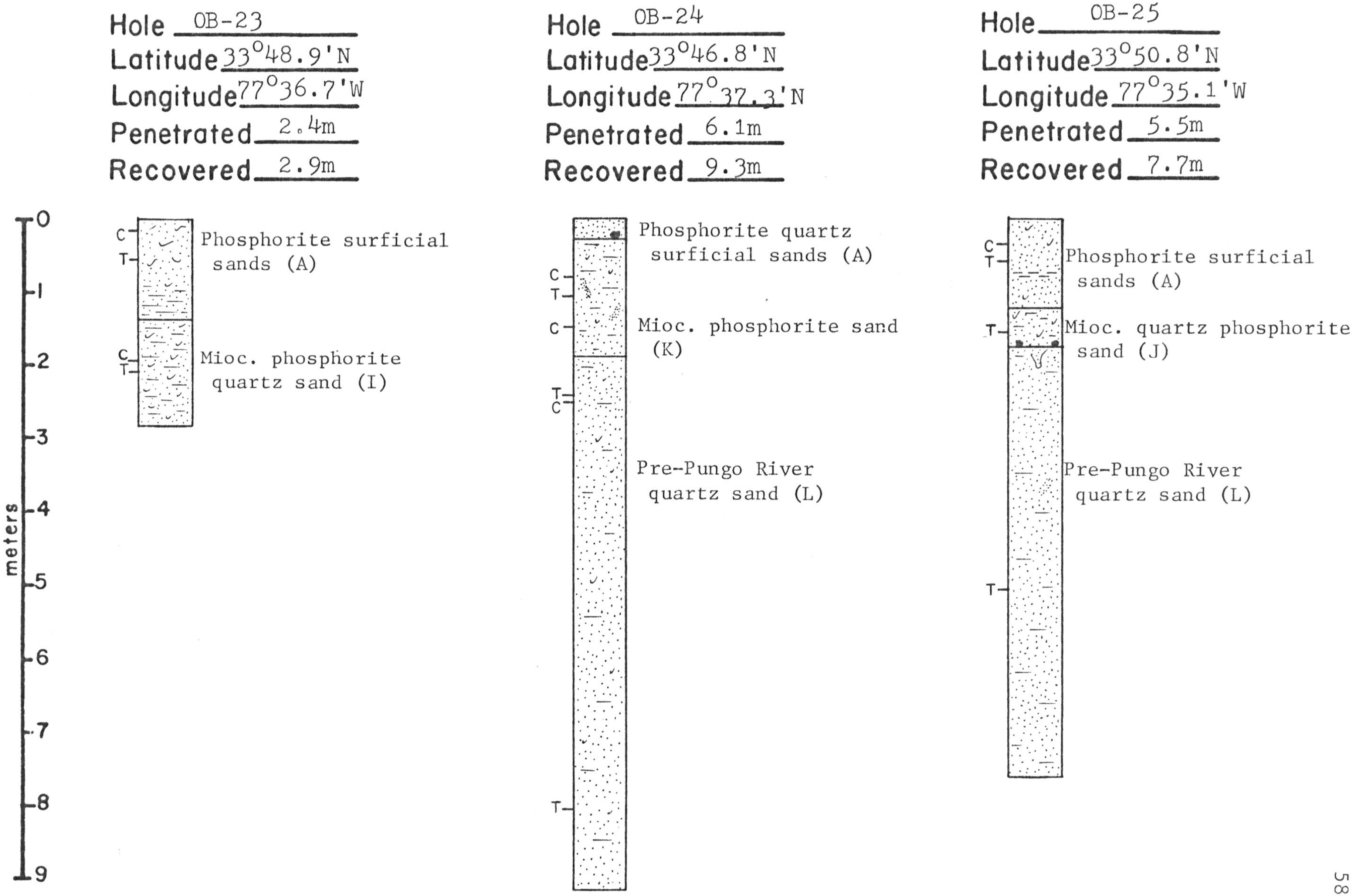


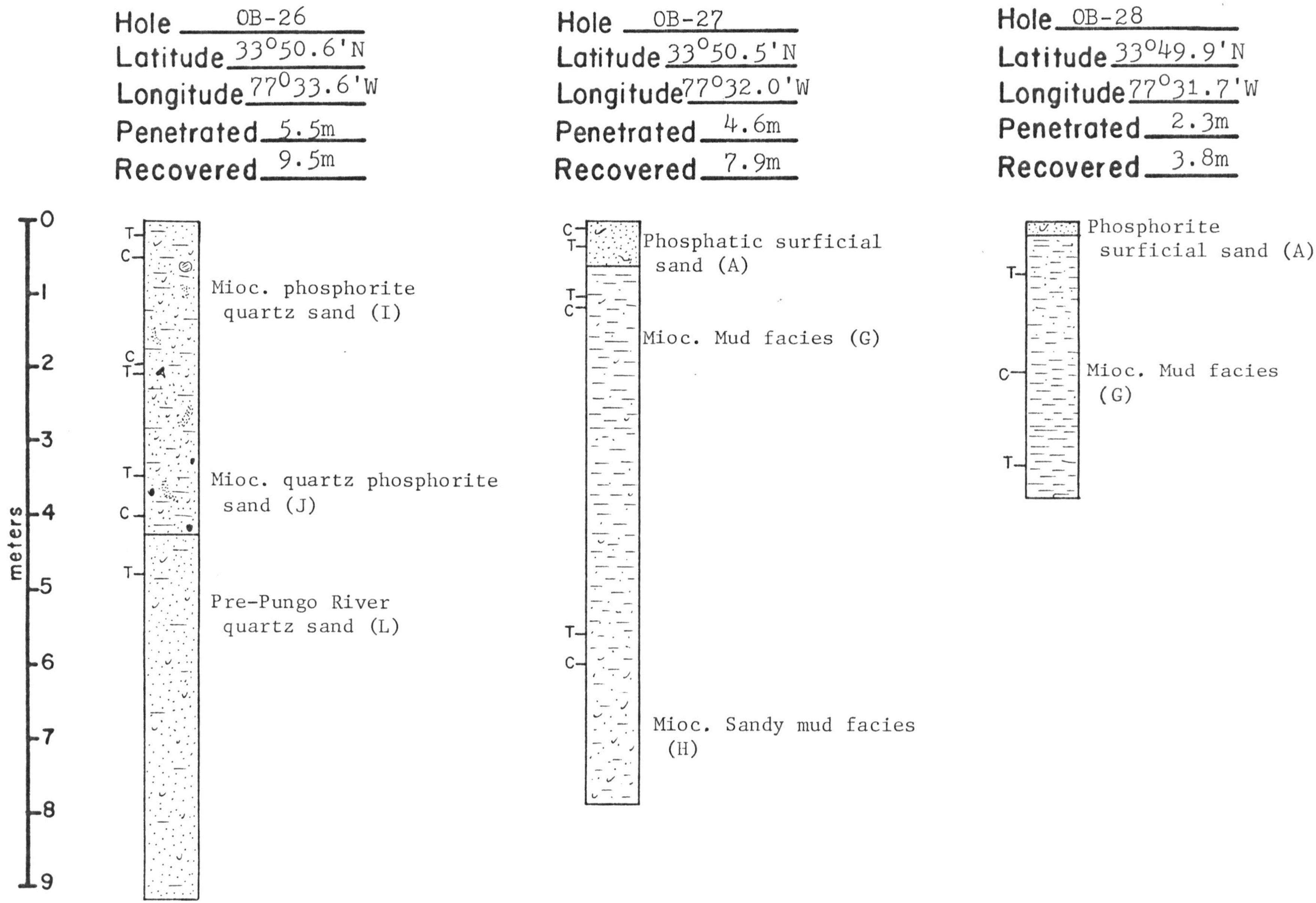


Hole OB-17
Latitude 33°42.4'N
Longitude 77°34.2'W
Penetrated 5.2m
Recovered 6.3m
Hole OB-18
Latitude 33°43.7'N
Longitude 77°40.3'W
Penetrated 6.6m
Recovered 8.9m
Hole OB-19
Latitude 33°43.7'N
Longitude 77°41.3'W
Penetrated 5.3m
Recovered 6.5m
meters
0
1
2
3
4
5
6
7
8
9
Phosphatic surficial sand (A)
Pleis. muddy shelly quartz sand (C)
Mioc. Mud facies (G)
Phosphorite surficial sands (A)
Pleis. muddy shelly quartz sand (C)
Pre-Pungo River quartz sand (L)
Phosphatic surficial sands (A)&(B)
Pre-Pungo River quartz sand (L)

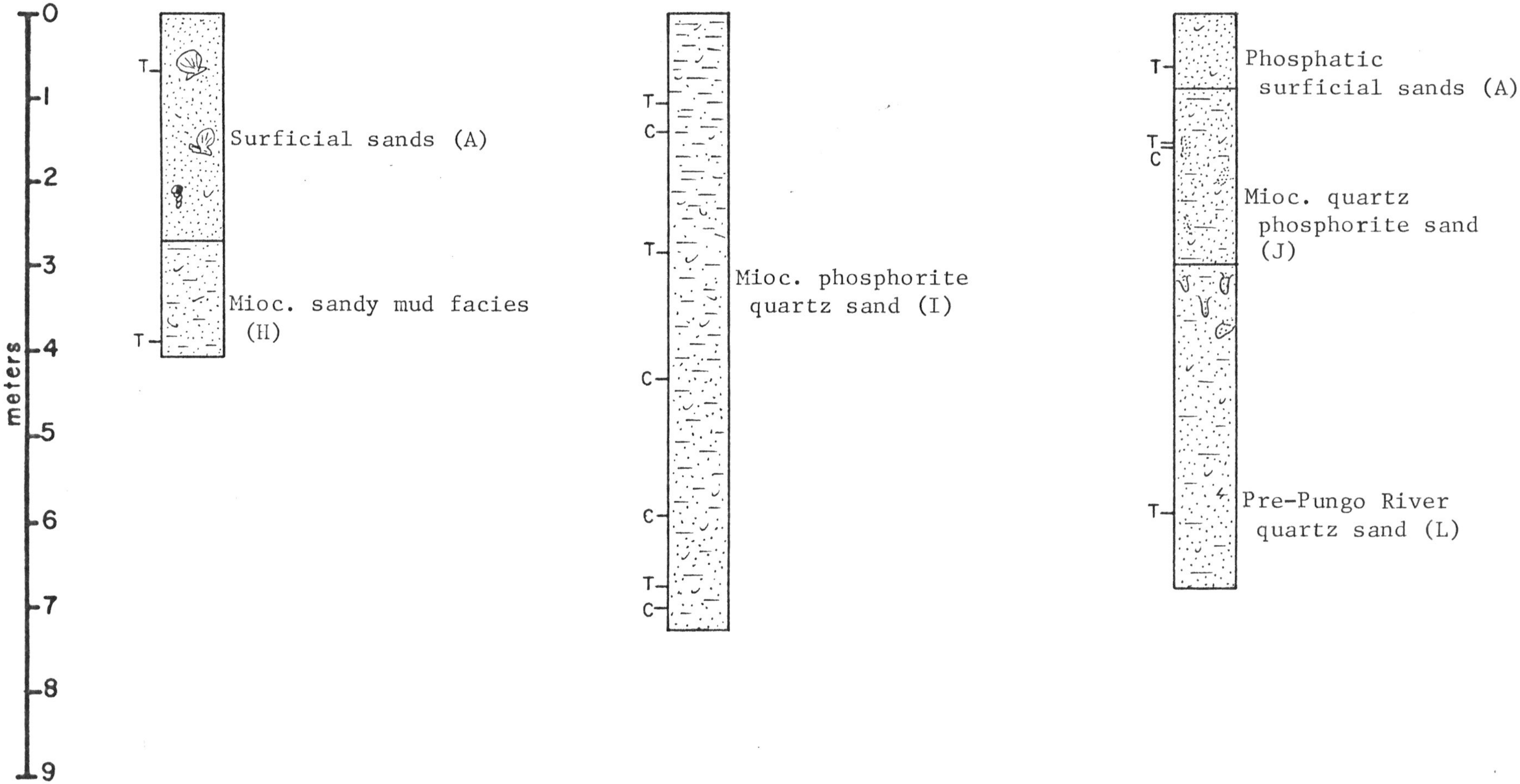


Hole OB-20
Latitude 33°45.2'N
Longitude 77°36.8'W
Penetrated 4.4m
Recovered 6.5m
Pleis. calcarenite rock and sand (B)
Mioc. phosphorite quartz sand (I)
Hole OB-21
Latitude 33°46.3'N
Longitude 77°37.6'W
Penetrated 3.1m
Recovered 3.3m
Phosphorite surficial SAND (A)
Pleis. muddy shelly quartz sand (C)
Mioc. Mud facies (G)
Hole OB-22
Latitude 33°45.8'N
Longitude 77°37.5'W
Penetrated 4.5m
Recovered 5.7m
Phosphatic surficial sand (A) and (C)
Pleis. calcarenite rock and sand (B)
phosphorite quartz sand (I)
Mioc.
quartz phosphorite sand (J)
meters
0
1
2
3
4
5
6
7
8
9


Hole OB-23
Latitude 33°48.9'N
Longitude 77°36.7'W
Penetrated 2.4m
Recovered 2.9m
Phosphorite surficial sands (A)
Mioc. phosphorite quartz sand (I)
Hole OB-24
Latitude 33°46.8'N
Longitude 77°37.3'N
Penetrated 6.1m
Recovered 9.3m
Phosphorite quartz surficial sands (A)
Mioc. phosphorite sand (K)
Pre-Pungo River quartz sand (L)
Hole OB-25
Latitude 33°50.8'N
Longitude 77°35.1'W
Penetrated 5.5m
Recovered 7.7m
Phosphorite surficial sands (A)
Mioc. quartz phosphorite sand (J)
Pre-Pungo River quartz sand (L)
meters
0
1
2
3
4
5
6
7
8
9
C
T


Hole OB-26
Latitude 33°50.6'N
Longitude 77°33.6'W
Penetrated 5.5m
Recovered 9.5m
Mioc. phosphorite quartz sand (I)
Mioc. quartz phosphorite sand (J)
Pre-Pungo River quartz sand (L)
Hole OB-27
Latitude 33°50.5'N
Longitude 77°32.0'W
Penetrated 4.6m
Recovered 7.9m
Phosphatic surficial sand (A)
Mioc. Mud facies (G)
Mioc. Sandy mud facies (H)
Hole OB-28
Latitude 33°49.9'N
Longitude 77°31.7'W
Penetrated 2.3m
Recovered 3.8m
Phosphorite surficial sand (A)
Mioc. Mud facies (G)
meters
0
1
2
3
4
5
6
7
8
9
T
C

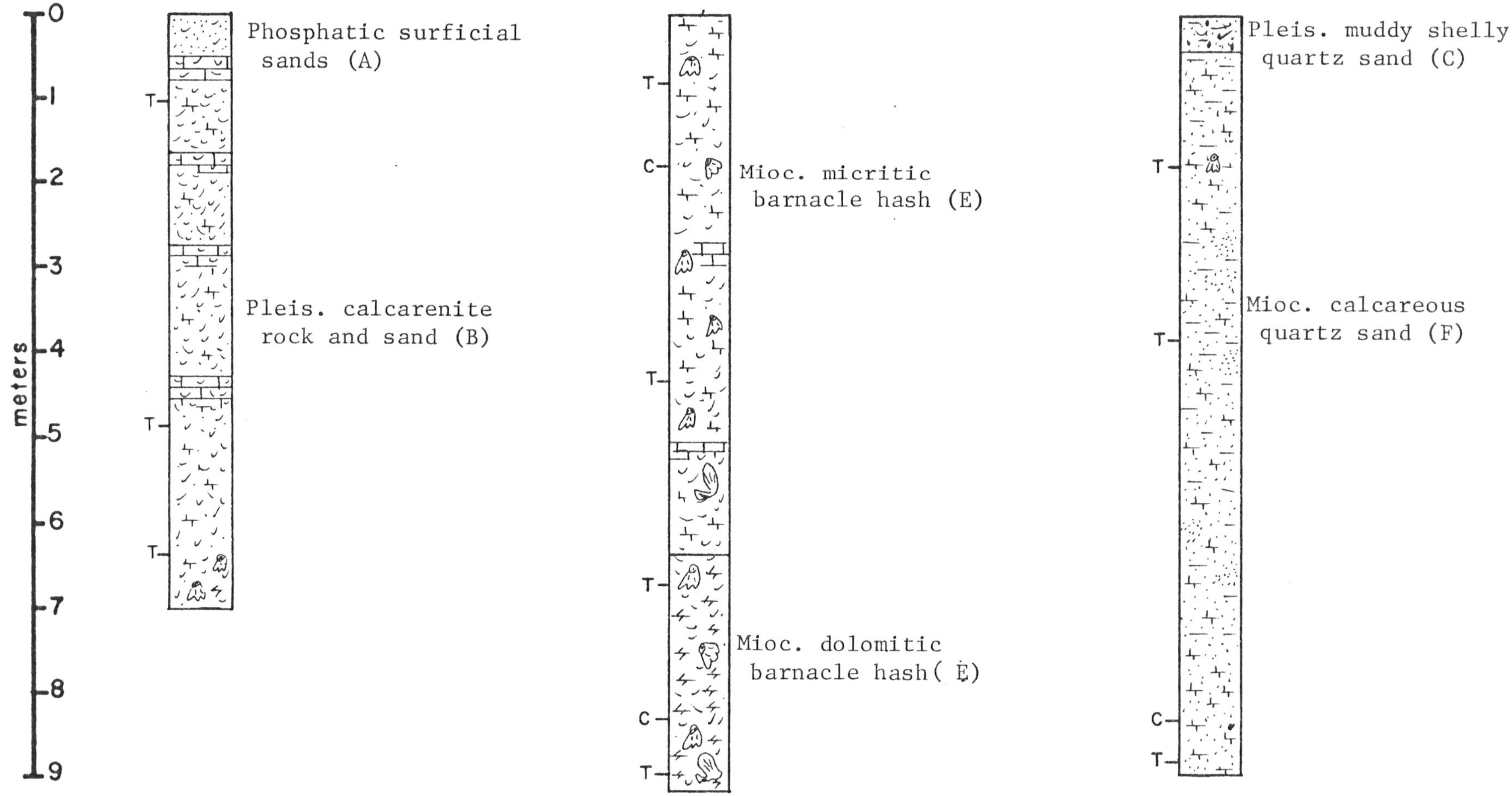
| | | |
|---|---|---|
| Hole OB-29 | Hole OB-29B | Hole OB-30 |
| Latitude 33°52.4'N | Latitude 33°52.4'N | Latitude 33°54.9'N |
| Longitude 77°32.1'W | Longitude 77°32.1'W | Longitude 77°32.0'W |
| Penetrated 3.7m | Penetrated 3.9m | Penetrated 5.1m |
| Recovered 4.1m | Recovered 7.3m | Recovered 6.8m |

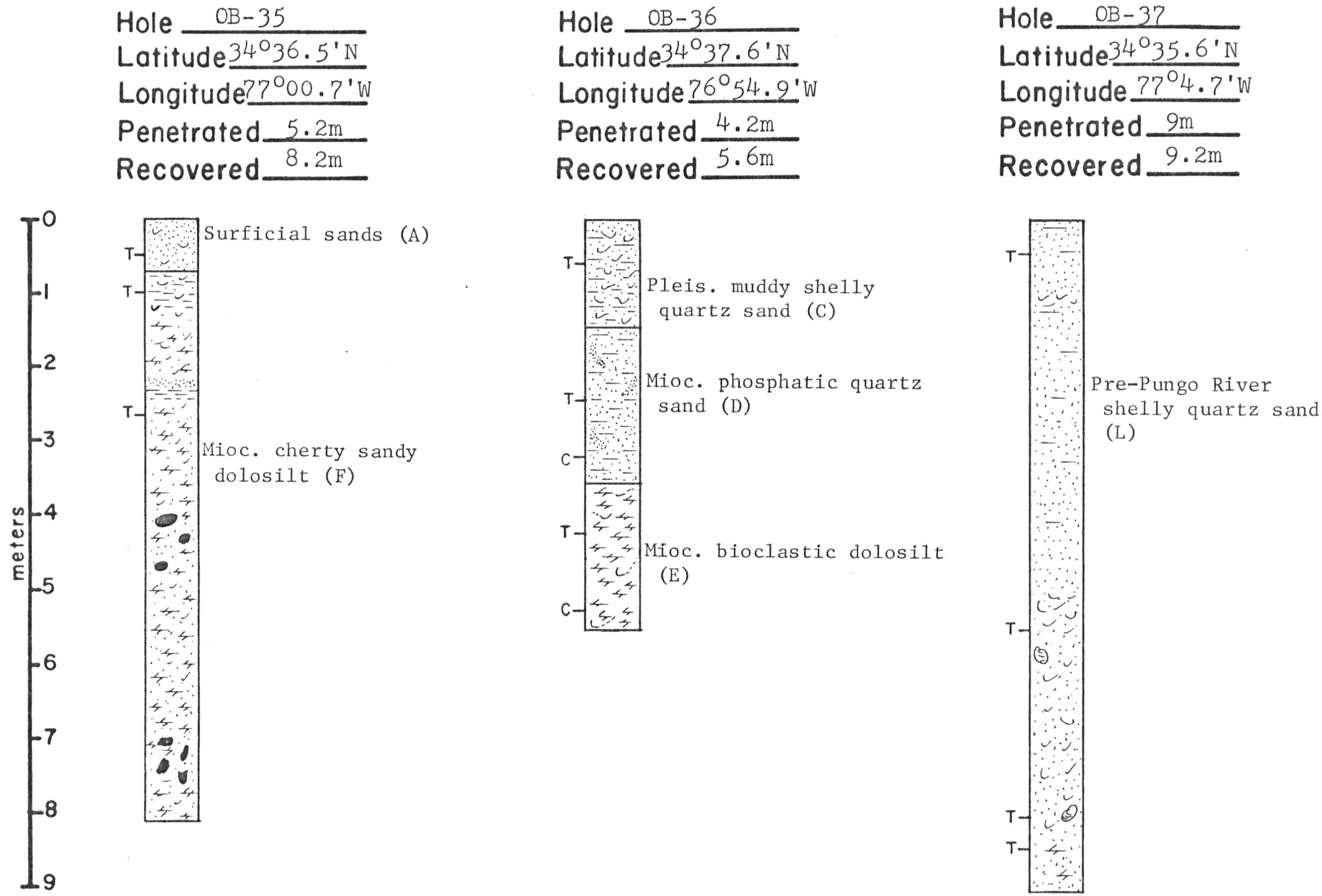


Hole OB-31
Latitude 33°50.5'N
Longitude 77°33.6'W
Penetrated 8.1m
Recovered 7.0m

Hole OB-33
Latitude 34°37.1'N
Longitude 76°56.2'W
Penetrated 8.8m
Recovered 9.4m

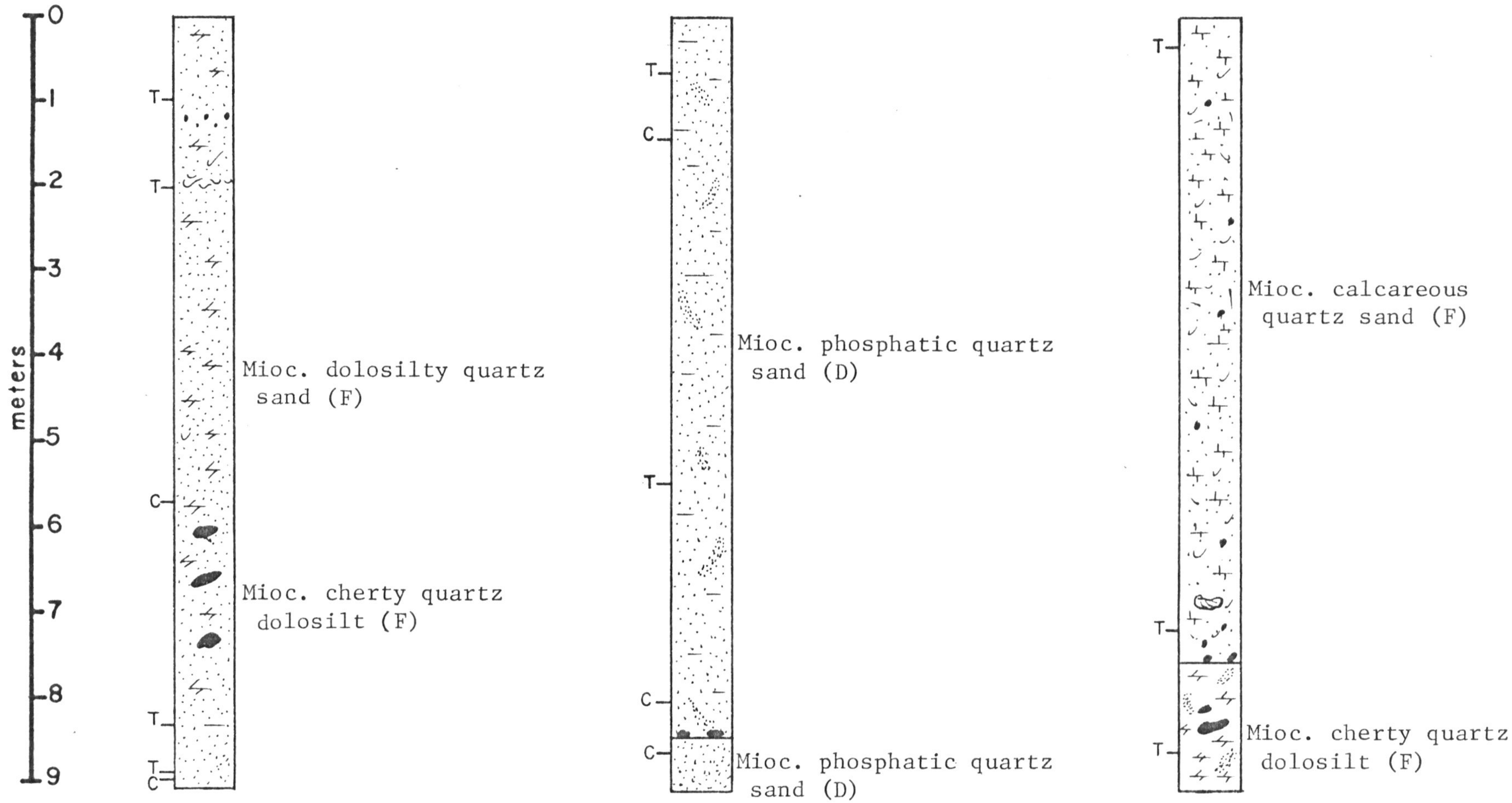
Hole OB-34
Latitude 34°36.6'N
Longitude 76°58.2'W
Penetrated 6.8m
Recovered 9.0m



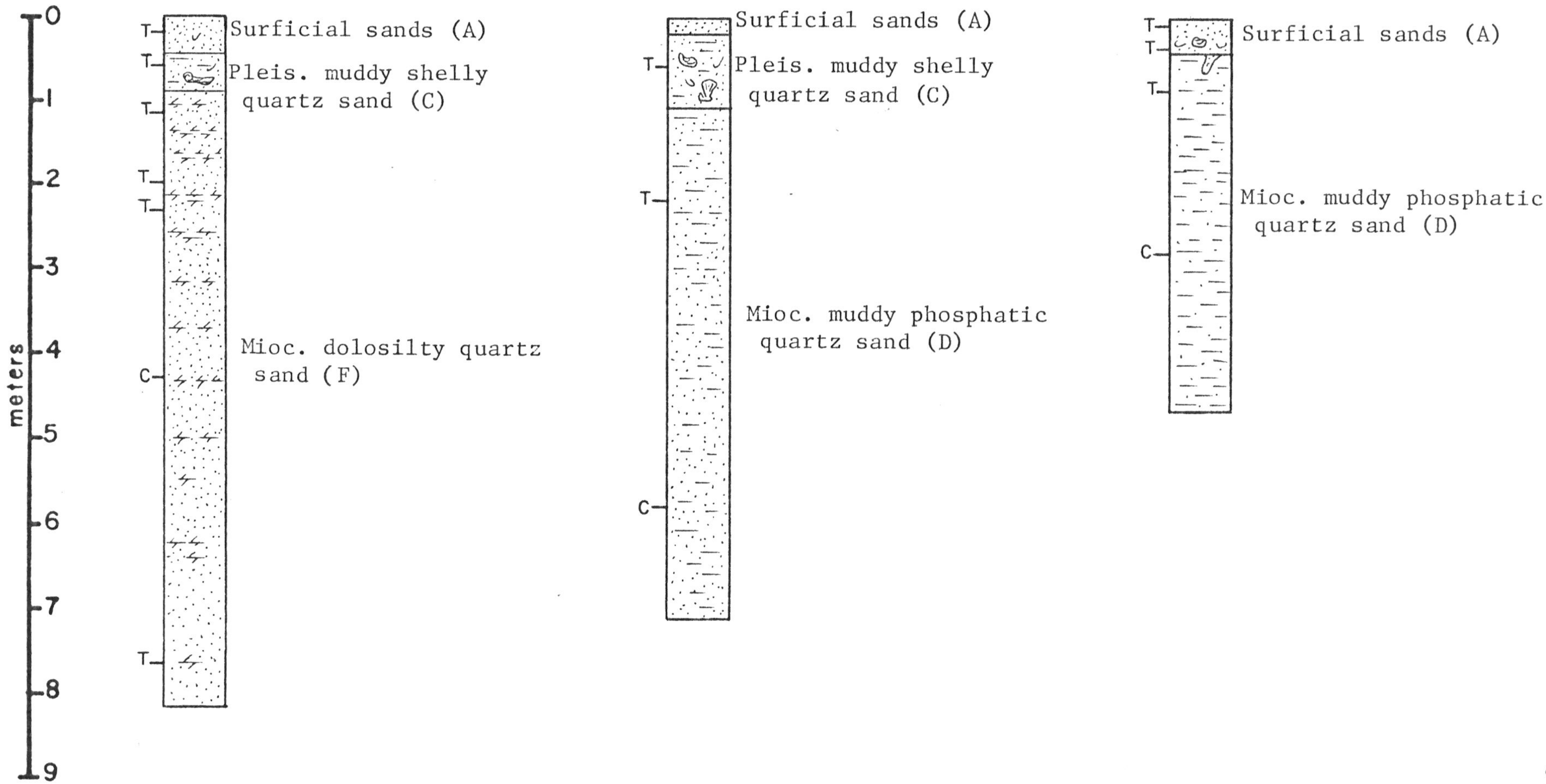


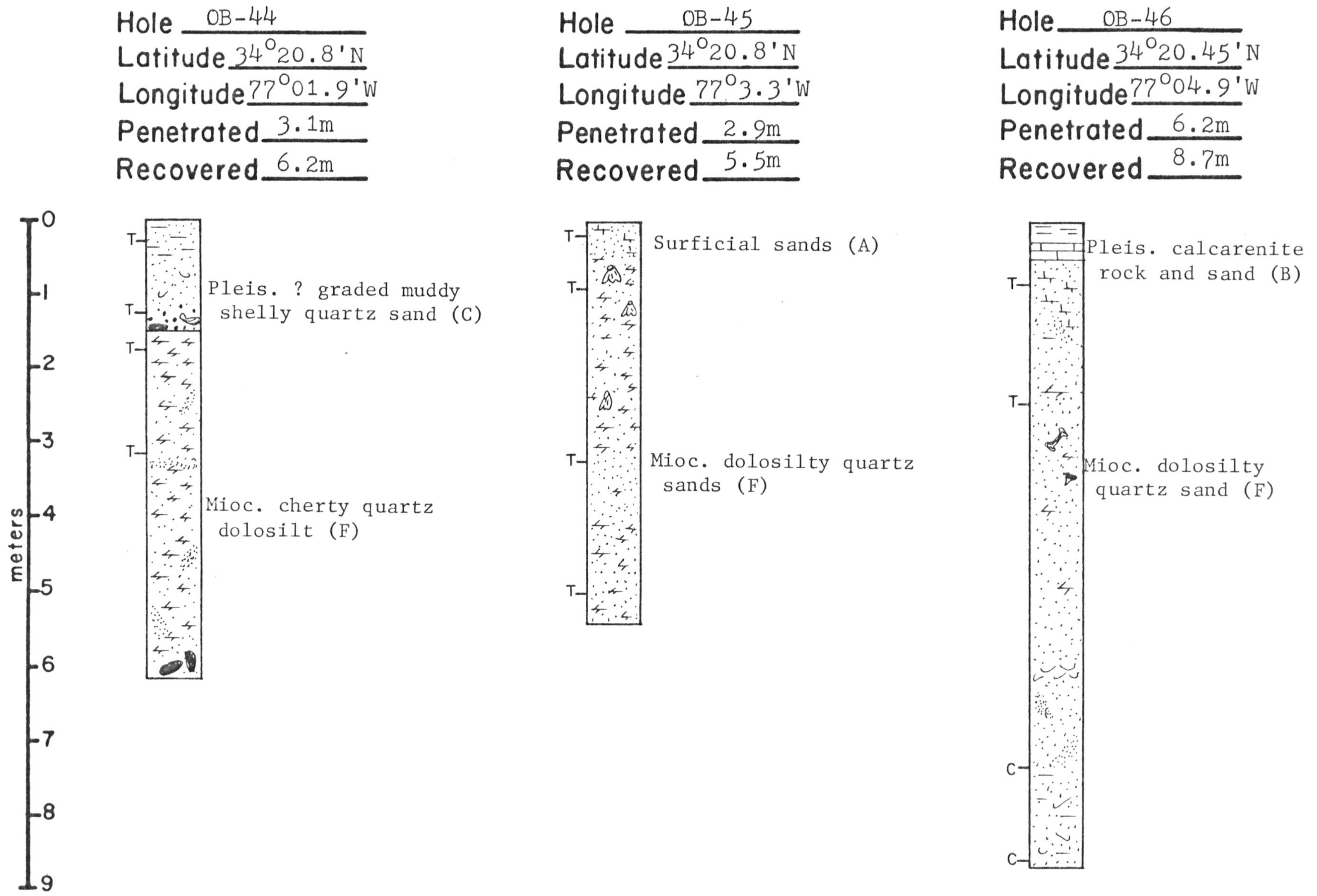
Hole OB-35
Latitude 34°36.5'N
Longitude 77°00.7'W
Penetrated 5.2m
Recovered 8.2m
Hole OB-36
Latitude 34°37.6'N
Longitude 76°54.9'W
Penetrated 4.2m
Recovered 5.6m
Hole OB-37
Latitude 34°35.6'N
Longitude 77°4.7'W
Penetrated 9m
Recovered 9.2m
meters
0
1
2
3
4
5
6
7
8
9
T
C
Surficial sands (A)
Mioc. cherty sandy dolosilt (F)
Pleis. muddy shelly quartz sand (C)
Mioc. phosphatic quartz sand (D)
Mioc. bioclastic dolosilt (E)
Pre-Pungo River shelly quartz sand (L)

| Hole OB-38 | Hole OB-39 | Hole OB-40 |
|---|---|---|
| Latitude 34°26.2'N | Latitude 34°26.4'N | Latitude 34°26.0'N |
| Longitude 77°0.5'W | Longitude 76°58.5'W | Longitude 77°01.0'W |
| Penetrated 8.4m | Penetrated 7.3m | Penetrated 6.6m |
| Recovered 9.2m | Recovered 9.3m | Recovered 9.3m |



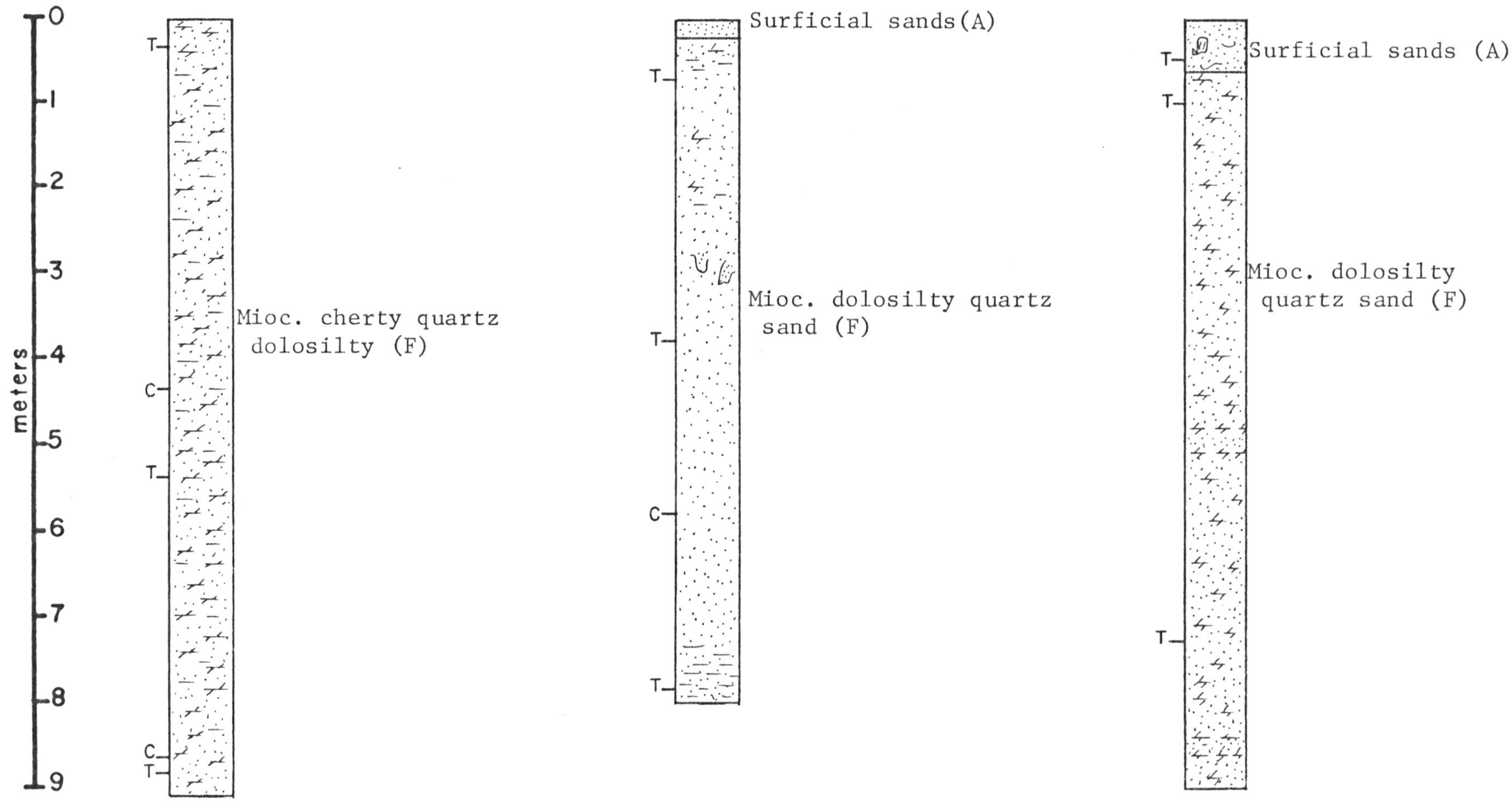
| Hole | OB-41 | OB-42 | OB-43 |
|---|---|---|---|
| Latitude | 34°21.05'N | 34°21.3'N | 34°21.2'N |
| Longitude | 76°59.8'W | 76°57.2'W | 76°57.5'W |
| Penetrated | 6.8m | 5.0m | 3.2m |
| Recovered | 8.2m | 7.2m | 4.7m |

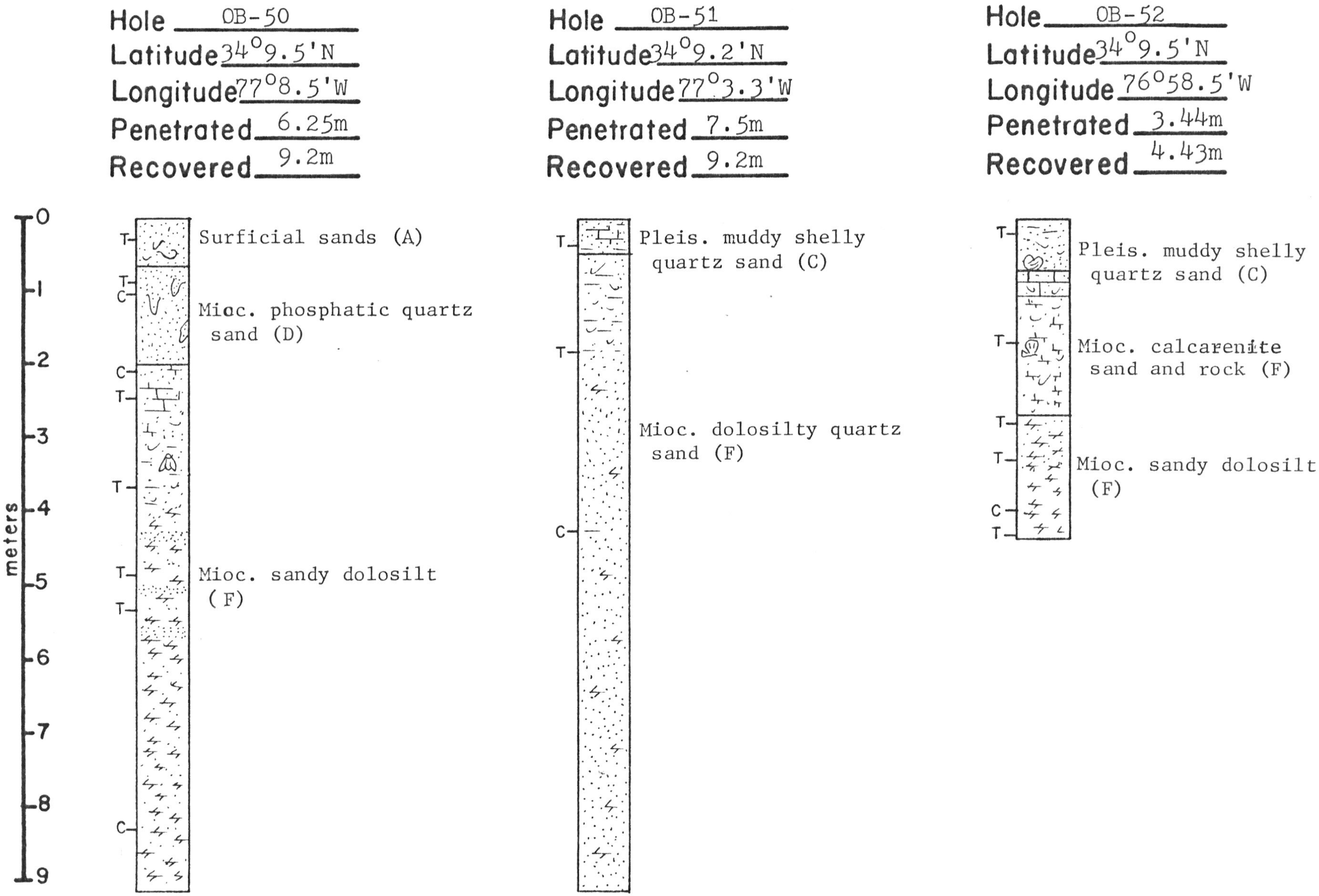




Hole OB-44
Latitude 34°20.8'N
Longitude 77°01.9'W
Penetrated 3.1m
Recovered 6.2m
Hole OB-45
Latitude 34°20.8'N
Longitude 77°3.3'W
Penetrated 2.9m
Recovered 5.5m
Hole OB-46
Latitude 34°20.45'N
Longitude 77°04.9'W
Penetrated 6.2m
Recovered 8.7m
meters
0
1
2
3
4
5
6
7
8
9
T
C
Pleis. ? graded muddy shelly quartz sand (C)
Mioc. cherty quartz dolosilt (F)
Surficial sands (A)
Mioc. dolosilty quartz sands (F)
Pleis. calcarenite rock and sand (B)
Mioc. dolosilty quartz sand (F)

| Hole | OB-47 | OB-48 | OB-49 |
|---|---|---|---|
| Latitude | 34°9.5'N | 34°9.4'N | 34°9.7'N |
| Longitude | 77°17.7'W | 77°13.2'W | 77°15.5'W |
| Penetrated | 6.1m | 6.0m | 6.6m |
| Recovered | 9.3m | 8.1m | 9.2m |

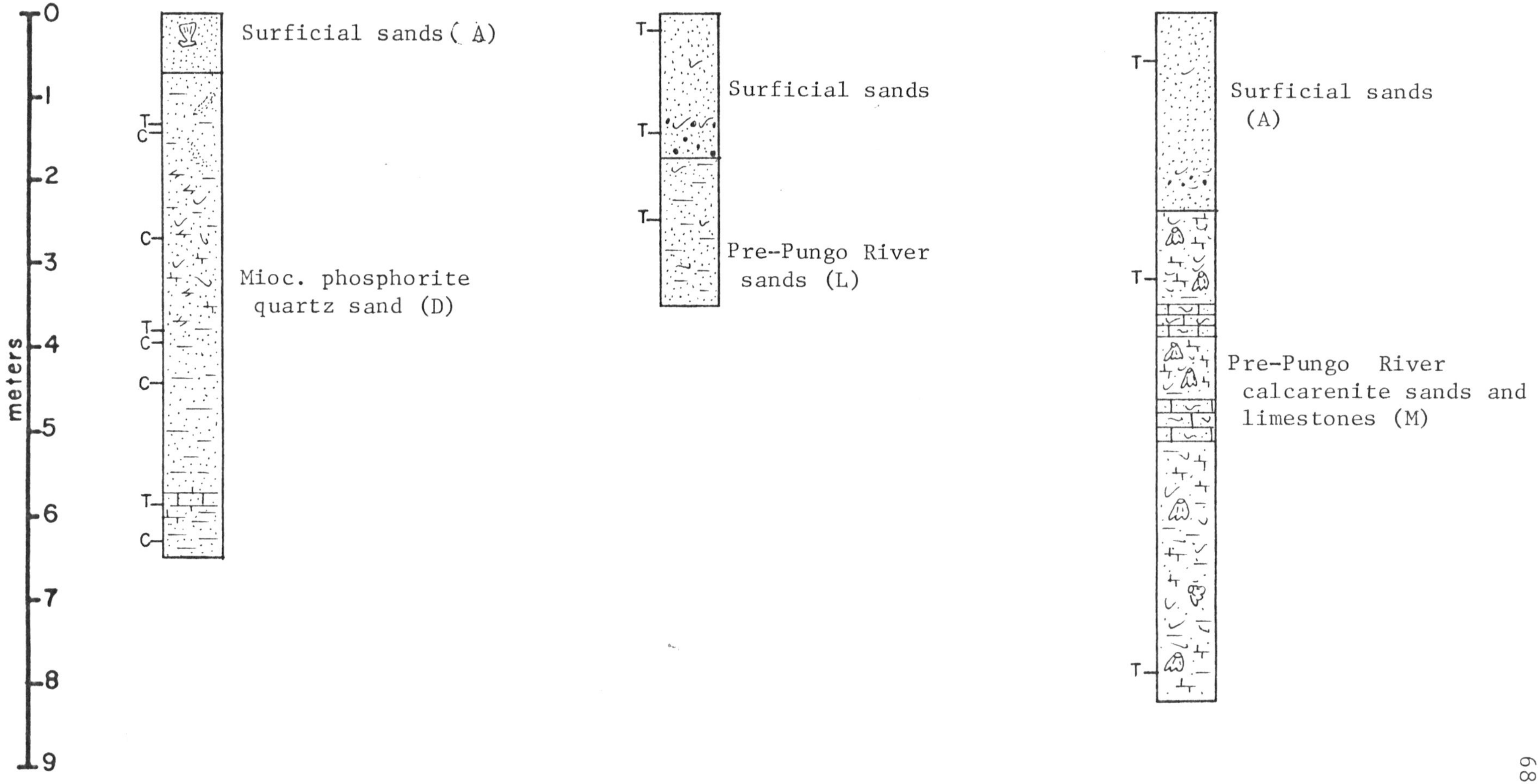



Hole OB-50
Latitude 34°9.5'N
Longitude 77°8.5'W
Penetrated 6.25m
Recovered 9.2m
Hole OB-51
Latitude 34°9.2'N
Longitude 77°3.3'W
Penetrated 7.5m
Recovered 9.2m
Hole OB-52
Latitude 34°9.5'N
Longitude 76°58.5'W
Penetrated 3.44m
Recovered 4.43m
meters
0
1
2
3
4
5
6
7
8
9
Surficial sands (A)
Mioc. phosphatic quartz sand (D)
Mioc. sandy dolosilt (F)
Pleis. muddy shelly quartz sand (C)
Mioc. dolosilty quartz sand (F)
Pleis. muddy shelly quartz sand (C)
Mioc. calcarenite sand and rock (F)
Mioc. sandy dolosilt (F)

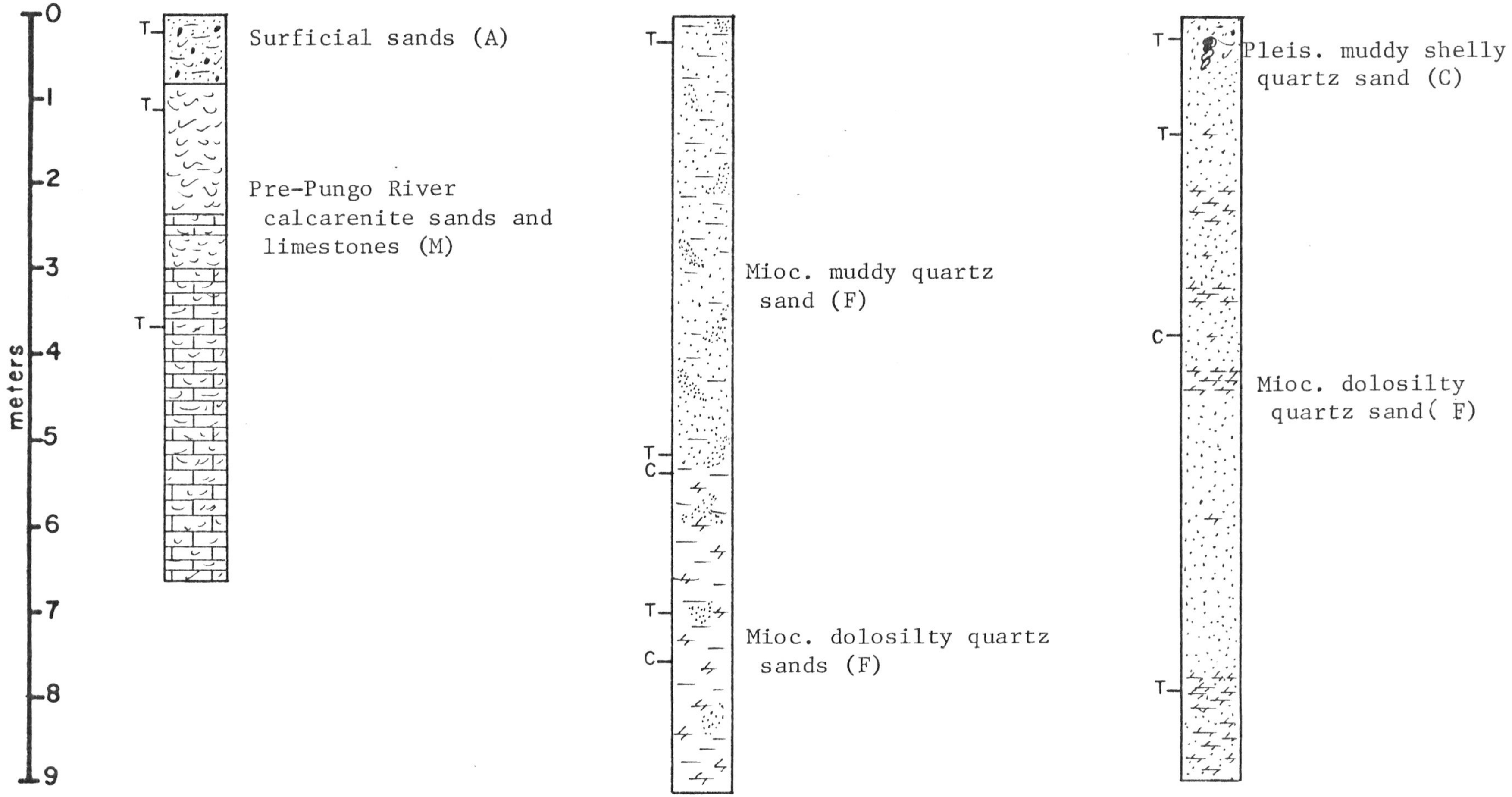
Hole OB-53
Latitude 34°9.6'N
Longitude 76°54.9'W
Penetrated 3.5m
Recovered 6.6m

Hole OB-54
Latitude 34°00.9'N
Longitude 77°27.8'W
Penetrated 3.0m
Recovered 3.6m

Hole OB-55
Latitude 34°00.6'N
Longitude 77°29.5'W
Penetrated 7.5m
Recovered 8.3m

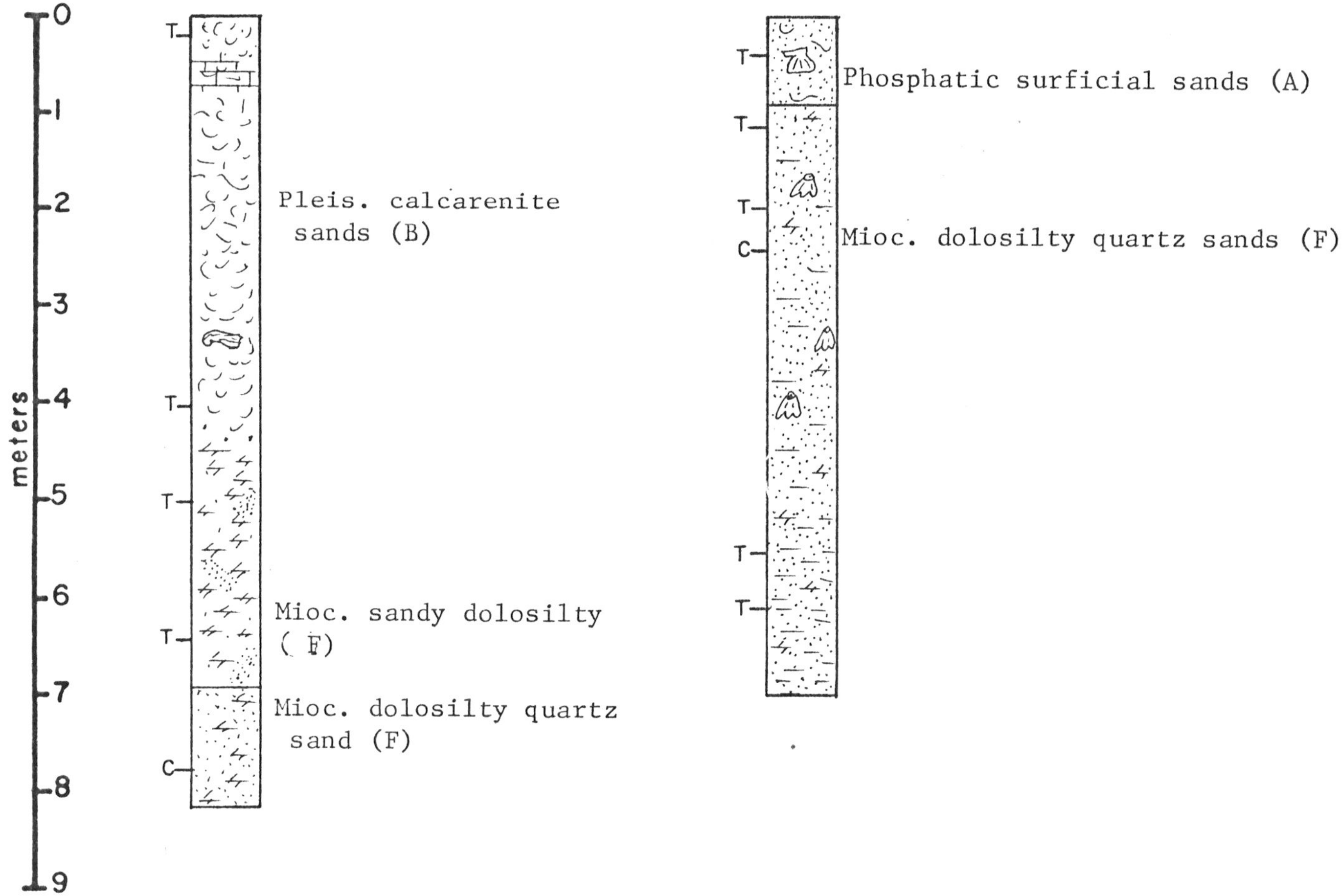


| Hole OB-56 | Hole OB-57 | Hole OB-58 |
| --- | --- | --- |
| Latitude 34°00.8'N | Latitude 34°00.0'N | Latitude 34°00.0'N |
| Longitude 77°23.7'W | Longitude 77°14.3'W | Longitude 77°7.4'W |
| Penetrated 9.0m | Penetrated 6.7m | Penetrated 5.9m ? |
| Recovered 6.7m | Recovered 9.3m | Recovered 9.0m |



Hole OB-59
Latitude 34°00.6'N
Longitude 76°59.3'W
Penetrated 7.4m
Recovered 8.2m

Hole OB-60
Latitude 34°9.8'N
Longitude 76°50.8'W
Penetrated 5.0m
Recovered 7.0m



# APPENDIX II: BULK ROCK DATA

| HOLE | DEPTH(M) | $P_2O_5$ | MgO | CaO | $Al_2O_3$ | $Fe_2O_3$ | ACID INSOL. |
|---|---|---|---|---|---|---|---|
| OB-1 | 4.5-4.75 | 3.90 | 1.92 | 6.63 | 0.75 | 0.64 | 65.70 |
| | 6.0-6.25 | 4.72 | 1.60 | 10.13 | 1.18 | 0.71 | 68.73 |
| | 7.0-7.25 | 6.09 | 0.82 | 11.50 | 0.70 | 0.57 | 70.84 |
| | 8.9-9.1 | 5.21 | 1.02 | 9.82 | 1.13 | 0.68 | 69.90 |
| OB-2B | 4.75-5.0 | 1.96 | 0.95 | 2.26 | 1.46 | 1.25 | 84.11 |
| | 6.1-6.25 | 4.55 | 0.82 | 7.29 | 1.18 | 0.85 | 75.18 |
| OB-3 | 8.7-9.1 | 1.59 | 4.57 | 46.43 | 0.46 | 0.34 | 5.02 |
| OB-4 | 5.75-6.0 | 3.81 | 0.45 | 5.47 | 1.05 | 0.57 | 78.63 |
| | 8.9-9.1 | 3.74 | 0.42 | 9.77 | 0.77 | 0.39 | 74.64 |
| OB-6 | 5.75-6.0 | 2.08 | 0.60 | 1.71 | 1.57 | 1.04 | 81.27 |
| | 7.4-7.6 | 2.70 | 0.17 | 3.66 | 0.20 | 0.15 | 85.92 |
| OB-7 | 4.0-5.0 | 0.72 | 0.30 | 7.45 | 0.34 | 0.65 | 78.78 |
| OB-8 | 2.0-4.0 | 0.68 | 0.40 | 6.59 | 0.32 | 0.80 | 82.20 |
| OB-9 | 3.0-3.1 | 3.55 | 1.45 | 11.56 | 1.71 | 0.86 | 63.83 |
| OB-10 | 3.0-3.25 | 0.76 | 0.58 | 16.20 | 0.46 | 0.71 | 62.92 |
| OB-11 | 0.9-1.0 | 15.93 | 0.85 | 26.99 | 1.11 | 0.54 | 37.76 |
| OB-14 | 1.25-1.35 | 6.15 | 0.97 | 25.00 | 0.80 | 0.36 | 43.67 |
| | 3.0-3.1 | 11.65 | 0.72 | 21.42 | 0.94 | 0.54 | 50.19 |
| | 4.75-4.85 | 12.23 | 0.92 | 24.28 | 0.89 | 0.50 | 43.30 |
| | 5.9-6.0 | 0.60 | 1.95 | 18.87 | 0.42 | 0.46 | 57.49 |
| OB-15 | 0.9-1.0 | 1.66 | 2.25 | 12.17 | 0.99 | 1.00 | 62.17 |
| OB-16 | 1.1-1.25 | 1.02 | 3.55 | 4.90 | 1.94 | 1.54 | 64.91 |
| OB-17 | 0.4-0.5 | 1.01 | 0.62 | 12.14 | 0.17 | 0.78 | 70.79 |
| | 3.0-3.1 | 2.07 | 3.25 | 12.22 | 1.70 | 1.32 | 58.31 |
| | 5.9-6.0 | 1.49 | 1.77 | 12.05 | 1.19 | 0.82 | 64.29 |

| HOLE | DEPTH(M) | $P_2O_5$ | MgO | CaO | $Al_2O_3$ | $Fe_2O_3$ | ACID INSOL. |
|---|---|---|---|---|---|---|---|
| OB-18 | 0.45-0.55 | 6.63 | 0.78 | 24.66 | 0.30 | 1.20 | 46.65 |
| | 1.0-1.1 | 3.46 | 0.87 | 21.66 | 0.36 | 1.30 | 51.88 |
| OB-19 | 0-0.2 | 3.90 | 0.99 | 23.66 | 0.35 | 2.05 | 48.69 |
| OB-20 | 3.25-3.35 | 7.85 | 1.57 | 20.42 | 1.51 | 0.75 | 46.59 |
| | 4.9-5.0 | 10.55 | 1.32 | 28.21 | 1.20 | 0.54 | 36.47 |
| | 5.75-5.85 | 12.38 | 1.15 | 28.69 | 1.10 | 0.46 | 35.82 |
| OB-21 | 2.9-3.3 | 1.43 | 1.15 | 11.70 | 1.38 | 1.59 | 57.04 |
| OB-22 | 0-0.3 | 4.82 | 0.44 | 36.41 | 0.24 | 1.07 | 27.98 |
| | 3.34-3.4 | 7.21 | 1.93 | 20.81 | 1.57 | 0.86 | 45.83 |
| | 4.8-4.9 | 11.09 | 1.57 | 26.89 | 1.15 | 0.53 | 37.10 |
| OB-23 | 0.2-0.3 | 4.96 | 0.55 | 17.95 | 0.21 | 0.82 | 60.44 |
| | 2.0-2.1 | 4.83 | 1.70 | 12.85 | 2.01 | 0.97 | 58.31 |
| OB-24 | 0.8-0.85 | 21.69 | 0.92 | 39.47 | 0.82 | 0.50 | 14.29 |
| | 1.5-1.67 | 20.96 | 0.77 | 36.17 | 0.80 | 0.93 | 21.95 |
| | 2.5-2.55 | 1.04 | 2.49 | 30.08 | 0.64 | 0.50 | 34.00 |
| OB-25 | 0.45-0.55 | 10.81 | 0.75 | 26.33 | 0.26 | 0.68 | 42.85 |
| OB-26 | 0.5 -0.6 | 8.39 | 1.27 | 21.57 | 1.37 | 0.64 | 46.77 |
| | 2.0-2.1 | 15.71 | 1.22 | 33.34 | 1.19 | 0.50 | 26.58 |
| | 4.0-4.1 | 12.16 | 0.85 | 22.60 | 1.09 | 0.54 | 47.27 |
| OB-27 | 0-0.3 | 1.00 | 0.45 | 9.55 | 0.14 | 0.36 | 76.82 |
| | 1.0-1.3 | 0.80 | 1.70 | 2.47 | 1.46 | 2.62 | 73.82 |
| | 5.9-6.0 | 2.62 | 1.07 | 15.78 | 1.04 | 0.61 | 60.21 |
| OB-28 | 2.0-2.3 | 0.72 | 1.70 | 2.48 | 1.49 | 2.64 | 73.38 |
| OB-29B | 1.4-1.5 | 2.78 | 1.07 | 11.34 | 1.18 | 0.64 | 63.98 |
| | 4.4-4.5 | 3.59 | 0.87 | 13.62 | 0.85 | 0.46 | 65.20 |

| HOLE | DEPTH(M) | $P_2O_5$ | MgO | CaO | $Al_2O_3$ | $Fe_2O_3$ | ACID INSOL. |
|---|---|---|---|---|---|---|---|
| OB-29B | 5.9-6.0 | 6.29 | 0.82 | 26.12 | 0.80 | 0.39 | 42.05 |
| | 7.1-7.2 | 10.76 | 0.95 | 28.63 | 0.94 | 0.46 | 37.05 |
| OB-30 | 1.5-1.6 | 14.25 | 0.90 | 24.92 | 0.99 | 0.53 | 42.55 |
| OB-33 | 1.8-2.3 | 0.21 | 1.12 | 52.25 | 0.09 | 0.28 | 2.19 |
| | 8.25-8.5 | 1.35 | 1.30 | 34.94 | 1.30 | 0.93 | 23.93 |
| OB-34 | 8.0-8.25 | 1.19 | 2.15 | 21.75 | 0.47 | 0.43 | 50.24 |
| OB-36 | 3.25-3.5 | 2.02 | 0.65 | 3.69 | 1.08 | 0.79 | 81.63 |
| | 5.25-5.39 | 0.42 | 8.84 | 37.09 | 0.66 | 0.46 | 9.80 |
| OB-38 | 5.75-6.0 | 1.84 | 1.79 | 3.66 | 0.21 | 0.12 | 82.64 |
| | 8.8-9.1 | 1.98 | 0.21 | 1.83 | 0.10 | 0.06 | 88.14 |
| OB-39 | 1.0-2.0 | 1.35 | 0.64 | 1.69 | 1.09 | 1.38 | 82.87 |
| | 8.0-8.25 | 2.79 | 0.67 | 3.81 | 1.32 | 0.86 | 82.25 |
| | 8.5-8.75 | 3.11 | 0.75 | 26.93 | 0.53 | 0.86 | 43.06 |
| OB-41 | 4.3-4.5 | 1.71 | 0.35 | 5.09 | 0.18 | 0.43 | 84.26 |
| OB-42 | 5.8-6.0 | 2.24 | 0.75 | 1.16 | 1.08 | 1.10 | 81.86 |
| OB-43 | 2.8-3.0 | 1.74 | 1.0 | 0.67 | 2.16 | 1.75 | 79.80 |
| OB-46 | 7.3-7.5 | 1.72 | 0.30 | 3.50 | 0.38 | 0.43 | 84.52 |
| | 8.9-9.1 | 1.67 | 0.35 | 5.64 | 0.33 | 0.39 | 73.01 |
| OB-47 | 4.3-4.5 | 0.96 | 2.40 | 4.02 | 1.13 | 0.71 | 75.13 |
| | 8.75-9.13 | 3.16 | 3.25 | 8.66 | 1.04 | 0.64 | 67.19 |
| OB-48 | 5.8-6.0 | 0.72 | 0.25 | 1.83 | 0.25 | 0.29 | 87.79 |
| OB-50 | 1.0-1.5 | 1.34 | 1.20 | 8.35 | 0.33 | 0.54 | 75.81 |
| | 2.0-3.0 | 2.17 | 0.69 | 25.20 | 0.33 | 0.36 | 49.99 |
| | 8.0-9.0 | 1.48 | 1.64 | 3.02 | 1.46 | 2.10 | 75.52 |
| OB-51 | 4.3-4.5 | 1.77 | 1.05 | 1.95 | 0.98 | 0.50 | 82.17 |

| HOLE | DEPTH(M) | $P_2O_5$ | MgO | CaO | $Al_2O_3$ | $Fe_2O_3$ | ACID INSOL. |
|---|---|---|---|---|---|---|---|
| OB-52 | 3.9-4.4 | 1.42 | 8.23 | 18.79 | 1.15 | 1.18 | 39.52 |
| OB-53 | 1.25-1.5 | 3.77 | 0.79 | 7.88 | 1.06 | 0.67 | 75.93 |
| | 2.75-3.0 | 5.45 | 0.80 | 9.43 | 1.15 | 0.68 | 71.50 |
| | 3.75-4.0 | 8.46 | 1.05 | 15.98 | 1.19 | 0.68 | 59.64 |
| | 4.25-4.5 | 9.77 | 1.55 | 18.67 | 1.76 | 0.82 | 50.84 |
| | 6.25-6.5 | 5.78 | 1.12 | 18.16 | 1.22 | 0.78 | 55.94 |
| OB-57 | 5.25-5.5 | 1.34 | 1.17 | 1.83 | 1.14 | 0.82 | 83.43 |
| | 7.0-8.0 | 1.62 | 5.43 | 10.70 | 1.51 | 2.41 | 57.00 |
| OB-58 | 3.75-4.0 | 1.73 | 0.12 | 2.21 | 0.14 | 0.29 | 86.72 |
| OB-59 | 7.75-7.9 | 2.56 | 0.65 | 10.79 | 0.38 | 0.50 | 71.92 |
| OB-60 | 2.0-3.0 | 0.88 | 1.00 | 8.03 | 0.80 | 1.00 | 76.89 |