U.S. DEPARTMENT OF THE INTERIOR

U.S. GEOLOGICAL SURVEY

SIZE ANALYSIS, VISUAL ESTIMATION OF PHOSPHATE AND OTHER MINERALS, AND PRELIMINARY ESTIMATION OF RECOVERABLE PHOSPHATE IN SIZE FRACTIONS OF SEDIMENT SAMPLES FROM DRILLHOLES GAT-90, TYBEE ISLAND, AND GAS-90-2, SKIDAWAY ISLAND, GEORGIA

by

James R. Herring[1], Frank T. Manheim[2], Kathleen Farrell[3], Paul Huddlestun[3], and Brian Bretz[1]

Open-File Report 91-586

[1]U.S. Geological Survey, MS 939, Box 25046, Denver CO 80225; [2]U.S. Geological Survey, Woods Hole, MA 02543; [3]Georgia Geologic Survey, Atlanta, Georgia 30334

CONTENTS

ILLUSTRATIONS

TABLES

ABSTRACT

This report, which continues a series of studies of the phosphatic Neogene sediments from the Georgia coastal plain and continental shelf, documents the estimation of minerals, especially that of phosphate, in bulk and size-separated samples taken from two boreholes drilled in coastal, northeastern Georgia near Savannah. The principal method of investigation is visual microscopic identification of mineral phases in bulk sediment samples and in wet-sieved, size-separated fractions. The reasons for releasing this report are to provide: 1) preliminary core analysis information; 2) sediment and mineral identification that can be tied to the offshore seismic stratigrapic framework; 3) preliminary estimates of phosphate resources in the area; and 4) information crucial to the planning of subsequent studies of the coastal and shelf sediments in the region. The results of this report suggest that these coastal sediments contain zones of phosphorite enrichment that approach the presently mined deposits in grade and tonnage of phosphate.

Core GAT-90 was drilled on Tybee Island to a depth of 52 m, and Core GAS-90 was drilled on Skidaway Island to a depth of 58 m. Compositionally, the sediments from both cores have varying proportions of detrital quartz and aluminosilicate minerals, carbonate, and phosphate. In both boreholes the most phosphatic zone is the Tybee Phosphorite Member of the middle Miocene Coosawhatchie Formation, which occurs from 24.6 to 27.0 m depth in Borehole GAT-90 and from 33.1 to 41.1 m depth in Borehole GAS-90-2. The phosphate-rich samples of the Tybee Member of the middle Miocene Coosawhatchie Formation average 46 percent of the sample mass as phosphate grains >170 mesh in size. The remainder of the sample is about 25 percent fine-grained material (<170 mesh) and about 25 percent >170 mesh quartz. There is little mineral matter other than quartz and phosphate in the >170 mesh fraction of this interval. Clearly, this phosphatic sediment would produce a screened phosphate product comparable to that mined by industry in the southeastern U.S. at present.

Size separations usually were >18, 18-60, 60-170, and <170 mesh, although one of the <170 mesh samples from each borehole was separated into five additional size fractions with the smallest fraction being the <325 mesh. These extended size separations indicate that screening at >170 mesh recovers 93 to 96 percent of the phosphate that is in the >325 mesh fraction.

The important results of these studies are: 1) zones of phosphorite enrichment of several meters thickness occur in sediments of these drillholes and, based on several companion studies, extend over the Georgia Shelf; 2) size separation of this sediment to >170 mesh produces enriched phosphate that is about equal to the material presently produced in mines in the southeastern U.S.; 3) in these zones of phosphatic enrichment, phosphate to quartz ratios in the >170 mesh sediment and the amount of fine-grained material (<170 mesh) are similar to presently-mined, onshore phosphate rock deposits in the southeastern U.S.; and 4) resource estimates of recoverable (>170 mesh) phosphate in the most phosphatic horizon in the two boreholes, ranging from 1.5 to 8.5 m in thickness, indicate recoverable phosphate mineral resources of between 1.5 and 3.6 tons/m^2.

INTRODUCTION

This study continues a series of investigations of the phosphatic Neogene sediments from the Georgia coastal plain and continental shelf. The primary intent of the report is to document the estimation of sedimentary components, especially that of phosphorite, in bulk and size-separated samples taken from two boreholes drilled in coastal, northeastern Georgia. The boreholes were drilled on two coastal islands, Skidaway and Little Tybee, which are located approximately 15 km southeast and east, respectively, of Savannah, Georgia. Figure 1 shows the location of the boreholes and lists the locations and drilling depths, and Figure 2 and Figure 3 show preliminary lithologic logs for the boreholes. The principal method of investigation is visual microscopic identification of mineral phases in bulk sediment samples and wet-sieved, size-separated fractions. A subsequent article will detail the chemical analysis of the bulk and size-separated sediment samples from these boreholes. The principal reasons for releasing this report are to provide: 1) preliminary core analysis information; 2) sediment and mineral identification that can be tied to the offshore seismic stratigraphic framework; 3) preliminary estimates of phosphate resources in the area; and 4) information crucial to the planning of subsequent studies of the coastal and shelf sediments in the region. The results of this report suggest that these coastal sediments contain zones of phosphorite enrichment that approach the presently mined onshore phosphate deposits in their percentage content and overall tonnage of phosphate. As a point of clarification, the use of the latter term, phosphate, throughout this report refers to phosphate minerals and not P_2O_5 content.

This study is part of a national mandate to characterize sediments in the Exclusive Economic Zone (EEZ). The sediments of the offshore region of the EEZ of the U.S. have been identified as the source of an extraordinary amount of potential mineral wealth, and this wealth may include phosphatic minerals whose abundance is potentially large but still poorly known. Specifically, this study focuses on the occurrence of phosphate in onshore, coastal sediments of northeastern Georgia. These sediments are a landward continuation of the offshore Continental Shelf sediments, and they occur on what presently is land simply because they were deposited during past, higher stands of sealevel. This study of the Georgia coastal sediments resulted from earlier research investigations of the sediments of the Georgia shelf that have shown the existence of enormous resources of phosphorite. For the past century, it has been known or suspected that vast amounts of phosphatic material occur in the upper 100 m of coastal and shelf sediment of northeastern coastal and offshore Georgia. Phosphorite deposits were already observed by Murray (1885); however, it was not until the work of Manheim and others (1980) and Poppe (1981), extensive borehole studies on land (Furlow 1969 and references therein), and recent work on the shelf off Georgia (Kellam and others, 1989; Popenoe, in press; and Herring, Popenoe, and others, in press) that the sheer volume of the deposits has been revealed. The Georgia coastal and offshore phosphatic sediments are part of a large system of Neogene phosphatic sediments on the east coast and continental shelf of the U.S. that ranges in location from south of the Florida Keys to the Scotian Shelf (Manheim and others, 1980; Manheim and Herring, 1989 and references therein; and Riggs, 1984). In these areas, the offshore deposits are a continuation of the Neogene phosphatic province on land, which, at present, provides about 87 percent of the phosphate mined in the U.S. This entire system of phosphorite deposits appears linked to a complex interaction among sea level, ocean currents, and a depositional system that furnished abundant phosphate to the sediments and provided for subsequent concentration and preservation of the phosphorite (Riggs, 1984).

Characterization of the Neogene phosphatic sediments offshore of the southeastern U.S. is important primarily because of the phosphate rock resource potential of the sediments. Phosphate rock is used principally to produce fertilizer products and is our Nation's most important agricultural mineral resource. Two key aspects of phosphate assure its future need: 1) it is bioessential to all life; and 2) it has no substitutes. Consequently, the present and increased future demand for phosphate to assure adequate food production in the world is unequivocal. Although the U.S. at present is the world's largest producer of phosphate rock, satisfying both its domestic need as well as providing a major share of world export market, domestic production of phosphate rock will decline in 15 to 20 years unless new sources are found and added to producible reserves

(Herring and Stowasser, in press). Consequently, the U.S. may lose current export revenue and, worse, may have to import fertilizer to supply the domestic agricultural sector's demand.

The U.S. has immense phosphate rock resources, both onshore and offshore, but most of these are not economically recoverable at present. Should economically feasible recovery from the offshore extensions of the Miocene phosphorite deposits in the southeastern states become possible, the production from them would continue to assure an adequate supply of phosphate for U.S. food production well into the future. Major deposits, perhaps amounting to several hundred billion tons of phosphate rock, are suspected to occur offshore North Carolina and Georgia. In the northern Georgia offshore field alone, it has been suggested that more than 100 Mt (million metric tons) of phosphate occur (Riggs, 1984; Marvasti and Riggs, 1987), and the Georgia coastal area proximal to the cores discussed in this report has been estimated to contain 6,500 Mt of phosphorite ore, or about 1500 Mt of phosphate concentrate (Furlow, 1969). Furthermore, Herring and others (in press) have inventoried the phosphate resources of the Georgia shelf sediment over an area that includes the eight 100-m deep TACTS Boreholes and extends northwest to the Savannah Light Tower borehole then southwest to include the boreholes discussed in this report. Phosphatic sediments occur throughout these sediments; however, the richest phosphorite beds are in the middle Miocene (Serravallian) rocks, where they constitute as much as 70 percent of the rock mass. On the Georgia shelf, the Serravallian section extends over 20,000 km^2 and averages 35 m in thickness and 20 percent carbonate fluorapatite. Thus, this section on the shelf contains approximately 200,000 Mt of phosphate rock. A useful perspective on these tonnages is provided by comparing them with the U.S. production of phosphate rock, which for the past 6 years has averaged 46 Mt annually.

Finally, there are additional justifications for this study--other resources, for example heavy minerals, occur in these sediments besides phosphate, and there are environmental considerations that concern extraction of all resources from these offshore sediments, as well. All of these considerations demand detailed understanding of the sediment composition such as provided in this and subsequent reports.

Previous Work

Biostratigraphy and lithostratigraphy of these and similar age Miocene to Holocene rocks of the Georgia Coastal Plain have been described by Huddlestun (1988). However, little published borehole control on stratigraphy of the sediments to between 50 and 100 m depth exists in the area of these boreholes, either onshore or immediately offshore, except for some description of the offshore TACTS Cores (Manheim, 1988; Manheim and Herring, 1989; Herring, Manheim, Briggs, and others, in press; Herring and Manheim, in press; Herring and Manheim, 1989a; Herring and Manheim, 1989b; Manheim and others, 1989; Manheim and others, 1991; Manheim and others, in press). Manheim and others (1991) have released some preliminary hydrology, lithostratigraphy, and phosphorite concentration data on the Tybee Borehole. The stratigraphy and economic geology of the local area (eastern Chatham County) phosphate deposit was discussed by Furlow (1969). Other pertinent information includes a project report assessing Georgia offshore minerals that was prepared for the Georgia Geologic Survey (Zellars-Williams, 1988). The shallow seismic stratigraphy of the Georgia Continental Shelf and Slope, interpreted using high-resolution seismic-reflection data, are described by Popenoe (1991). This latter study includes interpreted cross sections and isopach and structure-contour maps of the surface through Oligocene sediment. Some seismic stratigraphic analyses exist of sediments in the nearby offshore and are detailed in the study by Kellam and others (1989) and references therein.

METHODS

Coring and Sampling

The boreholes were drilled February 1990, using a truck-mounted, rotary table drill rig. Sediments were cored at 1.5 m (5 ft) drilling intervals with a 7.62 cm (3 in) outside diameter hollow nose drill bit using NX wireline core barrel with a 4.76 cm (1.875 in) internal diameter. Preliminary lithologic logs for the boreholes are given in Figure 2 and Figure 3.

In this study, 46 samples were taken from Borehole GAS-90-2, of which 16 samples were size separated, and 32 samples were taken from Borehole GAT-90, of which 6 samples were size separated. Sediment samples were obtained by quartering sections of core along their length after first removing drilling mud and debris from the outside of the core. Loose, disaggregated samples were subsampled using cone-and-quarter splitting to homogenize the sample and reduce sample size to between 50 and 100 g. Samples were stored in plastic bags to retard desiccation and shipped to Denver for processing. Most of these samples are channel samples. That is, a slice of the core of uniform width was taken over the entire length of the sample interval that is listed in the data tables. The intent of this type of sampling is that the analyses represent the average composition over the entire interval. Because of limited recovery, some sections are poorly represented in the channel samples; this is especially true of post-Miocene strata. Overall core recovery, however, is quite good--for Borehole GAT-90, the channel samples represent 91 percent of the drilled intervals while for Borehole GAS-90-2 the sampled intervals represent 88 percent of the total depth of the borehole. Tables 1 and 2 include a list of all samples, including the recovered masses of the size fractions, for both boreholes. Sample depths listed in these tables are those reported by drillers during coring and are assumed to be accurate even though there have been subsequent minor revisions in the thicknesses and depths of the various lithostratigraphic formations and members.

Approximate phosphate contents were estimated for each bulk sample. Those samples that contained more than about 10 percent phosphate were screened and the size fractions analyzed. Samples with the lesser amount of phosphate were dried at 75° C then ground to pass 100 mesh in preparation for chemical analysis. The phosphate-enriched samples were sonicated in distilled water to disperse clay and remove it from the surfaces of other, coarser minerals. Samples were then wet sieved to separate the sediment into 4 or 8 size fractions and each fraction was processed similar to the bulk samples by drying and grinding to <100 mesh. For the size analysis study, the size cutoffs used were, in standard mesh screen sizes, >18, 18-60, 60-170, and <170. These size cutoffs are used because they are equivalent to the present size separations used to process phosphate ore, called matrix, in the southeastern U.S.: 1) the >18 mesh fraction, called pebble, is a commercial product and most is manufactured directly into phosphoric acid without any additional beneficiation; 2) the fraction from 18 mesh to about 150 mesh, called feed, is a combination of mainly quartz and phosphate and is beneficiated using mineral flotation to remove quartz; the beneficiated phosphate, called concentrate, also is a commercial product, most of which is supplied to the phosphoric acid manufacturing plant; 3) the <150 mesh fraction, called the fine-grained portion or fines, is a waste product and is discarded. Carbonate shell debris compromises the quality of phosphoric acid production and, because of difficulty of chemical separation, is an undesirable component of the feed size material. In this study, the fine fraction has been set at <170 mesh; however, in order to characterize the amount of phosphate in the fine-grained fraction (<170 mesh) in greater detail, the <170 mesh fraction from a sediment sample from the enriched phosphate zone of each borehole was further separated in an extended sieving experiment. The additional sieve cutoff sizes used were 170-200, 200-230, 230-270, 270-325, and <325. This latter size cutoff represents the limit of what effectively can be removed by sieving. Size cutoffs for all sieves used in this work are listed in Table 3.

Table 3. Standard Mesh Size Cutoff Openings, in mm and µm

Sieve Size	Opening, mm	Opening, µm
18	1.0000	1000.0
60	.2500	250.0
170	.0880	88.0
200	.0740	74.0
230	.0625	62.5
270	.0530	53.0
325	.0440	44.0

Analytical Techniques - Estimation of Sedimentary Components

Microscopic examination of the samples shows that the sediments from the two boreholes discussed in this report have varying proportions of detrital quartz and aluminosilicate minerals, carbonate, and phosphate. Carbonate detritus can be a major component of the sediments, especially in the shallower sections of core, and consists of dolomite and shell debris composed of calcite and aragonite. Silica, besides its presence in quartz and biogenic debris, also occurs in aluminosilicate minerals, mostly in illite-smectite clay but also in minor feldspar. The mineral abundance estimations given in this report are visual estimations by volume using optical microscopy and are checked against a set of reference standards of known composition or against standard comparison sheets for estimating percentage composition. Masses of the various mineral fractions have been estimated by assuming all minerals to be of uniform density, specifically that of quartz and average aluminosilicate minerals, about 2.7 g cm^{-3}. While this density appears slightly low for phosphate minerals (pure apatite is 3.2 g cm^{-3} and carbonate fluorapatite is about 2.9 g cm^{-3}), experience shows that most of the phosphate granules commonly encountered in these offshore sediments, because of their biogenic origin and enhanced porosity, have dry densities ranging from 2.7 to 2.85 g cm^{-3}.

RESULTS

Figures 4 and 5 show the profile of the concentration of sedimentary components for each hole. The major minerals in the two cores discussed in this report consist of varying proportions of detrital quartz and aluminosilicate minerals, carbonate, and phosphate. The detrital siliciclastic component includes coarse-grained quartz as the dominant phase, less common silt-size aluminosilicate minerals, mostly feldspar, and minor quartz, and a silt- to clay-size fraction that is composed mainly of aluminosilicate minerals and minor quartz. Quartz abundance is usually inverse to that of phosphate (Figures 5 and 6). The second major sediment component is varying quantities and types of biogenic detrital material, including minor organic carbon. Most of this is calcium carbonate shells derived from planktic and benthic forams and mollusks. Occasionally, this material forms a coarse shell hash that occurs in layers and is especially common in the surficial 20 m and in an occasional deeper horizon of the sediments in both boreholes. Minor abundances of dolomite, most likely originating from the conversion of biogenic carbonate, is included in this fraction. There also are minor occurrences of siliceous biogenic sediment from sponge spicules, diatoms and radiolaria, and, when these occur, they are usually dispersed throughout the sediment. In both boreholes, the middle sections contrast with the upper sections in having a greater portion of the detritus as aluminosilicate minerals. The third major sediment component is phosphate. The sediments are phosphatic (>2 percent phosphorite) throughout most of their length in both boreholes; however, the richest phosphorite bed is the Tybee Phosphorite Member of the Coosawhatchie Formation, which occurs in the middle Miocene (Serravallian) rocks. Throughout the strata, the phosphate grains are usually rounded to well rounded and opaque black to transparent light yellow brown. A mild, slow evolution of CO_2 occurs when these grains are submerged in 2N HCl, indicating that carbonate ions substitute into the phosphate minerals. Based on X-ray analysis, the predominant phosphate mineral is francolite (carbonate fluorapatite or CFA) (McClellan and others, 1986). Phosphatic sediment ranges from silt to sand-sized, with about 80% of the phosphate granules >0.05 mm in diameter. Few of the phosphate granules in the >170 mesh fraction of the size-separated samples are >1mm in diameter: for Borehole GAS-90-2, only 4 percent of the mesh phosphate is >18 mesh; and in the 7 samples from Borehole GAT-90, in which the phosphate is coarser in size than in the other borehole, an average of 32 percent of the phosphate is in the >18 mesh fraction. Phosphatic material also includes fish teeth, mostly from sharks, and a minor component of collophane as phosphatized fossil parts, mostly brachiopod plates. Finally, Pliocene to Holocene samples occasionally contain woody material or peat, both as discrete layers and flecks occurring throughout the bulk sediment.

The Tybee Island Borehole, GAT-90, consists of 32 composited channel samples that sampled 88 percent of the length of the core. Most samples from this borehole were processed as bulk samples, as the typical bulk phosphate content was estimated to be about 5 percent or less. However, six samples, ranging from 40 to 65 g, were size-separated into 4 fractions, and a duplicate of one of these, the most phosphatic, was separated into 8 fractions. The Tybee Phosphorite Member occurs from 24.6 to 27.0 m depth in this borehole, but, clearly, there are phosphatic horizons immediately above and below the lithostratigraphic pick of the Tybee interval (Table 2; Figure 3).

The Skidaway Island Borehole, GAS-90-2, has excellent sample coverage throughout its length. The Miocene to Oligocene interval includes, in order of increasing age, the Coosawhatchie, Marks Head, Parachucla, and Lazaretto Creek formations (Figure 2), and this interval constitutes 35 of the 46 borehole samples, with 97 percent of the interval included in composited channel samples. Of these, 13 samples have been further analyzed as size-separated fractions. In Core GAS-90-2, the Tybee Member occurs from 33.1 to 41.1 m depth. There is a 0.45 m unsampled section within this interval and a 0.91 m thick clay parting interval, from 35.36 to 36.27 m, that contains negligible phosphate. Another phosphatic interval, the Ebenezer Beds of the Coosawhatchie Formation, occurs from about 19 to 23 m and contains about 20 percent phosphate. Minor enrichments of phosphate, up to about 5 percent, are present in the clay sequences of the overlying late Pleistocene Satilla Formation. It is likely that some or most of this latter phosphate originated from reworking of older, deeper sediment. In the TACTS cores, recent evidence indicates that primary phosphate extends into lower Pliocene rocks or perhaps even into younger strata (Manheim, Huddlestun and others, 1991).

For the GAS Borehole, the weighted averages (average for the entire interval, which considers each composite sample's phosphate concentration times the length represented by that composite sample) of the bulk phosphate percentage estimations for the deeper intervals are: Ebenezer Beds, 12; Berryville Clay Member, 1; Tybee Phosphorite Member, 23; Marks Head, 2; Parachucla, 3; and Lazaretto Creek, 2 percent, respectively. The late Pleistocene and undifferentiated Pleistocene interval, the upper 20 m, has 9 samples with 88 percent coverage of the length of this section represented by composited channel samples. The weighted average bulk phosphate estimate for the entire Pleistocene section is 3 percent of the sample mass. However, there are apparent local enrichments as indicated by two channel-sampled intervals that had 7 and 10 percent phosphate.

Analytical results for the estimated sediment components of the bulk and size-separated samples are given in Tables 1 and 2. Concentration trends of the phosphate in the bulk sediment samples and the > 170 mesh size-separation samples are generally similar (Figures 4 and 5); however, there is a distinct underestimation of phosphate in the bulk sediment samples compared to the >170 mesh samples in phosphate-enriched zones. The estimation of phosphate in bulk samples is especially difficult for clayey samples, particularly those in which the phosphate abundance is high--greater than about 10 percent of the sample. The reason for this is that the clay often coats the phosphate and other sediment grains and prevents identification. In these clay-rich samples, phosphate is commonly underestimated as shown in Figures 4 to 6, and this occurs, especially, in those samples in which the phosphate content is greater than about 25 percent of the bulk sample. Consequently, plots of the estimations of bulk phosphate concentration in the cores should be taken only as a crude approximation of the amount of phosphatic material present, and it is possible that some of these estimations are particularly low in the more phosphatic sections. The chemical analyses of the samples, to be reported in a subsequent publication, will reveal any discrepancies between estimated and actual phosphate content. In contrast to the bulk sample estimations, the size-separated sediment samples have clay removed from all but the finest size fraction, and the visual estimates of phosphate in the coarser size fractions should be considered to be far more reliable than those of the bulk samples.

For the Tybee Phosphorite Member in the GAS Borehole, the bulk sample estimations of phosphate clearly underestimate true phosphate content as shown by their comparison to >170 mesh estimations (Figure 6). In this interval, the weighted average of the bulk phosphate percentage estimations is 23 compared to that of the >170 mesh phosphate percentage of 37. In the >170 mesh samples within the Tybee interval but below the clay parting (samples 36.5 to 39.8 m), the weighted average phosphate concentration is 54 percent of total sample (bulk sediment) mass. The 3 m thick interval of the Tybee Member above the clay parting also is phosphatic, containing as much as 36 percent of dry sample mass as >170 mesh phosphate.

For the 8.5 m-thick, continuously-sampled (except for the unsampled interval from 39.17 to 39.62 m and the 0.91 m thick clay parting interval, from 35.36 to 36.27 m) phosphatic interval through the Tybee Member (samples 33.1 to 40.4 m), the weighted average phosphate content is 41 percent of dry sediment mass. The weighted average of quartz in the >170 mesh portion in the Tybee interval below the parting is 30 percent of sample mass and for the entire Tybee interval (8.5 m section) is 25 percent. Consequently, the sum of phosphate plus quartz for the Tybee interval below the parting is 84 percent of the sample mass, and this means that no more than 16 percent of the mass of the sediment in the interval could be either fine-grained material (<170 mesh) or coarse (>170 mesh) minerals other than phosphate or quartz. In fact, the weighted average of <170 mesh material (fines) for this interval is 15.9 percent, consequently there is negligible mass (<0.1 percent of sample mass) of minerals other than quartz and phosphate in the >170 mesh fraction. For the entire 8.5 m interval, the weighted average of fines is 33.4 percent, which means that only 0.5 percent of the mass of the sample is minerals other than phosphate or quartz in the >170 mesh fraction. Finally, the >170 mesh phosphate to >170 mesh quartz ratio for the Tybee Member is about 1:1.

Size separation of the phosphate-rich samples shows that the majority of the mineral mass for phosphate and quartz is in the fine silt size fraction (Tables 4 to 6). Respective mineral percentage abundances for phosphate, quartz, or carbonate are reported for each size fraction in Tables 4 and 5. The respective mineral abundances for each size fraction refer to the percentage of total minerals in that size fraction; therefore, the mass fraction for a given mineral in a specific size class, also listed in Tables 4 and 5, is found as the product of percentage occurrence of that mineral in the size fraction times the percent of total mass of that size fraction. Detrital quartz varies in its relative amount in the various size fractions and shows increasing abundance in the smaller size fractions. Most of the >170 mesh quartz occurs in the 60-170 mesh fraction in both boreholes, averaging 60 percent of the >170 mesh quartz in Borehole GAS-90-2 and 69 percent in Borehole GAT-90. Phosphate granules also vary in their relative abundance in the various size fractions and in Borehole GAS-90-2, like quartz, are more abundant in the smaller size fractions (Table 6). Most of the >170 mesh phosphate granules are in the 60-170 mesh fraction for each borehole, averaging 63 percent of the >170 mesh phosphate of the samples in Borehole GAS-90-2 and 46 percent in Borehole GAT-90. Size-separated samples of the Tybee Borehole commonly have a greater fraction of >170 mesh phosphate in the >18 mesh fraction than those from the Skidaway samples in both the set of samples from the Tybee interval as well as the set of all samples. For the Tybee interval in the Tybee Borehole the >18 mesh phosphate expressed as a fraction of >170 mesh phosphate averages 25 percent compared to 3 percent in the same interval for the Skidaway borehole (Table 6).

An extended size separation using sieving was performed on one phosphatic sample from each borehole, and the results are included in Tables 4 and 5. For the GAT Borehole, the extended size separation sample (25.47 m) recovers 95 percent of the >325 mesh phosphate mass by sieving at 170 mesh. In Borehole GAS-90-2 the extended size separation sample is from 33.09 m depth, and, although the sample is phosphatic, it has the least phosphate of the Tybee interval. Extended sieving shows that a size cutoff of 170 mesh recovers 82 percent of >325 mesh phosphate. This sample is somewhat different from those in the rest of the Tybee interval--the extended size separation sample has more fine-grained (<170 mesh) material, thus the percentage of >170 mesh phosphate in the sample is considerably less than in the remainder of the samples from the Tybee Member. Also, the extended size sample has a >170 mesh phosphate to quartz ratio of 8.6, which is considerably larger than that of the average of 1.8 for the Tybee interval from 36 to 40 m. In other words, this extended size sample differs slightly from the remainder of the underlying Tybee Member interval in that it is enriched in fine-grained material and deficient in coarse-grained quartz relative to phosphate. These differences suggest that the extended-size sample was deposited in a more offshore or transgressive ocean setting than the underlying Tybee Member. Also, the phosphate in this sample is more skewed toward the fine grained size fraction, with the ratio of 60-170 mesh portion to >170 mesh equal to 83 percent compared to the 36 to 40 m interval average of 63 percent, and this also supports the suggestion that the sample locality was deposited in deeper water than the depositional location for the underlying Tybee interval. In summary, the 82 percent recovery of >325 mesh phosphate by sieving at 170 mesh may not be representative for phosphatic samples in the GAS Borehole, and consequently, higher recoveries throughout the borehole, perhaps more in line with the 95 percent of the Tybee interval in the GAT Borehole, might be expected.

A final point worth making about the extended size separation samples is that these analyses were made on separate splits of the samples rather than simply resieving the <170 mesh fraction. As such, these samples therefore represent duplicate analyses of the size fractions down to <170 mesh and offer some measure of the precision of the sample splitting and degree of sample homogeneity. For the duplicated samples, the agreement between percent water contents and mass distribution for the 4 size fractions is usually 2 percent or better, with most disagreement in the size fractions coming in the >18 mesh portion. The latter size is almost always a minor fraction of the mass of the samples, therefore its discrepancies are unimportant. What most greatly determines variations in the >170 mesh abundance of phosphate and quartz is their respective percentage abundances in the 60-170 mesh fraction. This size fraction has the greatest mass abundance for both extended size separation samples; also, it consists only of quartz and phosphate. Therefore, an increase in the percentage abundance of one mineral component is accompanied by a forced decrease in the other mineral.

Minor pyrite occurs in the sediments and can be detected in hand specimen or using optical microscopy of the size-separated fractions. It tends to occur in clay- and phosphate-rich portions of the sediment. Minor glauconite also occurs in these sediments; it seems to be most abundant in the phosphate-rich sections.

Water contents have been calculated for the size-separated samples by summing the dried masses of the size fractions of that sample. The water contents range from 19 to 47 percent of the wet weight of the samples with a mean value of 29 percent for the GAT size-separated samples and 30 percent for the GAS samples. Assuming an average dry grain density of 2.8 g cm^{-3} for minerals in seawater, these water contents would correspond to porosities ranging from 39 to 71 percent, respectively, with a mean of 54 percent. No salt correction was applied to this calculation as the correction is negligible compared to the assumption about the average grain density. These water contents and porosities should be considered to be minimal values, as no special provisions were taken to prevent water loss from the samples other than quickly bagging them in plastic after core sampling.

DISCUSSION

The thickness and depth of the Serravallian rocks in the Tybee and Skidaway boreholes tie well into the model of the Georgia Shelf sediments that is determined from the previously obtained USGS network of seismic reflection records of the Georgia shelf sediments. On seismic records, this section shows minor local variations and generally thickens eastward and crops out on the Continental Slope underneath a capping of younger rocks (Herring and others, 1991). The phosphorite content of the shelf sediments has been sampled and characterized, but the outcrop on the Continental Slope to the east has not been sampled. Throughout most of this section the phosphatic grains range from silt- to sand-sized, with about 80 percent of the phosphate granules between 0.05 and 0.25 mm in diameter.

There are occurrences of phosphorite in Pliocene to Quaternary sediments. Some of these occurrences clearly are of primary origin in the offshore TACTS strata (Manheim and others, 1991), but others may result from reworking of older strata. The above observations suggest that primary deposition, as opposed to secondary enrichment, of phosphorite should not occur in sediments deposited in estuarine to bay-like or nearshore environments but, instead, should occur farther offshore in transgressive conditions, which may be linked with dolosilt and mudstone sequences found on the fringes of deltaic deposits. On the other hand, major zones of phosphate (secondary) enrichment occur chiefly at major unconformity boundaries (tops of Oligocene, lower and middle Miocene, upper Miocene, and lower and upper Pliocene) and at prominent intrastratal reflectors representing low sealevel stands corresponding to minor unconformities. These enrichment zones of phosphatic sediment begin immediately beneath the various unconformities and continue well into the overlying sediment.

In the Tybee and Skidaway boreholes, there are minor occurrences of phosphorite in Pliocene to Quaternary sediments that contain peaty sediments. This phosphorite is believed to be secondary as the peaty composition clearly indicates a nearshore environment that could have received reworked phosphatic rock from nearby landward deposits. Consequently, we believe that most of this minor occurrence of phosphorite in Pliocene to Quaternary sediment results from reworking of older strata.

The association of phosphatic enrichment with unconformities suggests a correlation between phosphogenesis and sea level transgression events. Upwelling of deep water landward of the Gulf Stream, but which changed location through time, provided a continual source of phosphate. This phosphate, mostly dissolved but also perhaps particulate, moved landward across the shelf under the influence of Ekman transport of Gulf Stream counterflow and/or offshore wind. Deposition of primary phosphate occurred in interstitial waters of sediments that contained sufficient organic matter to supply phosphorus and mediate phosphate growth, but insufficient organic matter to create an anoxic environment. The evidence from rare earth and other trace elements in nearby offshore boreholes (the TACTS cores) suggests that the phosphorite accumulated under anoxic to suboxic conditions and was reworked under mildly oxidizing conditions. Sedimentologic observations indicate that deposition occurred rather high on the continental slope or on the continental shelf perhaps quite close to shore.

The mineral phases in the two boreholes suggest varying depositional processes. Phosphate co-occurs with clay but inversely correlates with detrital quartz and carbonate, indicating a low-energy depositional environment. In contrast, the variance in distribution of quartz both horizontally and vertically in the shelf sediments likely results from varying degrees of high energy redistributive processes on the continental shelf during deposition.

Phosphate is most concentrated in middle Miocene (Serravallian) strata in the northern part of the shelf, especially at the middle Miocene-post Miocene and other unconformities. Traces to 10 percent phosphate in post Miocene sediments are considered to be reworked from older deposits. However, small phosphate pellets (>150 μm) in fine-grained, organic enriched sediments are believed to be primary. This is supported by the occurrence of pellets in the state of formation within foraminifera and coincident with foraminifera in a distinct bimodal size distribution (Manheim, Farrell, and others, 1991; Manheim, Herring, and others 1991). We believe that the phosphate originated from upwelling of nutrient-laden seawater onto the deeper shelf and upper slope during transgressive seas. These conditions produced organic-enriched muds and subsequent phosphogenesis; pellets were later concentrated by erosion and winnowing during sea level regressions.

Estimation of Recoverable Phosphate

The phosphate resources for the phosphatic intervals of the two boreholes are listed in Table 7. Almost all samples from both boreholes contain phosphatic sediment, but most of the samples have bulk sediment phosphate concentrations <5 percent, and this material has been ignored for resource estimates. Resource estimates of the potentially recoverable phosphate are based the size-separated samples and, hence, the >170 mesh phosphate grains. Recovery tonnages are given per unit area assuming extraction of the stated thickness intervals. Seismic records of these sedimentary units show that there are minor local variations in thickness but, for the most part, thickness changes gradually and usually less than 1 m of thickness per 1 km of lateral extent.

For the GAS Borehole, the resources have been calculated for a 2.9 m thick interval that extends from 36.27 to 39.17 m (samples 36.5 to 39.0), which is the Tybee interval below the clay parting, and for an 8.5 m interval that also includes the entire Tybee interval. In the latter interval we assume that the 0.45 m of unsampled section within the interval are the same average composition as the rest of the interval and that the 0.91 m thick clay parting interval, from 35.36 to 36.27 m, with its average bulk phosphate concentration of about 1 percent, contains no phosphate (samples 33.1 to 40.4). Both of the phosphate-enriched intervals contain <1 percent minerals other than quartz and phosphate in the >170 mesh fraction, therefore conventional mineral separation techniques to separate phosphate concentrate from quartz could be used on this sediment. Recoverable phosphate for an ore zone (matrix) thickness of 2.9 m is 2.2 metric tons/m^2 (T/m^2). If the mined thickness were expanded to the 8.5 m interval, the amount of recoverable phosphate would increase by 65 percent, but the amount of fines (<170 mesh) would increase by 350 percent. Also, the amount of recovered quartz, which would necessitate added cost for chemical separation, would increase by 83 percent. If the overlying 3.5 m thick phosphatic interval in the Ebenezer Beds, which extends from 19.66 to 23.16 m (samples 20.0 to 22.4), is included in the resource estimate, the amount of recoverable phosphate increases to 4.1 T/m^2, but recovered quartz increases to 4.7 T/m^2 and fines increase to 4.6 T/m^2. The Ebenezer interval has a weighted average >170 mesh phosphate content of only 11.5 percent and, therefore, is subeconomic by present standards.

For the GAT Borehole the resources have been calculated for the single most enriched phosphate sample, a 1.5 m thick interval, and for the 4.6 m, continuously sampled interval that extends from 23.2 to 27.7 m (76 to 91 feet; samples 23.9 to 27.0). The 1.5 m thick, most phosphatic interval contains 1.5 T/m^2 of recoverable phosphate or about 68 percent of the recoverable phosphate of the Tybee interval in the GAS Borehole. This decrease in the recoverable phosphate is due to the thinner Tybee interval in the GAT Borehole. If the GAT Borehole mined section is expanded to 4.6 m in thickness, in order to include the entire Tybee interval, the amount of recoverable phosphate increases to 2.3 T/m^2. Like the GAS section, this trades off additional recoverable phosphate for proportionally greater amounts (per ton of recovered phosphate) of fine-grained material that requires disposal and of quartz that requires chemical separation from the phosphate. However, there is an additional negative aspect to the expanded interval--the >170 mesh recovered fraction would also contain undesirable waste carbonate shell debris equal to 6.7 percent of total mined sediment mass (including fines). Most of this carbonate debris is >18 mesh in size and occurs in the interval from 26.21 to 27.74 m (sample 27.0). While it would be easy to remove this carbonate debris by discarding recovered ore that is >18 mesh, this would also remove any >18 mesh phosphate from the recovered ore. A third scenario shows the effect of screening the matrix and limiting the recovery to the fraction from 18 to 170 mesh. Recoverable phosphate, now 18-170 mesh, rather than >170 mesh, would decrease from 37.5 percent of mined sediment mass to an average of 31.9 percent, and recovered quartz would decrease from 29.7 to 26.7 percent. Recoverable phosphate resources would decrease from 2.3 to 1.9 T/m^2, and the recovered material would be slightly enriched in quartz, which would require a higher cost of chemicals for quartz removal per ton of recoverable phosphate. Also, the fines plus the >18 mesh material, which require disposal, would increase from 1.6 to about 2.6 T/m^2. In summary, the small gain in recoverable phosphate by mining the expanded interval but removing >18 mesh carbonate and other material, from 1.5 to 1.9 T/m^2, would be offset by having to handle 3 times the amount of matrix and nearly 2 times the amount of disposable material, as well as incur slightly increased cost per ton of product for quartz removal.

The extended-sieving size separations indicate that screening at 170 mesh recovers 82 to 95 percent of the phosphate that is in the >325 mesh fraction. In other words, the amount of phosphate in the 170 to 325 mesh fraction is usually a minor part of the screenable (>325 mesh) phosphate mass. The phosphatic sediment discussed in this report, if screened using this 150 mesh cutoff, would produce slightly less recoverable phosphate than the resource estimates based on the 170 mesh recovery data. Nonetheless, if these sediments were screened at 170 mesh, the average >170 mesh phosphate contents relative to the bulk sediment are greater than the U.S. industrial recovery ratio of phosphate rock pebble plus feed fractions to crude ore, which averages about 29 percent. As a minor point, some industrial screening cutoff for processing phosphate ore presently is 150 mesh.

The phosphatic feed material has a quartz to phosphate ratio of nearly 1:1, which suggests that presently available mineral separation techniques could be used to separate the quartz from the phosphate and produce a concentrated ore product. Also, the Tybee interval and the immediately adjacent underlying and overlying intervals considered in the resource estimates have only negligible mass of other minerals in the >170 mesh fraction. Therefore, there is little other mineral matter that could interfere with ore processing. Other than the >170 mesh phosphate and quartz fractions, the remaining mass of the sample is nearly all fines and would be discarded if this ore were processed using currently available industrial processing techniques. Clearly, the phosphatic sediment of the Tybee Member would produce a screened phosphate ore at least comparable in feed quantity and quality to that processed by industry in the U.S. at present.

SUMMARY

The two boreholes discussed in this report have varying proportions of detrital quartz and aluminosilicate minerals, carbonate, and phosphate. Phosphatic sequences contain as much as 74 percent phosphate (>170 mesh phosphate relative to the bulk sediment) in the middle Miocene (Serravallian) strata in both boreholes, especially in the Tybee Phosphorite Member of the Coosawhatchie Formation (24.6 to 27.0 m in Borehole GAT-90 and 33.1 to 41.1 m in Borehole GAS-90-2). The >170 mesh samples within this member had a weighted average phosphate concentration of 49.7 percent. The important results of these studies are: 1) zones of phosphorite enrichment of several meters thickness occur throughout sediments of the Georgia Shelf; 2) size separation of this sediment to >170 mesh produces enriched phosphate on the order of the grade commercially mined at present at onshore localities in the southeastern U.S.; 3) phosphate to quartz ratios in the >170 mesh sediment and the amount of fine-grained material (<170 mesh) in the bulk samples are about equivalent to that in operating phosphate-rock mines in the southeastern U.S. In summary, the phosphatic intervals of both boreholes have ore grade and phosphorite/quartz ratios similar to the phosphate deposits presently mined on land.

ACKNOWLEDGMENTS

The manuscript was reviewed by Earl Shapiro of the Georgia Geologic Survey and James Cathcart of the USGS. This study was supported in part by the joint Minerals Management Service/Georgia Task Force on Offshore Hard Minerals.

REFERENCES

Furlow, James W., 1969, Stratigraphy and economic geology of the eastern Chatham County phosphate deposit: Georgia Geologic Survey, Bulletin 82, 40p.

Herring, J.R., Popenoe, P., and Manheim, F.T., 1991, Overview of phosphorite occurrence and development on the Georgia Shelf: Geol. Soc. Amer., Northeastern and Southeastern Sections, Abstract with Programs, p. 44.

Herring, J.R., Manheim, F.T., Briggs, P.H., Bartel, A.J., and Skipp, G.L., in press, Preliminary Bulk Chemical Analysis of Phosphatic Sediments from the TACTS Boreholes, Georgia EEZ. Part I. Holes B, D, F, G, and H: U.S. Geological Survey, Open File Report 91-xxx.

Herring, J.R., and Manheim, F.T., in press, Cd, As, V, and other metals in phosphatic sediments from the TACTS Boreholes, Georgia EEZ. Part I. Holes B, D, F, G, and H: U.S. Geological Survey, Open-File Report 91-xxx.

Herring, J. R. and Manheim, F.T., 1989a, Geochemistry of the Neogene phosphatic sediment on the Georgia Shelf: Geol. Soc. Amer., Absts. with Programs, v. 21, p. A275.

Herring, J.R. and Manheim, F.T., 1989b Concentrations of Cd and As in sediments of the Georgia Shelf--anthropogenic or natural?: Trans., Amer. Geophys. Union, v. 70, p. 1045.

Herring, James. R., Popenoe, Peter, Manheim, Frank.T., and Huddlestun, Paul F., in press, Phosphatic Miocene sediments of the Georgia continental shelf--important resources for the future: submitted to Geol. Soc. Amer., Absts. with Programs.

Herring, J.R., and Stowasser, William F., in press, Phosphate--our Nation's most important agricultural mineral commodity and its uncertain future: submitted to Geol. Soc. Amer., Absts. with Programs.

Huddlestun, Paul F., 1988, A revision of the lithostratigraphic units of the Coastal Plain of Georgia--the Miocene through Holocene: Georgia Geologic Survey, Bulletin 104, 162 p.

Kellam, J.A., Shapiro, E.A., and Henry, V.J., 1989, Mineral resource assessments for the Continental Shelf of Georgia as a part of the Continental Margins Studies Program: seismic interpretation of the phosphatic Miocene-age Hawthorne Group, Marine Geology, v. 90, p. 59-68.

Manheim, F.T., Farrell, K., Huddlestun, P.F., Herring, J.R., and Krause, R.E., 1991, The Tybee Island corehole, Georgia: preliminary hydrology, lithostratigraphy, and phosphorite concentration: Geol. Soc. Amer., Northeastern and Southeastern Sections, Abstract with Programs, p. 62.

Manheim, F.T. and Herring, J.R., 1989, Location and core background data, p. 4-24 *in*: Phosphorite potential in the Continental Shelf off Georgia: Results of the TACTS core studies, USGS Open-File Report 89-559.

Manheim, F.T., Herring, J.R., Popenoe, P., and Huddlestun, P.F., 1991, Characterization and extent of pelletal phosphorite deposits in Tertiary strata off Georgia: new data from the TACTS core drillings: Geol. Soc. Amer., Northeastern and Southeastern Sections, Abstract with Programs, p. 62.

Manheim, F.T. (ed.), 1988, Phosphorite potential in the Georgia EEZ: results of the TACTS core studies: Georgia Hard Minerals Task Force, 80 p.

Manheim, F.T., Huddlestun, P.F., Herring, J. R., and Popenoe, P., in press, Primary phosphorite development beneath the shelf along the Atlantic margin of the U.S.: temporal extension of the middle Tertiary phosphogenic system into post-Miocene time: submitted to Geol. Soc. Amer., Absts. with Programs.

Manheim, F.T., Popenoe, P., Huddlestun, P. and Herring, J.R., 1989, Phosphorite in Miocene strata off Georgia: implications of the TACTS corehole data : Geol. Soc. Amer., Absts. with Programs, v. 21, p. A344.

Manheim. F. T., Pratt, R. M., and McFarlin, P.F., 1980, Composition and origin of phosphorite deposits of the Blake Plateau: SEPM Spec. Pub. No. 29, p. 117-137.

Marvasti, A. and Riggs, S., 1987, Potential for marine mining of phosphate within the U.S. Exclusive Economic Zone (EEZ): Marine Minerals, v. 6, p. 291-300.

McClellan, G.H., Van Kauwenburgh, S.J., and Isphording, W.C., 1986, Mineralogical overview of phosphorite deposits *in* Textoris, D.A., ed., Guidebook, Southeastern U.S. 3rd Annual Midyear Meeting: Soc. Econ. Paleontol. and Mineralog, p. 341-344.

Murray, John, 1885, Report on the specimens of bottom deposits (collected by the U.S. Coast Survey steamer "Blake" 1877-1880): Harvard Univ., Mus. Comp. Zoology Bull., v. 12, no. 2, p 37-61.

Poppe, Lawrence J., ed., 1981, Data file on the 1976 Atlantic Margin Coring (AMCOR) Project of the U.S. Geological Survey: U.S. Geological Survey Open-File Report 81-239, 96 p.

Popenoe, Peter, 1991, Maps and cross sections depicting the shallow seismic stratigraphy of the Continental Shelf and Slope off Georgia from interpretation of high-resolution seismic-reflection data: U.S. Geological Survey Open-File Report 91-397, 35 p.

Pratt, R.M., and McFarlin, P.F., 1966, Manganese pavements on the Blake Plateau: Science, v. 151, p. 1080-1082.

Riggs, Stanley R., 1984, Paleoceanographic model of Neogene phosphorite deposition, U.S. Atlantic Continental Margin: Science, v. 223, p. 123-131.

Zellars-Williams Company, 1988, Georgia offshore minerals assessment: Georgia Geologic Survey, Proj.Report 14, 246 p.

ILLUSTRATIONS

Figure 1. Locations of the boreholes used in this study. Borehole GAS-90-2 is located at 31° 58' 58" N, 81° 1' 21" W, and has a total depth of 58 m, while Borehole GAT-90 is located at 32° 1' 20" N, 80° 51'5" W, and has a total depth of 52 m.

Figure 2. Preliminary lithologic log for Borehole GAS-90-2. P's indicate phosphatic zones, and inverted omega symbols indicate burrowing zones.

Figure 3. Preliminary lithologic log for Borehole GAT-90. Symbols are the same as for Figure 2.

Figure 4. Borehole GAS-90-2 bulk and >170 mesh phosphate estimations. Concentrations are expressed as a percentage of dry, bulk sediment.

Figure 5. Borehole GAT-90 bulk, >170 mesh phosphate, and >170 mesh quartz estimations. Concentrations are expressed as a percentage of dry, bulk sediment.

Figure 6a. Relationship between initial estimates of carbonate fluorapatite (CFA or phosphate) in bulk sediment samples from Borehole GAS-90-2 and estimates in those same samples after sieving to remove clay coatings from minerals in the >170 mesh fraction. The estimation of CFA in the sieved samples is much more reliable than those for the bulk sediment samples. Note that the bulk sediment estimations underestimate phosphate, especially when the phosphate content is greater than about 25 percent. Figure 6b shows the inverse relationship between >170 mesh phosphate and >170 mesh quartz for the same samples. The data for both bulk and >170 mesh phosphate values refer to the percent of phosphate in the bulk sediment.

Figure 1. Location map of GAS-90-2 and GAT-90 Boreholes

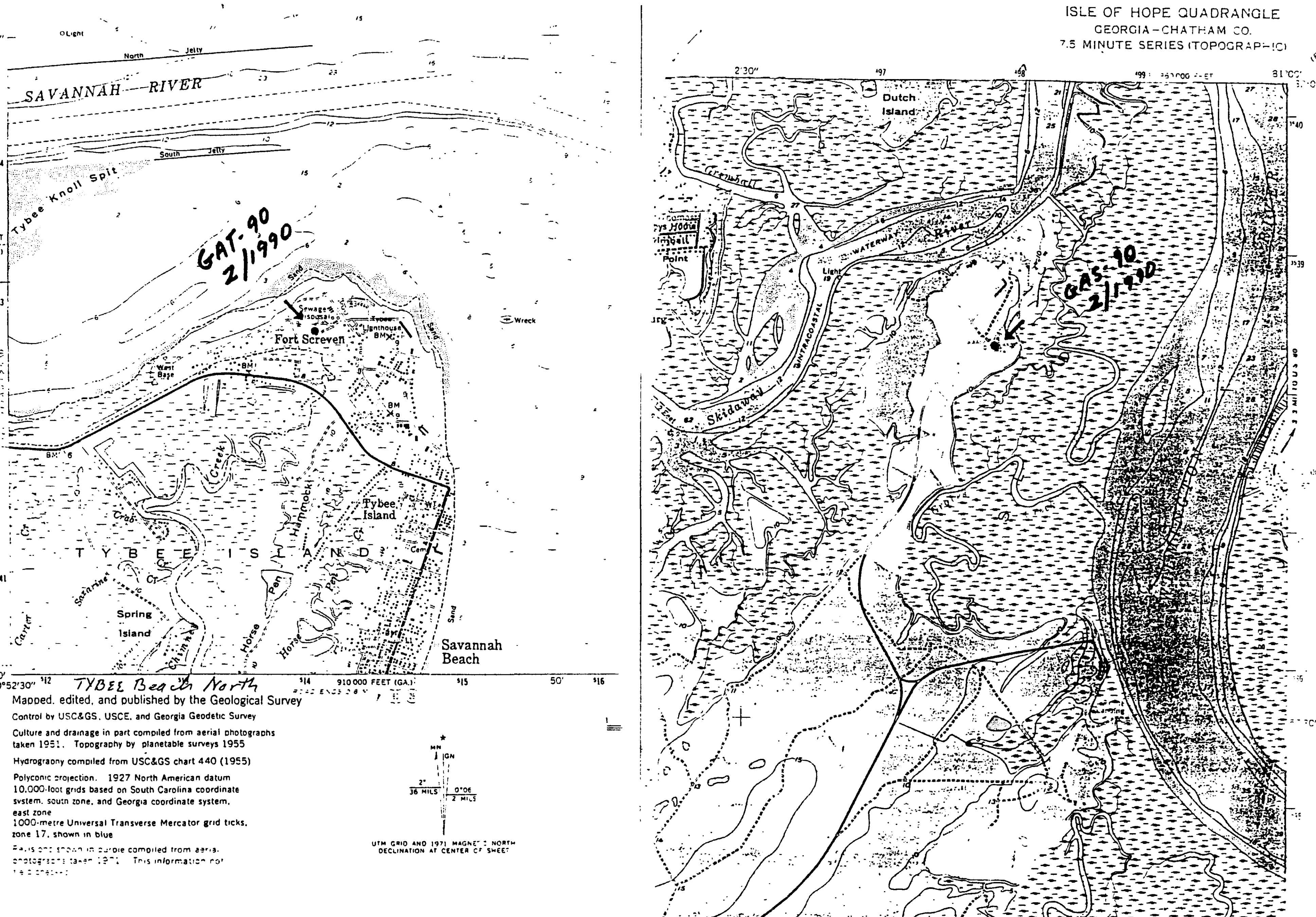

Figure 2. Core GAS - 90 - 2, Skidaway Island, Georgia

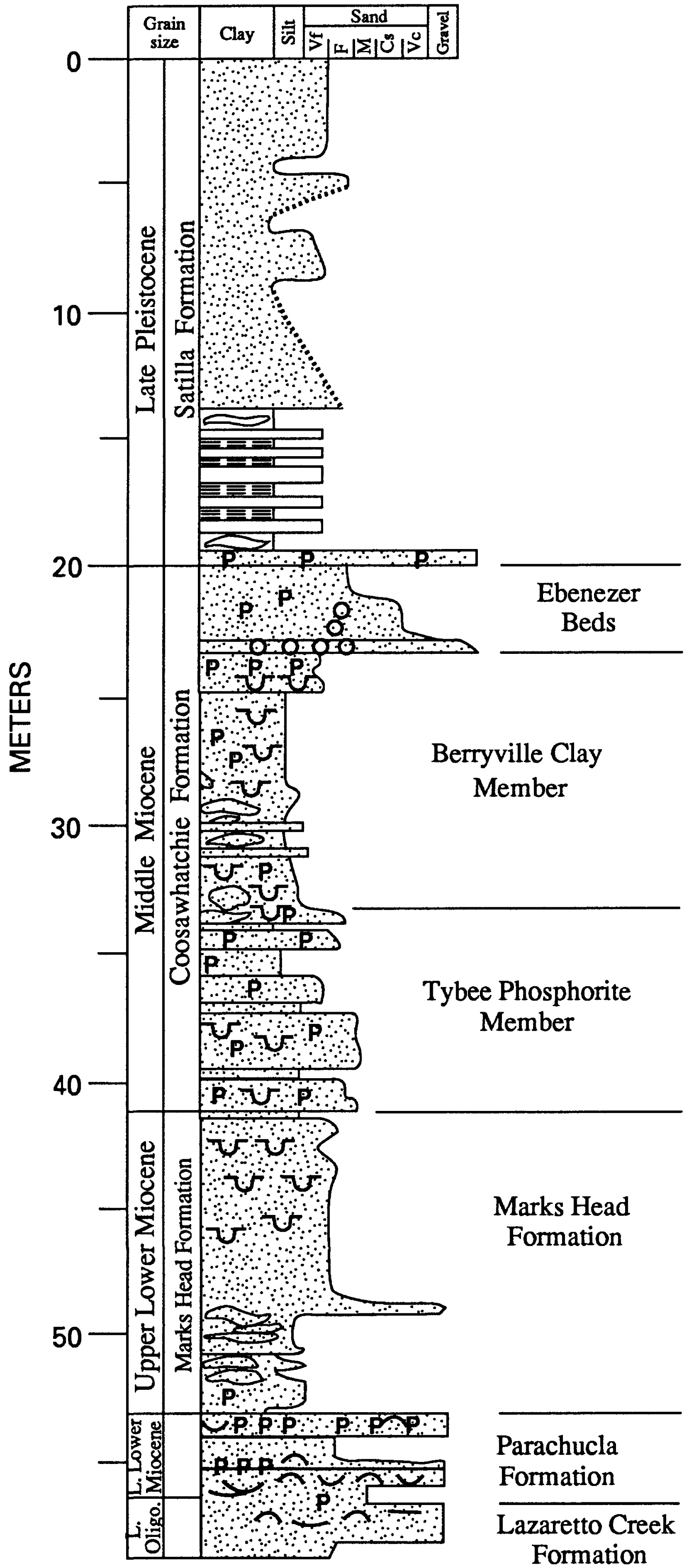

Figure 3. Core GAT- 90, Tybee Island, Georgia

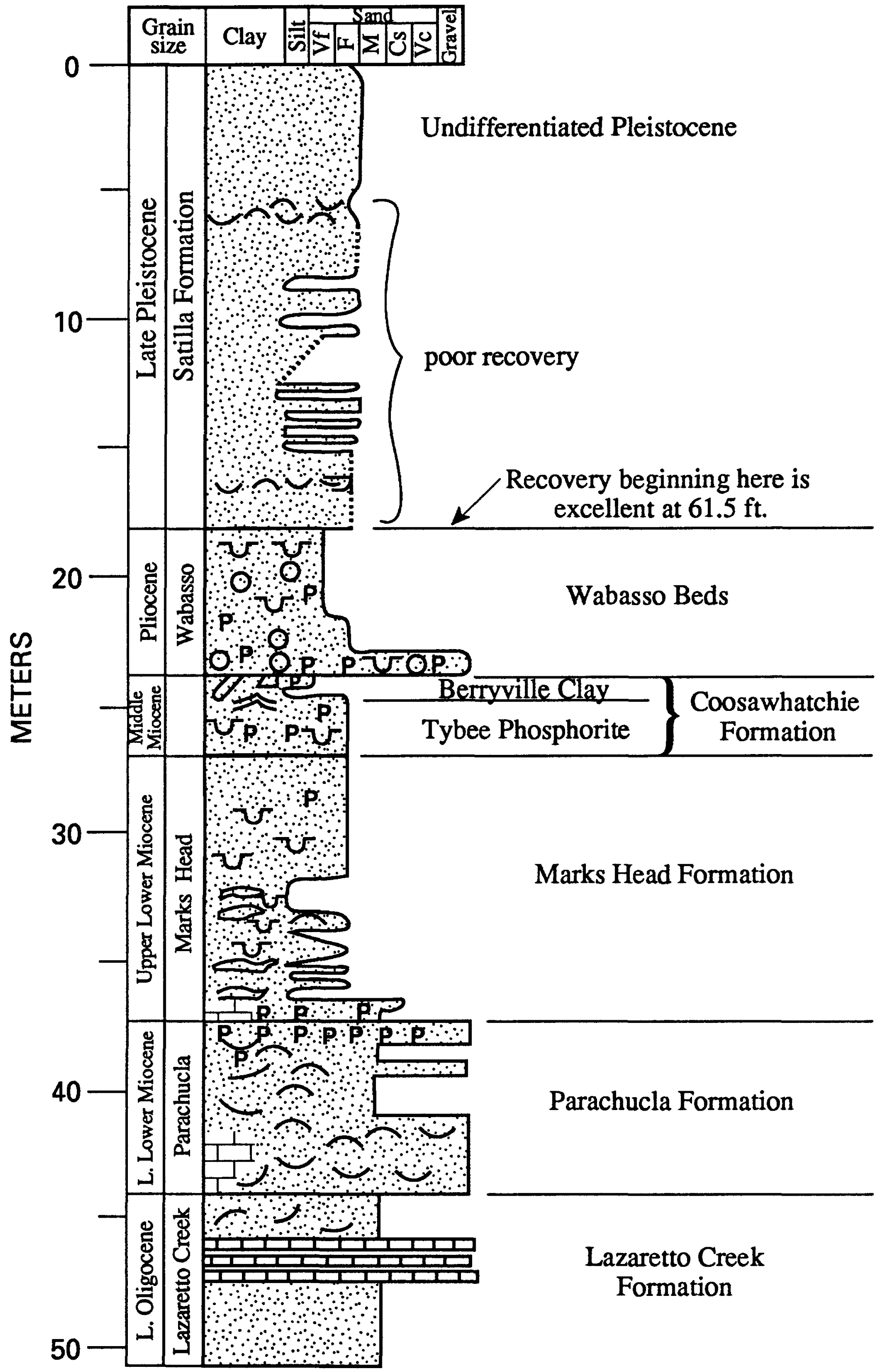

Figure 4

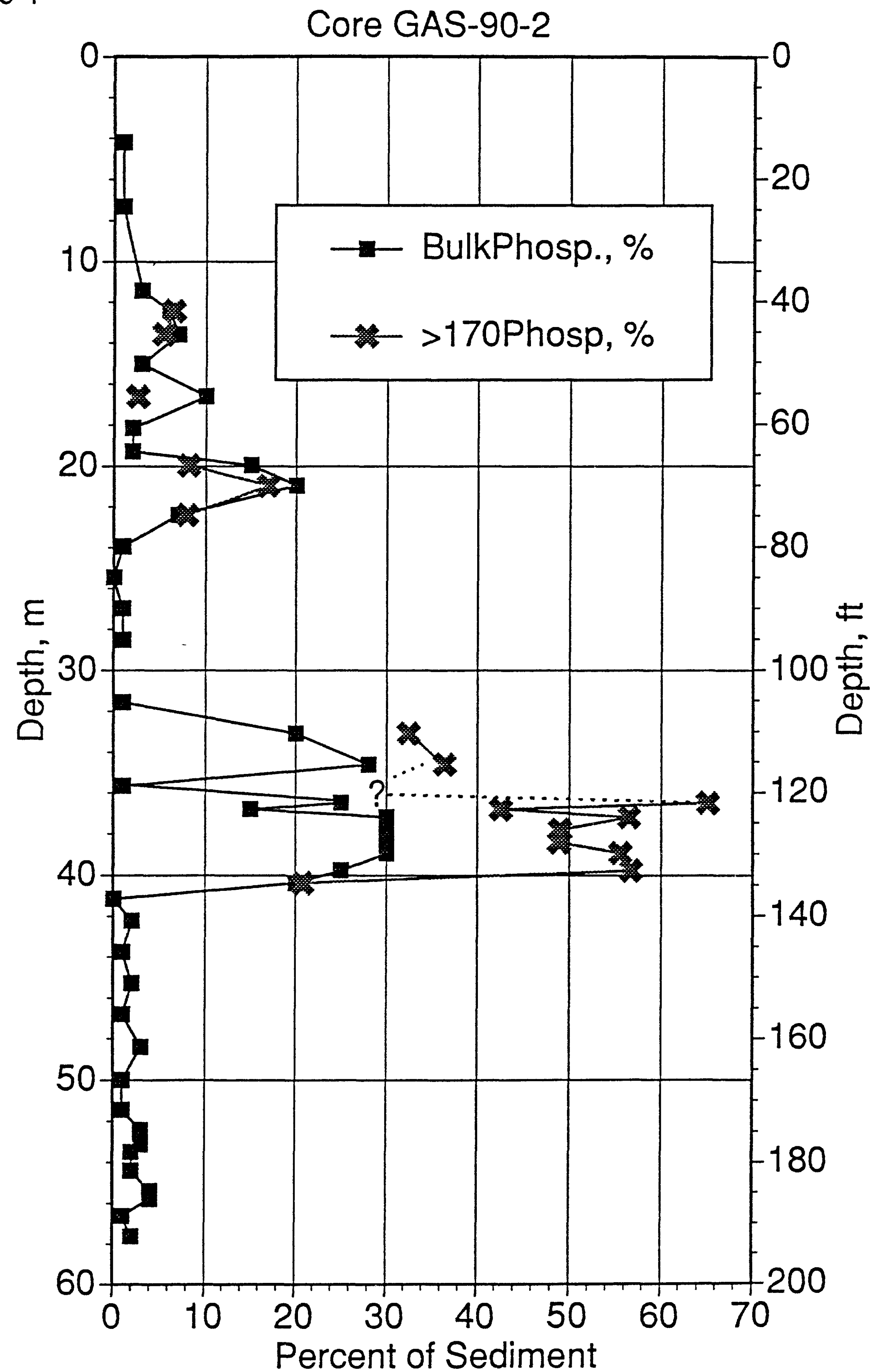
Core GAS-90-2
BulkPhosp., %
>170Phosp, %
?
Depth, m
Depth, ft
Percent of Sediment
0
10
20
30
40
50
60
70
100
120
140
160
180
200

Figure 5

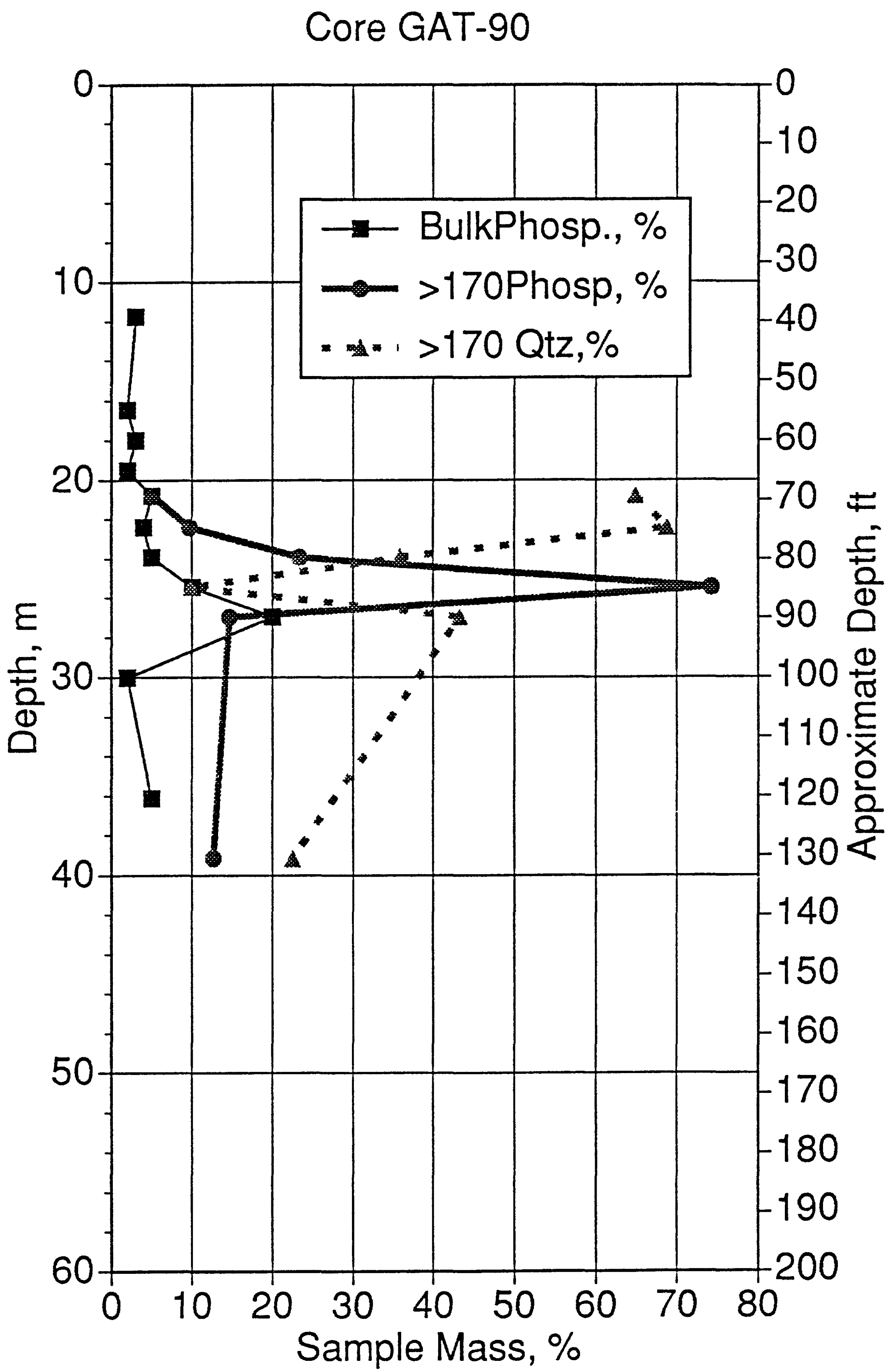
Core GAT-90
BulkPhosp., %
>170Phosp, %
>170 Qtz,%
Depth, m
Approximate Depth, ft
Sample Mass, %
0
10
20
30
40
50
60
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
170
180
190
200
0
10
20
30
40
50
60
70
80

Figure 6a.

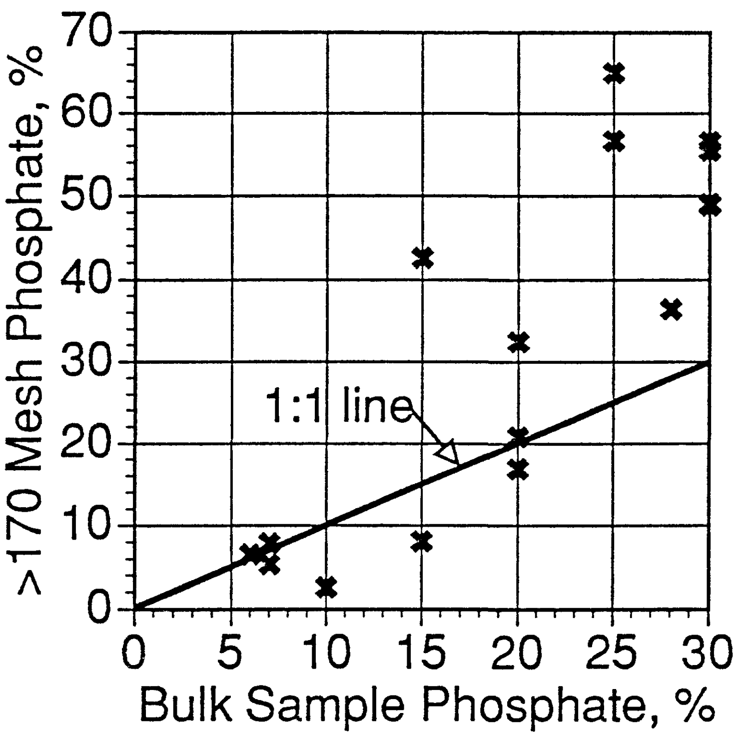

Figure 6b.

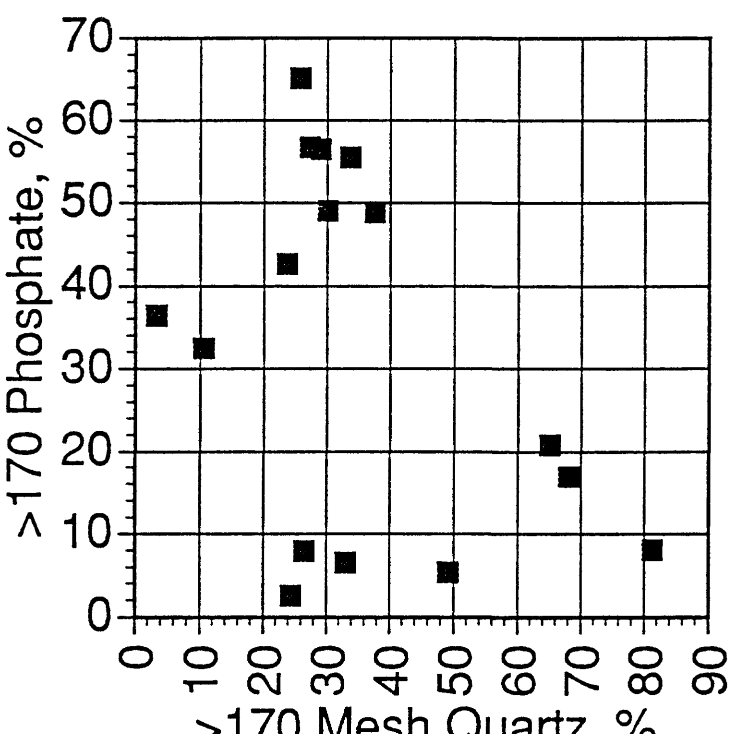

Table 1. Borehole GAS-90-2 Visual Estimates on Bulk and Size Separate Samples

MidDepth, m	Top Depth, ft	Bottom Depth, ft	Interval, ft	type, mesh	mass, g	mass, %	Phosphate, %	>170Phosp, %	Quartz, %	>170 Qtz,%	Carbonate, %	Other
4.19	6.5	21	14.5	BULK			1	1.0				
7.32	22	26	4	BULK			1	1.0				
11.43	36	39	3	BULK			3	3.0				
12.42	39	42.5	3.5	BULK	32.86	100.00	6	6.5		32.9		
				>18	5.85	17.80	2	0.4	1	0.2	97	
				18-60	2.17	6.60	50	3.3	10	0.7	40	
				60-170	11.72	35.67	8	2.9	90	32.1	2	
				<170	13.12	39.93						
13.56	42.5	46.5	4	BULK	33.17	100.00	7	5.4		49.1		
				>18	0.3	0.90	30	0.3	10	0.1	60	
				18-60	1.24	3.74	34	1.3	58	2.2	4	
				60-170	18.08	54.51	7	3.8	86	46.9	5	
				<170	13.55	40.85						
15.01	46.5	52	5.5	BULK			3	3.0				
16.61	52	57	5	BULK	25.42	100.00	10	2.6		24.4		
				>18	0.01	0.04	90	0.0	10	0.0		
				18-60	0.14	0.55	55	0.3	32	0.2	3	10
				60-170	7.07	27.81	8	2.2	87	24.2	3	2
				<170	18.2	71.60						
18.14	57	62	5	BULK			2	2.0				
19.28	62	64.5	2.5	BULK			2	2.0				
19.96	64.5	66.5	2	BULK	33.51	100.00	15	8.1		81.3		
				>18	4.27	12.74	5	0.6	95	12.1		
				18-60	11.1	33.12	12	4.0	88	29.1		
				60-170	14.58	43.51	8	3.5	92	40.0		
				<170	3.56	10.62						
20.96	66.5	71	4.5	BULK	34.37	100.00	20	16.9		68.0		
				>18	6.37	18.53	11	2.0	89	16.5		
				18-60	10.88	31.66	25	7.9	75	23.7		
				60-170	11.94	34.74	20	6.9	80	27.8		
				<170	5.18	15.07						
22.40	71	76	5	BULK	25.77	100.00	7	7.9		26.5		
				>18	0.02	0.08	15	0.0	85	0.1		
				18-60	1.05	4.07	60	2.4	40	1.6		
				60-170	7.78	30.19	18	5.4	82	24.8		
				<170	16.92	65.66						
23.93	76	81	5	BULK			1	1.0				
25.45	81	86	5	BULK			0	0.0				
26.97	86	91	5	BULK			1	1.0				
28.50	91	96	5	BULK			1	1.0				
30.02	96	101	5	BULK				0.0				
31.55	101	106	5	BULK			1	1.0				
33.07	106	111	5	BULK	22.58	100.00	20	32.4		10.6		
				>18	0.15	0.66	99	0.7	1	0.0		
				18-60	1.64	7.26	99	7.2	1	0.1		
				60-170	7.93	35.12	70	24.6	30	10.5		
				<170	12.86	56.95						
34.59	111	116	5	BULK	24.22	100.00	28	36.4		3.3		
				>18	0.04	0.17	75	0.1	23	0.0	2	
				18-60	0.39	1.61	93	1.5	2	0.0	5	
				60-170	9.68	39.97	87	34.8	8	3.2	5	
				<170	14.11	58.26						
35.66	116	118	2	BULK			1	1.0				
36.12	118	119	1	BULK				0.0				
36.50	119	120.5	1.5	BULK	26.64	100.00	25	65.1		25.8		
				>18	0.55	2.06	80	1.7	20	0.4		
				18-60	6.6	24.77	75	18.6	25	6.2		
				60-170	17.06	64.04	70	44.8	30	19.2		
				<170	2.43	9.12						
36.80	120.5	121	0.5	BULK	13.29	100.00	15	42.6		23.7		
				>18	0.22	1.66	68	1.1	32	0.5		
				18-60	3.62	27.24	52	14.2	48	13.1		
				60-170	4.97	37.40	73	27.3	27	10.1		
				<170	4.48	33.71						
37.19	121	123	2	BULK	32.95	100.00	30	56.4		28.9		
				>18	1.41	4.28	55	2.4	45	1.9		
				18-60	13.97	42.40	50	21.2	50	21.2		
				60-170	12.75	38.69	85	32.9	15	5.8		
				<170	4.82	14.63						
37.80	123	125	2	BULK	30.69	100.00	30	49.0		30.1		
				>18	1.28	4.17	70	2.9	30	1.3		
				18-60	12.4	40.40	50	20.2	50	20.2		
				60-170	10.58	34.47	75	25.9	25	8.6		
				<170	6.43	20.95						
38.40	125	127	2	BULK	38.58	100.00	30	48.9		37.6		
				>18	1.65	4.28	70	3.0	30	1.3		
				18-60	18.27	47.36	40	18.9	60	28.4		
				60-170	12.22	31.67	85	26.9	25	7.9		

Table 1. Borehole GAS-90-2 Visual Estimates on Bulk and Size Separate Samples

				<170	6.44	16.69						
38.94	127	128.5	1.5	BULK	38.01	100.00	30	55.5		33.7		
				>18	1.38	3.63	55	2.0	45	1.6		
				18-60	19.73	51.91	48	24.9	52	27.0		
				60-170	12.77	33.60	85	28.6	15	5.0		
				<170	4.13	10.87						
39.78	130	131	1	BULK	31.44	100.00	25	56.7		27.3		
				>18	0.59	1.88	50	0.9	50	0.9		
				18-60	12.17	38.71	60	23.2	40	15.5		
				60-170	13.62	43.32	75	32.5	25	10.8		
				<170	5.06	16.09						
40.39	131	134	3	BULK	30.18	100.00	20	20.8		65.1		
				>18	0.58	1.92	50	1.0	50	1.0		
				18-60	10.8	35.79	15	5.4	85	30.4		
				60-170	14.52	48.11	30	14.4	70	33.7		
				<170	4.28	14.18						
41.15	134	136	2	BULK			0	0.0				
42.21	136	141	5	BULK			2	2.0				
43.74	141	146	5	BULK			1	1.0				
45.26	146	151	5	BULK			2	2.0				
46.79	151	156	5	BULK			1	1.0				
48.39	156	161.5	5.5	BULK			3	3.0				
49.99	161.5	166.5	5	BULK			1	1.0				
51.44	166.5	171	4.5	BULK			1	1.0				
52.43	171	173	2	BULK			3	3.0				
53.13	173.6	175	1.4	BULK			3	3.0				
53.49	175	176	1	BULK			2	2.0				
54.41	176	181	5	BULK			2	2.0				
55.40	181	182.5	1.5	BULK			4	4.0				
55.78	182.5	183.5	1	BULK			4	4.0				
56.62	185	186.5	1.5	BULK			1	1.0				
57.61	186.5	191.5	5	BULK			2	2.0				

Table 2. Borehole GAT-90 Visual Estimates on Bulk and Size Separated Samples

MidDepth, m	Depth, Top, ft	Depth, Bottom, ft	Interval, ft	type, mesh	mass, g	mass, %	Phosphate, %	>170Phosp, %	Quartz, %	>170 Qtz,%	Carbonate, %
2.44	5	11	6	BULK							
4.11	11	16	5	BULK							
6.34	20.3	21.3	1	BULK							
5.18	14	20	6	BULK							
10.52	32	37	5	BULK							
11.73	37	40	3	BULK			3				
12.80	40	44	4	BULK							
13.79	44	46.5	2.5	BULK							
14.86	46	51.5	5.5	BULK							
16.46	51.5	56.5	5	BULK			2				
17.98	56.5	61.5	5	BULK			2				
19.51	61.5	66.5	5	BULK			2				
20.80	66.5	70	3.5	BULK	32.52	100.00	5	5.0		64.8	
				>18	1.01	3.11	77	2.4	20	0.6	3
				18-60	1.25	3.84	15	0.6	80	3.1	5
				60-170	22.09	67.93	3	2.0	90	61.1	7
				<170	8.17	25.12					
22.40	71	76	5	BULK	34.76	100.00	4	9.7		68.8	
				>18	2.4	6.90	80	5.5	20	1.4	
				18-60	1.88	5.41	15	0.8	84	4.5	1
				60-170	23.49	67.58	5	3.4	93	62.8	2
				<170	6.99	20.11					
23.93	76	81	5	BULK	29.35	100.00	5	23.4		35.8	
				>18	3.67	12.50	80	10.0	20	2.5	
				18-60	3.34	11.38	40	4.6	60	6.8	
				60-170	10.36	35.30	25	8.8	75	26.5	
				<170	11.98	40.82					
25.47	81	86	5	BULK	48.07	100.00	10	74.3		9.9	
				>18	1.66	3.45	83	2.9	17	0.6	
				18-60	11.71	24.36	85	20.7	15	3.7	
				60-170	27.07	56.31	90	50.7	10	5.6	
				<170	7.63	15.87					
26.97	86	91	5	BULK	50.04	100.00	20	14.7		43.3	
				>18	14.14	28.26	15	4.2	20	5.7	65
				18-60	10.67	21.32	17	3.6	82	17.5	1
				60-170	13.63	27.24	25	6.8	74	20.2	1
				<170	11.6	23.18					
28.50	91	96	5	BULK							
30.02	96	101	5	BULK			2				
31.55	101	106	5	BULK							
33.07	106	111	5	BULK							
34.59	111	116	5	BULK							
36.12	116	121	5	BULK			5				
39.17	126	131	5	BULK	47.01	100.00		12.7		22.5	
				>18	17.1	36.38	5	1.8	10	3.6	85
				18-60	8.73	18.57	27	5.0	43	8.0	30
				60-170	10.24	21.78	27	5.9	50	10.9	23
				<170	10.94	23.27					
40.69	131	136	5	BULK							
42.06	136	140	4	BULK							
43.74	141	146	5	BULK							
45.26	146	151	5	BULK							
46.79	151	156	5	BULK							
48.08	156	159.5	3.5	BULK							
49.38	159.5	164.5	5	BULK							
50.37	164	166.5	2.5	BULK							

Table 4. Borehole GAS-90-2 Size-Separated Samples

	A	B	C	D	E	F	G	H	I	J	K	L	M
1	Sample (depth, m)	Interval, ft	WetWt, g	DryWt (TotWt), g	% H2O	%Wt>18	%Wt18-60	%Wt60-170	%Wt<170	%Wt>170	>170/<170	>18CFA,%	18-60CFA,%
2	12.43	3.5	44.35	32.86	25.91	17.80	6.60	35.67	39.93	60.07	1.50	2	50
3	13.57	4	49.81	33.17	33.41	0.90	3.74	54.51	40.85	59.15	1.45	30	35
4	16.62	5	45.14	25.42	43.69	0.04	0.55	27.81	71.60	28.40	0.40	90	55
5	19.98	2	42.19	33.51	20.57	12.74	33.12	43.51	10.62	89.38	8.41	5	12
6	20.97	4.5	43.28	34.37	20.59	18.53	31.66	34.74	15.07	84.93	5.64	11	25
7	22.42	5	41.52	25.77	37.93	0.08	4.07	30.19	65.66	34.34	0.52	15	60
8	33.09	5	39.48	22.58	42.81	0.66	7.26	35.12	56.95	43.05	0.76	99	99
9	34.62	5	45.67	24.22	46.97	0.17	1.61	39.97	58.26	41.74	0.72	75	93
10	36.52	1.5	37.57	26.64	29.09	2.06	24.77	64.04	9.12	90.88	9.96	80	75
11	36.83	0.5	18.8	13.29	29.31	1.66	27.24	37.40	33.71	66.29	1.97	68	52
12	37.21	2	43.89	32.95	24.93	4.28	42.40	38.69	14.63	85.37	5.84	55	50
13	37.82	2	41.97	30.69	26.88	4.17	40.40	34.47	20.95	79.05	3.77	70	50
14	38.43	2	51.52	38.58	25.12	4.28	47.36	31.67	16.69	83.31	4.99	70	40
15	38.96	1.5	48.02	38.01	20.85	3.63	51.91	33.60	10.87	89.13	8.20	55	48
16	39.80	1	44.23	31.44	28.92	1.88	38.71	43.32	16.09	83.91	5.21	50	60
17	40.41	3	41.67	30.18	27.57	1.92	35.79	48.11	14.18	85.82	6.05	50	15
18	average	2.97	42.44	29.61	30.28	4.68	24.82	39.55	30.95	69.05	2.23	51.56	51.19
19													
20	**Extended Size Sep.:**		WetWt, g	DryWt, g	%H2O	>18Wt, g	18-60Wt, g	60-170Wt, g	<170Wt, g	%Wt>18	%Wt18-60	%Wt60-170	%Wt<170
21	33.09Ext	5	59.05	32.99	44.13	0.11	2.05	12.12	18.71	0.33	6.21	36.74	56.71
22	33.09	5	39.48	22.58	42.81	0.15	1.64	7.93	12.86	0.66	7.26	35.12	56.95
23													
24	**<170 mesh:**												
25	mesh fraction:	170-200	200-230	230-270	270-325	<325	Tot 170-325						
26													
27	Wt, g	2.52	1.31	1.57	1.11	12.2	6.51						
28	% Wt	7.64	3.97	4.76	3.36	36.98	19.73						
29													
30	CFA vol, %	50	30	30	20								
31	CFA wt, g	1.26	0.39	0.47	0.22								
32	CFA, % Total	3.82	1.19	1.43	0.67		7.11						
33													
34													
35													
36	Qtz vol, %	50	70	70	80								
37	Qtz wt, g	1.26	0.92	1.10	0.89								
38	Qtz, % Total	3.82	2.78	3.33	2.69		12.62						

Table 4. Borehole GAS-90-2 Size-Separated Samples

	N	O	P	Q	R	S	T	U	V
1	60-170CFA,%	TotCFA18-170, %	TotCFA>170,%	CFA,(18-170)/>170, %	>18Qtz,%	18-60Qtz,%	60-170Qtz,%	TotQtz18-170, %	TotQtz>170,%
2	8	6.16	6.51	94.53	1	10	90	32.76	32.94
3	7	5.12	5.40	94.97	10	60	86	49.12	49.21
4	8	2.53	2.56	98.62	10	32	87	24.37	24.38
5	8	7.46	8.09	92.13	95	88	92	69.18	81.28
6	20	14.86	16.90	87.94	89	75	80	51.53	68.03
7	18	7.88	7.89	99.85	85	40	82	26.39	26.45
8	70	31.77	32.43	97.97	1	1	30	10.61	10.62
9	87	36.27	36.39	99.66	23	2	8	3.23	3.27
10	70	63.41	65.06	97.46	20	25	30	25.41	25.82
11	73	41.46	42.59	97.36	32	48	27	23.17	23.70
12	85	54.09	56.44	95.83	45	50	15	27.00	28.93
13	75	46.06	48.98	94.04	30	50	25	28.82	30.07
14	85	45.87	48.86	93.87	30	60	15	33.16	34.45
15	85	53.47	55.47	96.40	45	52	15	32.03	33.67
16	75	55.72	56.65	98.34	50	40	25	26.31	27.25
17	30	19.80	20.76	95.37	50	85	70	64.10	65.06
18	50.25	30.75	31.94	95.90	38.50	44.88	48.56	32.95	35.32
19	Extended Size Sep., cont'd:								
20	%Wt>170	>170/<170	>18CFA,%	18-60CFA,%	60-170CFA,%	TotCFA18-170	TotCFA>170,%	CFA,(18-170)/>170	>18Qtz,%
21	43.29	0.76	100	99	88	38.48	38.82	99.14	
22	43.05	0.76	99	99	70	31.77	32.43	97.97	1
23									
24									
25									
26									
27									
28									
29									
30									
31									
32									
33									
34									
35									
36									
37									
38									

Table 4. Borehole GAS-90-2 Size-Separated Samples

	W	X	Y	Z	AA	AB	AC	AD
1	Qtz,(18-170)/>170	>18Carb,%	18-60Carb,%	60-170Carb,%	TotCarb18-170	TotCarb>170,%	Carb,(18-170)/>170	TotMinls>170,%
2	99.46	97	40	2	3.35	20.62	16.3	100
3	99.82	60	5	5	2.91	3.45	84.3	98.2
4	99.98		3	3	0.85	0.85	100	97.8
5	85.11							100
6	75.75							100
7	99.75							100
8	99.94							100
9	98.84	2	5	5	2.08	2.08	99.8	100
10	98.40							100
11	97.77							100
12	93.34							100
13	95.84							100
14	96.28							100
15	95.15							100
16	96.56							100
17	98.52							100
18	95.66	53.00	13.25	3.75	2.30	6.75	75.10	
19	**Extended Size Sep., cont'd:**							
20	18-60Qtz,%	60-170Qtz,%	TotQtz18-170	TotQtz>170,%	Qtz,(18-170)/>170			
21	1	12	4.47	4.47	100			
22	1	30	10.61	10.62	99.94			
23								
24								
25								
26								
27								
28								
29								
30								
31								
32								
33								
34								
35								
36								
37								
38								

Table 5. Borehole GAT-90 Size-Separated Samples

	A	B	C	D	E	F	G	H	I	J	K	L	M
1	Sample (depth, m)	Interval,ft	WetWt, g	DryWt (TotWt)	% H2O	%Wt>18	%Wt18-60	%Wt60-170	%Wt<170	%Wt>170	>170/<170	>18CFA, %	18-60CFA,%
2	20.97	4.5	42.52	32.52	24	3.1	3.8	67.9	25.1	74.9	3	77	15
3	22.42	5	47.68	34.76	27	6.9	5.4	67.6	20.1	79.9	4	80	15
4	23.94	5	49.02	29.35	40	12.5	11.4	35.3	40.8	59.2	1.4	80	40
5	25.47	5	65.74	48.07	27	3.5	24.4	56.3	15.9	84.1	5.3	83	85
6	26.99	5	61.48	50.04	19	28.3	21.3	27.2	23.2	76.8	3.3	15	17
7	39.19	5	57.45	47.01	18	36.4	18.6	21.8	23.3	76.7	3.3	5	27
8													
9	average	4.9	54.0	40.3	25.7	15.1	14.1	46.0	24.7	75.3	3.4	56.7	33.2
10	aver 76-91'	5.0	58.7	42.5	28.7	14.8	19.0	39.6	26.6	73.4	3.3	59.3	47.3
11													
12													
13	**Extended Size Sep.:**												
14	25.47 Ext	5	40.59	28.96	29	3.9	22.7	58.4	15.1	84.9	5.6	60	50
15	25.47	5	65.74	48.07	27	3.5	24.4	56.3	15.9	84.1	5.3	83	85
16													
17	**<170 mesh:**												
18	mesh fraction:	170-200	200-230	230-270	270-325	<325	Tot 170-325						
19													
20	Wt, g	1.14	0.43	0.33	0.19	2.28	2.09						
21	%Wt	3.94	1.48	1.14	0.66	7.87	7.2						
22													
23	CFA vol, %	50	50	50	45								
24	CFA wt, g	0.57	0.22	0.17	0.09								
25	CFA, % Total	1.97	0.74	0.57	0.3		3.58						
26													
27													
28	Qtz vol, %	50	50	50	55								
29	Qtz wt, g	1.97	0.74	0.57	0.36								
30	Qtz, % Total	0.57	0.22	0.17	0.1		1.05						

Table 5. Borehole GAT-90 Size-Separated Samples

	N	O	P	Q	R	S	T	U	V	W	X
1	60-170CFA, %	CFA18-170,%	TotCFA>170,%	CFA,(18-170)/>170	>18Qtz,%	18-60Qtz,%	60-170Qtz,%	TotQtz18-170,%	TotQtz>170,%	Qtz(18-170)/>170	>18Carb,%
2	3	2.6	5	52.2	20	80	90	64.2	64.8	99	3
3	5	4.2	9.7	43.1	20	84	93	67.4	68.8	98	
4	25	13.4	23.4	57.2	20	60	75	33.3	35.8	93	
5	90	71.4	74.3	96.1	17	15	10	9.3	9.9	94.1	
6	25	10.4	14.7	71.1	20	82	74	37.6	43.3	86.9	65
7	27	10.9	12.7	85.7	10	43	50	18.9	22.5	83.8	85
8											
9	29.2	18.8	23.3	67.6	17.8	60.7	65.3	38.5	40.8	92.5	51.0
10	46.7	31.7	37.5	74.8	19.0	52.3	53.0	26.7	29.7	91.3	65.0
11											
12											
13	Extended Size Sep., cont'd.:										
14	85	60.9	63.3	96.3	40	50	15	20.1	21.6	92.8	
15	90	71.4	74.3	96.1	17	15	10	9.3	9.9	94.1	
16											
17											
18											
19											
20											
21											
22											
23											
24											
25											
26											
27											
28											
29											
30											

Table 5, Page 2

Table 5. Borehole GAT-90 Size-Separated Samples

	Y	Z	AA	AB	AC	AD
1	18-60Carb,%	60-170Carb,%	TotCarb18-170,%	TotCarb>170,%	Carb(18-170)/>170	TotMinls>170,%
2	5	7	4.9	5	98.2	100
3	1	2	1.4	1.4	100	100
4			0	0		100
5			0	0		100
6	1	1	0.5	18.9	2.6	100
7	30	23	10.6	41.5	25.5	100
8						
9	9.3	8.3	2.9	11.1	56.6	100.0
10	1.0	1.0	0.2	6.3	2.6	100.0
11						
12						
13	Extended Size Sep., cont'd.:					
14						100
15						100
16						
17						
18						
19						
20						
21						
22						
23						
24						
25						
26						
27						
28						
29						
30						

Table 6. Phosphate (CFA) and quartz abundance in size fractions as a percentage of >170 abundance of that mineral

	CFA (size fraction/>170 mesh), %				Quartz (size fraction/>170 mesh), %		
SAMPLE	>18	18-60	60-170		>18	18-60	60-170
GAT-90							
20.97	47.8	11.4	40.8		1.0	4.7	94.3
22.42	56.8	8.3	34.8		2.0	6.6	91.4
23.94	42.8	19.5	37.7		7.0	19.1	73.9
25.47	3.9	27.9	68.2		6.0	37.0	57.0
26.99	28.9	24.7	46.4		13.1	40.4	46.5
39.19	14.3	39.5	46.2		16.2	35.5	48.4
AVERAGE:	32.4	21.9	45.7		7.5	23.9	68.6
MINIMUM:	3.9	8.3	34.8		1.0	4.7	46.5
MAXIMUM:	56.8	39.5	68.2		16.2	40.4	94.3
GAS-90-2							
12.4	5.5	50.7	43.9		0.5	2.0	97.5
13.6	5.0	24.1	70.9		0.2	4.5	95.3
16.6	0.0	12.9	87.1		0.0	0.8	99.2
20	7.9	49.1	43.0		14.9	35.9	49.3
21	12.0	46.9	41.1		24.2	35.0	40.8
22.4	0.2	31.1	68.7		0.3	6.2	93.5
33.1	2.1	22.2	75.6		0.1	0.7	99.2
34.6	0.4	4.1	95.5		1.4	1.0	97.6
36.5	2.6	28.6	68.8		1.6	24.0	74.4
36.8	2.7	33.2	64.1		2.3	55.1	42.6
37.2	4.2	37.5	58.3		6.7	73.3	20.1
37.8	6.0	41.2	52.8		4.2	67.1	28.7
38.4	6.2	38.8	55.1		3.7	82.5	13.8
39	3.6	44.9	51.5		4.8	80.2	15.0
39.8	1.7	41.0	57.3		3.5	56.8	39.7
40.4	4.6	25.9	69.5		1.5	46.8	51.8
AVERAGE:	4.0	33.3	62.7		4.4	35.7	59.9
MINIMUM:	0.0	4.1	41.1		0.0	0.7	13.8
MAXIMUM:	12.0	50.7	95.5		24.2	82.5	99.2
Tybee Interval Average	3.8	37.9	58.3		3.8	62.7	33.5

Table 7. Estimated Recoverable Phosphate Resources, Boreholes GAT-90 and GAS-90-2

	Depth, m	Sediment Thickn., m	H2O, %	Porosity, %	>170 Phos., %	>170 Quartz, %	<170 fines, %	Recoverable Ore (Matrix), Tonnes/m^2: Dry Sed. Mass, g	Recoverable CFA	>170 Qtz	<170 Fines	Recoverable Matrix, kiloT/hectare: Recoverable CFA	>170 Qtz	<170 Fines	CFA/Qtz ratio	Fines/ton CFA, T
GAS-90-2																
Tybee Member	36.27-39.17	2.9	25.9	50	54	30	15.9	4.1	2.2	1.2	0.65	22	12	6.5	1.83	0.30
8.5 m interval	32.3-40.8	7.6	34.2	59	41.4	24.7	33.4	8.7	3.6	2.2	2.9	36	22	29	1.64	0.81
3.5 m interval	19.66-23.16	3.5	28.1	52	11.5	52.3	36.3	4.7	0.54	2.5	1.7	5.4	25	17	0.22	3.15
GAT-90																
Tybee Member	24.69-26.21	1.5	27	51	74.3	9.9	15.9	2.1	1.5	0.2	0.32	15	2	3.2	7.50	0.21
4.6 m interval	23.16-27.74	4.6	28.7	53	37.5	29.7	26.6	6.1	2.3	1.8	1.6	23	18	16	1.28	0.70
above 4.6 m interval, screened 18-170 mesh					31.9	26.7	26.6	6.1	1.9	1.6	1.6	19	16	16	1.19	0.84