

UNITED STATES DEPARTMENT OF THE INTERIOR  
GEOLOGICAL SURVEY

Assessment of Undiscovered Phosphate Resource  
Potential of the Dominican Republic

by

Richard P. Sheldon<sup>1</sup> and Robert C. McDowell<sup>2</sup>

Open-File Report 85-732

Prepared in cooperation with Dirección General de Minería,  
Santo Domingo, Dominican Republic

This report is preliminary and has not been reviewed for conformity with U.S. Geological Survey editorial standards and stratigraphic nomenclature.

<sup>1</sup>Consultant, Washington, D.C.

<sup>2</sup>Reston, VA

# TABLE OF CONTENTS

	PAGE
List of figures and tables.....	ii
Executive summary.....	1
Introduction.....	2
Known phosphogenic provinces of the Caribbean region.....	2
Neogene marine phosphorites.....	3
Upper Cretaceous marine phosphorites.....	4
Guano-derived phosphate rock.....	5
Possible phosphogenic provinces of the Dominican Republic.....	6
Miocene rocks.....	6
Paleogene rocks.....	10
Upper Cretaceous rocks.....	12
Guano-derived phosphate rock.....	12
Igneous apatite.....	13
Rocks of very low to no potential.....	13
Ranking of potential phosphate areas.....	13
High feasibility of economic exploitation.....	15
Medium feasibility of economic exploitation.....	17
Low feasibility of economic exploitation.....	18
Suggested phosphate resource development program.....	18
Miocene formations.....	19
Eocene formations.....	20
Cretaceous and Paleocene formations.....	20
Guano-derived phosphate rock.....	21
Igneous apatite.....	22
Summary of development program.....	22
References cited.....	24
Appendices.....	27
A Phosphate rock nomenclature.....	28
B Interpretation of chemical analyses of phosphatic rocks.....	32
C Semi-quantitative geochemical field test for phosphate.....	33
D Guano-derived phosphate rock in Thailand.....	34
E Igneous apatite potential in Ethiopia.....	58
F Selected additional references on phosphate petrology.....	63
G Problems of stratigraphic nomenclature.....	64

## LIST OF FIGURES

Figure 1.	Surface ocean circulation.....	3a
Figure 2.	World distribution of sea-floor phosphorite.....	3b
Figure 3.	Present-day and postulated pre-Middle Miocene surface circulation-North Atlantic and Caribbean.....	3c
Figure 4.	Stable isotopes in planktonic foraminifera on each side of the Isthmus of Panama.....	7a
Figure 5.	Upwelling processes.....	7b
Figure 6.	Hispaniola regional tectonic map.....	7c
Figure 7.	A. El Marco de la Placa Caribe B. Generalized physiographic map of Hispaniola.....	7c
Figure 8.	Structure cross-section along Rio Colorado, north of Neiba.....	8a
Figure 9.	Locality map of Dominican Republic.....	9a
Figure 10.	Generalized lithologic log of Candelon No. 1.....	11a
Figure 11.	Flowchart of undiscovered phosphate resource development program.....	23

## LIST OF TABLES

Table 1.	Chemical and normative analyses of Cenozoic volcanic rocks of Dominican Republic.....	14
Table 2.	Ranking of phosphate target areas of Dominican Republic.....	16

## EXECUTIVE SUMMARY

An assessment of undiscovered phosphate resource potential of Dominican Republic shows that a high probability exists for multiple small (less than 100,000 tons) deposits of high-grade guano-derived phosphate in areas of karst topography in the northeastern part of the country. Deposits, if they exist, would have a medium feasibility of economic exploitation due to the rugged terrane.

A medium probability exists for the occurrence of phosphate in Miocene rocks of the San Juan-Azua valleys area, but deposits, if they exist, would have a high feasibility of economic exploitation. Miocene rocks of the Santo Domingo and East Cibao-El Valle area have a low to medium probability of containing phosphate rock and a high feasibility of economic exploitation.

Eocene rocks of ranges adjacent to the western San Juan Valley have a medium probability of existence of phosphate and a medium feasibility of economic exploitation.

Cretaceous rocks near the Pueblo Viejo mine have a low probability of containing phosphate, but would be ideally situated for economic exploitation if a sulfuric acid plant is located at the mine site.

Cenozoic volcanic rocks of the southern Cordillera Central have a low to very low probability of containing phosphate rock, a medium feasibility of economic recovery, but offer the possibility of being a valuable soil amendment.

Other rocks of Dominican Republic have no apparent probability of containing phosphate rock, or too low a feasibility of economic exploitation.

A program for further evaluating and discovering these undiscovered potential resources would take about three geologist-years effort plus supporting scientific services, a core drilling program of about 15 shallow holes, and several weeks of helicopter support.

Completion of this second phase of phosphate resource assessment, if phosphate deposits are found, would allow planning of the third phase of phosphate resource development, consisting of inferred reserve delineation and estimation.

## INTRODUCTION

The possibilities of the existence of undiscovered phosphate rock in the Caribbean and Central American region were examined at a workshop held at East Carolina University in Greenville, North Carolina on July 9-13, 1984. This workshop was jointly sponsored by the U.S. Geological Survey and East Carolina University and was attended by geologists from eight Latin American countries, including the Dominican Republic. Because of the projected supply of sulfuric acid from the sulfide ore zone of the Pueblo Viejo mine, the discovery of a phosphate deposit in the Dominican Republic became an important objective. Thus, a program of assessing the phosphate potential of the country was initiated by the Direccion General de Minería with the help of the U.S. Geological Survey.

Richard Sheldon (USGS-retired and consultant) and Robert McDowell (USGS) were called on to assist the Minería in carrying out the first phase of this project, from November 5 to December 5, 1984. The working team consisted of Dr. Ivan Tavares, Mr. Edwin Garcia and Mr. Robert Kulstad of the Minería and Sheldon and McDowell. Two weeks were spent in Santo Domingo going over the literature on the geology of Dominican Republic to identify potential phosphate target areas. Reconnaissance field trips were taken to the San Juan and Azua Valleys, Sierra Neiba, Cordillera Central and Cordillera Oriental, Haitises, and the coastal plain near Santo Domingo. A draft of this report was left at the Minería at the end of the project to assist in a timely beginning of the next phase of phosphate resource development.

This project required the team to pool their scientific knowledge of the geology of Dominican Republic with their knowledge of the geology of phosphate rock. Other geologists of the Minería made significant contributions by supplying assistance and geologic data, and their help is gratefully acknowledged.

This report is organized in the following way. The known occurrences of phosphate rock in the Caribbean region are presented, and the origins of those deposits are analyzed in terms of paleoceanography, paleogeography and paleotectonics. The relevance of known Caribbean phosphogenic provinces to Dominican Republic is described, and formations with a potential for containing phosphate rock are identified. In the next section, these target areas for phosphate rock are ranked, and in the final section, suggested programs are outlined to further evaluate and prospect the target areas.

### KNOWN PHOSPHOGENIC PROVINCES OF THE CARIBBEAN REGION

Three phosphogenic provinces are known in the Caribbean region: 1) Neogene marine phosphorites of the southeastern United States (US), Cuba, Venezuela and perhaps Mona Island between Puerto Rico and Dominican Republic, 2) Upper Cretaceous phosphorites of northern South America, and 3) bat and sea bird derived phosphate rock in the West Indies.

## Neogene marine phosphorites

### World occurrences

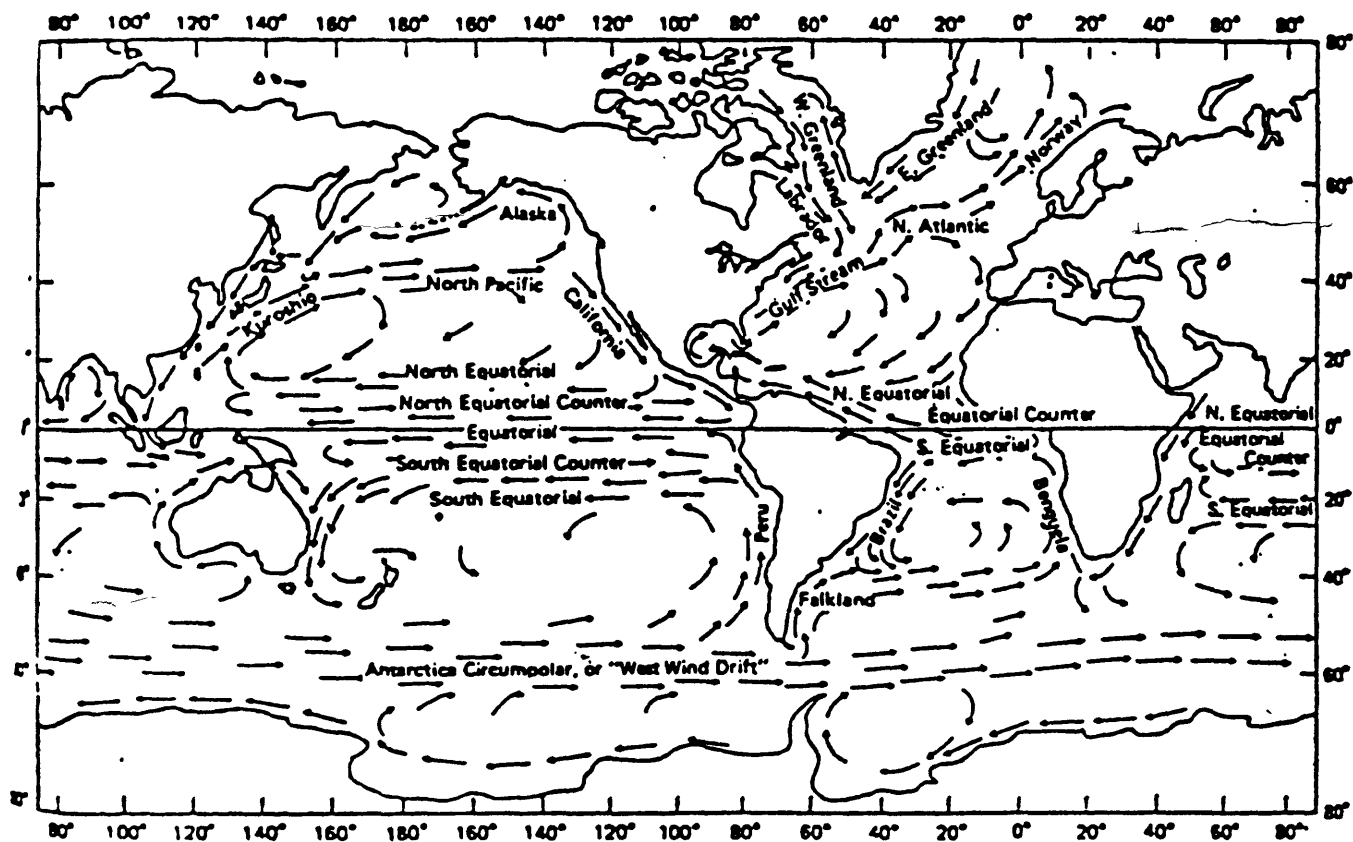
Marine lower Neogene phosphorite was deposited where upwelling eastern boundary currents flowed over shallow water areas at trade wind latitudes (5 to 40°) (McKelvey, 1963, 1967; Sheldon, 1964, 1980, 1981) (figures 1 and 2). This gave rise to deposits in Western North and South America, as discussed below, and also in offshore areas of Spain, Portugal and Northwest Africa in the Northern Atlantic, and Namibia and South Africa in the Southern Atlantic, and offshore of Western Australia. The paleo-Gulf Stream, which was a western boundary current, produced a phosphogenic province of a different kind at higher latitudes in the Caribbean area. No other major western or eastern boundary current, or Neogene deposits are known in the world, although minor deposits are found in Indonesia, Philippines and New Zealand.

### Caribbean region occurrences

Phosphorite of Miocene and lower Pliocene age occurs in Florida and North Carolina in the southeastern US and in adjacent Continental Shelf areas (Riggs, 1984). In Cuba, Oligocene-Miocene phosphorite crops out on the southwest flank of the central mountain range in the vicinity of Havana (Pokrishkin, 1967). In Venezuela, Miocene phosphorite that in part has been weathered extensively and redeposited as secondary phosphate rock occurs in the vicinity of Riecito on the northern coastal area (Rodriguez, 1984). On Mona Island between Puerto Rico and the Dominican Republic, phosphate rock occurs above an unconformity on Miocene-Pliocene limestone and under a Pliocene-Pleistocene limestone. This phosphate rock may be of bat-guano origin, similar to the younger secondary phosphate deposits associated with caves and replacing the Pliocene-Pleistocene limestone (Altschuler in Kaye, 1959), but alternatively may be of marine origin.

The marine Neogene phosphorite deposition of the Caribbean region was related to the Miocene Gulf Stream (Riggs, 1984), which suggests the possibility of other marine phosphorite deposits on other shallow water areas that were washed by this ancestral current system (figure 3).

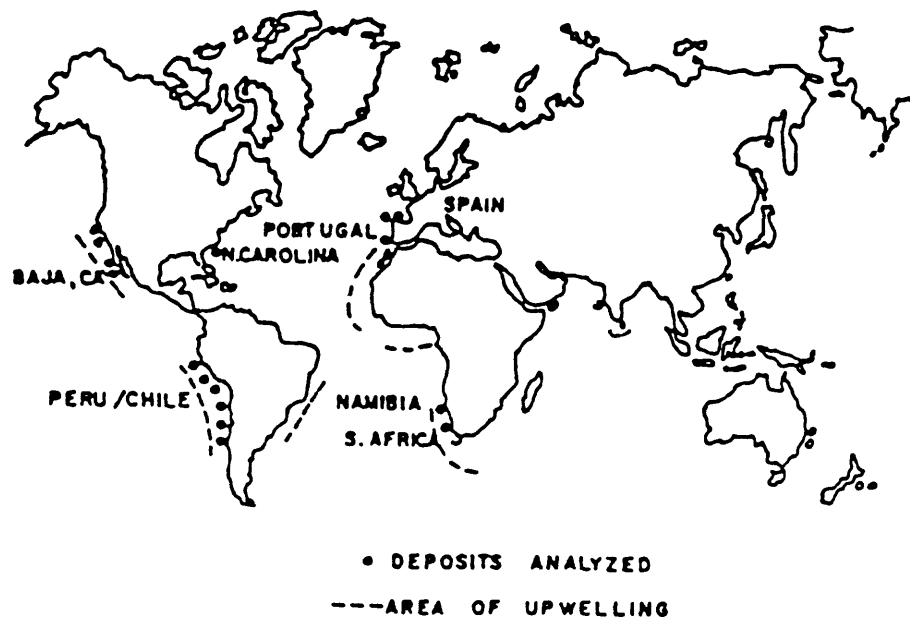
A problem of correlation and age of Caribbean phosphate sedimentation exists. Riggs (1984) reported that the phosphorites of the southeastern US are early to middle Miocene and early Pliocene. Pokrishkin (1967) assigned an Oligocene-early Miocene age to the phosphorites of Cuba. Rodriguez (in press) gives a middle to late Miocene age to the Venezuelan phosphorites. If these ages are correct, phosphogenesis occurred from Oligocene to Pliocene time, not necessarily continuously, but probably episodically as indicated by individual stratigraphic sections. Major Neogene phosphorites of the world are Miocene, and appear mainly to be middle Miocene. Establishing the age of episodes of phosphogenesis in the Caribbean region will take further comparative paleontologic work, but at present it appears likely that the main phosphogenesis of southeastern US and Venezuela was also middle Miocene.



Stowe (1979)

Figure 1. Surface ocean circulation

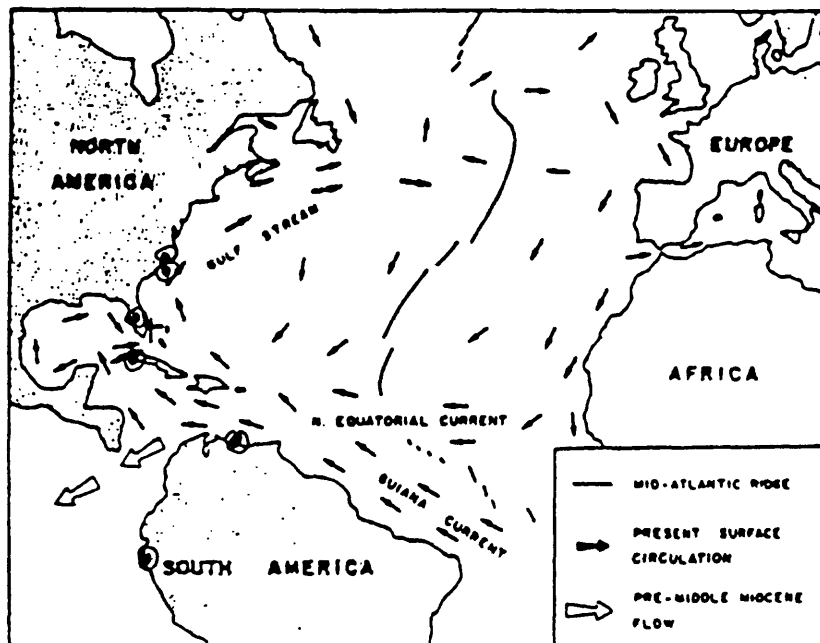
Figure 2. World distribution of sea-floor phosphorite



Burnett (unpublished)



Figure 3. Present-day and postulated pre-middle Miocene surface circulation



① Miocene phosphate deposits

Mullens and Neumann (1979)

Miocene marine phosphorites are also known in Southern California, US and Baja California, Mexico, as well as in Western Peru and Chile (figures 2 and 3). These are different phosphogenic provinces than the Miocene- Pliocene Gulf Stream phosphogenic province, because they were related to the ancestral California and Humboldt (Peru) eastern boundary currents of the Pacific Ocean. Because an isthmus between North and South America probably existed in Middle Miocene time it appears that the Caribbean and Pacific Miocene marine phosphogenic provinces were oceanographically unrelated, although they were climatologically related. If this is true, the presence of the Miocene Pacific phosphorites has little bearing on the Caribbean phosphorite potential.

## Upper Cretaceous marine phosphorites

### World occurrences

Marine phosphorites occur in a circum-global belt at low paleolatitudes (Sheldon, 1980). A belt of major economic phosphorites of late Cretaceous age occurs in the Middle East in Turkey, Syria, Jordan and Israel, and these are conformably overlain by Paleogene phosphorites. Smaller Cretaceous phosphorite deposits occur in the Paris Basin in France and Belgium, Greece, Tunisia, Algeria, Morocco, and Western Sahara. The major phosphorites of North Africa are early Tertiary in age. A belt of Cretaceous phosphorites occurs in northern South America, as discussed below. None of these deposits appears to be associated with boundary currents comparable to those of the gyral circulation in the ocean today. Cretaceous sediments deposited at the paleoceanographic positions where Cretaceous boundary currents would be expected are essentially non-phosphatic. This indicates that different oceanographic current system and climatic conditions were operating in late Cretaceous time. In the late Cretaceous, strong circum-global equatorial upwelling must have occurred, whereas in Neogene time, trade-wind belt upwelling occurred.

Thus, the distributional model used for phosphate exploration in the Upper Cretaceous rocks must be different from that used in Neogene rocks. On the basis of their different distributions, two phosphorite families were set up, the trade-wind-belt family and the equatorial-belt family (Sheldon, 1980).

### Caribbean occurrences

Upper Cretaceous phosphorite occurs in the La Luna Formation in Columbia and Venezuela and in equivalent rocks in Ecuador. The La Luna Formation is composed of five phosphate-bearing cycles of sedimentation, which were caused by eustatic sea level changes and probable changes in the oceanic paleocurrent systems. Similar but less well-developed cyclic sedimentation occurs in the Upper Cretaceous phosphatic sequences in other parts of the world. A typical tripartite cycle consists, from base to top, of sandstone, a middle unit of phosphorite, chert, and black limestone, and an upper black shale unit. On a world-wide basis, phosphorites are found in each late Cretaceous stage, although in northern South America, phosphorite is known only in the Coniacian, Santonian, Campanian and Maestrichtian. The major phosphorite in Columbia is Santonian in age (Cathcart and Zambrano, 1967).

## Guano-derived phosphate rock

### General occurrence

Altschuler (1973) summarized the conditions of guano accumulation:

"Accumulations of excrement form ...(an) important category of phosphate deposits. The subject has been treated in masterful detail by Hutchinson, who noted that massive fecal concentration occurs only when large colonies of "organisms (which) are large, feed over a wide (and highly productive) trophophoric field, and return to a limited site for rest and reproduction. For persistent accumulation the site must be relatively free of predators and of frequent or heavy rain. Only the roosts of birds and bats fulfill these requirements to any geochemically important degree."

"The requirements for substantial deposits of phosphatic bat guano (chiropterite) are met in dry caves of karst terrains, in warm, fertile regions. The cave areas of the West Indies, Indonesia, and Thailand are notable past and present-day examples. Many caverns in the limestone belts of Bohemia, Appalachia, and Texas and New Mexico still support bat colonies, but their guano, for the most part, was deposited in pre-Holocene and, presumably, warmer periods. The requirements for bird guanos are fulfilled on arid islands, and subordinately, on coastal headlands adjoining highly productive regions of the sea."

"Thus, most insular guano is found on small islands, in belts of the world ocean marked by major divergences in circulation, where colder, nutrient-rich, subsurface water is brought to the surface by pronounced upwelling. Such fertile belts, flourishing in plankton and fish, are notable on the west sides of the continents in tropical and trade-wind latitudes, at the inner edges of the Peru, California, Benguela, and West Australian currents. The Peruvian guano islands, the deposits of the Mejillones Peninsula in Chile, and of Saldanha Bay in South African are well-known examples of such geophysical control. Fertile belts of upwelling occur in the boundary zones of the westward-flowing north and south equatorial currents with equatorial countercurrents. Cold water wells up and flows transversely poleward from the divergence. Many major Pacific Island phosphate deposits owe their existence to this current configuration. Thus Nauru, Ocean, Howland, Baker, and Jarvis Islands all lie close to 0 latitude in the South Pacific equatorial divergence...."

The calcium phosphates derived from guanos may be purely residual accumulation. They also occur as mixtures of phosphatized, wave-washed, calcareous debris, cemented by both precipitated and residual calcium phosphate. These occur as continuous, thin crusts over hundreds of small islands in the Pacific, the Caribbean, and the seas of southeast Asia, and are called "crust guanos" or atoll phosphates. Reflecting a component of residual guano, these deposits are collectively termed phosphatic guano. Lastly, the calcium phosphates may consist largely of massive varieties of precipitated and matasomatic (or replacement) deposits mixed to varying degree with finer, and less cohesive, particulate calcium phosphate, and subdivided texturally into "coherent" and "incoherent." These are no longer guanos. The large economically exploited insular deposits of Nauru, Ocean, Makeea, Christmas, and Curacao are of this type.

A study of bat-guano-derived phosphate rock in Thailand (Sheldon, 1984a) is given in Appendix D.

#### Caribbean occurrences

Bird-guano phosphate rock is known in Curaco. Bat-guano deposits are known in many parts of the Caribbean, but to our knowledge the only bat-guano-derived phosphate rock in the Caribbean region was reported by Altschuler (in Kaye, 1959) on Mona Island, where hydroxyapatite is associated with the cave guano deposits in the Pliocene-Pleistocene limestone.

#### POSSIBLE PHOSPHOGENIC PROVINCES OF THE DOMINICAN REPUBLIC

Known individual phosphate deposits of the Caribbean region have been well enough explored to determine their probable lateral extents. However, because phosphogenic provinces originally covered the areas where upwelled phosphate-rich ocean waters flowed over shallow shelves, it is possible that the full extents of the known phosphogenic provinces of the Caribbean region have not been defined. One major problem is that late Cenozoic plate tectonic activity has broken up and dislocated original areas of sedimentation. Thus, the presently known phosphate deposits may be only fragments of originally larger provinces, and undiscovered phosphate may remain to be found in other fragments. Following this line of reasoning, it was pointed out at the 1984 workshop on phosphorite potential of the Caribbean and Central American region that areas in the Caribbean and Central American region where no phosphate occurrences are known should be assessed for their phosphate resource potential.

The phosphate potential of Hispaniola on first analysis appears to be in Miocene terrain where the ancestral Gulf Stream may have deposited phosphate, and in late Cretaceous terrain, which may have been in the same current system as the northern South American phosphogenic province. In addition, Paleogene cherty limestone in the Dominican Republic may have been deposited in a phosphogenic province comparable to those of the same age in North Africa, Annan seamount in the Atlantic and many seamounts in the Pacific.

Review of the literature, discussions with geologists of the Dirección General de Minería, and reconnaissance field trips have refined these ideas on the phosphate potential of the Dominican Republic. These ideas are discussed below.

#### Miocene rocks

The track of the Miocene Gulf Stream can be partly traced by the occurrence of Miocene phosphorite deposits in the Caribbean region (figure 3). The ancestral Gulf Stream appears to have flowed in a similar path as the modern Gulf Stream, as indicated by the phosphorites of coastal Venezuela, Cuba and southeastern US.

The Gulf Stream is formed by the equatorial current of the South Atlantic gyre being diverted by northeastern South America to flow into the northern hemisphere and join the equatorial current of the North Atlantic gyre, to give the uniquely large and deep flowing present day Gulf Stream (figure 1). At the present time, the Isthmus of Panama prohibits the Gulf Stream from flowing into the Pacific Ocean, which it otherwise would do. This causes a segment of the Gulf Stream to be diverted through the Gulf of Mexico, around the Florida peninsula, where it joins the other segment, which flows along the north side of the Greater Antilles (figure 3). The Miocene Gulf Stream would have had the same characteristics at times when the isthmus existed between North and South America. An isthmus existed in at least middle Miocene time, as indicated by land mammal migrations, and in post-Miocene time, as indicated by stable isotope studies of planktonic foraminifera on each side of the Isthmus of Panama (figure 4), and a partial restriction may have existed earlier.

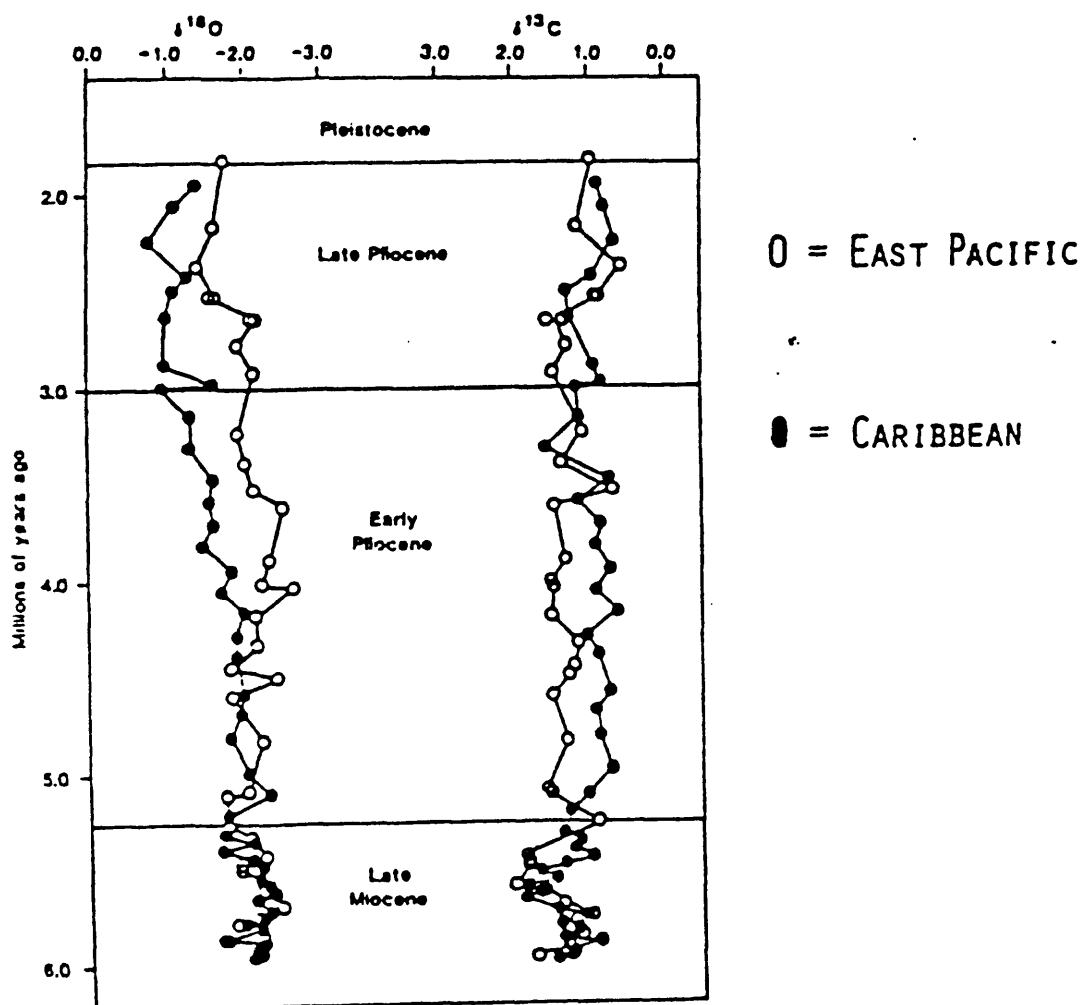
It is reasonable to hypothesize that the middle Miocene Gulf Stream flowed westward along the shelves of both the north and south sides of Hispaniola. The Cuban Miocene phosphorite on the southern Cuban shelf suggests that part of the current on the south side of the Greater Antilles may have flowed westward along the shelf. The Mona Island phosphorite, if it is marine and Miocene in age, may indicate flow of a Gulf Stream segment through the Puerto Rico-Hispaniola strait. It is also reasonable to hypothesize that any bathymetric obstructions to the Gulf Stream flow would cause obstruction upwelling (figure 5), similar to that in the southeastern US (Riggs, 1984) and perhaps the deposition of phosphorite. Such obstruction upwelling could occur on both the northern and southern shelves of Hispaniola.

If the Miocene paleogeography of Hispaniola could be reconstructed, the Miocene paleoceanography could be hypothesized, which would assist phosphate resource assessment. However, paleogeographic reconstruction is made extremely difficult by post-Miocene plate-tectonic rifting, spreading, and transcurrent faulting. Critical questions concern the presence or absence of the present straits between Hispaniola and Puerto Rico and Hispaniola and Cuba, and the Miocene position of the Presqu'ile-Barahona peninsula.

The question of the time of formation of the Hispaniola-Puerto Rico strait has not been addressed by geologic papers we have read. To use the Mona Island phosphate rock as evidence of the existence of a strait in Miocene time would be not only uncertain, but circular reasoning. Thus, at this time, judgement must be suspended.

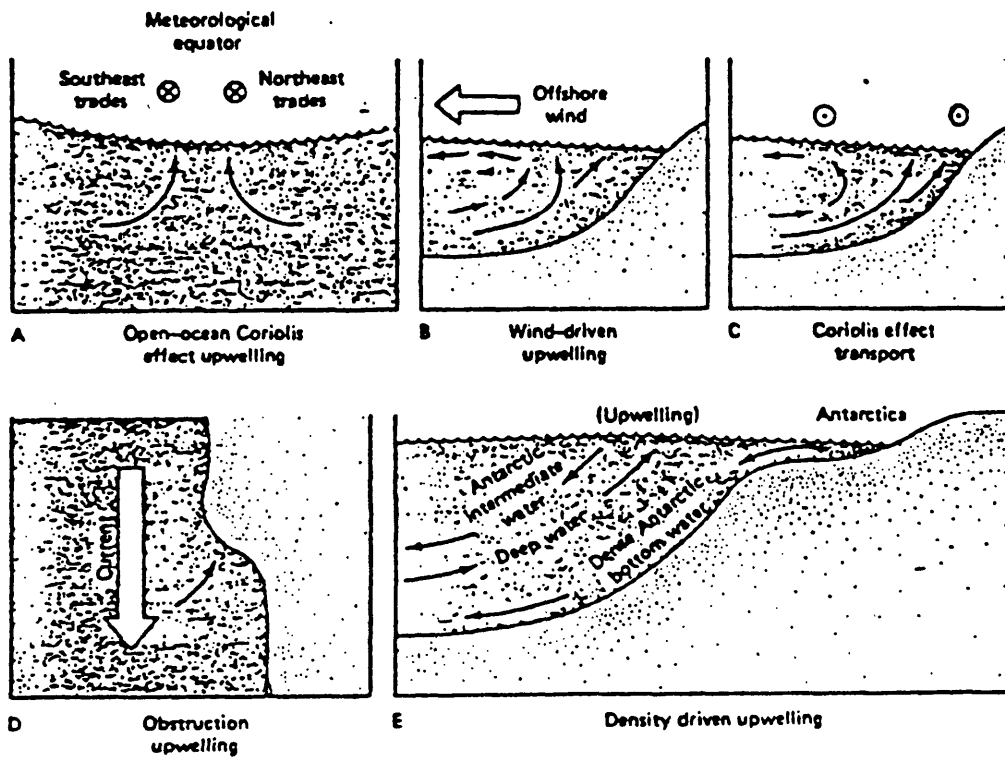
The question of the Hispaniola-Cuba strait can be addressed using available studies. Nemec (1980) presented a structural model of Hispaniola. A similar model was presented by Bourgois and others (1980). These models are shown in figures 6 and 7. Nemec showed the Muertos Trench, the northward dipping thrust fault on the north side of the Enriquillo-Cul de Sac Basin, and the trace of the old Muertos trench west of Haiti as a single fault system. This suggests that the Presqu'ile-Barahona peninsula and the Enriquillo-Sul de Sac Basin form an accreted exotic block sutured to the main part of Hispaniola along the Muertos subduction zone. Supporting evidence for this is the sedimentary facies discontinuity between the Miocene evaporitic sequence of the Enriquillo Basin and the Miocene marine sediments of the San Juan Basin,

Figure 4. Stable isotopes in planktonic foraminifera  
on each side of the isthmus of Panama



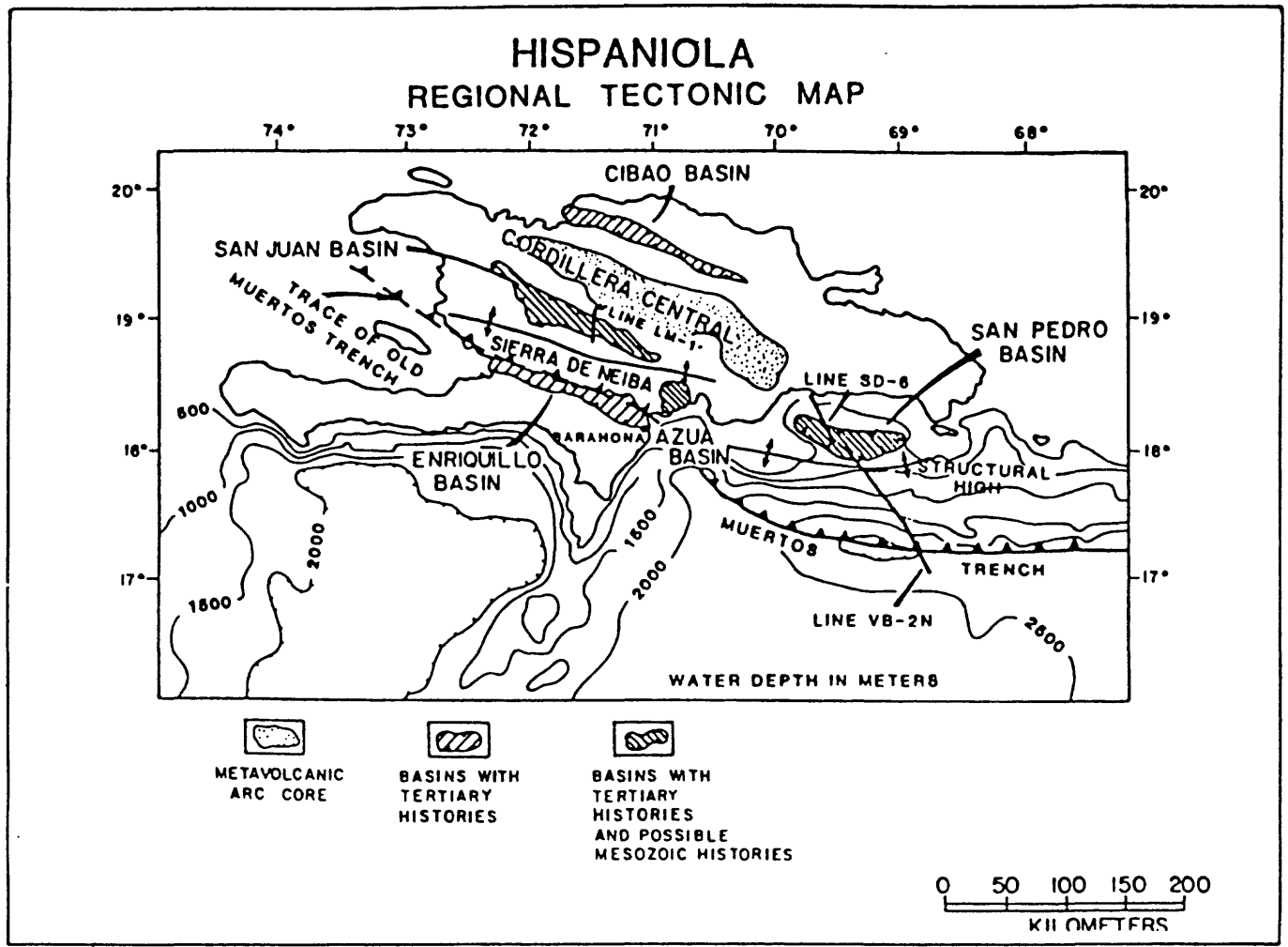
Keigwin (1982)

Figure 5. Upwelling processes

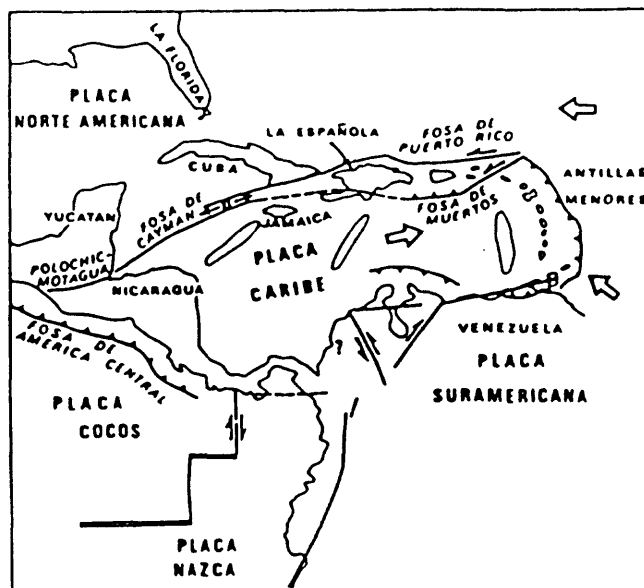


Pipkin et al. (1977)

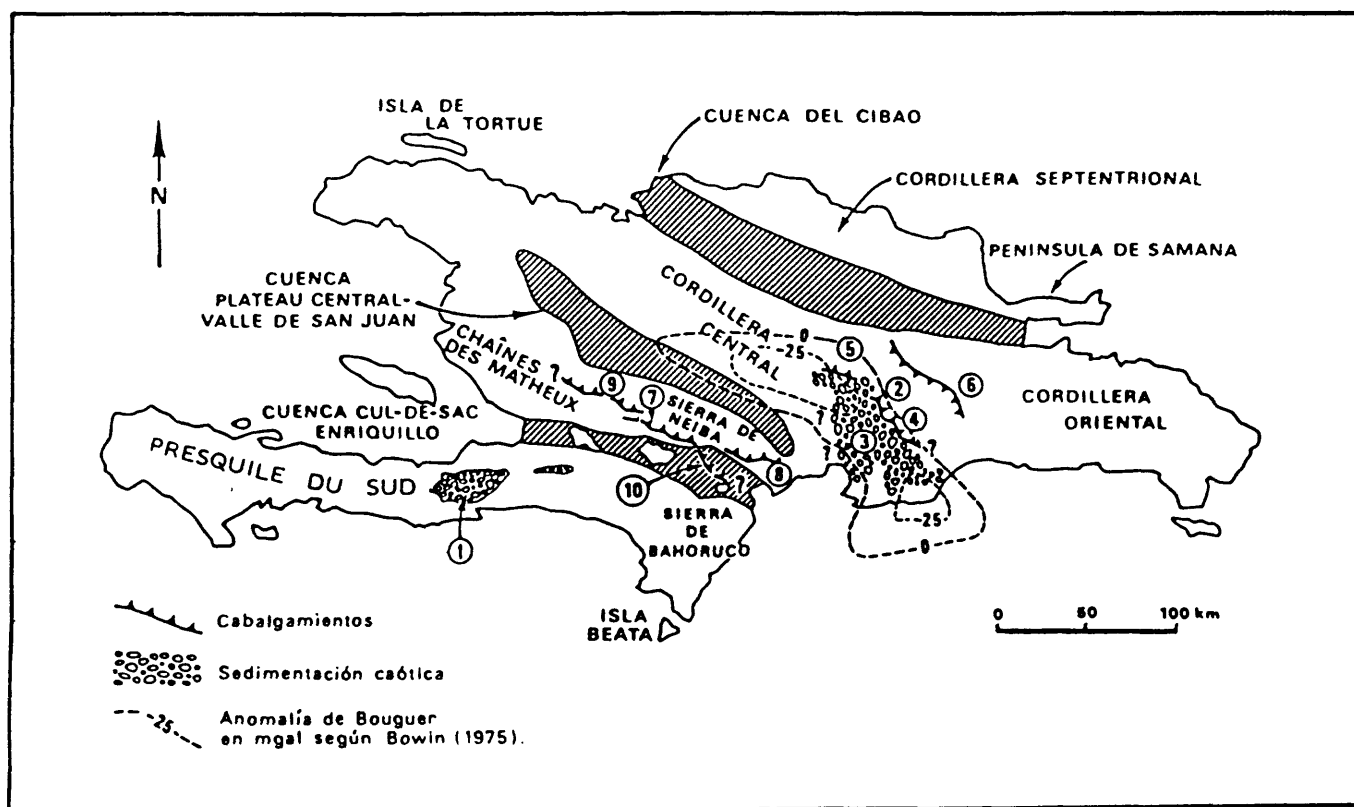
Figure 6. (NEMEC, 1980)







A. El marco de la Placa Caribe (según Molnar y Sykes, 1969; Malfait y Dinkelman, 1972; Jordán, 1976; Mascle, *et al.*, 1976).



B. Ubicación de los datos estudiados en el texto.

Figure 7. A. El Marco de la Placa Caribe  
B. Generalized physiographic map of Hispaniola  
(Bourgios and others, 1980)

which show a southward increase of deep-water facies. A deep canyon that is cut by the Rio Colorado in Sierra Neiba north of Neiba exposes a highly folded and faulted structural section. In a reconnaissance study of this section, Bourgois and others (in press) interpreted southward overthrusting on north-dipping faults involving Tertiary rocks (figure 8). The Miocene rocks exposed in the section consist of a thick contorted section of marine shale and limestone, rich in microfossils. Just to the south in the Enriquillo Basin, Miocene rocks are in part evaporitic, giving additional evidence of a Miocene facies discontinuity. The degree of contortion of the beds appears to increase to the north in the section north of Neiba. The structural block under the uppermost limestone is composed of a megabreccia of limestone and volcanics and perhaps is a tectonic breccia. It appears possible that this structural zone represents the suture zone between the main Hispaniola block and the Presqu'ile-Barahona block. Comparable tectonics in this trend are not known in areas outside of the possible suture zone (I. Tavares, oral communication, 1984). The original position of this possible accreted block may have been southeastern Cuba, where a straight coastline associated with a parallel belt of undated intrusives (Case and Holcombe, 1980) shows the characteristics of rifting. Nemec's and Bourgois and others' models show that north-south spreading of the rifted segments may have been on the Cayman Trough spreading center, and post-Miocene eastward movement of the exotic block may have been due to left lateral transcurrent faulting on the south side of the Cayman Trough caused by the eastward movement of the Caribbean plate. If this interpretation were true, the exotic accreted block would have been in the position of the present strait between Hispaniola and Cuba. Initial rifting could have created a narrow, restricted marine evaporite basin analogous to the Jurassic evaporites of the Gulf of Mexico, Cretaceous evaporites of West Africa and eastern South America and Miocene evaporites of the Red Sea.

An alternative model to explain the sedimentary facies relationship is that the Enriquillo pull-apart basin existed in Miocene time, and that evaporitic sedimentation corresponded to Miocene clastic deposition in the San Juan-Azua area. These conditions would require a Miocene uplift in the Sierra Neiba region and formation of the restricted Enriquillo Basin. However, folding and faulting of the Sierra Neiba is thought to be Pliocene (Lewis, 1980). The inclusion of Miocene rocks in the faulting on the south side of Sierra Neiba (Bourgois and others, in press) indicates that the folding and faulting is post-Miocene. Also, the deep water facies and northern provenance of the clastic fraction of the Miocene strata of the San Juan Basin gives no indication of Miocene uplift in the Sierra Neiba.

If the accreted exotic-block model were true, the Miocene paleogeography would be greatly different than the present geography. A shelf and slope sequence along the south side of the Cuba-Hispaniola island would have been deposited on the western part of the shelf, and possibly phosphorite would have accumulated in favorable sites along the eastern part of this shelf on present Hispaniola.

The Miocene rocks of the San Juan-Azua Basin may have been in an analogous position to the Cuban phosphorite. In exposures in the northern part of the basin, Miocene rocks exhibit a non-marine facies of conglomerate

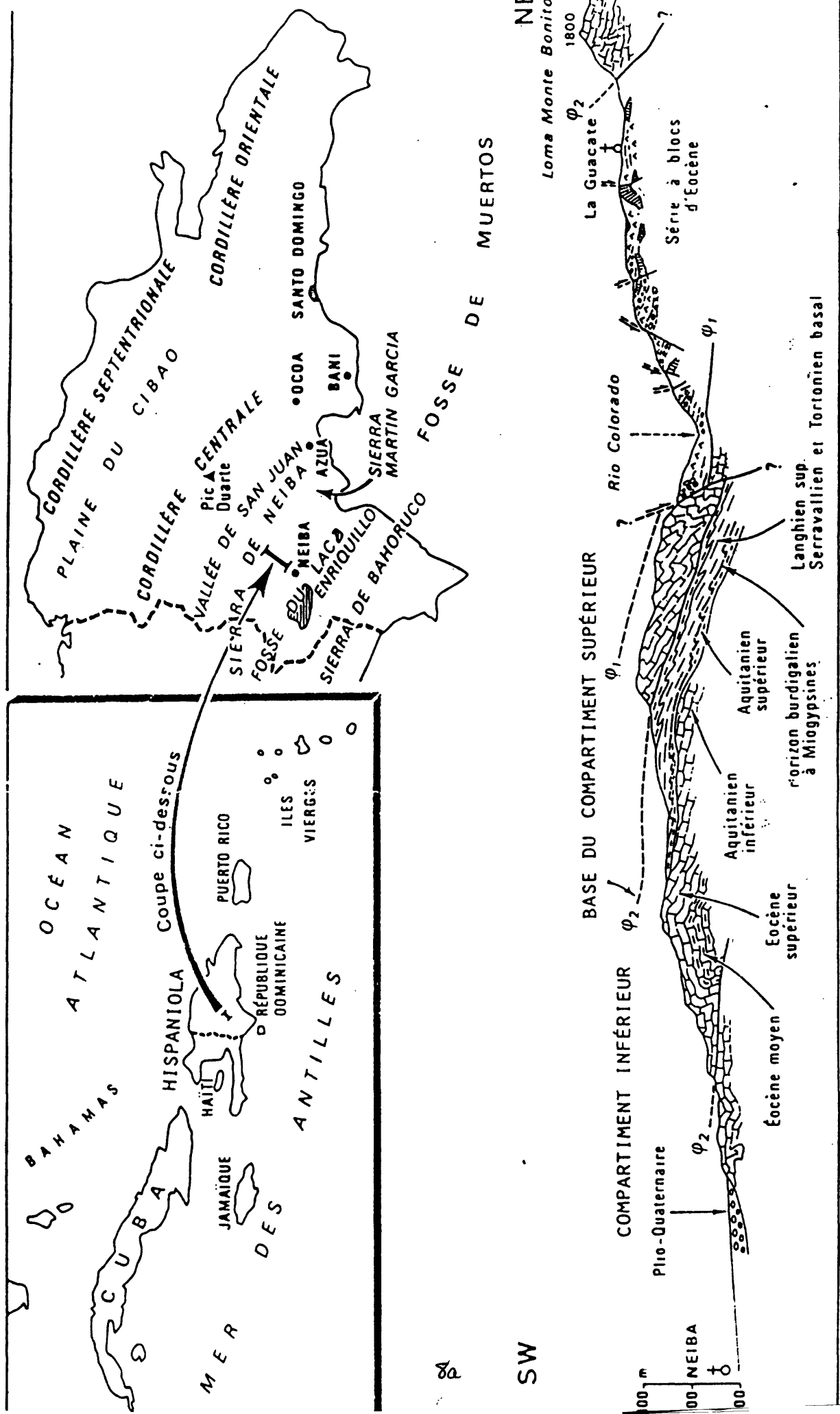


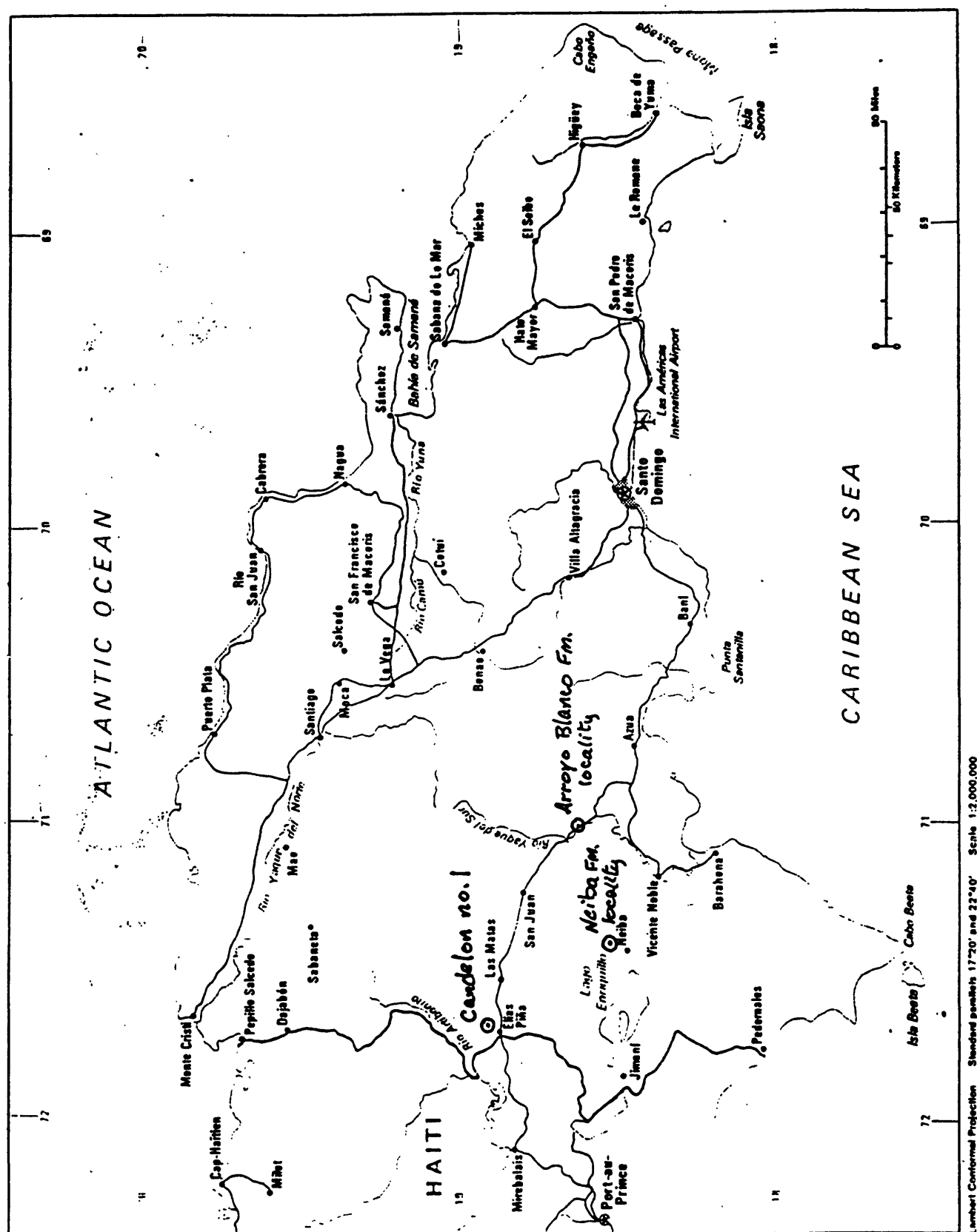
Figure 8. Structure cross-section along Rio Colorado, north of Meiba. (Bourgeois and others, in press)

and sandstone, which in part grades southward into marine sandstone and shale. At one locality northwest of Azua (figure 9), the lower part of the Aroyo Blanco formation contains two beds, about 10 meters thick, of dark greenish gray marine shale. These beds are exposed in a cut made for an irrigation canal. The shale contains abundant calcite fossils, including small fragile pelecypods and foraminifera, and rare glauconite grains. The shale is slightly phosphatic, probably less than 1% P<sub>2</sub>O<sub>5</sub>. To the west, in the section north of Neiba, the Miocene rocks consist of marine shale and limestone, with abundant microfossils. Thus, the facies of shallow-water marine Miocene sediments exists in the San Juan-Azua Basin.

The Miocene strata northwest of Santo Domingo was deposited on a shelf facing the Caribbean Sea to the south. This is east of the possible accreted block, and shows the paleogeography hypothesized for the Miocene of the San Juan Basin. The Miocene beds crop out along the edge of the coastal plain, but have not been well described in publications of which we are aware. A visit to an outcrop northwest of San Cristobal showed a cross-bedded and channeled sequence of sandstone. The rock is characterized by a flat foraminifera. The sediments probably accumulated in the outer beach environment, but more study is required. The Miocene section is fairly thick in this general area and should be further examined by shallow drilling to establish the stratigraphic sequence and possibility of occurrence of phosphatic sediments.

On the northeast side of the Dominican Republic in the Samana Bay region, Miocene sediments are widespread and thick. A study by Douglas-Robertson and Associates (1983) of the East Cibao-El Valle coal region has given new data and interpretations of the Miocene paleogeography and paleotectonics. They concluded that Samana Bay was formed in late Miocene time when the Samana Peninsula block rifted and moved northwest. They indicated that the middle Miocene rocks are more marine to the north. Alternatively the Middle Miocene paleogeography may have been a more simple shelf. If the Hispaniola-Puerto Rico strait were open, obstruction upwelling could have been caused by the eastern Dominican Republic shelf, causing phosphorite sedimentation on the northeast side of the shelf, in a manner analogous to that related to the Ocala Uplift in Florida and the Cape Fear Arch in North Carolina (Riggs, 1984).

The Miocene rocks of Dominican Republic contain coral debris and coral reef deposits. The question arises whether or not this should be taken as a negative factor in Miocene phosphate potential, as the two sediments are not generally associated. Corals are absent in rocks containing tradewind, eastern-boundary-current phosphorites, due to the low temperature of the upwelled water. The Miocene phosphorites of the southeastern US do not contain corals, but they occur mostly north of the present coral limit, which was probably at a comparable or even farther southern position during the Miocene glacial stages. However, corals are present in the phosphatic sequences of Miocene rocks in Cuba (Pokrisnkin, 1967) and Venezuela (Rodriguez, in press), so the presence of corals in Miocene rocks definitely cannot be taken as a negative factor in assessing phosphate potential of the Dominican Republic. It is conceivable that coralline limestone was deposited during Miocene interglacial stages in the southern part of the phosphogenic



province. Phosphorites are associated also with dolomite, which is probably significant sedimentologically in that there is a general association of dolomite and phosphorite in most phosphorites of all ages.

### Paleogene rocks

Paleocene and Eocene phosphorite deposits of North Africa make up a major portion of world phosphate resources (Slansky, 1980). Additional important deposits occur in southwestern USSR and West Africa. Phosphorites of Paleogene age also are known on Annan seamount in the Atlantic west of Africa and on a number of seamounts in the Pacific Ocean. These phosphorites originally were deposited at low paleolatitudes (Sheldon, 1980). The Paleogene phosphogenic episode was a continuation of the late Cretaceous episode described earlier, and the global distribution patterns and cyclic sedimentation of the two are similar.

No Paleogene phosphorite is known in the Caribbean region or Central American region, but the Paleogene paleogeography and paleoceanography of parts of the region may have been favorable for phosphorite sedimentation.

According to several plate tectonic reconstruction models, the islands of the Greater Antilles were part of an lower Cretaceous volcanic arc, formed above an east-dipping subduction zone, with the Pacific plate subducted under a seafloor formed by the rifting and spreading between North and South America (Walper, 1980). The volcanic arc made an Isthmus between North and South America in Early Cretaceous time that was broken up and moved northeastward in Late Cretaceous time by Caribbean plate movement. The volcanic arc was reactivated by southwest-dipping subduction under the volcanic arc.

If this model is correct, the Eocene sediments of southwestern Hispaniola were deposited on the southwest margin of the volcanic arc in a back arc basin during the second phase of Caribbean tectonics (Nemec, 1980; Maurasse and others, 1980). Shelf, crystalline limestone of the Plaisance Formation was deposited adjacent to the volcanic arc, and lithographic limestone and marl were deposited in deeper water, away from the volcanic arc; those limestone units make up the Neiba Formation.

It was suggested above in the discussion of Miocene rocks that the Presqu'ile-Barahona Peninsula might be an accreted block. If true, the block may have been formed by the break-up of the volcanic arc by collision of the western part of the volcanic arc with the Bahama Platform and fragmentation along left-lateral transcurrent faults. The change in direction of Caribbean plate movement to the east may have caused rifting and spreading along transcurrent faults. If the Presqu'ile-Barahona block were formed in this way, the sequence from north to south in the Cordillera Central-Sierra Neiba of Cretaceous volcanics, shelf limestone and deeper water limestone should be repeated in the Barahona Peninsula. The geologic-tectonic map of Case and Holcombe (1980) shows Cretaceous volcanics and the description of Eocene rocks by Dohm (1942a, b) includes shelf limestone south of the volcanics. However, Dohm's description of the Eocene rocks of the Barahona Peninsula is too brief to adequately describe the facies.

Some low-latitude shelves of Eocene age in other parts of the world that were washed by equatorial upwelled waters were the sites of phosphorite sedimentation. The Plaisance shelf limestone may have been deposited in a similar paleoceanographic position and may contain phosphorite. Some possible supporting evidence for this hypotheses is the presence of chert nodules and beds in the Plaisance throughout its full extent in Hispaniola. In the section of the Plaisance examined north of Neiba, chert beds and nodules occur at regular intervals interbedded with the limestone. No volcanic tuff was observed in the section. The chert beds are probably not of volcanic origin. The limestone beds associated with chert are slightly phosphatic, and the combination may indicate a general upwelling oceanic regime. The gamma-ray log of the oil well test Candelon No. 1, shows a slight gamma-ray anomaly in the Plaisance Formation, and the lithologic log indicates scattered dark gray pellets at a depth of 12,600 ft (figures 9 and 10). Below are scattered brownish green pellets described as glauconite. These characteristics may indicate the presence of phosphatic rocks and/or glauconitic rocks.

The Plaisance Formation has been called a shelf limestone because of its crystallinity. This speculation should be further examined. The Plaisance is a thin, even-bedded unit with little evidence of current structures in the rock. The crystalline limestone beds are interbedded with lithographic limestone, which is assigned a deep-water origin. Hand lens examination indicates that the lithographic limestone beds have scattered foraminifera and the crystalline beds contain in many cases a micritic (lithographic) matrix. The crystalline beds may be foraminiferal ooze, but this could only be determined by petrographic study. It seems possible that the lithographic limestone is formed of coccolith ooze and the crystalline limestone is formed of foraminiferal ooze. If true, the variation of lithologies may not indicate depth of water as much as the paleoecology of coccolith and foraminifera and the oceanic current regime. It still may be that water depth is an important factor in their sedimentation, but the question is, was it a shelf environment? Phosphorite sedimentation requires depths of water less than a few hundred meters. Was the water depth of Plaisance-type sedimentation that shallow?

The features of Plaisance-Neiba sedimentation are quite similar to the Upper Cretaceous sedimentation in the Paris Basin, France, which also contains chert nodules, as well as phosphorite, in small silled basins within the main Basin. Good background reading on the Paris Basin is Jarvis (1980). The Plaisance-Neiba sedimentation is also similar to the Upper Cretaceous limestone-marl sedimentation of Greece, where phosphorite also occurs. However, this occurrence has never been adequately described in the literature. The Plaisance has potential for phosphate in all of its areas of occurrence, which include the southern Cordillera Central, Sierra Neiba and Sierra Bahoruco. It would seem that the most likely areas to contain phosphorite would be the shallowest, so the northern occurrences of the rocks, which are nearest to the volcanic core of the island and should contain the shallowest water marine environment, should get the most attention. It seems less likely that the Neiba contains phosphorite.

In late Eocene time, subduction under the northern part of the island renewed a minor amount of volcanism and caused uplift of the island (Lewis, 1980). This caused basinward gravity sliding of shelf deposits on both the

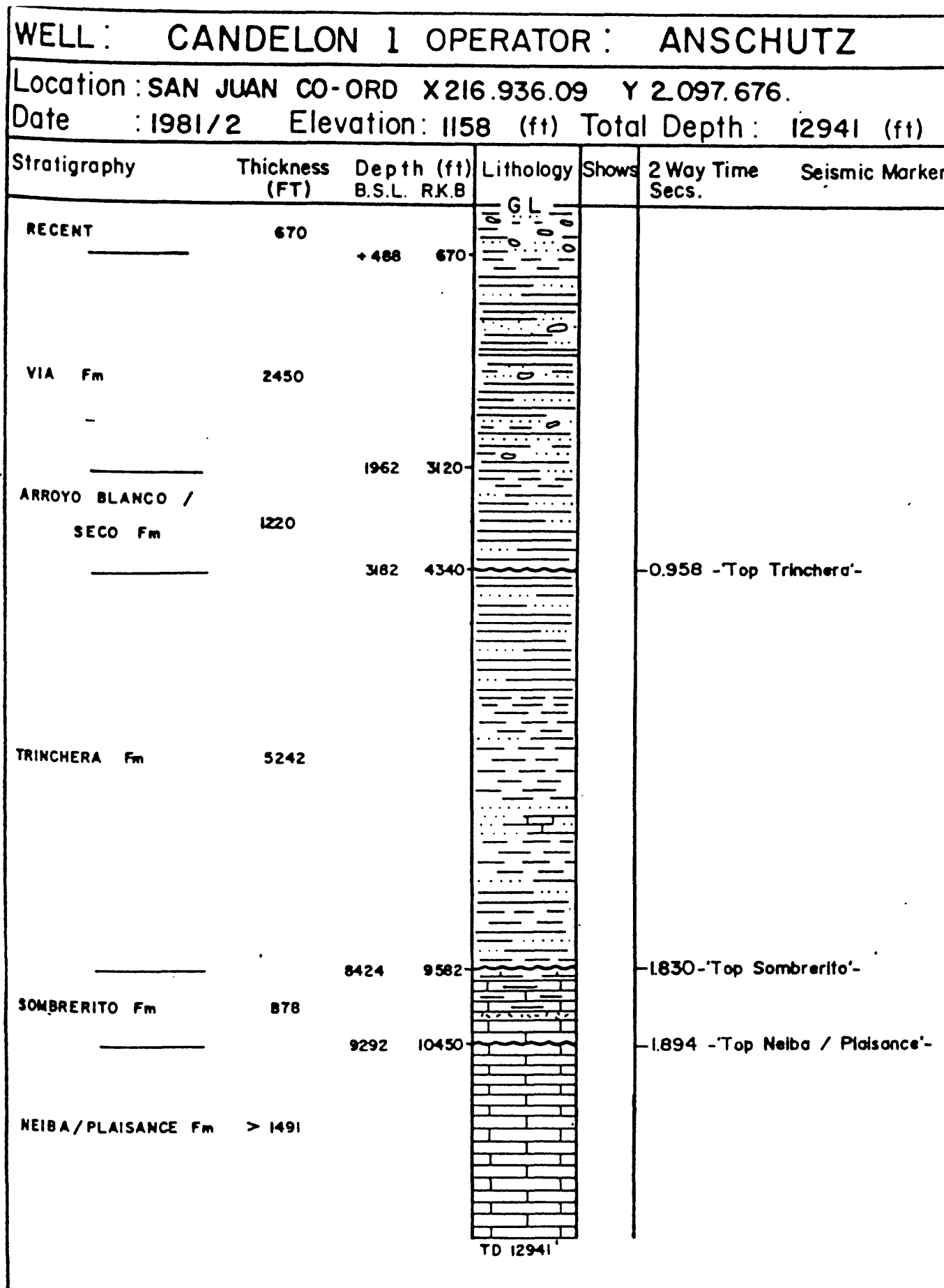


Figure 10. Generalized lithologic log of Candelon No. 1



north and south sides of the island. The upper Eocene olistolithic and conglomeratic deposits of the Bani and Azua area on the south side of Cordillera Central were formed in this way. Because of the chaotic, rapid and deep water sedimentation, the upper Eocene rocks are of no interest for phosphate potential.

Paleocene limestones are known in small outcrops in several parts of Cordillera Central, e.g. the Rio del Medio Series in the Padre las Casas area of the southern Cordillera Central (Lewis, J. F., unpublished map). The limestone commonly contains chloritized material and chert, both perhaps of volcanic origin. The Paleocene epoch included a major phosphogenic episode in other parts of the world, suggesting the possibility that the Paleocene of Dominican Republic may also contain phosphatic rocks.

#### Upper Cretaceous Rocks

There is no possibility that the Upper Cretaceous phosphogenic province of northern South America extends into the Greater Antilles. The northern South American phosphorites were deposited in an Upper Cretaceous fore-land basin east of the Upper Cretaceous subduction zone on the northwest side of South America. At the time this occurred, the Lower Cretaceous volcanic arc that eventually formed the Greater Antilles islands had already broken up and was moving eastward on the Caribbean plate (Walper, 1980).

However, the back-arc basin of Paleogene age on the southwest side of Hispaniola, discussed above, originated apparently in late Cretaceous time. Upper Cretaceous dark, slightly phosphatic limestone was deposited in this environment and includes beds of associated volcanic tuff and chert. This is well illustrated in the section in the southern Cordillera Central in the Montera Quadrangle north of Bani. Because late Cretaceous time included about five phosphogenic episodes, the arguments for back-arc-basin phosphate sedimentation in the Paleogene of Hispaniola apply equally to the Upper Cretaceous.

Upper Cretaceous limestone is found in the Cordillera Central and Cordillera Oriental. Middle Eocene to Cretaceous lithic fragments of shelf sediments are abundant in the upper Eocene olistostrome unit, so that an opportunity exists to sample the original Cretaceous and pre-upper Eocene shelf sediments by searching the lithic fragments for phosphate and dating them paleontologically.

#### Guano-derived Phosphate Rock

Karstic areas of high rainfall and extensive limestone outcrops exist in eastern Dominican Republic. Bat guano cave deposits have been reported at several localities in this region. The cave guano deposits themselves are too small to have any significant resource value. However, the presence of the bat guano deposits suggests the possibility of apatite deposition in solution channels developed along fractures and bedding planes in the limestone below. A review of this process, developed in Thailand where a number of such apatite deposits exist, is given in Appendix D. The same arguments apply to Dominican Republic. As mentioned above, the tabular apatite deposit on Mona

Island above the unconformity between the Mio-Pliocene and Plio-Pleistocene limestones may be of bat guano origin or marine origin. If of bat guano origin, it would indicate the presence of a type IIb deposit (solution channel deposits along low angle bedding planes or unconformities).

### Igneous Apatite

Alkalic, subsilicic, iron-rich volcanic rocks of Cenozoic age occur in the southern Cordillera Central. These volcanics appear to be associated with the pull-apart basin of the San Juan-Azua valleys region (Mann, 1983). This is a conceivable environment for mineral-rich igneous deposits, including apatite-rich rocks. Normative apatite in the alkali-olivine basalt is 1.85% (table 1). Although low, the possibility exists that volcanic rocks with larger amounts of apatite occur in the volcanic province.

### Rocks of Very Low to No Potential

Many other rock units exist in the Dominican Republic that are described in the literature. From their descriptions, it was judged that their phosphate potential was very low to nonexistent. They are described in general terms below.

The Lower Cretaceous volcanic rocks making up the core of the volcanic arc do not have a phosphate potential.

Oligocene rocks consist of conglomerate, rhythmically bedded shale and sandstone, and limestone. Sedimentation was rapid, and only the sections containing limestone could conceivably be phosphatic. No marine phosphate deposits of definite Oligocene age are known in the world, probably because little vertical circulation occurred in the ocean. The Oligocene rocks of Dominican Republic are therefore judged to have a very low phosphate potential.

The Miocene evaporite environment of the Enriquillo Basin is not favorable for phosphate sedimentation because the large amount of current activity necessary to supply phosphorus to form a large deposit is incompatible with a small evaporite, restricted-basin environment. However, any normal marine sediments in the Enriquillo Basin should be examined for phosphatic sediments. The potential, however, appears to be low.

Pliocene-Pleistocene reefoidal limestone exists in many places in the coastal areas of Dominican Republic. The Pliocene-Pleistocene is not a favorable time for major phosphorite sedimentation. The potential of these rocks for marine phosphorite is considered very low, but their bat guano-derived phosphate potential is high, as discussed earlier.

### RANKING OF POTENTIAL PHOSPHATE AREAS

A resource assessment of undiscovered phosphate of a country can be produced by the application of phosphate petrology to the geology of the country. Because of incomplete knowledge, the undiscovered resource assessment is always a progress report. New theories of phosphate or new understanding of the indigenous geology will possibly make the assessment

Table 1. Representative whole rock chemical analysis and normative values of late cenozoic volcanics of Hispaniola

(Vespucchi, 1980)

	Haitian Nepheline Basalt	Alkali- Olivine Basalt	Phlogopite Basalt	Basaltic Andesite	Trachy- Andesite	Dacite	Rhyolite
SiO <sub>2</sub>	38.64	42.40	50.45	53.42	59.23	65.25	79.53
Al <sub>2</sub> O <sub>3</sub>	11.14	10.96	16.11	14.46	15.18	15.84	11.1
Fe <sub>2</sub> O <sub>3</sub>	5.35	10.48*	4.47	5.78	3.77	3.16	1.0
FeO	5.31		2.40	3.37	2.14	0.49	0.32
MgO	13.04	12.96	7.61	8.12	4.36	1.83	0.18
CaO	14.40	13.34	6.21	9.01	5.27	4.82	0.26
Na <sub>2</sub> O	3.43	1.85	1.60	2.43	3.81	4.34	0.23
K <sub>2</sub> O	1.90	0.16	3.95	1.82	3.08	2.73	9.11
MnO	0.14	0.15	0.12	0.17	0.12	0.11	0.02
TiO <sub>2</sub>	2.85	2.26	0.94	0.65	0.68	0.45	0.11
P <sub>2</sub> O <sub>5</sub>	0.71	0.80	0.38	0.17	0.23	0.17	0.0
H <sub>2</sub> O <sup>+</sup>	3.01	-	3.45	0.44	1.74	0.26	0.76
H <sub>2</sub> O <sup>-</sup>	0.29	-	2.13	0.18	0.35	0.23	0.22
	100.21	95.36	99.82	100.02	99.96	99.68	102.93
Norm							
Q			3.14	5.50	10.17	18.51	44.00
Or		0.95	23.34	10.76	18.20	16.13	53.84
Ab		6.33	13.54	20.56	32.24	36.73	1.95
An	9.39	21.08	25.11	23.17	15.22	15.68	1.29
Ne	15.72	5.10					
Lc	8.80						
Di	25.02	32.27	2.50	15.95	7.33	5.55	
Hy			17.79	13.46	7.46	1.99	0.45
Ol	15.26	23.50					
Mt	7.76		5.40	8.37	5.32	0.60	0.78
Il	5.41	4.29	1.79	1.23	1.29	0.85	0.21
Ap	1.55	1.85	0.88	0.39	0.53	0.39	

obsolete. There is also uncertainty in both phosphate theory and country geology, which introduces uncertainty into the assessment. The process is dependent, therefore, on the experience and intuition of the geologists making the assessment.

For these reasons, the assessment of the undiscovered phosphate potential of Dominican Republic contains much uncertainty. The purpose of the assessment is to identify target areas for prospecting, so it is important to make a liberal assessment. That is to say, it is a worse mistake to exclude a target area that actually contains phosphate than to include a target area that does not. For the assessment to lead to efficient prospecting, the target areas must be ranked as high, medium and low. This is clearly an intuitive process. It includes two factors: 1) the probability of existence of the deposit and 2) the feasibility of economic exploitation of a deposit, if found. For effective resource development, the second factor is the prime factor, because a large phosphate deposit in a country is of little value if it is too deeply buried or too structurally disturbed for economic mining or too remote or in too rugged country for economic exploitation. Thus, in this assessment, the deposits are primarily ranked by feasibility of economic exploitation and secondarily by probability of existence.

The magnitude thickness, grade and quality of deposits are also critical factors in a phosphate resource. However, these characteristics usually cannot be assessed in advance of discovery, so that they cannot be taken into account in assessing undiscovered resources.

The ranking of the target areas gives the suggested order of priority of further investigation and prospecting, all other things being equal. However, all other things are usually not equal, so that the priority of investigation will have to be re-evaluated by the Direccion General de Minería. The other factors would include availability of drilling equipment, availability of funds (for more expensive prospecting), and in some countries (not including Dominican Republic) availability of political access.

The target areas for phosphate prospecting are ranked in table 2, and are discussed below.

#### High Feasibility of Economic Exploitation

The Miocene rocks of Dominican Republic in general are flat lying or only slightly folded. Exceptions are the Southern Sierra Neiba and the Enriquillo Valley. They occur in low lying valleys or coastal plains, where road networks already exist. Thus, low-cost strip mining would be possible for deposits at or near the surface, and transportation costs would be low, depending on where the processing plant is to be built.

The Miocene rocks of the San Juan Valley appear to have a medium probability of existence of phosphate deposits, as its paleogeographic position seems most analogous to the Cuban phosphorites. Also, a full suite of facies is available for prospecting.

Table 2. Ranking of phosphate target areas of Dominican Republic  
by feasibility of economic exploitation and probability of existence

<u>Feasibility of economic exploitation</u>	<u>Probability of existence</u>
I HIGH	
Miocene of San Juan-Azua Valleys	medium
Miocene NW of Santo Domingo	low to medium
Miocene of East Cibao-El Valle	low to medium
II MEDIUM	
Eocene of Sierra Neiba and southern Cordillera Central	medium
Guano-derived phosphate of eastern Dominican Republic	high
Igneous apatite	low-very low
III LOW	
Upper Cretaceous limestone	low
Paleocene limestone	low

The outcrops of Miocene strata observed in this project in the Santo Domingo area are probably a beach facies, containing abraded coral fragments. To the south, in the subsurface, a marine facies undoubtedly occurs. The boundary between the two facies would be the most likely horizon for phosphate accumulation.

The marine facies Miocene rocks crop out in the eastern Cibao-El Valle area. The non-marine, lignitic facies of the Vanigua Formation probably is not phosphatic. The overlying Cevicos Limestone contains abundant corals. Cyclic sedimentation is reported from drill holes in the Guan Estero and floodplains of the Yuna River (Douglas-Robertson & Assoc., 1983, p. 3-8), which may indicate glacial-interglacial episodes. The sedimentary sequence becomes generally more marine to the north, giving perhaps a better chance for the occurrence of phosphorite. The probability of existence of phosphorite in the area is given as low to medium.

#### Medium Feasibility of Economic Exploitation

The Eocene rocks of the Sierra Neiba and southern Cordillera Central, the Cenozoic volcanic rocks of the southern Cordillera Central, and the karstic terrane with a guano-derived phosphate potential in the northeastern part of the country are given a medium feasibility of economic exploitation. The possible shallow-water facies of the Plaisance Formation of Eocene age occurs in mountainous terrane in the northeastern part of the San Juan Valley, where phosphate would be difficult to mine and would be relatively far from the planned sulfuric acid plant. The karstic areas are mainly virgin, undeveloped regions without roads and with rugged topography. The Cenozoic volcanic rocks of the Cordillera Central region occur in mountainous terrane, which would make mining difficult.

The Eocene Plaisance formation of the Sierra Neiba and southern Cordillera Central is thought to have the highest phosphate potential of the Eocene sequence, as discussed above. In Haiti, the Plaisance shows a shallow bank facies (Maurasse, 1980?), with a basal conglomerate, echinoid and pelecypod fragments in a thickly bedded biocalcarenite. The descriptions of the Plaisance Formation of Dominican Republic suggest a somewhat deeper water deposit. The Plaisance outcrops examined in Rio Colorado north of Neiba were calcarenites, but in hand-lens examination appeared to be made up of a foraminiferal ooze, and could have been deposited in water too deep for phosphate sedimentation, as discussed above. Assuming that shallow water shelf sediments occur in the Plaisance Formation of Dominican Republic, the probability of occurrence of phosphorite is given as medium.

The probability of guano-derived phosphate existing in the karstic terrane of northeastern Dominican Republic is given as high. It is likely that any deposit will be high-grade but small (less than 100,000 tons). If multiple deposits occur, the total resource could reach several million tons, which is still a small resource. However, if a sulfuric acid phosphate fertilizer plant is constructed in Dominican Republic, a market will exist for small-scale phosphate production, and a valuable industry, creating jobs in the mining and transportation sectors, could be developed. At 100 pesos per ton of phosphate, a deposit of 100,000 tons would be worth 10 million pesos.

Even if a sulfuric acid plant is not constructed, guano-derived phosphate could be ground and applied directly to acid soils with expectable good agronomic results, because the mineral in the deposits would be the more soluble hydroxyapatite variety of apatite.

The probability of existence of igneous apatite in the late Cenozoic volcanoes of the southern Cordillera Central is low to very low, and perhaps should not be included in this undiscovered phosphate resource assessment. The tectonic environment of the Dominican Republic pull-apart basins (Mann, 1983) is certainly different from the rift valley systems of cratonic areas, such as East Africa, where apatitic carbonatites and ijolites are found (Notholt, 1980). However, Notholt points out (p. 289) that igneous apatite deposits occur in other tectonic environments. Tuttle and Gittens (1966) is an excellent reference on igneous apatite deposits. A short review of East African igneous apatite deposits is given in Appendix E. If some of the late Cenozoic volcanic rocks of the southern Cordillera Central are enriched in phosphate, but insufficiently to make beneficiation of apatite feasible, it is possible that the ground volcanic rock would be a valuable soil amendment. It would require agronomic testing to determine this.

#### Low Feasibility of Economic Exploitation

The Upper Cretaceous and Paleocene limestones of the southern Cordillera Central have a low feasibility of economic exploitation, because outcrops are small, structural deformation is strong, mining would have to be underground, and the rocks occur in mountainous terrane. The one exception to this is the area near the Pueblo Viejo mine. If a sulfuric acid plant is constructed near the mine site, a nearby phosphate deposit would be ideally placed.

The probability of existence of phosphate is also low for the Upper Cretaceous and Paleocene limestone, primarily because the chert occurring in the rock appears to be of volcanic origin, indicated by its association with volcanic tuff. On the other hand, the limestones tested generally showed a slight enrichment in phosphate, and deposition may have been under an equatorial upwelling-current regime. Maurasse (1980?) indicates that Upper Cretaceous limestone of the Barahona Peninsula is probably uplifted Caribbean seafloor of a back-arc basin tectonic environment. If so, the water depths would have been too deep for phosphorite sedimentation. Because of their proximity to the Pueblo Viejo mine, the Hatillo and Las Canas limestones, of early and late Cretaceous age, respectively, should be investigated even though their potential for phosphate appears to be low.

#### SUGGESTED PHOSPHATE RESOURCE DEVELOPMENT PROGRAM

The present undiscovered phosphate resource assessment has identified and ranked target areas that potentially contain phosphate rock. Specific studies to further evaluate these target areas and to prospect for phosphate rock are presented below in order of priority.

## Miocene Formations

A. The Miocene phosphorite deposits of Cuba and Venezuela should be visited. The Cuban deposit is analogous and particularly relevant to the further assessment of the Miocene rocks in the southern part of Dominican Republic. Seeing these deposits will show what to look for in Dominican Republic. The southeastern US phosphate deposits should also be visited. In May 1985, the ICGP Project 156 field workshop/seminar will be held in the southeastern US. One or more geologists from Dominican Republic should attend that meeting, which will be focussed on Miocene phosphorite. Financial assistance should be available for one geologist from the Dominican Republic from Project 156 funds.

B. The cores and cuttings of the Miocene marine sediments drilled by Douglas-Robertson and Associates for the Eastern Cibao-El Valle Coal Project should be located and studied further. The samples should be described petrographically and chemically tested for phosphate qualitatively, and if positive, tested semiquantitatively.

C. Stratigraphic sections of Miocene rocks should be measured, with emphasis on the marine facies. Highest priority for this work should be in the San Juan-Azua Valleys. The rocks should be carefully described, the thickness of each bed of different lithology measured, fossils collected and correlations between sections made. The second priority study is the Miocene in the Santo Domingo area. The Eastern Cibao-El Valle should have third priority. However, if study of the Douglas-Robertson samples shows phosphate, the East Cibao-El Valle area would have first priority.

For phosphate assessment and prospecting, it is essential that both the lithostratigraphic and biostratigraphic frameworks of the Miocene rocks be established as well as possible. Several shallow stratigraphic holes should be drilled to obtain complete sections, as phosphatic beds are generally soft and unexposed.

D. When the above study is completed, a preliminary stratigraphic nomenclature, based primarily on lithogenetic units, should be set up. A discussion of the problems of the present nomenclature practices for Eocene rocks in Dominican Republic is given in Appendix G, but the discussion applies equally to Miocene rocks. At that point, a facies analysis could be made and suitable environments for phosphate sedimentation identified. The understanding of the rocks would then be sufficient to design a core drilling program, assuming that phosphatic beds have been identified.

About one geologist-year of effort should be sufficient to carry out this phase of the work on the Miocene up to, but not including, a systematic core drilling program. Part-time assistance from paleontologists and petrographers would be required. Also it may be helpful to obtain short-time assistance from foreign specialists at critical stages of the study. A particularly able phosphate geologist experienced in southeastern US and Baja California Miocene phosphate rocks is S. R. Riggs, at East Carolina University. Stratigraphic studies similar to the one proposed here have been carried out in the US, and



published examples will be sent to the Minería. If phosphate is present in Miocene rocks, they should be identified during this phase. If phosphate is not found, a review of the study should be made to decide whether to discontinue or continue the study.

#### Eocene Formations

A. The mechanical logs, lithologic log and cores and cuttings of Candelon #1 oil well test should be examined. Cores and cuttings should be tested for phosphate. Small individual grains, such as the dark gray pellets described in the lithologic log, can be dropped into a test tube containing Shapiro solution. Because the size of the grain (if it is about one millimeter in diameter) approximates the size of the measuring spoon, this procedure will tell roughly if the grain is apatite or not. If these grains are apatite, it will prove that phosphatic sediments exist in the Plaisance Formation.

B. Sedimentary petrographic studies of the Eocene rocks should be undertaken, particularly on the Plaisance rocks, to identify marine sediments deposited in water shallow enough for phosphate sedimentation (less than about 200 meters). This can be done by determining the energy of the environment from calcarenite petrography, paleoecology and presence of current features. The problem is differentiating turbidites or deep water foraminiferal ooze from shallow water, wave-sorted sediments. If shallow water environments are identified, phosphate prospecting should be emphasized in these and adjacent units.

C. A lithostratigraphic and biostratigraphic study similar to that proposed for the Miocene rocks should be undertaken for the Eocene rocks. The area of first priority should be in the ranges adjacent to the western San Juan Valley. In order to know what to look for, it is important for the geologist carrying out this work to become familiar with the literature on phosphate deposits formed in environments comparable to the Eocene of Dominican Republic. The most analogous deposit is the Upper Cretaceous of the Paris Basin. The paper by Jarvis will be sent to Minería, and other papers in French will be sent if available.

D. Given encouragement of a phosphate potential from the above studies, several holes should be drilled to obtain complete stratigraphic sections of the prospective units.

This phase of study of the Eocene rocks should be comparable to that of the study of the Miocene rocks in terms of level of effort. About one geologist-year and appropriate scientific support would be required.

#### Cretaceous and Paleocene Formations

Cretaceous and Paleocene rocks have been ranked low in both feasibility of economic exploitation and probability of existence of phosphate rock. Thus their study would have lowest priority. One exception is the Cretaceous limestone in the vicinity of the Pueblo Viejo mine, where it is possible that

the ore processing plant and the sulfuric acid plant will be located. A phosphate deposit in the vicinity of the proposed plant would be ideally located for exploitation. Therefore, these rocks should be thoroughly investigated. The procedure would be somewhat similar to those described for the Miocene and Eocene rocks. Emphasis should be placed on the Las Canas Limestone of Late Cretaceous age, because Late Cretaceous time included multiple episodes of phosphogenesis, whereas none are known in Early Cretaceous time.

Initially sections of the limestone should be measured, beds tested for phosphate, and stratigraphic units correlated. If phosphatic rocks are located, stratigraphic core holes should be drilled.

It is estimated that this work would take about four geologist-months to complete.

#### Guano-derived Phosphate Rock

A. Mineria geologists should visit Mona Island to examine the apatite deposits associated with caves in the Pliocene-Pleistocene limestone and the apatite deposits found at the unconformity between the Miocene-Pliocene and Pliocene-Pleistocene limestones. The paper by Kaye (1959) should be studied before the trip. The purpose of the visit is to become familiar with this type of phosphate deposit. Also the issue of whether the unconformity phosphate is marine or guano-derived should be settled by petrographic and chemical analysis.

B. The cave guano deposits known in the areas of karst topography in Dominican Republic should be examined for apatite deposits, either on the cave floors or in solution channels below the caves.

C. Topographic maps of karstic terrane should be examined. Areas of high limestone cliffs adjacent to fertile valleys should be identified.

D. Field reconnaissance to the areas identified in C above should be made and large caves identified. Helicopter reconnaissance would be the most effective means. Apatite-solution channel deposits below the caves are commonly darker than the limestone because of their contained organic matter, and commonly can be identified visually from a distance if they have been exposed by erosion.

E. Ground reconnaissance to caves identified in D above should be made to discover solution channel apatite. If discovered, subhorizontal solution channel deposits along bedding planes or unconformities and lower down on the limestone monoliths should be searched for.

This general approach is further outlined in Appendix D. This phase should not require more than about four geologist-months of effort. Z. S. Altschuler, who worked on the mineralogy and geochemistry of the Mona Island phosphate, and who is now retired from the USGS, but working part-time under contract for the USGS, could give valuable assistance on this phase of the work, particularly on analysis of mineralogic and geochemical results.

If subhorizontal deposits are found, resource assessment would follow conventional lines of development exploration by trenching, tunneling and core drilling.

### Igneous Apatite

A reconnaissance of Cenozoic volcanoes should be made to collect samples of different rock types. Particular attention should be paid to the alkalic, subsilicic, basic volcanic rocks. Perhaps a helicopter reconnaissance would be most efficient and effective. About two geologist-months of work would be required.

### Summary of Development Program

The program recommended above is summarized in Figure 11. The letters for each program task coincide with the letters of the previous section. It was assumed in making this flow chart that two geologists will work full time on the project, and that they will be supervised by one part-time geologist and supported by appropriate part-time geologists and chemists for special scientific services. It may be more practical, however, for an igneous petrologist to undertake the studies of igneous apatite potential, and perhaps another geologist might undertake the studies of the guano-derived phosphate potential. If so, most of the project work indicated for 1986 could be carried out in 1985.

This flow chart would be subject to radical revision if phosphate is discovered in the early months of 1985. For example, if significant phosphorite is discovered in Miocene rocks, work on the rocks of other ages scheduled to follow should be delayed and a major effort should be undertaken on the Miocene phosphorite.

The time allotted for each portion of the work is only approximate, but the level of effort on this discovery phase of the program should not greatly exceed the estimated time. This is basically reconnaissance prospecting work and should not be turned into long-term research efforts.

At the end of the collection of data on each age rock, the data should be analyzed and a short report written. The results should be reviewed and decisions made regarding whether to continue the study of that time-rock unit. If phosphorite is found or if no indications of phosphorite are found, the decision will be relatively easy, but if indications of phosphate are found, the decision will be difficult and phosphate specialists probably should be brought in to assist in making it. If a decision is made not to abandon the study, the program for the continued study should be planned by the review group. If phosphorite has been discovered, a program of development exploration should be formulated. It is important that the overall program be flexible to allow for such contingencies.

Many scientific problems worthy of more effort will emerge from this program. One effective way to encourage such additional work is to identify problems that would make good thesis problems for graduate students in both Dominican Republic and foreign universities.

1985	<p>MIocene</p> <p> <u>A<sub>1</sub></u>  <u>B</u> </p> <p> <u>C<sub>1</sub></u>  <u>C<sub>2</sub></u> </p> <p> <u>A<sub>2</sub></u> </p> <p> <u>D</u> </p> <p> A - Foreign field trips  1. Cuba and Venezuela, 2. US  B - Eastern Cibao drill samples  C<sub>1</sub> - Stratigraphic studies  C<sub>2</sub> - Core drilling  D - Analysis of results, review and decision </p>
	<p>EOCENE</p> <p> A - Candelon #1 studies  B - Petrographic studies  C - Stratigraphic studies  D - Core drilling  E - Analysis of results review and decision </p> <p> <u>A</u>  <u>B &amp; C</u> </p> <p> <u>D</u> </p> <p> <u>E</u> </p>
1986	<p>Cretaceous Pueblo Nejo</p> <p> <u>A</u>  <u>B</u> </p> <p> A - Stratigraphic studies  B - Analysis of results, review and decision </p>
	<p>Guano-derived phosphate</p> <p> <u>A</u>  <u>B</u>  <u>C</u>  <u>D</u>  <u>E</u>  <u>F</u> </p> <p> A - Mona Island trip foreign  B - Reconnaissance to known guano caves  C - Geomorphologic analysis  D - Aerial reconnaissance  E - Field reconnaissance  F - Analysis of results, review and decision </p>
	<p>Igneous Apatite</p> <p> Field reconnaissance and sampling </p>

Figure 11. Flowchart of undiscovered phosphate resource development program.

## REFERENCES CITED

- Altschuler, Z. S., 1973, The weathering of phosphate deposits - geochemical and environmental aspects: In Griffith, E. J., Beeton, A., Spencer, J. M. and Mitchell, D. T., eds., *Environmental phosphorus Handbook*, Wiley, New York, p. 33-96.
- Bourgois, J., Vila, J., Llinas, R. and Tavares, I., 1980, Tectonicas sobrepuestas in la Espanola (Antillas Mayores), *Trans. 9th Caribbean Geological Conference*, Santo Domingo, Dominican Republic, vol. 1, p. 35-38.
- Bougois, J., and others, (in press), Title unknown.
- Case, J. E. and Holcombe, T. L., 1980, Geologic-tectonic map of the Caribbean region: U.S. Geological Survey Misc. Invest. Series map I-1100.
- Cathcart, J. B. and Zambrano, O. F., 1967, Roca fosfatica en Colombia: *Colombia Bol. Geol.*, v. 15, no. 1-3, p. 65-152.
- Dohm, C. F., 1942a, A geology report of the Cerros de Sal, Valle Enriquillo, Republica Dominicana: Unpublished report.
- \_\_\_\_\_, 1942b, Geology of the Sierra de Neiba, and Valles San Juan and Enriquillo: Unpublished report.
- Douglas-Robertson & Associates, 1983, Report on East Cibao/El Valle Coal Project: Unpublished report to Rosario Dominicana, S.A., Dominican Republic.
- Jarvis, I., 1980, The initiation of phosphatic chalk sedimentation - the Senonian (Cretaceous) of the Anglo-Paris Basin: *In* Bentor, Y. K., ed., *Marine phosphorites - geochemistry, occurrence, genesis*, Soc. Econ. Paleon. and Mineral., Spec. Pub. 29, p. 167-192.
- Kaye, C. A., 1959, Geology of Isla Mona, Puerto Rico: U.S. Geological Survey Professional Paper 317-C, p. 141-178.
- Keigwin, Lloyd, 1982, Isotopic paleoceanography of the Caribbean and East Pacific; role of Panama uplift in late Neogene time: *Science*, v. 217, no. 4557, p. 350-353.
- Lewis, J. F., 1980, Resume of the geology of Hispaniola: *Field Guide*, 9th Caribbean Geological Conference, Santo Domingo, Dominican Republic, p. 5-31.
- Mann, W., 1983, Cenozoic tectonics of the Caribbean: Ph.D dissertation, State University of New York at Albany, 688 p.
- Maurasse, F. J., 1980?, Survey of the geology of Haiti. (Paper includes 1982 references).

- Maurasse, F. J., Pierre, L., Louis F. and Rigaud, G., 1980, Cenozoic facies distribution in the southern Peninsula of Haiti and the Barahona Peninsula Trans. 9th Caribbean Geological Conference, Santo Domingo, Dominican Republic, vol. 1, p. 161-174.
- McKelvey, V. E., 1963, Successful new techniques in prospecting for phosphate deposits: Natural Resources, vol. II of U.S. Papers for the United Nations Conference on the Applications of Science and Technology for Less Developed Areas, 355 p.
- \_\_\_\_\_, 1967, Phosphate deposits: U.S. Geological Survey Bulletin 1252-D, p. D1-D22.
- Mullens, H. T., and Neumann, A. C., 1979, Geology of the Miami Terrace and its Paleo-oceanographic implications: Marine Geology, v. 30, p. 205-232.
- Nemec, M. C., 1980, A two phase model for the tectonic evolution of the Caribbean: Trans. 9th Caribbean Geological Conference, Santo Domingo, Dominican Republic, vol. 1, p. 23-34.
- Notholt, A. J. G., 1980, Igneous apatite deposits - mode of occurrence, economic development and world resources: In Sheldon, R. P. and Burnett, W. C., eds., Fertilizer Mineral Potential in Asia and the Pacific, East-West Center, Honolulu, Hawaii, p. 263-285.
- Pipkin, B. W., Gorsline, D. S., Casey, R. E., and Hammond, D. E., 1977, Laboratory Exercises in Oceanography: Freeman, San Francisco, 775 p.
- Pokrishkin, V., 1967, Areas de prospeccion y estudio de fosforitas en la Republica de Cuba: Revista "Tecnologia", no. 2, p. 3-16, La Habana, Cuba.
- Riggs, S. R., 1984, Paleooceanographic model of Neogene phosphorite deposition, U.S. Atlantic continental margin: Science, vol. 223, no. 4632, p. 123-131.
- Rodriguez, S. E., 1984, Phosphate districts in Venezuela: Report distributed to Workshop on phosphate potential of Caribbean Basin and Central America, East Carolina University, Greenville, North Carolina, July 8, 1984.
- Rodriguez, S. E., in press, Phosphorite deposits of Venezuela: In Notholt and others, World Phosphate Resources, Cambridge University Press.
- Shapiro, Leonard, 1952, Simple field method for the determination of phosphate in phosphate rocks: American Mineralogist, v. 37, p. 341-342.
- Sheldon, R. P., 1964, Paleolatitudinal and paleotectonic distribution of phosphorite: U.S. Geological Survey Professional Paper 301-C, p. 106-113.
- \_\_\_\_\_, 1980, Episodicity of phosphate deposition and deep ocean circulation - a hypothesis: In Sheldon, R. P. and Burnett, W. C., eds., Fertilizer mineral Potential in Asia and the Pacific, East-West Center, Honolulu, Hawaii, p. 191-206. Also published in Soc. Econ. Paleontologists and Mineralogists Spec. Publication no. 29, p. 239-247.

- \_\_\_\_ 1981, Ancient marine phosphorites: *Ann. Rev. Earth Planet. Sci.*, vol. 9, p. 251-284.
- \_\_\_\_ 1984a, Phosphate resource assessment and exploration in Thailand: Unpublished United Nations report to Department of Mineral Resources, Bangkok, Thailand, 52 p.
- \_\_\_\_ 1984b, Phosphate resource potential of Ethiopia based on available reports: United Nations unpublished report to Institute of Geological Sciences, Addis Ababa, Ethiopia.
- Slansky, M., 1980, Ancient upwelling models - Upper Cretaceous and Eocene deposits around West Africa: In Sheldon, R. P. and Burnett, W. C., eds., *Fertilizer Mineral Potential in Asia and the Pacific*, East-West Center, Honolulu, Hawaii, p. 145-158.
- Stowe, K. S., 1979, *Ocean Science*: John Wiley, New York, 610 p.
- Tuttle, O. F., and Gittens, J., 1966, *Carbonatites*: John Wiley, New York.
- Vespucci, P., 1980, Preliminary account of the petrology of the late Cenozoic volcanic province of Hispaniola, *Trans. 9th Caribbean Geological Conference*, Santo Domingo, Dominican Republic, vol. 1, p. 379-389.
- Walper, J. L., 1980, Geologic evolution of the Greater Antilles: *Trans. 9th Caribbean Geological Conference*, Santo Domingo, Dominican Republic, vol. 1, p. 13-22.

## APPENDICES

Seven appendices to the report give information that may prove helpful to the phosphate resource development in Dominican Republic. Not all are specifically referred to in the text.

Appendix A gives a simplified phosphate rock nomenclature and lists important data on textures and structures in the rock that should be recorded when measuring a stratigraphic section.

Appendix B gives simple procedures for making mineralogic interpretations from chemical data of phosphate rocks. The main problem addressed is that of aluminum phosphate rock, which may occur in Dominican Republic.

Appendix C is a guide for using the Shapiro field chemical test for phosphate rocks.

Appendix D is from Sheldon (1984a) and gives results of a study of guano-derived phosphate in Thailand.

Appendix E is from Sheldon (1984b) and gives a brief summary on igneous apatites of East Africa relative to assessment of undiscovered igneous apatite in Ethiopia.

Appendix F is a selected annotated bibliography to supplement the geologic papers referred to in the text and listed in References Cited.

Appendix G discusses problems arising from stratigraphic nomenclature practices in Dominican Republic.



## APPENDIX A

### Rock Nomenclature for Describing Phosphorite

It is important to describe phosphorite beds as well as possible in order to be able to recognize individual beds from one section to another. Also, the petrographic character of phosphorites gives clues to the conditions of sedimentation, which can help in determining the lateral continuity of the bed. The petrographic character of the rock determines the feasibility of beneficiation of the rock to give high-grade concentrates for fertilizer manufacture. It is equally important to describe well the intercalated beds of other lithologies in order to help in correlation of beds from one section to another.

The petrographic character of pure phosphorites is determined by the type of grains. The most common is a structureless accretionary round grain called a pellet. A rock formed of pellets is called a pelletal phosphorite. The Wentworth size classification is used to describe grain size and is given below:

Diameter (mm)	adjective
1/16-1/8	very fine
1/8-1/4	fine
1/4-1/2	medium
1/2-1	coarse
1-2	very coarse

If the accretionary grain is structureless and larger than 2 mm, it is called a nodule, and a rock composed of nodules is a nodular phosphorite.

Accretionary grains that have an internal concentric structure are called oolites if between 1/16 and 2 mm and pisolites if larger than 2 mm.

Generally phosphorites are well sorted, so the grains fall into one or two size classes. They would be called, for example, "oolitic phosphorite, fine to medium grained." Some phosphorites are poorly sorted, and grains will fall into three or more size classes in which case, they would be, for example, "oolitic phosphorite, fine to very coarse grained."

Some coarser pellets or nodules are commonly composed of smaller pellets. Such a rock would be called, for example, "nodular phosphorite, nodules composed of very fine pellets." Some phosphorites are composed of coprolites made up of pellets and would be called "coprolitic pelletal phosphorite."

Another type of phosphorite is composed of grains finer than 1/16 mm, and the individual grains cannot be distinguished under a hand lens. The term "microphosphorite" is used for such rocks.

Other types of grains are composed of remains of fossils, which may or may not have been originally apatite. Grains from fish teeth, scales and bones, inarticulate brachiopods, conodonts and scolecodonts were originally apatite. Apatite foraminifera, which are common in late Mesozoic and early Tertiary phosphorites, are apatite-replaced carbonate foraminifera remains. A phosphorite composed of abraded fossil remains is a bioclastic phosphorite, which is the most common type.

Some phosphorites are a mixture of different grain types, for example, pellets and fossil fragments. Both adjectives should be used and the percentage of the various grains estimated. For example, "bioclastic, pelletal phosphorite, 10% bioclasts, 90% pellets."

Structures of phosphorites should also be described. This would include cross-bedding, bioturbation and lamination. If no structures of bedding is observed, the phosphorite is massive.

This basic classification is shown in the chart below, with adjectives given. The rock noun should follow the adjective.

grain size	structureless accretionary	concentric accretionary	abraded fossil	unabraded fossil
- 1/16	MICROSPHORITE			
1/16-2	PELLETAL	OOLITIC	BIOCLASTIC COQUINOIDAL	
+ 2	NODULAR	PISOLITIC		

Some microsphorite has been subjected to storm waves and microsphorite has been ripped up and more or less abraded. If the clasts are only slightly abraded, it is an "intraclastic microsphorite." If reworked into subrounded grains, it is a reworked microsphorite.

Some phosphorites are composed of reworked and redeposited apatite grains of different types of colors. They would be called reworked phosphorites, and the general range of grain types described.

Most phosphorites include minerals other than apatite, such as calcite, dolomite, quartz, clay and glauconite. The non-apatite minerals may form separate grains, cement or matrix, or replace the apatite grains. The percentage of the non-apatite minerals should be estimated, and if 20-50%, the adjectives, calcareous, dolomitic, sandy, argillaceous or glauconitic should be used. If greater than 50%, the rock becomes a phosphatic limestone, phosphatic dolomite, etc.

If a phosphorite is chemically analyzed for phosphate and acid insolubles, it can be accurately named by simple calculation. Multiply the phosphate by 2.6 to give the percentage of apatite. Assume the acid insoluble content to be the percentage of quartz or clay which is determined by hand lens. The remainder is carbonate or organic matter, which can be estimated by inspection. The rock then can be more accurately named.

The texture of the non-apatite minerals should be observed to determine whether it forms cement, matrix, individual grains or replaces apatite. Apatite itself commonly forms cement and makes a hard, high-grade phosphorite.

Organic matter is commonly present in phosphorite and colors the rock brown or black. Thus, it is important to record the color. A standard color chart is best for this purpose, but if one is not available, intuitively use the terms listed below.

no color

white	-	-	-
light gray	light brown gray	light green gray	light yellowish gray
med. gray	med. brown gray	med. green gray	med. yellowish gray
dark gray	dark brown gray	dark green gray	dark yellowish gray
black	-	-	-

Describe hardness as shown below:

hammer sinks into rock	soft
rock breaks easily with blow	medium hard
rock does not break easily with blow	hard

Other points:

1. Drop 10% HCl on rock and record the fizzing reaction: None, slight, moderate, strong. If it is a carbonate rock with no reaction on a fresh surface but the powder in a scratch fizzes, the rock is a dolomite. If only a little (20-30%) of the rock is a carbonate (by hand lens observation) and the fizz is moderate, the rock is calcareous. A strong fizz indicates the rock is a limestone. Apatite is a carbonate-bearing mineral ordinarily in sedimentary rocks, and it will fizz slightly when dissolved.
2. All suspected phosphatic rocks should be tested by the Shapiro semiquantitative test and the results used to name the rock.
3. Contacts between beds should be described using the following terms: Sharp, sharp and irregular, gradational, covered, fault contact.
4. Describe interbedding or lamination giving average thickness or interbeds of each rock type and the percentage of each rock type in bed.
5. Secondary films on joint surfaces should be recorded, giving color and reaction to acid. Bright yellow films are probably uranium minerals. Brown stains are probably iron oxide.

6. A lookout should be kept for aluminum phosphate minerals. Determine this with the Shapiro test.
7. A bed is a lithologic unit of constant character. It could be characterized by composition, hardness, texture, or structure. Any change in character is the basis for describing a new bed. Measure the thickness of the bed perpendicular to bedding!
8. For rocks that are not phosphatic, use standard rock terminology, but describe the rock features in comparable detail as for the phosphorites.
9. Collect fossils! Describe them in your notes.
10. Make sketches of unusual features, such as nodules, crossbedding, etc.
11. Collect a representative sample of each bed for later laboratory mineralogic and petrographic study.
12. Collect a channel sample of all phosphatic beds.

Properly measuring and sampling a section of phosphatic rocks is hard work and takes time. But careful measurement and accurate descriptions will allow the development of data that is absolutely essential to assessment of phosphate rock resources.

## APPENDIX B

### Analysis of Chemical Data

In analyzing chemical data of phosphate rock, take the following steps:

1. If the rock is fresh (no weathering, no hard pan), assume that the P205 is in apatite. The CaO/P205 ratio will be above 1.36, the average of Jhabua apatite. The amount that the ratio is above 1.36 will depend on the amount of other carbonate minerals.

2. If the sample is from a weathered zone, one of five conditions may exist.

a) The sample may contain calcite or dolomite. If so the P205 should be in apatite, and the CaO/P205 ratio will be above 1.36 depending on the amount of carbonate mineral.

b) The sample may be phoscrete, and if so, no calcite is likely. The CaO/P205 ratio should be as high as 1.46 due to a higher amount of C03 substitution for P04 in the apatite lattice.

c) Calcite and dolomite are leached out and original apatite residuum remains. CaO/P205 will be about 1.36.

d) Calcite and dolomite are leached out, and some apatite has been altered to crandallite. CaO/P205 ratio will be below 1.36. The F/P205 ratio will be below 0.1.

e) Calcite, dolomite and apatite are leached out, and the rock is composed of crandallite and/or wavellite. CaO/P205 ratio will be at or below 0.39. Al2O3/P205 ratio will be about 1.08, and F/P205 ratio will be zero. If weathering has altered all crandallite to wavellite, the ratios will be that of wavellite, but some Al2O3 may be in other alumina bearing minerals.

Sample deviations from these interpretative guidelines will be due to other phosphate minerals (vivianite and other iron phosphates), other fluorine minerals, and other calcium minerals. However, only iron phosphates are likely. The second alternative is an error in the chemical analysis. Finally, there is not definitive substitute for an x-ray mineralogic analysis, and all problem rocks should be x-rayed.

## APPENDIX C

### Field Chemical Test for Phosphate

Chemical testing for phosphate in the field is a simple procedure (Shapiro, 1951). The test basically consists of dissolving the rock in a dilute nitric acid solution containing ammonium molybdate and ammonium metavanadate. If phosphorus is present, the solution will turn yellow. When the process is controlled by using a specified amount of powdered sample in a specified volume of a standard solution and comparing the intensity of the yellow color to a set of standards, the phosphate content can be estimated to within about 5%.

Several precautions must be taken with this test. Because of the time required to grind the sample and run the test, the field geologist commonly puts the solution directly on the rock. A rock with a few tenths of a percent phosphate will give a yellow color and will commonly cause the geologist to overestimate the phosphate content of the rock. With practice and caution, however, this procedure is useful. If the solution on the rock turns yellow rapidly, the rock may have a significant amount of phosphate and should be then tested with the semiquantitative procedure.

If the phosphate occurs in the rock in the mineral apatite, the procedure works well, because apatite is soluble in dilute nitric acid. However, if the phosphate is in one of the more insoluble minerals such as variscite (aluminum phosphate) or crandallite (calcium aluminum phosphate), the dilute nitric acid will not dissolve the mineral, and the test would be negative. These aluminum phosphate minerals are the common weathering products of a phosphate rock composed of apatite, particularly in the laterite weathering environment. Shapiro gives the procedure for testing for aluminum phosphate rocks using strong acid solutions.

The test is simple enough that an intelligent, unskilled assistant can be taught to run it quite efficiently and accurately, allowing the geologist time to concentrate on the petrographic aspects of the rock.

A given set of comparison standards will only be accurate for the measuring spoon in the kit, so care should be taken not to mix measuring spoons, or to make sure that no significant differences exist between the volumes of the measuring spoons. It is also important to prepare the reagent accurately according to the quantities given in Shapiro.

## APPENDIX D

### Geology and Resource Potential of Guano-derived Phosphate Rock

At the present time, a little over 200,000 metric tons of medium to high grade phosphate rock of guano-origin have been delineated in eleven deposits in western Thailand (Table 1 and Figure 1). At \$35 per metric ton, this resource is worth about 7 million dollars. No phosphate fertilizer manufacturing plant exists in Thailand at the present time, so there is no market for this rock. A minor amount of phosphate rock is being mined by small mining operations for use in direct application of ground rock to agricultural lands.

It is generally accepted by DMR geologists who have worked on the deposits that the phosphate rock has been derived from cave guano and that the resource is too small and scattered to be significant to development of a national fertilizer supply. This may not be the case, however, because little resource assessment has been carried out other than making cursory geologic studies of known deposits. The geologic studies have been aimed at descriptions of the deposits, and little synthesis of this data has been made to develop concepts of origin and distribution. Thus it is premature to judge the size of the resource.

The present lack of economic demand for domestic phosphate rock has caused stagnation of the private phosphate mining industry. This condition may change if the planned construction of a sulfuric acid phosphate fertilizer plant in eastern Thailand materializes. Also, a small-scale technology for phosphate fertilizer manufacture has been developed by the Kettering Research Laboratory in the US (Treharne & others, 1980), field tested at three localities in the US, and is now being tested for its agricultural engineering feasibility in the Himalayan foothills in Uttar Pradesh, India. If proved feasible, this technology may be of use in Thailand.

Table 1. Guano-derived phosphate rock deposits in Thailand and a field inspection indicated original estimate of 10,000 mt too high.

references: 1. Japakasetr, 1982; 2. Suwanich, 1980; 3. Suwanich and Ratanjaruraks, 1980; 4. (author unknown) "Phosphate" --- pages 182-185; 5. Cape, 1981; 6. Utha-aroon

Class: 1. cave floor; 2. solution channel; 3. soil-limestone slopes; 4. laterite

Province	Deposit, number and name	resource	%P205	class		reference	other deposit name
				major	minor		
Lam Phun	1. Mae Tha	50,000	36	3	4	1, 2	
	2. Khao Mae Lek	100	30	1		2	
	3. Ban Mae Pa Phai	7,500	35	1		2	
Lampang	4. Kho Ka	100	30-40	2A		1	Ban Had-pu-dai
Phetchabun	5. Sap Sombun	12,000	20-35	2A	1	1, 3	
	6. Khao Cha-Ngok	15,000	20-25	1	2	3	Thep Phanom
	7. Khao Khana	1,500	10-27	2A	3	3	
Chainat	8. Khao Nong Nam Daeng	1,000a	28-32	2A		1	
	9. Khao Rang Kai	5,000	30	2A		1	
Kanchanaburi	10. Ban Na Kan	100,000	12-34	2B	3	1, 6	
Ratburi	11. Khao Phak Ma	3,000	20-34	2A	3	1	
Phetburi	12. Phetburi	?	?	?		5	
Prachuabkhirikan	13. Same	?	?	?		4	
Song Khla	14. Khao Rak Kiat	900	15-30	?		1	
Surattani	15. Surattani	?	?	?		4	



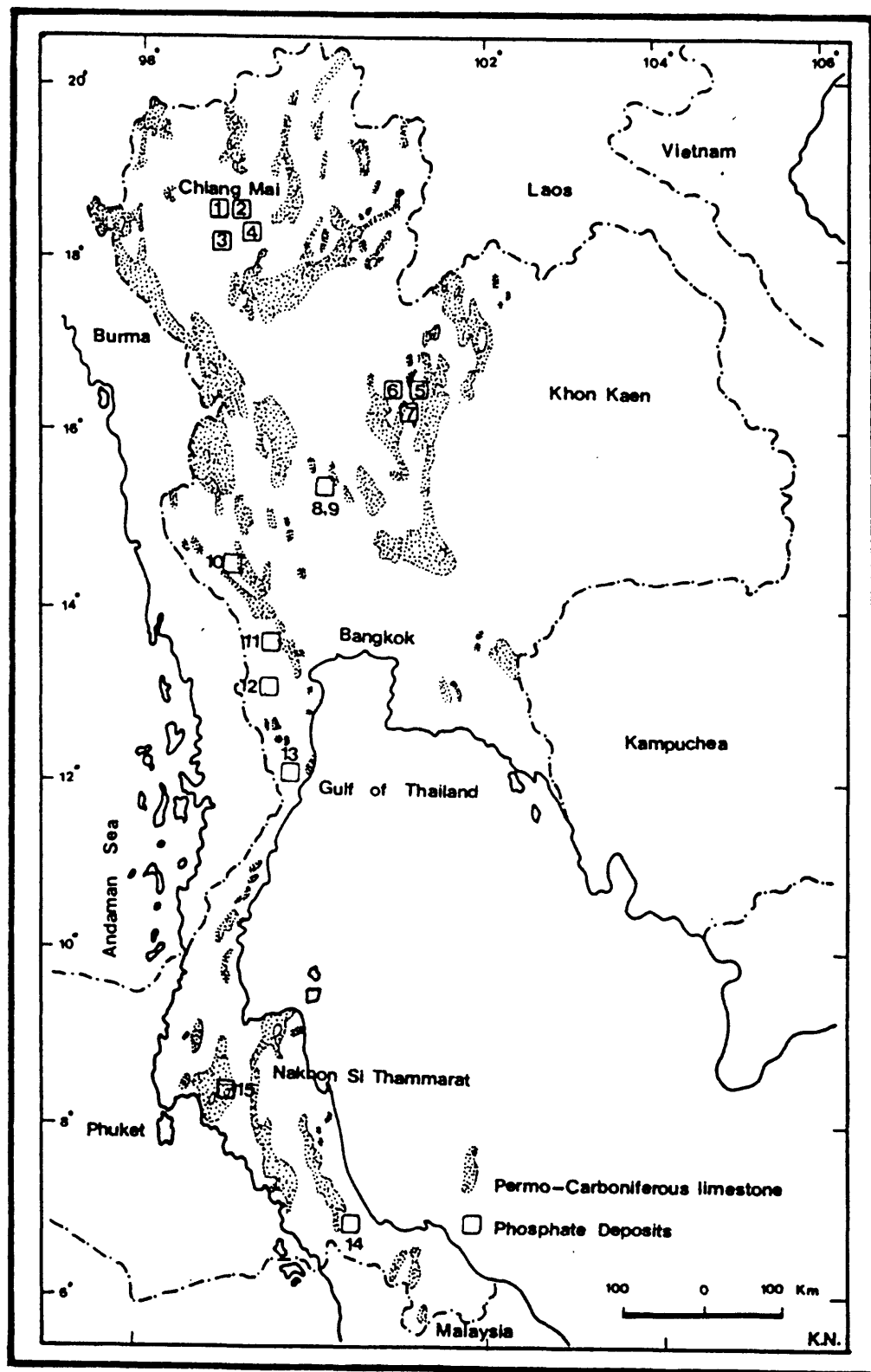


Figure 1. Distribution of Permo--Carboniferous limestone and guano-derived phosphate rock in Thailand (see table for phosphate rock locality names).

It can be expected that economic demand for domestic (and remote) phosphate may be created by these activities. If so, mining activity would be renewed, including prospecting for new deposits. For these reasons, it would be timely to initiate scientific studies to develop concepts of depositional processes of the guano-derived phosphate rock and to use such concepts for resource assessment. The discussion that follows is a preliminary attempt to do this, but it should not be taken as a completed synthesis, but only an attempt to present the problems.

### Regional Geology

Limestone is distributed widely in Thailand (Kuentag, 1983) (Figure 1). In particular, thick Permian limestone forms rugged, karstic mountain ranges in the western half of the country. The monolithic peaks of the karstic terrane are distinctive and are rounded and/or pointed on top and usually terminate in steep cliffs, which are vertically fluted and commonly overhang. The monoliths contain abundant solution channels, fissures and caves. The solution process forms peaks that allow quick runoff of rain water, which is initially slightly acidic, and minimal additional solution. This is the reason for the permanency of the limestone peaks in a humid tropical climate.

Abundant caves give an environment for large bat colonies. Slightly phosphatic bat excrement accumulates on the floor of the caves. Altschuler (1973, p. 68) stated, "The requirements for substantial deposits of phosphatic bat guano (chiropterite) are met best in dry caves of karst terrains, in warm, fertile regions. The cave areas of the West Indies, Indonesia, and Thailand are notable past and present-day examples. Many caverns in the limestone belts of Bohemia, Appalachia, and Texas and New Mexico still support bat colonies, but their guano, for the most part, was deposited in pre-Holocene and, presumably, warmer periods."

The distribution of guano-derived phosphate rock in Thailand is first determined by the existence of caves suitable for bat colonies. A second and equally important factor would be the population of winged insects, as the magnitude of food supply would determine the size of the bat population. A survey of the known guano-derived deposits indicates that they tend to occur in karstic terrain adjacent to low-lying fertile flood plains, where the winged insect population could be expected to be large. While this seems to be an ecologically reasonable hypothesis, the deposit distribution data on which it is based may be biased. The high karstic terrain is nearly inaccessible and certainly has been less explored for phosphate than the low hills near well-populated fertile plains. Thus, the high mountains may contain phosphate in amounts comparable to the low-lying areas. This question deserves additional geologic research as well as input by biologists knowledgeable of bat ecology. If it is true that the presently known phosphate deposit distribution does reflect the real distribution, a tool for resource assessment and exploration of guano-derived phosphate deposits will exist.

It also should be possible to roughly calculate the total number of bat-years required to produce a metric ton of apatite, if the phosphorus content of bat excrement and the daily production of excrement per bat are

determined. The size of caves and the average bat population could be estimated, and this in turn would allow rough calculations of the number of years required to produce any given deposit. Much uncertainty would be inherent in such estimates, but perhaps reasonable high-low limits could be set. Also, it would be particularly interesting to estimate the bat population carrying capacity of one hectare of fertile lowland, as this would allow an estimate of annual phosphate resource production per hectare of lowland.

### Phosphate Rock

The known deposits of guano-derived phosphate rock are listed in Table 1, along with the resource estimate, P<sub>2</sub>O<sub>5</sub> content and reference. The phosphate deposits occur in three basic forms, 1) tabular cave floor deposits and 2) tabular steeply dipping vein and gently dipping bedding plane deposits within the limestone monoliths, and 3) tabular deposits on valley slopes at soil-limestone contacts. These are shown diagrammatically in Figure 2. These four classes of deposits form a series. Class I cave floor deposits grade downward into class IIA steeply dipping vein deposits, which in turn tend to grade into class IIB gently dipping bedding plane deposits. Class IIB deposits tend to grade downward into class III soil-limestone slope deposits. The Class III deposits can be lateritized in a limestone-free weathering environment and grade upward into class IV aluminum phosphate laterite. The size distribution of the eleven known deposits whose resource has been estimated is shown in Figure 3. Most deposits are less than 25,000 metric tons, but the Mae Tha and the Ban Na Kan deposits contain an estimated 50,000 and 100,000 metric tons of phosphate rock respectively.

The chemical analyses of phosphate rock from two localities in Thailand and 4 localities from Philippine caves are given in Table 2.

The major mineral in the Thai deposits is hydroxy apatite with minor fluorine. At the Khao Rang Kai deposit, phosphate rock contains 73% apatite and 12% robertsite, a hydrous calcium manganese phosphate mineral (IFDC, 1983). There is little doubt that cave floor phosphate deposits contain a complex phosphate mineral suite, as bat excrement is presently accumulating. However, no mineralogic studies of this material are available. Aluminum phosphate minerals occur in lateritized apatite in the Mae Tha deposit.

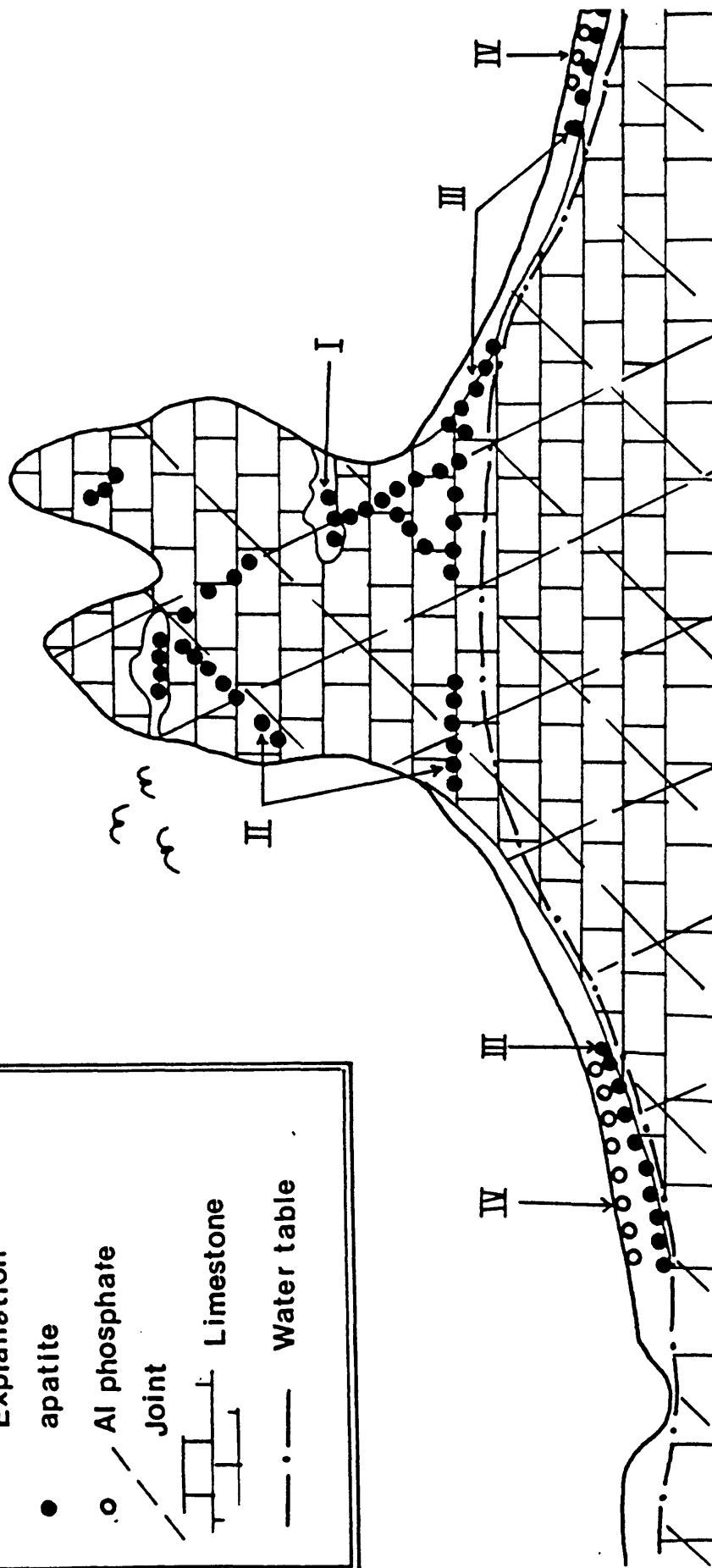
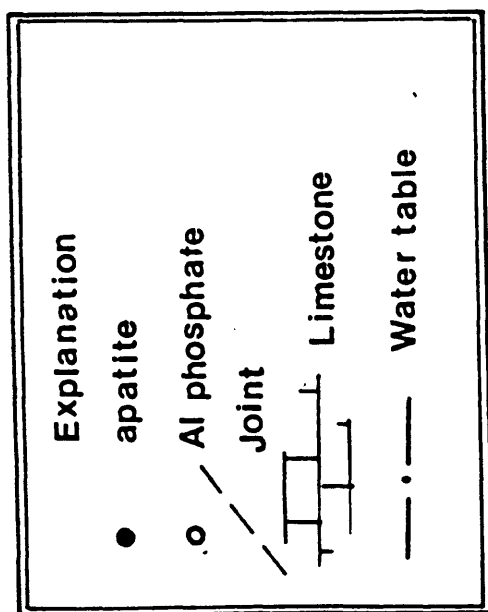


Figure 2. Model showing distribution of guano derived phosphate deposits and genetic classes.

I. cave floor, II. solution channel, III. soil-limestone slope, IV. laterite.

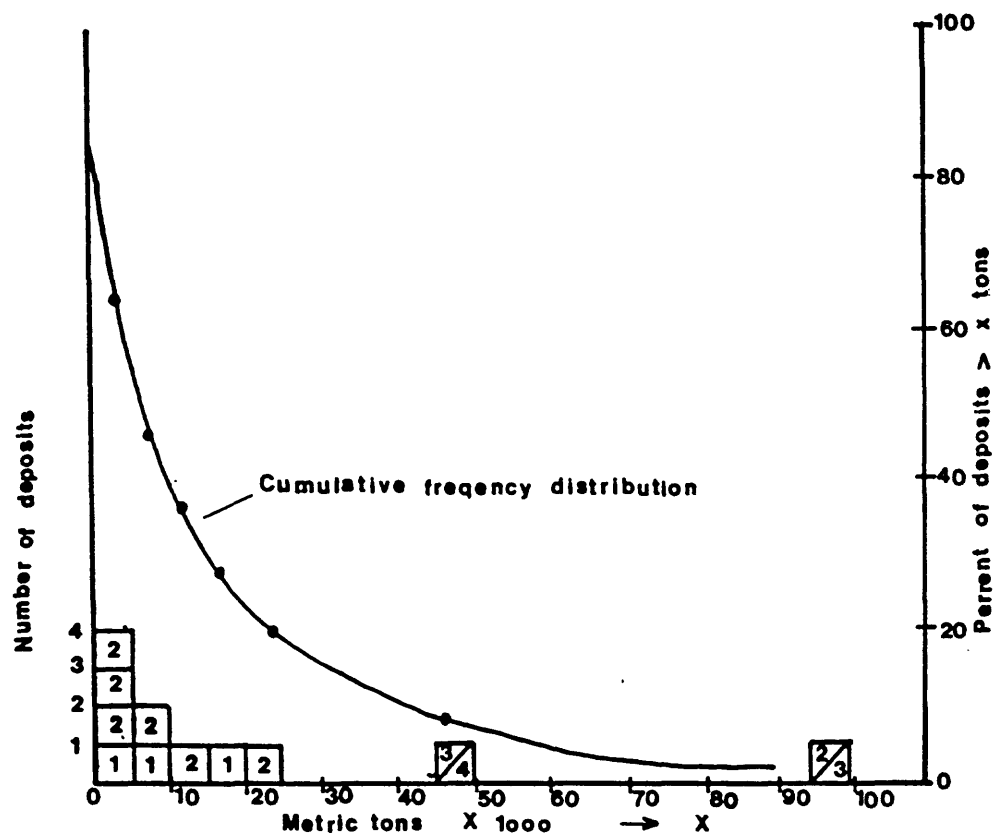


Figure 3. Size distribution of phosphate deposit, by: 1. Cave floor. 2. Solution channel. 3. Soil-limestone slope. 4. Laterite.

Table 2. Chemical analyses of Guano-derived phosphate rock.

Localities: 1. Khao Rang Kai; 2. Mae Tha; 3. Mantique, Isabel, Leyte, Philippines; 4. Binaguiohan Cave, Negros Occidental, Philippines, crandallite; 5. same as 4, strengite; 6. Calapnitan Cave, Camarinas Sur, Philippines, variscite.

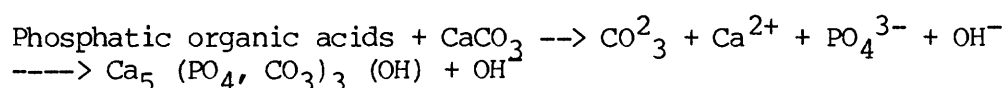
References: 1. IFDC, 1983; 2. Somboon Sektheera, 1974; 3. National Fertilizer Corp. Ltd., 1984; 4. Mae Tha Mining Company Report, 1971; 5. Vargas & Ugalde, 1983.

Element

	1	2	2	2	3	4	5	6
P <sub>2</sub> O <sub>5</sub>	34.3	38.2	38.5	38.1	34.4	20.6	35.4	57.1
CaO	48.0	52.8	59.0	50.7	52.3	14.9	0.2	0.1
CO <sub>2</sub>	6.8	2.0		1.6				
SiO <sub>2</sub>	2.0			2.4	1.5	11.5	16.3	2.4
F	1.1	0.7			2.5	0.3	0.9	1.1
Al <sub>2</sub> O <sub>3</sub>	0.7			1.4	1.0	17.9	7.3	25.3
Fe <sub>2</sub> O <sub>3</sub>	0.6			1.1	0.4	4.8	23.5	9.9
MgO	0.7		0.1	0.6	0.6	.04	0.3	0.3
C	0.2							
Na <sub>2</sub> O	0.2			0.1	0.5	0.03	0.02	0.01
K <sub>2</sub> O	0.07			0.05	0.02	0.27	1.47	0.05
S	0.06				0.24	0.03	0.04	0.03
Cl	0.02			0.01	0.07	0.14	0.04	0.04
MnO	3.6							
BaO	0.01							
SrO	0.01							
H <sub>2</sub> O	1.7		2.5					
LOI	11.3							
NAC sol.	7.2		6.8					
P <sub>2</sub> O <sub>5</sub>								
reference	1	2	3	4	5	5	5	5

## Genesis

The chemical system of formation of apatite is the result of bacterial decay and leaching of bat excrement and a series of reaction with bedrock limestone. This produces an evolutionary sequence of phosphate minerals from acidic to basic, with apatite as an end stage. Altschuler (1973, p. 74) stated, "The various calcic phosphates of cave and insular origins may display an evolutionary pattern in which the mineralogy and composition are determined by the incongruent solution of the more acid calcium phosphates, and their progressive recrystallization to apatite. With more intensive or prolonged leaching, deposits would be transformed from brushite-monetite to whitlockite to apatite - a sequence accompanied by a parallel decline in organic, nitrogenous, and ammoniacal compounds." Leaving out the intermediate steps of acidic, calcic phosphate mineral formation, the general chemical reaction is as follows:



The first deposition of apatite, which has a pelletal and botryoidal texture, is on cave floors, where acidic calcic phosphate minerals usually are also found at higher levels. The dissolution of limestone along fractures and bedding planes by acidic phosphate-rich solutions causes the formation of solution channels, which become lined with laminated, botryoidal and pelletal apatite, forming apatite veins in the limestone. Soil formed of the residue of leached limestone is deposited on the flanks of the limestone monoliths, and phosphate-rich acidic water, entering the soil as ground water, flows downwards. Where it encounters bedrock limestone under the soil, tabular bodies of pelletal, botryoidal and laminated apatite are formed. Also, in soil that contains limestone fragments, reaction with phosphate-rich acidic ground water would form pellets and nodules of apatite. It is probable that as the limestone monoliths are chemically eroded by rain water, cave floor and vein apatite becomes exposed at the surface, where it is eventually dissolved by leaching. The resulting phosphate-rich water would flow downward, depositing apatite where it met fresh limestone. Thus, a process of dissolution and redeposition would continually move phosphate down to lower levels as the mountain is chemically eroded. It could be expected that the final stage of this process would be the formation of tabular phosphate bodies close to streams on the flanks of old-age limestone monoliths. This low-lying phosphate would be subject to laterite weathering by rain water, which would dissolve it. Where clay minerals were present, aluminum minerals would be formed at the upper levels of the apatite rock body.

The age of the phosphate deposits have not been determined. If the genetic process described above is true, the oldest phosphate would be the vein deposits exposed at the tops of the limestone monoliths, and the lower phosphate formed from dissolution of the higher phosphate would be younger. The youngest, of course, would be the cave floor phosphate now forming. Thus, it is possible that the initial guano-derived phosphate in Thailand was formed tens or even hundreds of thousands of years ago, and that the process is still continuing.

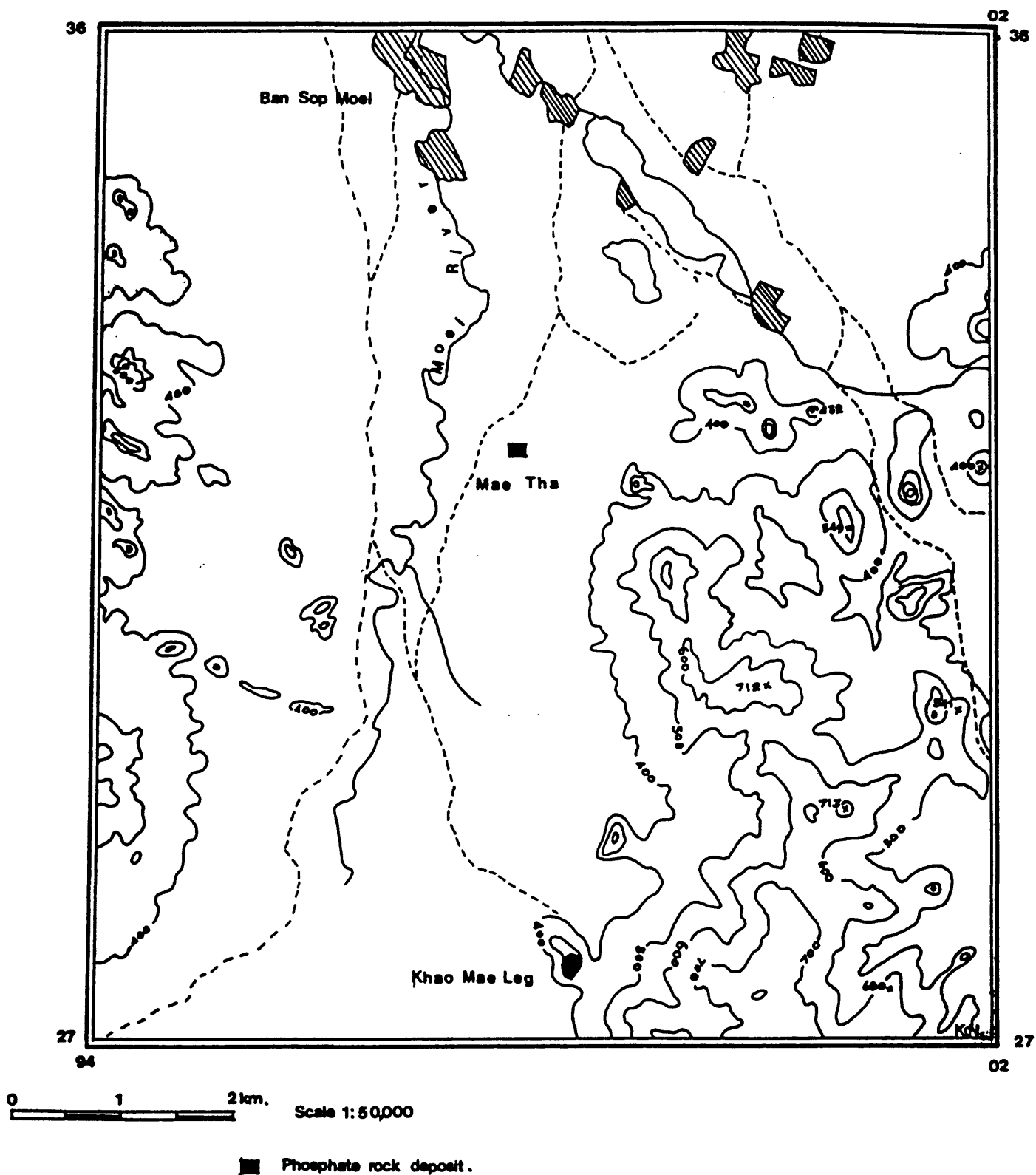


Figure 4. Topographic location of the Mae Tha phosphate rock deposit.



## Mae Tha Phosphate Rock Deposit

A geologic study of the Mae Tha deposit was made with the following results.

### Description

The Mae Tha phosphate deposit occurs near Lam Phun on a small terrace above stream valley (Figure 4). It is distributed over 0.25 square kilometers, and has a variable thickness, averaging about 8 meters thick and locally up to 40 meters thick. Two to five meters of overburden cover the deposit. The deposit lies on a solution surface above the Permian limestone, a relationship that can be seen in a small pit north of the main quarry. To the east of the deposit, a small karstic mountain range of Permian limestone occurs, with a steep slope down to the terrace. Several kilometers to the south, a small cave deposit of guano-derived phosphate rock occurs.

The phosphate has been shown to be hydroxy apatite with minor fluorine, on the basis of chemical analysis (Table 2). Some of the phosphate rock at Mae Tha is abnormally radioactive. This is undoubtedly due to adsorption of uranyl ion on apatite crystallites, a process that is well known (Altschuler, 1973). Uranium enrichment occurs mainly in the zone of apatite secondary enrichment under a weathering profile. The source of uranium is a problem in that bat excrement can be expected to contain little uranium. A logical source is from the dark Permian limestone, which would contain a small amount of uranium associated with organic matter. Because of the very low uranium concentrations in such rock, however, the process of supply of uranium to the phosphate deposit in sufficient quantities to give abnormal radioactivity would have had to act over a long period of time. The phosphate rock has a botryoidal and pelletal-oolitic secondary texture. Well-cemented phosphate rock occurs in irregular masses, rounded concretionary boulders (Figure 5), nodules, pellets and veins in an argillaceous bed of the terrace (Figure 6). One concretion with concentric structure, about 1 meter in diameter, was observed in the argillaceous bed, showing clearly its secondary origin (Figure 6). In general, the phosphate masses occur in a stratiform body with irregular surfaces. A bed of angular gravel, which probably is hill alluvium, is draped over large phosphate masses, probably indicating solution of the phosphate rock and settling of the gravel into the vacated space (Figure 7). Much of the argillaceous unit contains dispersed small white pellets and nodules. These grains are not apatite, as determined by a negative test with a 10% nitric acid ammonium molybdate-ammonium metavanadate solution. After dissolving the pellets in concentrated  $\text{HNO}_3$  -  $\text{H}_2\text{SO}_4$  by heating, it was shown that the grains contain about 30%  $\text{P}_2\text{O}_5$ . Thus, they are composed of aluminum phosphate minerals. A manganese-rich laterite of pelletal and nodular aluminum phosphate occurs at the surface of the deposit (Figure 8).

### Origin

The secondary textures and structures of the phosphate rock as well as its hydroxy apatite mineralogy show that the Mae Tha deposit was formed by phosphorus-rich, fluorine-deficient water. The deposition was on a solution

surface over Permian limestone. The source of the phosphorus could not have been from solution of marine phosphorite, because the apatite would have been a fluorapatite. The presence of a cave phosphate rock, whose phosphorus was probably of bat guano origin, strongly suggest that the origin of the phosphorus-rich water giving the Mae Tha deposit was also of bat guano origin.

The geomorphic position of the deposit is a problem. A possible answer is that water draining from the porous Permian limestone terrane east of the deposit was enriched in phosphorus from bat guano and apatite solution. The concentration of the phosphate rock in one area may have been caused by an underground drainage system from the karstic guano-rich and apatite-rich limestone range. The drainage system may have channelled phosphorus-rich



Figure 5. Phosphate rock concretionary boulder with internal nodular and pelletal texture. Mae Tha Deposit.

Figure 6. Secondary phosphate concretion. Phosphate nodules and pellets in clay surrounding concretion. Mae Tha deposit.





Figure 7. Subsidence of hill wash due to colution of underlying phosphate rock. Mae Tha Deposit.



Figure 8. Aluminum phosphate laterite. Mae Tha Deposit.

water from a large drainage area to a small portion of the terrace. This might be further investigated by a geomorphic analysis of the area surrounding the deposit. If it is true, it suggests an approach for exploration of additional deposits. Where the acid ground water met the limestone below the terrace near the stream, it would have dissolved the limestone. This would have given a solution with high pH and high calcium, phosphorus and hydroxide content, allowing the precipitation of hydroxy apatite over the limestone surface. This process would be similar to that forming insular phosphate rock deposits, which the Mae Tha phosphate rock closely resembles texturally and stratigraphically.

## Weathering

The Mae Tha deposit has been subsequently leached in an acid environment. The large boulders and irregular masses of phosphate rock are probably the result of this process and can be regarded as a solution residuum. The subsidence of the hill alluvium between the masses of phosphate rock supports this hypothesis.

Laterite weathering was probably a continuation of the same process of leaching. Acid ground water in the terrace, above the influence of the underlying limestone, would have dissolved the secondary apatite. Clay residuum from the dissolved limestone would be leached of its silica, giving an interstitial aqueous environment rich in phosphorus and alumina, which would have been favorable for the formation of aluminum phosphate minerals. The small white pellets and nodules of aluminum phosphate in the agillaceous unit were formed by laterite weathering. At the top of the phosphate unit, just below the gravel bed, concentrations of the pellets and nodules occur. These concentrations are stained with manganese oxide coatings, which is also typical of laterite weathering, and can be regarded as an aluminum phosphate.

## Resources

The Mae Tha deposit has been drilled the the DMR, allowing an estimate of 50,000 metric tons of proved reserves of phosphate rock, and outlining the limits of the deposit. It might be useful to further investigate the distribution and character of pellets and nodules in the agillaceous unit. It is possible that further underground below the aluminum phosphate zone, they are still apatite, and if so, may constitute an additional resource. It should be no problem to separate the pellets from the clay by washing. Thus the extent and character of the pelletal and nodula clay should be further studied.

## Ban Na Kan Phosphate Rock Deposit

The Ban Na Kan phosphate rock deposit in Kanchanaburi contains about 100,000 metric tons of reserves (Cherdsak Utha-aroon, 1984), making it the largest known guano-derived phosphate deposit in Thailand. The deposit was visited in the company of Mr. Supote Sae Lim, manager of the Thai S. Mineral Ltd., on May 25.

## Description

The Ban Na Kan deposit occurs northwest of Kanchanaburi in a small karstic hill of Permian limestone, overlooking the fertile plain of the Kwae Noi River to the south (Figure 9). The Permian limestone dips northeast at about 20 to 30°. The phosphate body is a tabular body about 1 to 4 meters thick and is about 80 meters wide in a north-south direction and 160 meters wide in an east-west direction. The phosphate body is oriented parallel to the bedding of the limestone. On the northeastern side of the hill, the phosphate body crops out on the hill slope, where it overlies limestone and underlies a weathered zone. The bed projects downward to the northeast where it would have merged with the valley floor before erosion. The P<sub>205</sub> content of the phosphate varies from 12 to 34%, depending on the amount of admixed calcite. The phosphate rock varies from white to dark brown, is laminated, pелletal and pisolitic, and in cavities shows a botryoidal texture. All of these textures clearly point to its secondary character. One other small phosphate deposit occurs about 300 meters to the southeast of the main body. Although the major portion of the body is conformable with the bedding of the Permian limestone, in the quarry on the southwest side of the deposit, vertical veins and irregular shaped phosphate bodies occur. A small cave in the limestone also occurs in this quarry.

There is little question that the Ban Na Kan phosphate is guano-derived. The original cave, on whose floor bat excrement was deposited, would have to have been higher than the present hill, and has probably been chemically eroded away, leaving the secondary phosphate exposed in the upper parts of the present hill. Judging from the amount of phosphate and its extent, the cave must have been large and opened southward, facing the Kwae-Noi River flood plain. Thus, the environment must have been quite favorable for bat colonies, that is a large cave close to a winged insect-rich lowland.

Leaching of the cave-floor bat excrement would have produced a phosphate-rich acidic solution. The solution would have flowed downward through high-angle fractures in the limestone until it reached a permeable bedding plane, along which it continued its downward flow northeastward toward the valley. Secondary apatite was deposited along this path where limestone was dissolved.

The Ban Na Kan deposit resembles the Mae Tha deposit in that it is a hill slope deposit, but differs in that the main phosphate deposition was along a gently dipping bedding plane in the limestone and the soil limestone

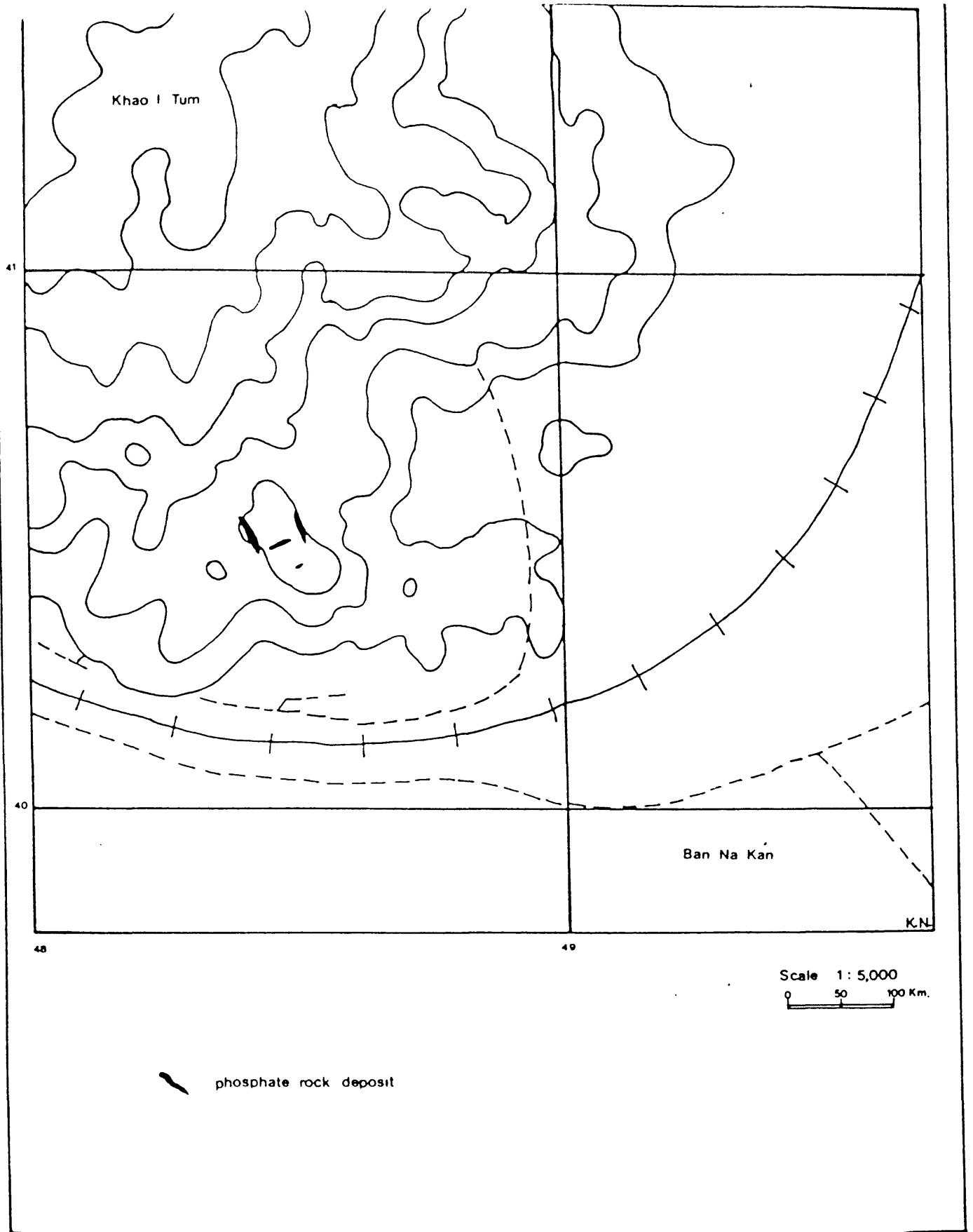


Figure 9. Ban Na Kan phosphate deposit, Kanchanaburi.

phosphate is poorly developed. The deposit can be classed primarily as a gently dipping, bedding plane solution channel deposit (class IIB) and secondarily as a soil limestone contact slope deposit (class III).

### Genetic Classification of Phosphate Deposits

The four different classes of phosphate rock, based on their physical, chemical and mineralogic character and their geometric shapes suggests a four-fold genetic classification. The first class is cave floor phosphate rock formed more or less in situ by leaching and decay of bat excrement and reaction with the limestone cave floor. The second class is a solution channel, secondary phosphate rock formed by wall rock reactions between limestone and solutions descending from cave floor phosphatic deposits or from apatite dissolved at higher levels by rain water. The third class is phosphate rock formed where ground water, fed by drainage from the phosphatized limestone monolith, comes in contact with limestone below the soil. A fourth class is lateritized aluminum phosphate formed from the third class deposits. This classification is summarized in Table 3 and illustrated in Figure 2. The class of the known phosphate deposits is given in Table 1.

### Speculative Phosphate Rock Resources

200,000 metric tons of phosphate rock has been estimated from the known deposits. Most of these estimates are poorly measured, but some are well measured and constitute reserves. The discovery of most of these deposits has been fortuitous, and many have been found by unschooled villagers. However, the Ban Na Kan deposit was found by a prospector searching for outcrops. It is my understanding that no systematic exploration has been carried out. If a program based on sound scientific principles were designed and carried out, how much additional phosphate rock might be found? This depends on the magnitude of the undiscovered resource and the efficiency of the exploration technique.

There is no way at present to estimate the magnitude of undiscovered resource, which would depend on the availability of caves, bat ecology and the duration of bat guano formation. Some limits on the magnitude can be very roughly derived from the size distribution of known deposits (Figure 3) and high-low guesses on the percentage of deposits found of the total number of existing deposits. Speculating that between 5% and 30% of the deposits have been found, and taking the 200,000 metric tons of known resources, one can speculate that 4,000,000 and 670,000 metric tons originally existed, and 3,800,000 to 470,000 metric tons remain undiscovered. Using the size distribution of known deposits as an index, 80% of undiscovered deposits will contain less than 25,000 metric tons of phosphate rock and 20% will contain more. The maximum size would be several hundred thousand tons.

The known size distribution is probably biased towards classes I and II, because these classes crop out on the limestone monoliths and are easier to locate than the class III deposits, which tend to be buried beneath the soil. Both class IIB and class III deposits tend to be large, judging from



the Mae Tha and Ban Na Kan deposits, whereas class I and class IIA deposits tend to be small. This bias would tend toward an underestimation of the undiscovered resource. Also resource estimates of known deposits tends to exclude phosphatic clay hill-slope deposits. Where the phosphate has not been lateritized and the pellets and nodules still consist of apatite, they could be an additional resource. Recovery could be made by simple washing. Disposal of the clay would introduce an environmental problem, but because deposits tend to be relatively small, the problem might not be too difficult to deal

Table 3 Genetic classification of Guano-derived phosphate deposits.

Class	Description
I	Cave floor phosphate deposits in limestone monoliths
II	Solution channel deposits in limestone monoliths
	A High-angle solution channel deposits along fractures
	B Low-angle solution channel deposits along bedding planes
III	Soil-limestone bedrock deposits on slopes of limestone monoliths
IV	Lateritized aluminum phosphate deposits of class III

with. Taking these two biases into account, the speculative resource could be raised by perhaps 10-20%.

Assuming a value of 800 baht a metric ton of phosphate rock, the value of the undiscovered speculative resource could be as high as 3,600 million baht. How much of this highly speculative resource would be found is unknown, but would depend on the effort put into geologic research to develop exploration techniques.

#### Potential Fertilizer Production

If a phosphate fertilizer plant based on the sulfuric acid process is built in Thailand, a market would be created for the guano-derived phosphate rock. The use of domestic phosphate rock would substitute its value for the foreign currency expenditures for importing phosphate rock from the world market.

The nitrogen phosphorus fertilizer generator discussed earlier may have a potential for utilizing the guano-derived phosphate rock in remote areas where deposits and microhydropower potential exist. No other resources are needed for this technology. The experimental work in India, discussed earlier, will help in determining the feasibility of this technology in Thailand, and the work should be carefully watched. If the technology is feasible, both nitrogen and phosphate fertilizer could be produced on a village level at remote locations, where modern fertilizers are the last to reach. It is estimated that an investment of about \$2,000 for a generator and water turbine would yield about \$800 worth of NP fertilizer a year. Jobs in the mining, transportation and machine maintenance sectors would be created (Sheldon & Treharne, 1980), and food production would be significantly increased where the fertilizer was used.

#### Geologic and Resource Development Program

A program to develop the guano-derived phosphate in Thailand should be carried out in three consecutive steps.

First, further geologic study of the known deposits should be carried out. The purpose would be to improve genetic concepts. This would require studies of hydrology of the slopes of karstic terrance, chemistry and mineralogy of the phosphate rock, laterite soil profiles, geometry and geomorphic setting of the phosphate rock deposits and ages of phosphate deposition.

The establishment of a well-supported hypothesis of genesis of the different classes of phosphate deposits would allow an assessment of phosphate rock resources. This would involve identification of target areas by analysis of geologic history of karstic limestone region. Class 11B and III deposits are probably the most important class to be assessed because of their easier mineability of slopes below the limestone monoliths and because of their large sizes.

The third step is exploration of these target areas. A possible exploration model is as follows:

1. Identify areas where fertile lowlands and old age karstic terrance are juxtaposed.
2. Identify valleys in karstic terrane.
3. Identify geomorphic situations where the Permian limestone (or karstic limestone of other ages) dips towards the valley.
4. Identify lower slopes of limestone karstic terrane that are underlain by limestone and covered with lateritized soil.
5. Where 1, 2, and 3; 1, 2, and 4; or 1, 2, 3, and 4 occur together, the area is a target for exploration.
6. Geologic reconnaissance for the following:
  - a) Class IIA and IIB phosphate deposits.
  - b) Stream pebbles of aluminum phosphate.
  - c) Hill slopes with aluminum phosphate laterite.
7. Hand auger soil sampling, pitting and shallow core drilling.

#### REFERENCES CITED

- Altschuler, Z. S., 1973: The weathering of phosphate deposits - geochemical and environmental aspects; in Griffiths, E. J. and others, Environmental Phosphorus Handbook, John Wiley & Sons Inc., pp. 33-96. (Reproduced in handout at seminar of phosphate potential in southeast Asia, Bangkok, January 19-21, 1983).
- Cape, J. J., 1981: Thailand-potential phosphate deposits; World Bank report.
- Gardner, L. S., Haworth, A. F. and Na Chiangmai, P., 1967: Salt resources of Thailand; Thai Department of Mineral Resources, Report of Investigations no. 11.
- Hite, R. J., 1983: Pleistocene ? stream channel control of Khorat Plateau sylvite deposits; Conference on Geology and Mineral Resources of Thailand.
- IFDC, 1983: Characterization of a phosphate rock sample from Thailand; International Fertilizer Development Center report.
- Japakasetr, T., 1982: Phosphate in Thailand; Thai Department of Mineral Resources report.
- Kuentag, C., 1983: Limestones of Thailand; Thai Department of Mineral Resources report.
- Mae Tha Mining Company report, 1971.
- NFDC, 1984: National Fertilizer Development Corporation report.
- Piyasin, S., 1972: Geology of Changwat Lampany Sheet, scale 1:250,000; Thai Department of Mineral Resources Report of Investigations no. 14, 90 p.
- Sektheera, S., 1974: Phosphate; Thai Department of Mineral Resources, Economic Geology Bulletin no. 4, 35 p.
- Sheldon, R. P. and Treharne, R. W., 1980: Local phosphate rock and limestone deposits as raw materials for local fertilizer supply: In Meyer and Carmen, eds., The Future of Small Scale Mining, McGraw Hill, New York.
- Suwanich, P., 1980: Phosphate exploration in Lampany and Lamphun Province; Thai Department of Mineral Resources report.
- Suwanich, P. and Ratanajaruraks, P., 1980: Phetchabun phosphate deposits; Thai Department of Mineral Resources report.
- Treharne, R. W. and others, 1980: Non-conventional manufacture of chemical fertilizers: Small scale fertilizer production technology; in Sheldon, Ahmed and Yang, eds., Fertilizer Raw Material Resources, Needs and Commerce in Asia and the Pacific, East-West Center, Honolulu, Hawaii.

Utha-aroon, C., 1984: Ban Na Kan phosphate deposit; Thai Department of Mineral Resources report.

Vargas, B. S. and Ugalde, R. P., 1983: Geology and exploration of phosphate deposits in the Philippines; Bureau of Mines and Geosciences report, Manila, Handout of workshop on Development of Phosphate Rock Resources in Southeast Asia, DMR, Jan. 24, 1983.

## APPENDIX E

### Ring Dikes in Western Ethiopia

Igneous apatite deposits occur in ring dike complexes in East Africa from the Republic of South Africa to Uganda (Deans, 1966). A list of these deposits is given in table 5, and descriptions of each deposit is given by Gittens (1966). The Palabora deposit of the Republic of South Africa is an important economic deposit, with production of apatite concentrate in 1980 amounting to 3.3 million tons. This was sufficient to rank South Africa as the seventh highest phosphate producer in the world in 1980. In Uganda, the Sukulu carbonatite intrusive contains 200 million tons of leached apatite ore containing 13% P<sub>2</sub>O<sub>5</sub>, as a residual soil over the carbonatite. The deposit is not in significant production, but offers considerable potential.

These two deposits are examples of the two main types of igneous apatite deposits in East Africa. The Palabora ore occurs as the rock phoscorite, a mixture of apatite, magnetite, serpentine and olivine; whereas, the Sukulu parent rock consists of calcite carbonatite containing 32% apatite. These ring dikes were formed by multiple intrusions of sub-silicic alkalic magma that erupted on the surface to form alkalic volcanoes. In Kenya, the Tinderet volcano is composed of nephelinitic agglomerate, nephelinite, phonelite and basinite, and is probably a part of an alkaline carbonatite complex. Grey carbonatite with apatite and pyrochlore is found on Legetet Hill on the southwest flank of Tinderet. Also in Kenya on Homa Volcano, apatite and magnetite give a flow banding to the carbonatite (Gittens, 1966, p. 421-22). The carbonatites are enriched in other elements in addition to phosphorus (Deans, 1966) and include C, F, Mn, Sr, Nb, Ba and rare earths (especially the lighter lanthanides). In some cases, enrichment in V, Cu, Zn, Mo, Pb, Th and U occurs. By-products of Palabora are copper, iron, phosphate, zirconium and potential by-products include thorium, uranium and vermiculite.

Table 5. Igneous apatite deposits of East Africa (Deans, 1966).

complex	deposits	synopsis of resources
Bukusu, eastern Uganda	phosphate	residual and secondary apatite deposits contain moderate reserves of ferruginous secondary phosphate rock @ 25% P <sub>2</sub> O <sub>5</sub> and large reserves of apatite-bearing soil @ c 11% P <sub>2</sub> O <sub>5</sub> .
	iron and titanium	moderate reserves of lot Ti and high Ti magnetite.
Tororo and Sukulu, eastern Uganda	cement and lime	Tororo sovite is basis of Uganda cement and lime industry.
	phosphate	Sukulu residual apatite-rich soils. 200 million tons @ 13% P <sub>2</sub> O <sub>5</sub> , c 25% magnetite and 0.25% Nb <sub>2</sub> O <sub>5</sub> as pyrochlore.
	niobium	minor by-product recovery planned.
	iron	magnetite concentrates stockpiled.
Panda Hill (Mbeya) SW Tanzania	niobium	125 million tons ore at 0.3% Nb <sub>2</sub> O <sub>5</sub> .
	apatite	potential by-product.
Kaluwe, Central Province Zambia	niobium	large potential reserve.
	phosphate	limited reserves of apatite-rich soils @ 10% P <sub>2</sub> O <sub>5</sub> .
Tundulu, southern Malawi	phosphate	apatite-rich rocks of Nathace Hill contain per 100' depth 800,000+ tons @ 20% P <sub>2</sub> O <sub>5</sub> and 1 million tons @ 10% P <sub>2</sub> O <sub>5</sub> .
	niobium	potential by-product.
Dorowa, southern Zimbabwe	phosphate	37 million tons of apatite-bearing fenites @ 20% P <sub>2</sub> O <sub>5</sub> and weathered carbonate-free rocks at 6-8% P <sub>2</sub> O <sub>5</sub> . In production.



Table 5 cont.

Glenover, western Transvaal, South Africa	phosphate	9,750,000 tons of secondary apatite rock @ 20-32% P <sub>2</sub> O <sub>5</sub> . In production.
	niobium	potential by-product.
Palabora, eastern Transvaal, South Africa	copper	315 million tons sulfide copper ore @ 0.69% Cu available open cast.
	iron	Annual by-production of 1.8 million tons magnetite anticipated from copper mine.
	phosphate	Large apatite reserves in phoscorite @ 6-8% P <sub>2</sub> O <sub>5</sub> .
	Th & U	Potential by-products for copper mine.
	Zr	by-product, phoscorite.
	vermiculite	large reserves.

Carbonatites are clearly associated with the East Africa rift system. Bailey (1974) makes the point that the rifts themselves are merely the fractured crests of crustal arches, and that the alkaline magmatism (with silica undersaturation) is associated with the crustal arches. The arches are formed by heat flux in the mantle. Greater heat flux gives flood basanites and basalts, as in Ethiopia, and the nephelinite-carbonatite phase of magmatism may appear both early and late in the heating cycles as the crust first is heated and then as heating wanes. The magma is believed to form by mantle differentiation. An alternative, less accepted, view is that the alkaline magmas formed as a result of anatexis, which is reviewed by Harris and Bailey (1974). It has been also thought in the past that carbonatites formed by limestone assimilation, but petrologic considerations indicate that this is not a viable hypothesis (Wyllie, 1974).

The rift valley province of Ethiopia is dominantly an alkali basaltic province, but has vast amounts of felsic volcanics. No carbonatites have been found in Ethiopia, although Mohr (1961) believes it is possible that the Bishoftu explosion craters originated by carbonate magmatism, indicated in part by the association of hyperalkaline rock fragments with carbonated rock springs. In Somalia, 90 miles southeast of Djibouti (Gittens, 1966, p. 461-62), the Darkainle intrusives are a complex of alkaline rocks and carbonatite in a narrow inclined sheet 21 miles long and 1.75 miles wide. The principal rocks are foliated and folded syenites and nepheline syenites. Carbonatites within the nepheline gneisses are in two forms, early concordant bands and lenses up to 300 meters in length and later discordant, thin veins. The carbonatites are greatly enriched in Ba, La, Sr, and Y, but no apatite is present. In southern Somalia, near the Modu Mode metaphosphorite-marble occurrence in the Bur Acaba uplift area, syenite intrusives occur associated with Th and U anomalies (Greenwood, 1982).

In the Wolega Province (Kazmin, 1973), small Oligocene-Miocene intrusives of alkaline granites and syenites occur. Also, well-developed ring dike structures are observable on LANDSAT imagery (A. Fernandez, personal communication, 1984). The question arises, does the alkalic-sub-silicic igneous province from South Africa to Uganda extend northwards into western Ethiopia? If they do, there is a possibility of the occurrence of igneous apatite bodies.

#### Jurassic Sedimentary Rocks in Ethiopia

A Sinclair Oil Company memorandum (which can no longer be located) reported "phosphate at 2600-2700' and 2840-2900' in fossiliferous oolitic limestone with anhydrite intercalations" in Sinclair well XEFl. This well is located near the Auradu-Jessoma contact in the northern Ogaden Basin. The depths and lithologies reported for the phosphate would probably place it in the Hamanlei Series of Jurassic age. The drill cuttings of Jurassic rocks in Tenneco well Calub #1, drilled southwest of XEFl were systematically analyzed for phosphate. No anomalous phosphate values were found, although at present, the index relating the drill sample depths to the laboratory sample numbers has not been located. Mr. V. Serguienko has been systematically investigating the Lower Hamanlei and the Adigrat Sandstone. He has discovered that fossiliferous, oolitic and finely crystalline carbonate rock of the transition

beds gives a positive P205 qualitative test. The amount of P205 appears to be low. One preliminary sample submitted for chemical analysis contained 0.4% P205, and other samples systematically collected have been submitted for analysis. Whether this zone is the same as that reported for the well XEF1 is undetermined, primarily because the mechanical and lithologic logs of XEF1 are not available at present.

From a regional point of view, the Jurassic rocks of Ethiopia do not appear to offer a phosphate rock potential.

## APPENDIX F

### Selected Additional References on Phosphate Petrology

McKelvey, V. E. and others, 1959, The Phosphoria, Park City and Shedhorn Formations in the western phosphate field: U.S. Geol. Survey Prof. Paper 313-A, p. 1-47.

This paper reviews the stratigraphy of the Permian rocks of the western US that contain the major phosphate deposits. In addition, it analyzes the American system of stratigraphic nomenclature, giving the philosophic basis and utility of the system (p. 9-11).

Sheldon, R. P. and Burnett, 1980, Fertilizer mineral potential in Asia and the Pacific: Resource Systems Institute, East-West Center, Honolulu, Hawaii, 470 p. This proceedings of a conference held in 1979 includes a collection of papers on phosphorites from many parts of the world.

Cathcart, J. B., Sheldon, R. P. and Gulbrandsen, R. A., 1984, Phosphate-rock resources of the United States: U.S. Geol. Survey Circular 888, 48 p.

U.S. Bureau of Mines and U.S. Geological Survey, 1981, Principles of a resource/reserve classification for minerals: U.S. Geological Survey Circular 831, 5 p.

U.S. Geological Survey, 1982, Sedimentary phosphate resource classification system of the U.S. Bureau of Mines and the U.S. Geological Survey: U.S. Geological Survey Circular 882, 9 p.

This set of three USGS Circulars gives the principles of classification used by the Department of Interior of the US, the operational definitions for assessing the phosphate resources of the US and the assessment of phosphate resources of the US. It can be used as an example of the procedures of assessing phosphate resources in any country.

Cook, P. J. and McElhinny, M. W., 1979, A re-evaluation of the spatial and temporal distribution of sedimentary phosphate deposits in the light of plate tectonics: Econ. Geology vol. 74, no. 2, p. 315-330.

The first and still relevant treatment of world-wide phosphorite deposits over time.

Sorenson, H., ed., 1974, The alkaline rocks: John Wiley.  
An overall treatment of the petrology of alkalic igneous rocks.

## APPENDIX G

### Problems of Stratigraphic Nomenclature

Identification and correlation of stratigraphic units in the Dominican Republic are difficult, in many cases, largely because of the way in which the formations were originally set up many years ago, before modern stratigraphic practices were established. Thus, many formations have been equated with a specific time interval, rather than with a distinct and recognizable lithotype. For example, the Neiba formation in the San Juan and Enriquillo basins has generally been regarded as restricted to the Late Eocene (Dohm, 1942, p. 5). Lithologically, however, it grades into similar rocks below (Plaisance Formation: Dohm, 1942, p. 6) and above (Sombrierito Formation: Wallace, 1947, p. 4, 6; Cooper, 1983, p. 5). In those reports where age determinations are lacking, and particularly on maps, the Neiba is thus combined with the adjacent formations (Hunter, 1941, p. 2; Wallace, 1947, p. 4; Cooper, 1983). In some cases the Neiba is given local lithologic definitions (for example, Maurasse, 1980, p. 37-39), but these are not everywhere consistent. Moreover, Cooper (1983, p. 23-25) has even suggested that the Neiba and Plaisance Formations are not sequential, but temporally equivalent.

These uncertainties and inconsistencies could be reduced by establishing strictly lithological definitions of stratigraphic units. Such definitions would include designation of type sections, with published measured sections, indicating boundary criteria. An additional benefit of this method is that any newly acquired data that revised the age assignment of a stratigraphic unit would not affect the nomenclature.

## Appendix G (continued)

### References Cited

- Cooper, J. C., 1983, Geology of the Fondo Negro, Dominican Republic:  
Unpublished Ph.D thesis, New York University.
- Dohm, C. F., 1942, The geology of the Sierra de Neiba and Valles San Juan and  
Enriquillo: Seaboard, Santo Domingo, 20 p.
- Hunter, James, 1941, The geology of the western portion of the Enriquillo  
Basin.
- Maurasse, F. J. M., 1980, survey of the geology of Haiti.
- Wallace, M. N., 1947, A review of the stratigraphy of the the Enriquillo  
Basin: Seaboard, Santo Domingo, 20 p.