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Phosphate-Rock Resources of the United States

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By JAMES B. CATHCART, RICHARD P. SHELDON, and ROBERT A. GULBRANDSEN

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An analysis of phosphate-rock resources, based on past estimates and all available recent information, indicates that sufficient phosphate exists in the United States to meet domestic demands for the foreseeable future

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ABSTRACT

In 1980, the United States produced about 54 million tons of phosphate rock, or about 40 percent of the world's production, of which a substantial amount was exported, both as phosphate rock and as chemical fertilizer.

During the last decade, predictions have been made that easily minable, low-cost reserves of phosphate rock would be exhausted, and that by the end of this century, instead of being a major exporter of phosphate rock, the United States might become a net importer. Most analysts today, however, think that exports will indeed decline in the next one or two decades, but that resources of phosphate are sufficient to supply domestic needs for a long time into the future.

What will happen in the future depends on the actual availability of low-cost phosphate rock reserves in the United States and in the world. A realistic understanding of future phosphate rock reserves is dependent on an accurate assessment, now, of national phosphate rock resources.

Many different estimates of resources exist; none of them alike. The detailed analysis of past resource estimates presented in this report indicates that the estimates differ more in what is being estimated than in how much is thought to exist.

The phosphate rock resource classification used herein is based on the two fundamental aspects of a mineral resource—(1) the degree of certainty of existence and (2) the feasibility of economic recovery.

The comparison of past estimates (including all available company data), combined with the writers' personal knowledge, indicates that 17 billion metric tons of identified, recoverable phosphate rock exist in the United States, of which about 7 billion metric tons are thought to be economic or marginally economic. The remaining 10 billion metric tons, mostly in the Northwestern phosphate district of Idaho, are considered to be subeconomic, minable when some increase in the price of phosphate occurs.

More than 16 billion metric tons probably exist in the southeastern Coastal Plain phosphate province, principally in Florida and North Carolina and offshore in the shallow Atlantic Ocean from North Carolina to southern Florida. This resource is considerd to be hypothetical because it is based on geologic inference combined with sparse drilling data.

Total resources of phosphate rock in the United States are sufficient to supply domestic demands for the foreseeable future, provided that drilling is done to confirm hypothetical resources and the chemistry of the deposits is determined. Mining and beneficiation techniques will have to be modified or improved, and new techniques will have to be developed so that these deposits can be profitably exploited.

INTRODUCTION

The United States produced in 1980 about 54 million metric tons of phosphate rock, which was 40 percent of world production. About 59 percent of this production was exported, 26 percent as phosphate rock and 33 percent as manufactured fertilizers and chemicals. The remainder was used domestically, largely (88 percent) for fertilizer and animal feed supplement to produce agricultural products (U.S. Bureau of Mines, 1980). A significant portion of these agricultural products was exported, so the phosphate rock that went into that portion was exported indirectly. Thus, most phosphate is exported directly or indirectly, and its value contributes positively to the U.S. balance of international payments. Although the marketable value of the phosphate rock produced in 1980 was only about $1.2 billion, the total value of the agricultural and chemical products depending on phosphate rock input is many times that. The continued ability of the U.S. phosphate industry to supply low-cost phosphate rock for export and domestic consumption is clearly of major importance to the Nation.

During the last decade, people have questioned whether the national endowment of phosphate rock in the ground is sufficient to support the national phosphate industry very far into the next century. A report by the U.S. Government Accounting Office in 1979, using information largely from producing companies and the U.S. Bureau of Mines, projected a significant decline in U.S. exports of phosphate by the mid-1980's and forecast that the Nation would become a net phosphate importing country in the first quarter of the next century. This decline, the report said, would be caused by the exhaustion of high-grade, easily mined, and beneficiated phosphate reserves in the Northwestern Phosphate Province in Idaho and adjacent States of Montana, Wyoming, and Utah, and more importantly, in the Southeastern Phosphate Province from Florida to North Carolina. These two provinces presently produce about 97 percent of the U.S. production and contain all but a minor portion of the Nation's phosphate resources.

A possible result of a significant decline in U.S. exports would be a greatly strengthened world market position and possible cartelization of a few phosphate exporting countries which have large resources of phosphate rock that could be exploited at low cost. This presumably would occur after the U.S. deposits that could be extracted at a low cost were exhausted. A rise in world phosphate prices could be expected, and the U.S. agricultural sector, forced to rely on imported high-priced fertilizer, would be weakened. In addition, some people fear that the very prospect of a weakened national phosphate-resource position might result in export restrictions on phosphate rock and phosphate products in the near future. Furthermore, a deteriorating phosphate industry would be in a weakening position in regard to allocation of railroad rolling stock, environmental regulations, severance taxation policies, and the like.

Analysts of the U.S. Bureau of Mines think that such a scenario is unlikely. Their current forecast (William Stowasser, written commun., 1981) is that exports of phosphate rock will decline during the decade of the 1980's. The reasons for the decline cited by analysts include the increasing cost of producing phosphate rock in the United States from lower quality deposits, the much higher cost of opening new mines, the high freight rates for shipping to European and Asian markets, and the competition from government-subsidized phosphate rock operations in foreign countries. The Bureau of Mines analysts anticipate that some of the lost export sales of phosphate rock will be made up by increased export sales of manufactured phosphate fertilizer and chemicals, that the United States will continue to export some phosphate rock, and that these factors will probably influence decisions to defer the construction of new phosphate mines in the 1980's. The domestic over-supply position forecast for the 1980's will be exacerbated by the decline in the export market demand for U.S. phosphate rock. The Bureau of Mines' analysts feel that none of the factors cited for the decline of exports appears to be reversible. For the long term, the phosphate industry probably will find it increasingly difficult to compete in international trade with phosphate rock, and as time progresses and North African and Middle East countries increase their manufacturing capacity for phosphate fertilizer, the competitive position of the U.S. producers of manufactured fertilizer will probably be eroded in international trade.

These Bureau of Mines analysts do not subscribe to the scenario that the United States will be importing phosphate rock from a cartelized world market, because the United States has adequate domestic resources and because most of the reasons cited for the decline of U.S. exports will also limit or prohibit importing phosphate rock into the United States.

What actually happens in the future to world phosphate rock prices and the U.S. position relative to the position of other phosphate exporting countries and when it happens will depend on the actual availability of low cost phosphate rock reserves in the United States and throughout the world. A realistic understanding of future phosphate rock reserves is dependent on an accurate assessment now of national phosphate rock resources.

Many estimates of phosphate-rock resources exist, no two of which are alike. Some view these different estimates as the result of a dispute among resource optimists and pessimists. However, detailed analyses of various estimates usually are due more to differences in what is being estimated than in how much is thought to exist. A large estimate may include rock that is only potentially economically available along with rock currently economically available; whereas, a lower estimate may include only the currently economically available rock. Differences in estimates may be due to differences in areas studied and price projections; to assumptions concerning mining techniques, ore processing techniques, and fertilizer manufacturing techniques; and finally to differences in the methods of assessment. Compatibility of resource estimates has been further hindered by technical language that may confuse specialists and nonspecialists alike.

A system of classifying phosphate rock resources is being devised by a joint subcommittee of the U.S. Bureau of Mines (USBM) and the U.S. Geological Survey (USGS) to give a single clear language to this complex subject and to permit *real* differences among estimates to be identified and analyzed. This emerging phosphate rock resource classification is based on the principles of classification originally devised by V. E. McKelvey (1972) and modified by a joint committee of the U.S. Bureau of Mines and the U.S. Geological Survey, as U.S. Geological Survey Circular 831 (USBM and USGS, 1981). This system will allow future resource estimates to be precisely stated. The classification is based on the two fundamental aspects of mineral resources (McKelvey, 1972): first, how well a resource is known and measured (degree of certainty of existence) and second, how feasibly a resource can be exploited with existing mining and processing technology at existing prices (feasibility of economic recovery). This system is illustrated in figures 1 and 2, in which the resource classes are named.

The system provides a format by means of which various estimates can be compared and significant differences can be identified. The comparison of past estimates is the subject of this part of this report.

RESOURCE CLASSIFICATION AND NOMENCLATURE

RESOURCE ESTIMATES BASED ON CERTAINTY OF EXISTENCE

Past published estimates of phosphate resources have not explicitly taken into account the degree of certainty of the existence of the resource. Mining companies of course are highly concerned with accurately estimating one category of resources, that is, their measured reserves prior to actual mining and their indicated reserves prior to trading or selling land. Reserves (fig. 1) can be measured by drilling on approximately an eighth-of-a-mile spacing, and reserves can be indicated with approximately a half-mile spacing. Such reserve estimates, however, are generally not published, although they may be reported on a confidential basis to the U.S. Bureau of Mines or the U.S. Geological Survey, either of which may publish aggregated reserve estimates. Publicly available estimates of the inferred reserve base are made by the U.S. Geological Survey or other geologic organizations, and the certainty of existence of the resource is based on geologic inference about the lateral continuity of the beds and the variability of their grade, thickness, and quality. (See p. 22 for definitions.) Geologic judgment is used to determine what part of the resource is inferred reserve base and what part can be regarded as hypothetical undiscovered resource. This judgment usually varies among geologists and is the source of significant differences of estimates. A purely arbitrary definition of the criteria for assigning a resource to the inferred reserve base has been set up by the Bureau of Mines-Geological Survey Resource Classification Subcommittee based on the density of drill holes (figs. 3, 4, 5) (USGS, 1982). If drill holes are spaced at any distance less than 1 mile, the resource is regarded as an identified resource (inferred reserve base), but if drill holes are more than 1 mile apart, the resource is regarded as an undiscovered (hypothetical) resource, with the caveat that the spacing may be greater if justified by geologic inference. This arbitrary definition divides the resource classes efficiently and is understandable to all workers, but it cannot be regarded as an adequate substitute for an accurate, scientific assessment of resource class boundaries. An interesting theoretical approach to this problem is the statistical method called kriging, by which the statistical variability of physical parameters of a bed can be areally mapped (Davie, 1977). A parameter such as thickness or feet-percent P_2O_5 can be selected as an index of the resource quantity, and then an arbitrary limit of the statistical variance of that parameter may be chosen to express an acceptable geologic certainty of existence or measurement of, for example, inferred resources. In this case, the delineation of areas where the resource has a variance less than the limit would show the areas of inferred resources, and the areas where the variance was higher would show the areas of hypothetical resources. This method would overcome the deficiencies of setting resource boundaries by the arbitrary drill-hole spacing method. However, the methodology is not available at present because it has yet to be developed to the point where it can be routinely applied. In any event, past phosphate resource estimates have used neither method but have relied on unspecified geologic judgments, and, as a result, inferred resources and hypothetical resources have not been systematically separated.

RESOURCE ESTIMATES BASED ON FEASIBILITY OF ECONOMIC RECOVERY

The criteria for resource classes based on the feasibility of economic recovery include (1) bed thickness, (2) the phosphate content, (3) the con-

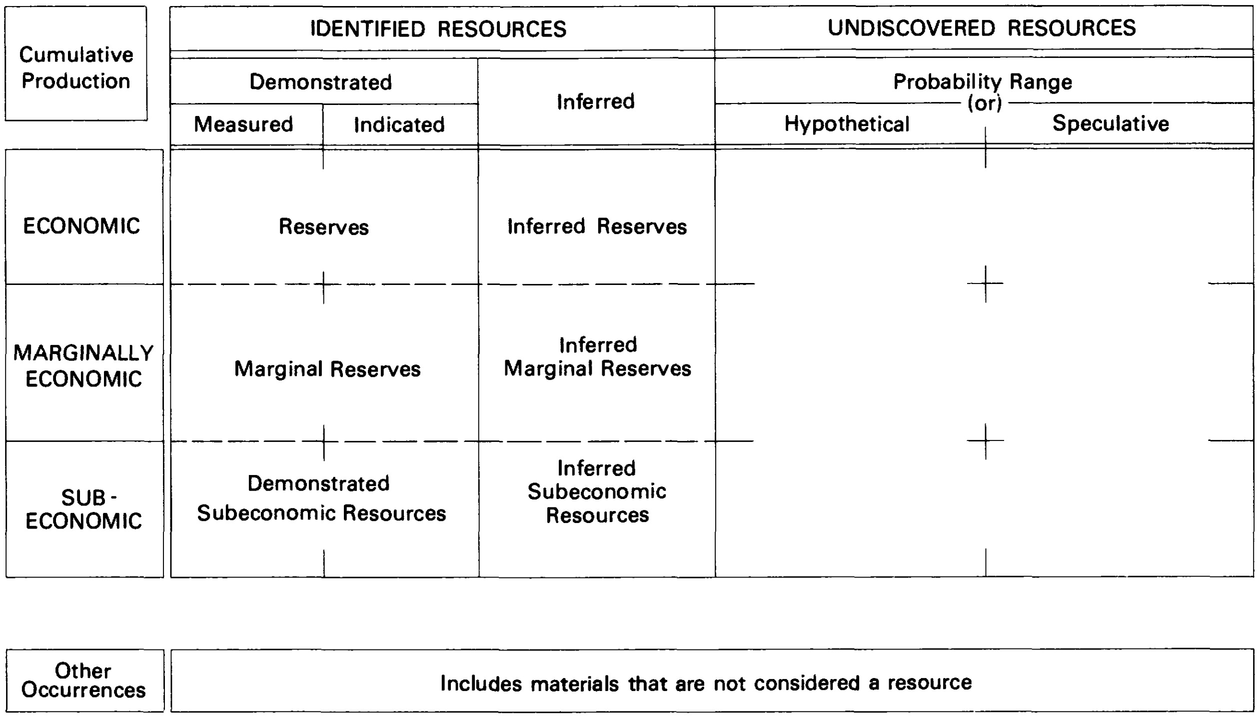

FIGURE 1.—Major elements of mineral resource classification. Column headings indicate degree of certainty of existence, row headings indicate possibility of economic recovery. From U.S. Geologicial Survey and U.S. Bureau of Mines (1981, p. 5).

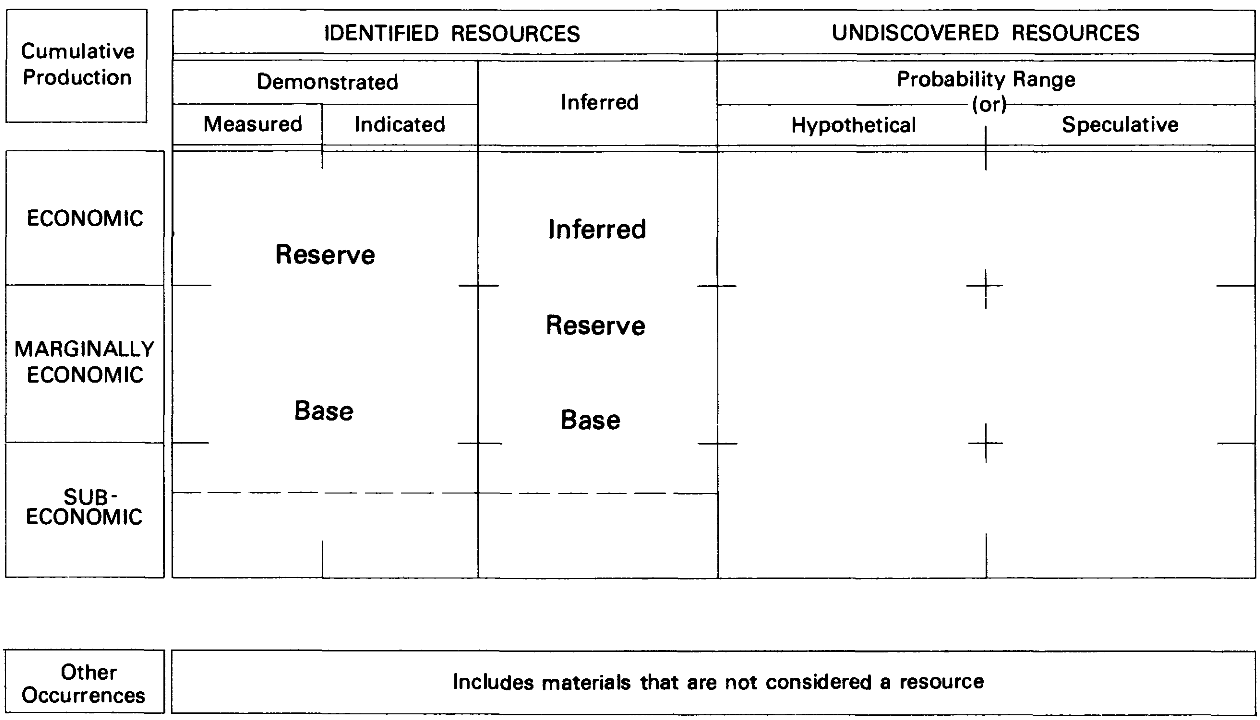

FIGURE 2.—Reserve-base and inferred-reserve-base classification categories. Column headings indicate degree of certainty of existence; row headings indicate possibility of economic recovery. From U.S. Geological Survey and U.S. Bureau of Mines (1981, p. 5).

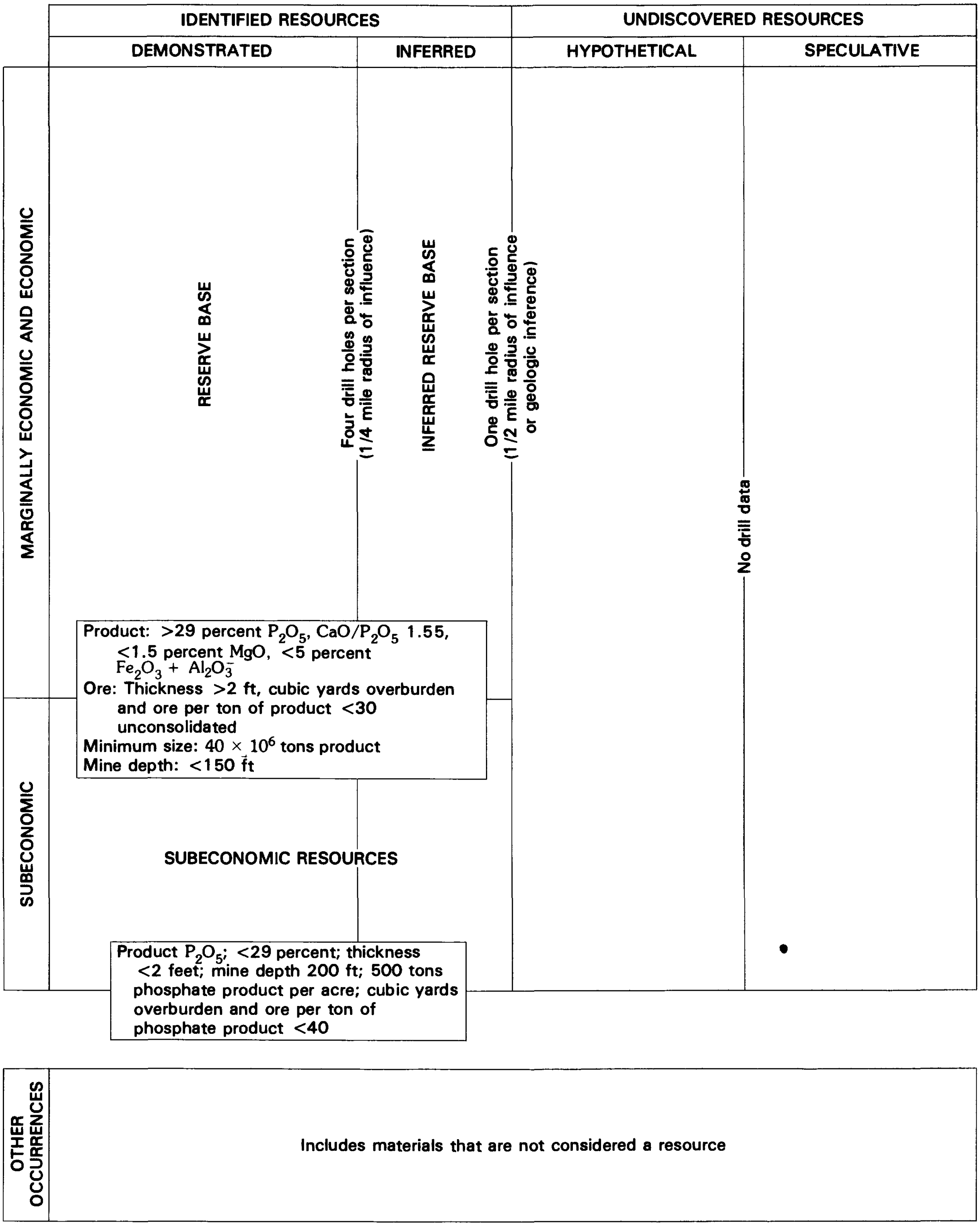

FIGURE 3.—Southeastern phosphate resource category definitions, strippable resources; present major industry economic and technology.

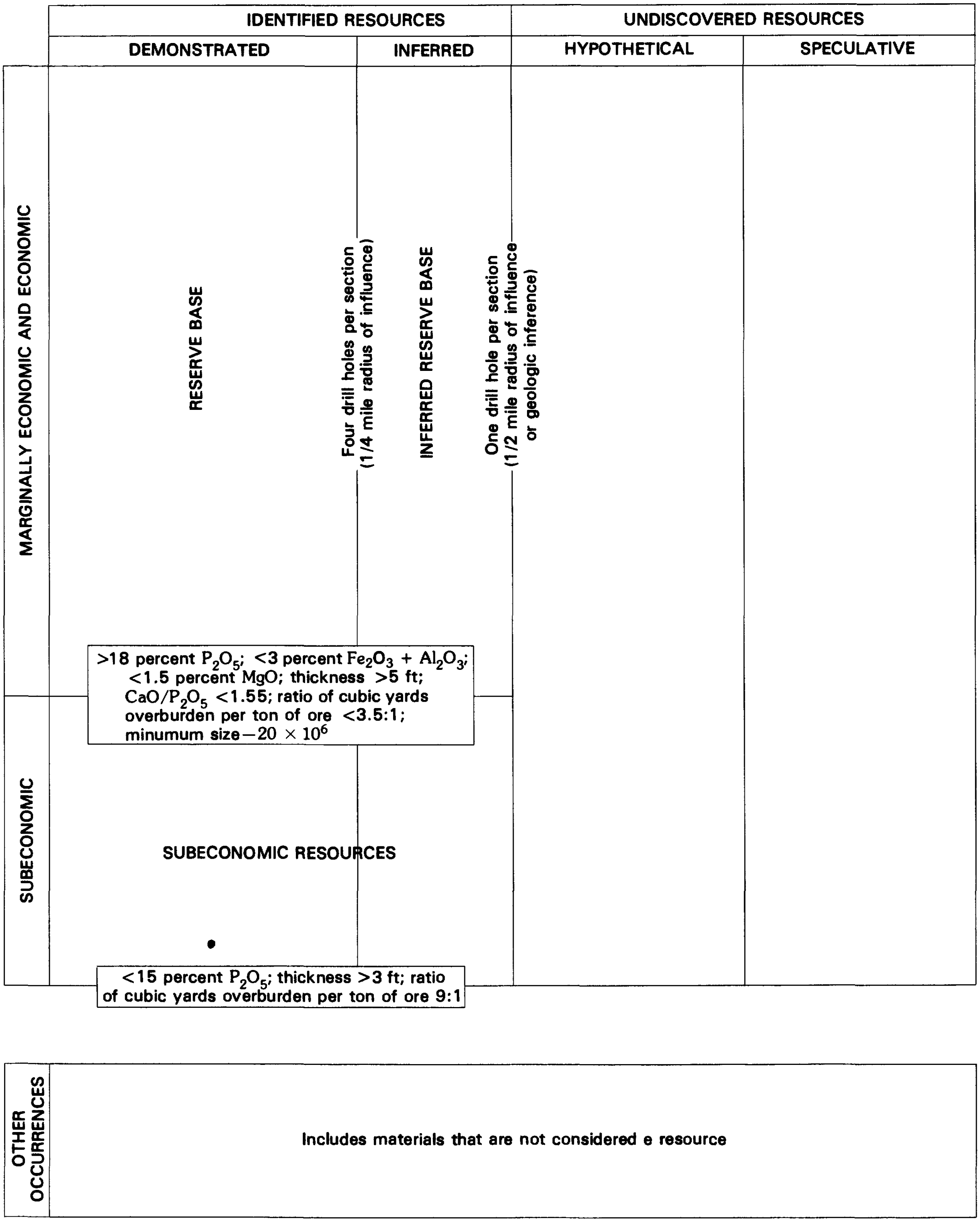

FIGURE 4.—Northwestern phosphate resource category definitions, strippable resources; present major industry economics and technology.

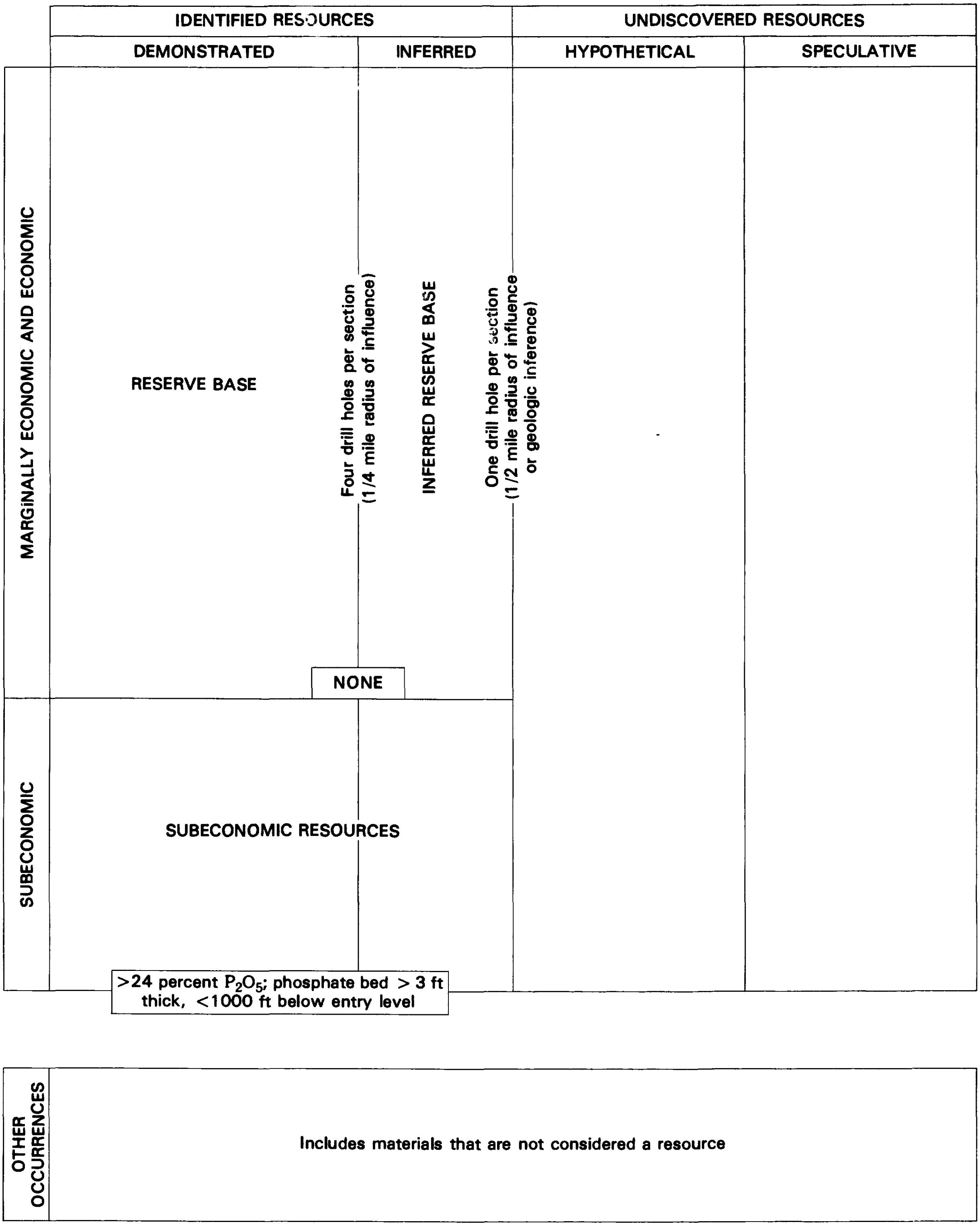

FIGURE 5.—Northwestern phosphate resource category definitions, underground resources.

tent of chemical components deleterious to the fertilizer manufacturing process, (4) the ratio of the total amount of material that has to be moved (overburden and ore) to the amount of phosphate recovered, (5) the total depth of the strip mine, (6) the size of the deposit, and (7) the percentage of the phosphate in the ground recovered by mining. These criteria have been used in one way or the other, implicitly or explicitly, in past phosphate resource estimates and are indicated for each estimate of resources that follow.

The details of the phosphate resource class divisions are being studied, and class boundaries criteria are summarized in figures 3, 4, and 5 of the present report. Resources are classed according to economic feasibility of recovery into three classes: economic, marginally economic, and subeconomic. The divisions are primarily made on economic and technologic grounds, which differ from one deposit to another depending on the costs of the mining, processing, and transporting operations. Also, the variations of price of the product cause variations in the resource categories. In order to avoid continually changing amounts of resources within classes based on feasibility of economic recovery, the reserve-base and inferred-reserve-base classes were set up to include all the rock from which reserves and inferred reserves and marginal and inferred marginal reserves are derived (fig. 2). The reserve base is defined strictly on physical parameters and not on technologic or economic factors, although these factors influence the choice of physical parameters. It is important to note that the reserve base and inferred reserve base are made up of rock in the ground and do not take into account the fact that not all the ore is recoverable. The estimates of phosphate resources in this report are all of the reserve-base and inferred-reserve-base classes unless otherwise noted. Thus, they are not to be confused with reserves or inferred reserves, and they are larger than reserves by the amount of rock that cannot be recovered and is left in the ground. Also, the reserve base and inferred reserve base are liberally estimated; thus, they include some rock that will turn out to be subeconomic, although this overestimation is kept to a minimum by adopting as nearly as possible current mining parameters.

Two other factors unrelated to the resource classification problem are of critical importance for the comparison of resource estimates. The first is areal coverage of the estimates. It is rare that any two estimates cover the same area. In some cases, this makes little difference because areal differences may be small or the resource excluded may be small, but in other cases it can be important. The second factor is the date of the estimate. Estimates are data dependent, and the amount of data available for an estimate increases over time. Usually, the latest estimates are more accurate for this reason. However, many estimates do not include a systematic display of the data used, so this factor is commonly difficult to analyze.

It was pointed out earlier that differences in estimates may relate—in addition to the areal coverage and the date of estimate—to differences in price assumptions or mining and processing in technology assumptions and also to the method by which the estimate has been made. Generally, such factors, although important in evaluating the estimate, are usually not explicitly stated so that resulting differences cannot be analyzed.

UNITED STATES PHOSPHATE RESOURCES

Phosphate is produced from three distinct types of deposits: (1) sedimentary phosphorites, (2) guano or guano-derived deposits, and (3) igneous apatite deposits.

Sedimentary phosphate deposits, or phosphorites, provide all of the phosphate used in the United States, as well as about 75 percent of the phosphate used in the world. Phosphorite occurrences are widespread throughout the United States, but phosphate is being produced today only from the Atlantic Coastal Plain Phosphate Province, the Northwestern Phosphate Province, and less importantly from Tennessee. Phosphate has been produced from many other States, and occurrences in these States are listed at the end of this report, but emphasis herein will be on the two major provinces just mentioned.

In the United States, guano or guano-derived deposits are very small; individual bat-cave deposits known from the arid Southwest contain up to a few thousand tons each, and small bird guano deposits are known from Florida and the Hawaiian Islands. These occurrences are not economically important and are not significant as sources for fertilizer phosphate.

Igneous apatites contribute about 20 percent of the total world production of phosphate. Deposits of igneous apatite are known in the United States (for example, nelsonite deposits in Virginia; apatite-magnetite deposits in New York and New Jersey; marginal apatite differentiates at Iron Springs, Utah; and apatite-rich iron ores at Pea Ridge, Missouri). No igneous deposits are being mined for phosphate, but some byproduct apatite was produced in the concentration of iron ore from the Pea Ridge deposits until several years ago. Production of apatite from igneous deposits will not be a significant factor in the supply of phosphate demands in the United States.

ATLANTIC COASTAL PLAIN PHOSPHATE PROVINCE

The largest phosphate resource of the United States is made up of the phosphate deposits of the Southeastern Coastal Plain States of North Carolina, South Carolina, Georgia, and Florida, including portions of their offshore continental shelves.

These phosphatic rocks were deposited over the shallow continental shelves of the region about 5–15 million years ago during the Miocene and Pliocene Epochs of the Tertiary Period. The deposition was in shallow bays and shelves when the sea level was higher than it is at present time. The phosphate deposits were not continuous over the whole region but occurred adjacent to the shallower parts of the shelf around local structural arches or platforms, and in some areas, particularly in deeper bays, phosphate was not deposited.

Subsequent lowering of the sea level caused some of the deposits to be reworked by waves and streams, concentrating the phosphate by removing lighter weight and finer grained material. During subaerial exposure, the deposits were weathered; light or moderate weathering continued to concentrate the phosphate, but intense weathering formed uneconomic aluminum phosphate minerals from the original calcium phosphate. Younger sediments, either marine or nonmarine, covered the phosphate deposits so that they are not exposed—or are exposed only along streams. Drilling is needed to explore for and outline these deposits. The phosphate deposits consist of flat-lying unconsolidated pelletal phosphate grains, quartz grains, and clay minerals, and weakly consolidated phosphate pellets, quartz grains, and clay cemented by carbonate minerals.

Thus, the geologic distribution of the phosphate deposits of the Atlantic Coastal Plain Province is sporadic, and the thickness and quality of the deposits vary widely from place to place. The specific deposits and their resources are described in detail in the sections that follow.

FLORIDA

IDENTIFIED RESOURCES

Estimates of the resources of phosphate in Florida have been made repeatedly since the discovery of the deposits in the 1880's. It is not necessary to recapitulate all of the estimates; but in view of the differences that some perceived as discrepancies between the recent estimates of only reserves by the U.S. Bureau of Mines and of total resources by the U.S. Geological Survey, as reported by the General Accounting Office (GAO, 1979), it seems appropriate to study the latest estimates and to recast these estimates into forms so that they can be readily compared. The most recent and complete resource estimates have been made by Zellars and Williams (1978), Fountain and Hayes (1979), and Mayberry (1981). The first two are estimates of total identified resources, whereas the last includes, in addition to identified resources, what we consider undiscovered (hypothetical) resources. Each report presents resources in a somewhat different manner, and these estimates are shown in table 1.

Zellars and Williams (1978, p. 7) stated: "For the Florida study, 'C' deposits were identified as 'active or projected,' 'R' for other identified quantifiable deposits, and 'L' for identified unquantifiable deposits." The deposits are shown in figure 6 as areas A and B and by the letters "R" or "L" for deposits that are isolated.

Summary of guidelines for the determination of identified resources (Zellars and Williams, 1978, table 19, p. 112) are

1. Deposit size—greater than 5 million tons where the overburden is less than 20 feet, or greater than 10 million tons where the overburden is more than 20 feet, or greater than 15 million tons where the overburden is greater than 30 feet.
2. Grade of phosphate product—greater than 27.5 percent P_2O_5.
3. Grade of flotation feed—greater than 4.6 percent P_2O_5.
4. There must be one ton of recoverable product for 10 yards of ore.
5. The ore zone must be greater than 5 feet thick.
6. Any product with more than 1.5 percent MgO will be separately classified.

TABLE 1.—*Comparison of estimates of identified resources of phosphate rock in Florida*

[In millions of short tons]

Zellars and Williams (1978) Identified resources (C and R deposits, this report)			Fountain and Hayes (1979) "Estimated recoverable" resources			Mayberry (1981) "Florida phosphate reserves"		
	Tons $x10^6$	P_2O_5 (percent)		Tons x106	P_2O_5 (percent)		Tons x106	P_2O_5 (percent)
North Florida	1,398	30.4	North Florida	1,764	30+	Operating mines and mines planned in next 20 years, including North Florida.	2,900	31.1
Central Florida	890	31.8	Central Florida	1,129	31	Private owners (throughout Florida).	500	30.7
South and East Florida	1,862	30.3	South Florida	3,050	30+	"New Discovery."	1,400	30.2
			East Florida	2,662	29+	Total minable with conventional technology.	4,800	30.7
						Minable with improved technology.	5,200	30.2
Total or average---	4,150	31+	Total---	8,605	30+	Total---	10,000	30.4

Fountain and Hayes (1979) did not specify the criteria they used in determining resources, but their guidelines probably are similar to those of Zellars and Williams (1978). Fountain and Hayes (tables 2–12, p. 109) gave a figure for "total phosphate resources," and "total potential phosphate product," which is defined as 100 percent of the phosphate product in the ground. This number is reduced by excluding resources that underlie urban areas, roads, lakes, swamps, and rivers. After this reduction, a "potentially minable phosphate product" is shown, and this number is further reduced by a factor of 50–65 percent—the recovery factor. The final number is what they call "estimated recoverable phosphate product," and this number is used in the tables in this report and should be comparable to the figures of Zellars and Williams.

Mayberry (1981) gave only broad data—in a different form than the others—but his text indicates that his numbers are for the recoverable phosphate product.

The numbers of Zellars and Williams (1978) and Fountain and Hayes (1979) for North Florida are similar (table 1). The numbers of Fountain and Hayes are slightly higher, but they include data for South Georgia which Zellars and Williams excluded. The numbers of these two estimates are also close for Central Florida, although Fountain and Hayes gave somewhat higher numbers than Zellars and Williams. However, for south and east Florida, the numbers of Fountain and Hayes are more than double those of Zellars and Williams. The higher numbers probably reflect differences in what is considered minable, but also the numbers reflect the increased prospecting in these areas after the report by Zellars and Williams was compiled. The numbers given by Mayberry (1981) are difficult to put into comparable categories because of different terms used, so the numbers shown in table 1 are modified only slightly from his original table. However, the total phosphate "minable with conventional technology" of Mayberry is about the same (4,800 million tons)

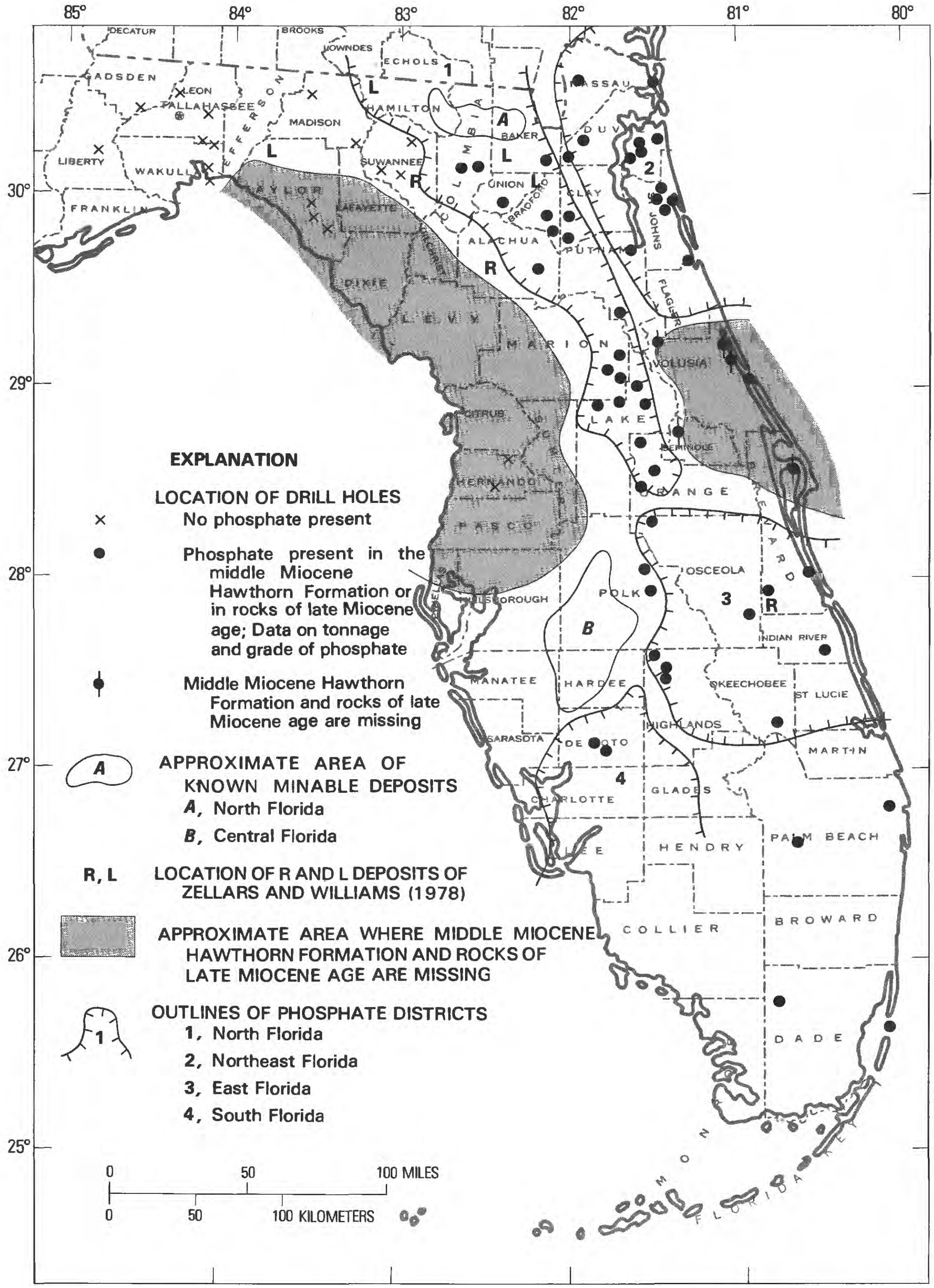

FIGURE 6.—Sketch map of Florida east of long 85°W., with outlines of phosphate districts, location of significant drill holes, and areas where the middle Miocene Hawthorn Formation and rocks of late Miocene age are missing.

as the total of identified resources of Zellars and Williams (4,150 million tons). The category of "minable with improved technology" of Mayberry certainly includes at least a part of the high numbers of Fountain and Hayes for south and east Florida.

Tonnages in table 1 are in short tons of P_2O_5 and were changed to metric tons of P_2O_5 and rearranged as shown in table 2 to fit them into the resource diagram of the USGS and USBM as shown in Circular 831 (1981). The numbers of Zellars and Williams for identified resources are arranged into the three categories (economic, marginally economic, and subeconomic) on the basis of their dollar figures. An economic resource is one where total production costs are less than 25 dollars per ton; marginally economic is 25 to 35 dollars per ton; and subeconomic is more than 35 dollars per ton (Zellars and Williams, 1978, table 22). These are all demonstrated measured resources. Zellars and Williams classified deposits as "C," "R," and "L." The "C" and "R" deposits are included in measured demonstrated resources, but the "L" category is for deposits for which not enough data exist to compute measured resources. The "L" deposits may be considered as not technically feasible to mine. It is not possible to give an accurate figure for resources of "L" deposits, but the areas of these deposits in relation to the area of the "C" and "R" deposits is such that they may contain about 200 million short tons.

The data in Fountain and Hayes (1979) are for total "potentially minable" phosphate rock. The breakdown into economic, marginally economic, and subeconomic (table 2) was made using the percentages of these categories as derived from the data of Zellars and Williams. Thus, for the north Florida deposits, 66 percent was in the economic category, 32 percent in marginally economic, and only 2 percent in subeconomic. Percentages for each category for the deposits in Central Florida and south and east Florida were computed in the same way. All data in Fountain and Hayes are for identified demonstrated resources.

Mayberry's numbers are divided differently. His figures were not broken down by area, but he does

TABLE 2.—*Identified phosphate rock resources of Florida, estimated by various authors*

[In millions of metric tons and millions of metric tons of P_2O_5; Tr., trace]

		Zellars and Williams (1978)			Fountain and Hayes (1979)			Mayberry (1981)		
		Tons x10^6	P_2O_5 (percent)	Tons P_2O_5 x10^6	Tons x10^6	P_2O_5 (percent)	Tons P_2O_5 x10^6	Tons x10^6	P_2O_5 (percent)	Tons P_2O_5 x10^6
Economic	North	845	30.4	260	1,056	> 30	320			
	Central	780	31.8	250	884	> 31	280	1,270	31.5	400
	South and East	1,000	30.3	300	3,052	> 30	920			
Marginally economic	North	404	30.4	120	512	> 30	160			
	Central	25	31.8	10	31	> 31	10	1,820	30.8	560
	South and East	527	30.3	160	1,600	30	490			
Sub-economic	North	20	30.4	Tr.	33	> 30	Tr.			
	Central	32	31.8	Tr.	10	> 31	Tr.	1,270	30.7	390
	South and East	166	30.3	50	500	> 30	150			
Other occurrences (Minable with new technology)		180	30+	60	No		data	4,700	30.2	1,420
Totals ---		3,979		1,210	7,650		2,240	9,060		2,770
Average ---			30.4			30.6			30.6	

give dollar figures, and these were used to divide his numbers into the three categories—economic, marginally economic, and subeconomic. Mayberry's numbers for "minable with improved technology" are put into "other occurrences" in the diagram.

HYPOTHETICAL RESOURCES

Hypothetical resources are deposits for which drilling information is sparse (less than one drill hole per section), or where only lithologic logs of drill holes are available, or where no drilling or outcrop data exist but where geologic inference indicates that deposits are present. These resources were estimated by us and are based on the latest available data. Tonnage and grade data are based on analyses of very sparse core samples and on geologic inference. Accordingly, all numbers (thickness, amount of recoverable phosphate, and area) are drastically reduced so that tonnage data are very conservative. In fact, numbers are so reduced that in some areas identified resources exceed hypothetical resources. For purposes of the following discussion of hypothetical resources, Florida has been divided into the following areas (fig. 6):

1. North Florida district, which includes all of Hamilton, Suwannee, Columbia, Baker, Union, and Bradford Counties, and parts of Clay, Alachua, Putnam, Marion, Lake, and Orange Counties.
2. Northeast Florida district, which includes all of Nassau, Duval, and St. John's Counties, and parts of Clay, Putnam, and Flagler Counties.
3. East Florida district, which includes all or most of Brevard, Indian River, Osceola, Highlands, St. Lucie, and Okeechobee Counties.
4. South Florida district, which includes all or parts of Hardee, DeSoto, Sarasota, Charlotte, Lee, Hendry, and Glades Counties.

The area on the east coast of Florida that is cross-hatched in figure 6 includes all of Volusia County, the south one-third of Flagler County, the northern part of Brevard County, and nearly all of Seminole County. Core samples from deep drill holes in this area had the same lithology and stratigraphy. The upper part consisted of loose sand of probable Holocene age underlain by slightly clayey sand containing some shell material (=Citronelle Formation of Pliocene age), which rested on the Ocala Limestone of Eocene age. The Miocene Hawthorn Formation and Oligocene Suwannee Limestone are missing. Evidently, this was a structural high during the deposition of the Hawthorn Formation. This barren area forms a natural division between the deposits of northeast Florida and those of East Florida. Although the total number of data points is small, it is believed that on the scale of the map, the lines drawn are relatively accurate.

NORTH FLORIDA DISTRICT

The first estimates of the resources of the North Florida district were made by Mansfield (1942), who stated that there was a total of about 300 million tons of known, probable, and possible reserves in Hamilton, Clay, Bradford, Lake, and Orange Counties. Resources tabulated in table 3 are in the east half of Hamilton County, the north half of Columbia County, and small bordering parts of Baker and Union Counties (fig. 6).

Hamilton County.—Mines and measured resources are in the east half of Hamilton County. Scattered data from the western half of the county indicate that the Hawthorn Formation is present but thin and that the resources are probably not large. Zellars and Williams (1978) have an L deposit in the western half of the county; resources for L deposits have been estimated, so no further resources will be tabulated for this county.

Columbia County.—Known deposits are indicated by Zellars and Williams (1978) in the northern half of Columbia County. Scattered drilling in the southern half of the county intersects phosphate-bearing sand and clay of the Hawthorn Formation, and possibly some phosphates reworked into younger beds. The area that may be underlain by phosphate is about 150 square miles, and the amount of phosphate present in these sediments may average about 10 percent (a conservative figure based on hand lens examination of cuttings). The beds of phosphatic sand and clay range from 3 to 13 m in thickness; if the average thickness is 3 m, these rocks contain about 2,000 tons per acre of phosphate particles. If one-fourth of the area is underlain by phosphate of this character, the hypothetical resources are about 50 million tons.

Baker County.—Many prospect holes have been drilled in Baker County, most of them within the Osceola National Forest, but Zellars and Williams show an R deposit in the northern part of the

TABLE 3.—*Summary of hypothetical phosphate rock resources of Florida, by county*

[Millions of metric tons]

County	Tons
North Florida district	
Hamilton	small
Columbia	50
Baker	100
Union	50
Bradford	50
Clay	50
Alachua	200
Marion, Putnam, Lake, and Orange	400
Total	900
Northeast Florida district	
Nassau	150
Duval	100
St. John's	150
Clay	100
Putnam	100
Flagler	50
Total	650
East Florida district	
Brevard	1,000
Osceola	1,000
Indian River	100
Okeechobee	100
Highlands	"scores of millions"
St. Lucie	"substantial, deeply buried"
Total	2,200+
South Florida district	
Hardee	150
Manatee	50
DeSoto	1,000
Sarasota	100
Hendry, Lee, Charlotte, and Glades	125
Total	1,425
Grand Total, hypothetical resources	5,000+

county and an L deposit in the southern part of the county. The Hawthorn Formation underlies the entire county, is thick, and contains some phosphate throughout. Only the top clastic part of the Hawthorn may be minable; the lower carbonate part will require new technology. The area of the county for which resources have not been computed is about 200 square miles; the thickness of the clastic phosphate beds in the Hawthorn and younger formations ranges from 3 to 15 m, and the amount of phosphate based on scattered samples is about 10 percent. Hypothetical resources, then, may be about 100 million tons.

Union and Bradford Counties.—Zellars and Williams show C and L deposits across the boundary of Union and Bradford Counties, and prospecting data indicate thin overburden, 30 percent P_2O_5, and about 15 percent acid insoluble. No prospect data exist for the western half of Union County, but all of the county is within the North Florida district, and the resources in this part of the county may be about 50 million tons. The eastern half of Bradford County is also within the district, and two deep drill holes show that the Hawthorn Formation is present and contains phosphate. Sparse data indicate that as much as 8 m of sandy and clayey phosphate rock are present under thin overburden. The few samples analyzed contained from 25 to 30 percent P_2O_5, and the amount of phosphate pellets that may be recoverable is a few thousand tons per acre. The eastern half of the county is estimated to contain about 50 million tons of phosphate.

Clay County.—The western third of Clay County is within the boundary of the district. This area is about 100 square miles, and two deep wells in this part of the county indicate that the Hawthorn Formation contains, in the top clastic part, about 2,000 tons per acre of recoverable phosphate. Total tonnage, then, may be about 50 million tons.

Alachua County.—Almost all of the eastern half of the county is within the district, and within this area there are a few prospect holes that have intersected potentially economic phosphate. An area in the northeastern part of Alachua County (fig. 6) has an average of 7,000 tons per acre of phosphate pellets that contain about 28 percent P_2O_5. This area is about 50 square miles in extent, so there may be as much as 100 million tons of resources, a figure that is comparable to the estimate of 30–50 million tons of "reserves" made by Pirkle (1957). In an area of about 1 square mile to the south and east of Gainesville, prospect data indicate about 7,000 tons per acre of pellets that contain about 29 percent P_2O_5. The area may contain 25 million tons.

The total area of the county that is within the district is about 500 square miles, of which perhaps 125 may be underlain by shallow phosphatic sediments. On the basis of tonnage of about one-third of that in the prospected areas, there is an estimated 100 million tons of phosphate as an additional resource. Total resources for the county, then, are 225 million tons.

Putnam, Marion, Lake, and Orange Counties.—The western part of Putnam County, the extreme eastern part of Marion County, the northern part of Lake County, and the western part of Orange County are within the North Florida district. Zellars and Williams indicated an R deposit that is close to the juncture of Lake, Orange and Seminole Counties, and drill data show that the area centered around Blackwater Creek does contain some phosphate near the surface. Data show that tonnages are as much as 10,000 tons per acre, but the average is closer to 2,500 tons per acre. Samples from several deep drill holes in the area show that phosphatic Hawthorn Formation is present, and recent drilling in the Ocala National Forest in Marion, Lake, and Putnam Counties has shown that the clastic upper part of the Hawthorn Formation contains abundant phosphate. Thicknesses of this upper unit range from 1 to about 10 m; tonnages range from 2,500 to 10,000 tons per acre, with an average of 28 percent P_2O_5. Overburden depths are from 20 to 35 m.

The total area of these counties that is within the district is about 750 square miles. Total resources, then, might be about 400 million tons, assuming an average value of about 2,500 tons per acre (a conservative figure) and that only 20 percent of the total area is underlain by phosphate.

Suwannee County.—Zellars and Williams reported that an L deposit of land-pebble type is present near Eridu, a small town in the northwest corner of the county. We have no data on this deposit, but we suspect that it may be reworked hardrock type phosphate in rocks of Pleistocene age. There may be other deposits of this type in the county, but drill data indicate that only "hardrock" deposits are present, particularly in the Steinhatchee district. We do not have enough data to give any hypothetical tonnages for this county.

NORTHEAST FLORIDA DISTRICT

The Northeast Florida district includes all of Nassau, Duval, and St. John's Counties, the eastern two-thirds of Clay County, the east half of Putnam County, and the northern two-thirds of Flagler County (fig. 6). Except for Flagler County, some drill data are available for all of these.

Nassau County.—All of Nassau County lies within the district, and sample data from one drill hole indicate a total of about 4,000 tons per acre of phosphate pellets with about 27 percent P_2O_5. A deep well in the eastern part of the county intersects the phosphate-bearing Hawthorn Formation. The thickness of clastic Hawthorn is about 10 m with 45 m of overburden (essentially barren of phosphate). The total area of the county is about 500 square miles, and except for the southeastern part of the county, all seems to be underlain by phosphatic Hawthorn Formation. Assuming an average of 2,000 tons per acre for about one-fourth of the area of the county, the amount of phosphate present would be 150 million tons.

Duval County.—All of Duval County is within the Northeast Florida district. No sample data are available, but six deep wells show that the entire county is underlain by the Hawthorn Formation. There are about 700 square miles in the county, but a large part of the county is within the urban area of Jacksonville; thus, it is likely that only about half of the total area may be available for mining. There are sample data for phosphate for a few holes in all of the counties surrounding Duval, and, projecting these data into the county, it is likely that the average phosphate amounts are 2,500 tons per acre and about 28 percent P_2O_5. Only the western third of the county (200 square miles) is available for mining, with total tonnages on the order of about 100 million tons.

St. John's County.—All of St. John's County, an area of about 500 square miles is within the Northeast Florida district. Samples from three core holes and several deep wells show that all of the county is underlain by phosphatic Hawthorn Formation. The clastic phosphate deposits range in thickness from 1.5 to about 30 m and contain from 3,000 to 10,000 tons per acre, with 25–30 percent P_2O_5. About half the county either is along the Atlantic Coast or contains urban areas which must be removed from consideration as phosphate resource areas; the total tonnage in the remaining half of the county may be 150 million tons.

Clay County.—The eastern two-thirds of Clay County is within the district. One core hole intersects phosphatic beds in the middle Miocene Hawthorn Formation, and an upper bed, which may be late Miocene in age, contains phosphate which is probably reworked from the Hawthorn. The upper bed is about 5 m thick and under 8 m of overburden, and the underlying clastic beds of the Hawthorn Formation are 16 m thick with variable amounts of phosphate. The total amount of recoverable phosphate pellets is about 6,000 tons per acre, with 25–30 percent P_2O_5. The amount of phosphate present in the county, using similar criteria as in the other counties, is about 100 million tons.

Putnam County.—The east half of Putnam County is within the Northeast Florida district. It is likely that this half of the county contains about as much phosphate as the west half (in the North Florida district), or about 100 million tons.

Flagler County.—The northern two-thirds of Flagler County is within the district. The southern part of the county is within the area where the Hawthorn Formation is missing. There are no prospect holes within the county nor have we been able to locate any records of deep drilling. Data from adjacent counties in which the Hawthorn is present indicate that at least 2,000 tons per acre of phosphate pellets may occur in the formation, and about 50 million tons of phosphate pellets may occur in the northern part of the county.

EAST FLORIDA DISTRICT

The East Florida district includes the southern two-thirds of Brevard County, and all of Indian River, St. Lucie, Osceola, Highlands, and Okeechobee Counties.

Brevard County.—The northern one-third of Brevard County is in the area where the Hawthorn Formation is absent; drill data show that this area has loose sand with shells overlying carbonate rock of the Eocene Ocala Limestone and contains no phosphate. Some drilling has been done in the county, particularly on the Deseret Ranch property. Results of this drilling are confidential, but Zellars and Williams (1978) considered this to be an R deposit, and the tonnage is combined with other tonnages for east and south Florida. Measured resources for this part of the county, then, are already listed. However, it seems likely that total resources in the county are extremely large. Mayberry (1981) has estimated the resources in Brevard County to be 3 billion short tons. Conservatively, then, there probably are at least 1 billion metric tons of hypothetical resources in this area.

Osceola County.—All of Osceola County is within the East Florida district. A core hole in eastern Osceola county (fig. 6) near the boundary with Brevard County had 6 m of phosphate rock under 45 m of overburden, and about 8,000 tons per acre of phosphate pellets with an average content of 30 percent P_2O_5. A drill hole in the northwestern part of the county penetrated the phosphate-bearing Hawthorn, and it is likely that the entire county is underlain by the Hawthorn Formation. Although it is difficult to calculate resources from such scattered data, it is possible that this county may contain about the same amount of phosphate as there is in Brevard County to the east, and, therefore, the total hypothetical resource is of the order of 1 billion tons.

Indian River County.—One deep well has been logged in the eastern part of Indian River County (fig. 6). This well had about 30 m of phosphate-bearing clastic rock of the Hawthorn Formation under about 40 m of overburden. The northwestern part of the county is adjacent to the Deseret Ranch area and probably contains phosphate. Total hypothetical resources in the county are conservatively estimated from these data to be about 100 million tons.

Okeechobee County.—Sparse drill data (lithologic logs only) indicate the presence of phosphate-bearing Hawthorn Formation throughout Okeechobee County. Again, with the very sparse data, it is very difficult to compute resources, but at least 100 million tons of hypothetical resources may exist in this county.

Highlands County.—About half of Highlands County is within the East Florida district. Three deep drill-hole logs are known from the county; all describe phosphate-bearing sediments of the Hawthorn Formation. There are no chemical data, and the phosphate-bearing rocks are covered by thick overburden. Hypothetical resources cannot be adequately estimated, although it is likely that a few score million tons are present.

St. Lucie County.—No drill-hole logs are known from St. Lucie County, but on the basis of data to the north and to the south, it is likely that the entire county is underlain by the Hawthorn Formation. The phosphate-bearing parts of the Hawthorn Formation are deeply buried, from perhaps 30 m in the western part of the county to as much as 160 m in the southeast. Resources cannot be adequately estimated, but substantial, deeply buried phosphate resources are present in this county.

SOUTH FLORIDA DISTRICT

The South Florida district is the southern extension of the classic land-pebble district. It includes parts of Hardee and Sarasota Counties and all of DeSoto, Charlotte, Hendry, Lee, and Glades Counties. Other counties in the southern part of Florida have not been included in this review, because, although phosphate-bearing rock of the Hawthorn Formation is present, the rock is deeply buried; one drill-hole log in Palm Beach County (fig. 6) has 300 m of overburden, and a hole in Dade County has 180 m of phosphate-bearing Hawthorn rocks under 100 m of overburden. The resources in these counties may be enormous, but they are so deep as to preclude mining, at least for the foreseeable future. They are, therefore, not considered any further in this summary.

Hardee and Manatee Counties.—Abundant prospecting information exists, and Zellars and Williams (1978) indicated large areas of C deposits in Hardee and Manatee Counties. Areas not covered by prospecting or by C deposits do contain abundant phosphate. Resources in these counties, using 3,000 tons per acre and an area of about 75 square miles, total about 150 million tons for Hardee County; resources for Manatee County may be about 50 million tons.

DeSoto County.—All of DeSoto County is underlain by the Hawthorn Formation. Drilling data indicate that the formation may be divided into an upper clastic unit that contains abundant phosphate and into a lower carbonate unit, also with phosphate but unminable under present technology. The overburden thickness ranges from 18 to 45 m; the upper clastic, phosphatic part of the Hawthorn is as much as 30 m thick. Zellars and Williams showed C deposits present in the northwestern part of the county, but data for the rest of the county have not been computed. A drill hole for which we have analytical data shows 10 m of clastic Hawthorn Formation that contains 13,000 tons per acre of phosphate particles with an average of about 30 percent P_2O_5. The county is about 450 square miles in area, and about 300 square miles are underlain by hypothetical resources. If the average tonnage is about 10,000 tons per acre, and if half the area is underlain by this type of material, total resources are about 1 billion tons—a conservative figure.

Hendry, Lee, Charlotte, and Glades Counties.—Phosphatic sedimentary rocks are known to be present close to the surface over a large area centered around the Caloosahatchee River in Hendry, Lee, Charlotte, and Glades Counties. We have no data on prospecting in this area; however, phosphate is present in the Hawthorn Formation, in unnamed sands of late Miocene age, in the Pliocene Tamiami Formation, in the Caloosahatchee Formation (Pliocene and Pleistocene), and in rocks of Pleistocene and Holocene ages.

The total area that may be underlain by shallow phosphate-bearing sediments is about 1,000 square miles, and if one-tenth of this area is underlain by 2,000 tons per acre of phosphate, total resources are 125 million tons. Much of the rock will probably contain calcite shells or cement.

Sarasota County.—Only the eastern one-third of Sarasota County is within the district. This area is adjacent to areas in Hardee and DeSoto Counties that contain C deposits (Zellars and Williams, 1978), and it is likely that the area is underlain by phosphate-bearing rock of the Hawthorn Formation. If the rock has 5,000 tons of phosphate per acre and if about 50 square miles of the eastern part of the county is underlain by this amount of phosphate, then total resources may be 100 million tons.

SUMMARY OF PHOSPHATE RESOURCES OF FLORIDA

The numbers used for identified resources for this report (table 4) are based on interpretation of the data of Zellars and Williams (1978), Fountain and Hayes (1979), and Mayberry (1981), plus our personal knowledge of the phosphate districts.

The total identified economic resources of North Florida are about 400 million metric tons, about equal to the figure of Zellars and Williams. The slightly higher figure of Fountain and Hayes includes deposits in south Georgia, which are not being considered here. Mayberry's numbers are comparable to the other two estimates.

For Central Florida, identified economic resources are estimated to be about 800 million metric tons, a number that is in between those given by Zellars and Williams and Fountain and Hayes.

For south and east Florida, we have used 2,000 million metric tons, a figure between those of Zellers and Williams and Fountain and Hayes. Mayberry's total tonnage numbers are even larger than the numbers of Fountain and Hayes.

TABLE 4.—*Summary of phosphate rock resources of Florida*

[In millions of metric tons]

	IDENTIFIED RESOURCES				HYPOTHETICAL RESOURCES			
		Tons $x10^6$	P_2O_5 (percent)	Tons P_2O_5 $x10^6$		Tons $x10^6$	P_2O_5 (percent)	Tons P_2O_5 $x10^6$
Economic	North	900	31.1	280	North Florida			
	Central	800	32.5	260		900	28+	250
	South and East	2,000	30.0	600				
Marginally economic	North	450	31.1	140	Northeast Florida	650	30.1	200
	Central	20	32.5	Tr.				
	South and East	1,000	30.0	300	South Florida	1,425	28.0	400
Subeconomic	North	20	31.1	Tr.				
	Central	10	32.5	Tr.	East Florida	2,200	29.5	650
	South and East	400	30.0	120				
Total--		5,600		1,700		5,175		1,500
Average--			30.3+				29.0+	
Grand total of identified and hypothetical resources--10,775 million metric tons containing 29 percent P_2O_5 = 3,200 million metric tons P_2O_5								

The reports of Zellars and Williams and Fountain and Hayes had the benefit of up-to-date information on what the phosphate companies consider reserves. Neither report considers any resources that were not, in effect, measured. Hypothetical resources are not considered, although the L deposit of Zellars and Williams might be considered hypothetical. Mayberry did list large tonnages that he said will be minable only with improved technology, and some of this material should probably be put into hypothetical resources.

Our figures for marginally economic and subeconomic categories were computed in the same way—as being somewhere between the data of the other authors.

GEORGIA

Phosphate resources in southern Georgia (principally in Echols and Lowndes Counties) are in the Hawthorn Formation, and these deposits are an extension of the North Florida district. A great deal of shallow drilling has been done in southern Georgia by many companies, but no leases have been executed. The amount of phosphate in tons per acre per foot of section is not high, and grades (in P_2O_5 content) are low. Resources are not known but are large, probably measured in hundreds of millions of tons, but reserves under present conditions are nil.

The phosphate deposit in the Savannah River area of north Georgia and southern South Carolina is in the Hawthorn Formation. Locally, the phosphate has been reworked, enriched, and concentrated in beds of late Miocene age (Furlow, 1969). The deposit is known to extend out to sea for at least 12 miles. Furlow (1969) indicated that the resource, on land, in Georgia is about 1 billion short tons of recoverable product that contains about 30 percent P_2O_5 (=about 300 million tons of P_2O_5). Total resources must be much greater.

Fountain and Hayes (1979) showed that the "estimated recoverable phosphate product" is 1.8 billion short tons (=about 500 million tons P_2O_5). Their data are for northern Georgia and southern South Carolina. This deposit is unminable because of environmental restrictions.

SOUTH CAROLINA

Phosphorite, probably of the Hawthorn Formation, is present in Jasper, Colleton, Hampton, and Beaufort Counties in southern South Carolina. This is an extension of the deposit in the Savannah River area in north Georgia. The resources in South Carolina are thought to be about 100 million metric tons of recoverable phosphate of about 31 percent P_2O_5 or about 30 million tons of P_2O_5. Total resources are much greater. These data are based on unpublished company drilling reports.

The first sedimentary phosphate mined in the United States was from the Charleston phosphate district of South Carolina. Deposits are thin, are erratic in distribution, and are of Pleistocene and Holocene ages (Malde, 1959); but the deposits are reworked from phosphate deposited in the Hawthorn Formation or the Cooper Marl. No reserves, as such, are left in this district, and total resources of the Pleistocene reworked material are small, but large, very low grade resources may remain in the Cooper Marl of Eocene and Oligocene age.

NORTH CAROLINA

The phosphate deposit of the Miocene Pungo River Formation (Kimrey, 1965) is in a basin on the north flank of a small high associated with the Cape Fear arch. In the western part of the basin, the Pungo River Formation consists of a single bed of phosphorite that ranges in thickness from 5 to about 25 m, but in the east, the Pungo River Formation thickens to about 75 m due to intercalation of beds of dolomite, sand, and clay. All beds contain some phosphate pellets; the basin is about 600 square miles in extent; and the total amount of possibly recoverable phosphate is about 10 billion tons. Fountain and Hayes (1979) pointed out that the "estimated recoverable phosphate products" total 9.4 billion short tons, with 29–32 percent P_2O_5, or a total of 2.8 billion tons of P_2O_5. We consider that most of this tonnage is subeconomic because of problems related to deep mining.

OFFSHORE

Phosphate pellets are known to occur offshore in the Atlantic Ocean from southern Virginia on the north to the southern tip of Florida. F. T. Manheim (written commun., 1978) stated that the phosphate deposits of the Blake Platform (fig. 6) are "* * * of larger magnitude than the Southern California offshore deposits." In a table in his report, he showed the tonnage of phosphate in the offshore California deposits as 2 billion tons.

Zellars and Williams (1979) showed that an area offshore from the Savannah River (12 miles offshore from Tybee Island; fig. 6) contains a deposit of 150 million short tons of recoverable phosphate product. This tonnage is conservative, but it represents that part of the deposit that might be minable today. Total resources are much larger.

A recent announcement by the National Science Foundation (newspaper reports, 16 February 1981) stated that research by Dr. S. R. Riggs of East Carolina University and Dr. A. C. Hine of the University of South Florida has discovered large phosphate deposits 60 miles off the coast of North Carolina (fig. 6). The deposit covers hundreds of square miles, and the total tonnage must be very large.

On the basis of these data, then, offshore resources of phosphate are very large, and although the resource must be considered hypothetical rather than as identified, it is possible that large tonnages may be minable in the foreseeable future.

ATLANTIC COASTAL PLAIN

The economic or potentially economic phosphate deposits of the Atlantic Coastal Plain are in rocks of Miocene age or are in younger rocks in which the phosphate was derived from Miocene rocks.

Phosphate deposits are known to occur from the southern tip of Florida to northern North Carolina and offshore in the Atlantic Ocean from North Carolina to Florida. Deposits are poorly consolidated sand, clay, and carbonate rock (limestone and dolomite) and combinations of these lithologies—all contain sparse to abundant phosphate nodules and pellets. The phosphate is concentrated at certain structural positions—in basins or on the flanks of positive areas (anticlinal highs) that were rising at the time of deposition of the phosphate (Cathcart, 1968). The phosphate in the rocks must be separated from the gangue minerals (quartz, clay, and carbonate) in order to produce an economic product.

The total amount of phosphate present in the Atlantic Coastal Plain is very large. Identified resources plus hypothetical resources total about 22 billion metric tons (table 5).

NORTHWESTERN PHOSPHATE PROVINCE

The rich phosphate of the Northwestern Phosphate Province was deposited about 250 million years ago on the continental shelf of the North American continent at the edge of the ancient Pacific Ocean. The original accumulation of phosphatic sediment in the area now part of Idaho, Utah, Montana, and Wyoming was one of the largest known in all of geologic history. It contained at least 1.7×10^{12} metric tons of P_2O_5, which is equivalent to 18 thousand billion metric tons of rock containing 9.6 percent P_2O_5, the average phosphatic rock of the Northwestern Province. However, subsequent geologic events have removed much of the deposit from man's reach. Younger sediments buried the phosphatic sediments as deep as 6 miles below the surface. Later, tectonic forces buckled and fractured the sedimentary rocks, including the phosphate, causing part to be uplifted and eroded away and part to be more deeply buried. Still later, lava flows in the central Idaho rift valleys further buried part of the phosphate rock.

The phosphate rock at depth is fresh and unweathered and consists of hard, black rock that is rich in organic matter and contains significant amounts of calcium and magnesium carbonate minerals. This phosphate rock makes up the major portion of the resource, but at present due to underground mining costs and the poorer grade and quality of the rock, it is not economic to mine. Thus, none of the deep underground fresh phosphate rock is included in the phosphate reserve of the Northwestern Province, with the exception of small underground mine reserves in Montana. Where the phosphate rock has been weathered, its grade has been increased due to the removal of calcium and magnesium carbonate minerals, some iron oxide, and organic matter—all of which

TABLE 5. *Summary of phosphate rock resources, Eastern United States*

[In millions of metric tons; (---) leaders, no data]

	Identified Resources			Hypothetical Resources[1]		
	Tons x10^6	P_2O_5 (percent)	Tons P_2O_5 x10^6	Tons x10^6	P_2O_5 (percent)	Tons P_2O_5 x10^6
Florida	5,600	30.3	1,700	5,175	29.0	1,500
Georgia	1,000	30+	300	1,000+	30	300
South Carolina	---	---	---	100+	30	30
North Carolina	1,000+	30	300	8,000+	30	2,400
Offshore Savannah R.	150	30	45	No data, must be very large		
Blake Plateau	---	---	---	Sparse data, must be very large		
Onslow Bay (offshore, North Carolina)	---	---	---	No data, must be very large		
Totals---	7,850		2,355	14,275+		4,230+
Averages---		30+			29.7+	

[1]Hypothetical resources were computed very conservatively so that the totals shown may be lower than the identified resources, which are based on company "reserves" data.

make the fresh rock uneconomic. The weathered rock, being close to or at the surface, can be easily mined and has the chemical and physical characteristics that make it a phosphate ore. This weathered phosphate makes up the reserves of the Northwestern Phosphate Field. These reserves are discussed in detail, by State, in subsequent sections.

PAST RESOURCE STUDIES

The phosphate deposits of the Northwestern Province for the most part occur on federally owned land, in contrast to those of the Southeastern Phosphate Province, which occur predominantly on privately owned land. Phosphate was discovered in 1889 in Cache County, Utah, and when it was realized that a significant and extensive deposit of bedded phosphate rock occurred on federally owned land, action was taken to withdraw the land from mineral entry. On December 9, 1908, the Secretary of the Interior established the western phosphate reserve by withdrawing from entry 4,541,300 acres of land in Idaho, Utah, and Wyoming. Somewhat later, he withdrew additional land in Montana.

DATA COLLECTION

In response to these actions, a study by the U.S. Geological Survey was initiated to map the geology of the area and assess the phosphate deposits in order to classify the appropriate areas as phosphate land for public entry subject to the provisions of the Federal leasing law. This geologic study resulted in the publication of the monograph *Geography, Geology, and Mineral Resources of part of Southeastern Idaho* (Mansfield, 1927). During and after World War II, the national need for vanadium and uranium stimulated an additional assessment of the phosphate deposits to determine their content of those trace elements. This resulted in the publication of a series of U.S. Geological Survey Circulars giving measured sections of the phosphatic beds in all of the four major States, as well as Nevada (table 6), publication of detailed geologic maps of much of the main phosphate area, and geologic analyses of the

TABLE 6.—*U.S. Geological Survey Circulars reporting phosphate stratigraphic data of the Northwestern Phosphate Province*

State	Years of data collection	Authors	Year of publication	USGS Circular number
Idaho	1947-48, Part I	McKelvey and others	1953b	208
	1947-48, Part 2	McKelvey and others	1953d	301
	1947-48, Part 3	O'Malley and others	1953	262
	1949, Part 1	Sheldon and others	1953	304
	1949, Part 2	Davidson and others	1953	305
	1950-51	Smart and others	1954	327
Montana	1947-48	Swanson and others	1953	209
	1948	Klepper and others	1953	260
	1949-50, Part 1	Cressman and others	1953	302
	1949-50, Part 2	Swanson and others	1953	303
	1951	Peterson and others	1954	326
Wyoming	1947-48	McKelvey and others	1953c	210
	1949-50	Sheldon and others	1953	307
	1951	Cheney and others	1954	324
	1952	Sheldon and others	1954	325
Utah	1947-48	Smith and others	1952	211
	1949-51	Cheney and others	1953	306
Montana, Idaho, and Utah	1953	Swanson and others	1956	375

stratigraphy of the deposits (Cheney, 1957; McKelvey and others, 1959; Sheldon, 1963; Cressman and Swanson, 1964). Subsequent additional detailed geologic mapping, which is still continuing, was initiated for the purpose of completing the classification of the phosphate lands according to the Federal leasing law and has resulted in collection of additional basic geologic data (Gere and others, 1966).

RESOURCE ASSESSMENTS

The data described in the preceding paragraph have been used for assessing the phosphate resources of the province. The U.S. Geological Survey has prepared assessments of Montana (Swanson, 1970, 1973), Wyoming (Sheldon, 1963), and Idaho (Gulbrandsen and Krier, 1980). The U.S. Bureau of Mines evaluated the western phosphate industry and its resources in Idaho, Montana, Utah, and Wyoming in a series of Reports of Investigations (Service and Popoff, 1964; Popoff and Service, 1965; Service, 1966; Coffman and Service, 1967; Service and Peterson, 1967). Assessments of surface phosphate resources in southeastern Idaho were made by Powell (1974) for the Idaho Bureau of Mines, and by the Garrand Corporation (1974), in part for the U.S. Forest Service. Under contract for the U.S. Bureau of Land Management, Dames and Moore, Inc. (1978), assessed the phosphate resources of Utah, including an analysis of the technology and economics of phosphate mining. Finally, Bauer and Dunning (1979), under contract to the U.S. Department of Energy, prepared a report on the uraniferous phosphate resources of the western phosphate field as part of the larger report on United States and world uraniferous phosphate deposits (De Voto and Stevens, 1979). This study also included an extensive analysis of the technologic and economic aspects of phosphate supply. The vast majority of the geologic data used in these assessments has been from the U.S. Geological Survey studies, although some additional data were collected by the various workers or were provided by industry.

The resource assessments noted have been based on the current technology of mining and processing phosphate rock. At present, mining in southeastern Idaho and Utah is by stripping of weathered surface deposits. Only in Montana is phosphate being mined underground. Phosphate mining and processing in both Utah and Montana are parts of integrated operations in conjunction with sulfuric acid production from copper ore processing. They are not economically based on phosphate production alone and, therefore, might be subeconomic if not for the integrated system.

The mining parameters generally accepted by industry relate to mining thickness, stripping ratios, depth or bank slope, phosphate grade, combined iron and alumina content, magnesium oxide content, carbonate content, and potential byproducts. These are discussed in the following sections.

ORE THICKNESS

The generally accepted minimum strip mining thickness for phosphate rock is 5 feet. However, in southeastern Idaho, this is not a problem as the mined units are thicker.

Stripping ratios.—Stripping ratios are measured in units of cubic yards of waste to short tons of ore and for present operations generally are less than 3.5 to 1. Garrand Corp. (1974) used this stripping ratio as the maximum for economic operations and used a ratio of 9 to 1 as a maximum for calculating the "ultimate (amount of phosphate rock) which may be mined from the area in the distant future." L. J. Garrand (oral commun., 1981) believes that these ratios still apply today, although Breza and others (1979, p. 125) stated that the trend is one of increasing strip ratio.

Depth of Mining.—A maximum depth of mining is not usually explicitly used; however, depth was defined by Powell (1974) as the downdip mining width, and he used a maximum of 250 feet for economic mining operations. Garrand Corp. (1974) used a 40° backslope for stripping resource calculations. In southeastern Idaho, where strip mining of the uniform phosphatic shale beds is carried out in steep terrain, the angle of backslope of the pit and the downdip width of the pit, combined with the stripping ratio, serve to limit the mining rather than the depth of the pit.

PHOSPHATE GRADE

The grade (P_2O_5 content) of the phosphate ore is critical to economic mining operations. The fertilizer industry originally required the phosphate rock feed to contain greater than 32 percent P_2O_5 for their phosphoric acid process so that rock greater than 32 percent is known as acid grade phosphate. With the introduction of the electric furnace process for the production of elemental phosphorus, which requires silica in the furnace mix to combine with the calcium of the phosphate mineral, apatite, phosphate ore with a silicate gangue of a grade between 24 and 32 percent P_2O_5 could be used, and this is known as furnace grade phosphate rock. Rock of lower grade, between 18 and 24 percent P_2O_5, is not suitable for either the acid or the electric furnace process without beneficiation, and is known as beneficiation grade phosphate rock. Finally, rock between 10 and 18 percent P_2O_5, generally not used in today's operations but commonly stockpiled for future use, is termed low-grade phosphate rock, and rock below 10 percent P_2O_5 is regarded as waste. These grade classes—acid, furnace, beneficiation, and low—are still used even though modern beneficiation technology, which treats all grades together to give a high-grade product, is beginning to make the classification outmoded. This trend seems likely to continue, and particularly when the presently subeconomic resources will have to be mined underground, different mining and processing technology will call for a reassessment of the grade boundaries. For this report, however, the old grade classification is used primarily because the published reports on northwestern phosphate have used this classification.

ORE QUALITY

The quality of northwestern phosphate rock ore depends on other compositional factors, including the contents of calcium and magnesium carbonate, combined ferric and aluminum oxide, magnesium oxide, and organic matter. Calcium and magnesium carbonates occur in the phosphate ore as calcite or dolomite, both of which are soluble in sulfuric acid and cause excess acid use in the process of making phosphoric acid. In the furnace process, calcite and dolomite are broken down at high temperature and combine with silica to form calcium and magnesium silicates, a reaction which wastes energy. Calcite or dolomite in phosphate ore increases the ratio between CaO and P_2O_5, and usually if this ratio exceeds 1.55, the rock or beneficiation product is not economic. The amount of magnesium in the feed for the acid process is deleterious because it causes hygroscopic products to form which cake and clog filters and pipes. Magnesium oxide in the ore or beneficiation product in excess of 1.5 percent makes the material uneconomic. Ferric and aluminum oxide in the feed for the acid process also cause the formation of hygroscopic products which hurt the processes so that if the combined Fe_2O_3 and Al_2O_3 content of the ore or beneficiation product is greater than 5 percent, the material is uneconomic. The weathered phosphate rock that is presently being mined in the Northwestern Field generally contains little enough calcite, dolomite, and iron and aluminum minerals that these contaminants are not a problem; however, fresh underground rock, which will be mined in the future, contains significantly larger amounts of calcite and dolomite. Finally, the content of organic matter in the ore makes processing difficult due to the clogging of filters and pipes if it is not removed by calcining; or if it is removed by calcining and is too abundant, it serves as an additional fuel and causes excessive heating. No general economic limits have been set on the content of organic matter (or as it is reported by the chemist, loss on ignition), and in general the ore that is presently being mined in the Northwestern Field is weathered to the point that the organic matter is too low to cause trouble; however, fresh rock has a much higher content, and this problem will have to be dealt with in the future when mining goes underground.

POTENTIAL BYPRODUCTS

The technology of processing phosphate rock and manufacturing phosphate fertilizer is changing so that byproducts can be recovered, thereby increasing the value of the ore. Uranium is now being recovered in some plants, and if all the uranium present in phosphate rock that is presently being used in the acid process were recovered, it would amount to about 15 percent of the national uranium production for 1978 (Altschuler, 1980a). Fluorine is being recovered as a byproduct of the manufacture of phosphoric acid. Other elements enriched in phosphorite and worth examining for byproduct recovery are vanadium, rare earths, silver, cadmium, chromium, molybdenum, arsenic, selenium, strontium, tellurium, and zinc (Altschuler, 1980b; Gulbrandsen, 1977). The organic content of the northwestern phosphate at the present time is considered a detriment except at those plants where it is counted on as a fuel for calcining to remove the organic matter and fluorine. It seems possible that future processing of fresh ore from underground mining will utilize the higher organic matter content for calcining the ore to facilitate the removal of calcium and magnesium carbonate by solution or slaking, or in any event the organic material will be utilized for its energy value. An unusual feldspar—buddingtonite which contains ammonium—was found to occur in large quantities in the Phosphoria Formation (Gulbrandsen, 1974). At the present time, there is no use for this mineral, but the beds constitute a large volume of rock that is being mined as waste along with the phosphate rock, and it seems possible that the rock may have some potential for making an ammonium fertilizer.

IDAHO

The phosphate resources of Idaho have been assessed systematically by four different studies, which include those of (1) Service (1966), and Coffman and Service (1967), (2) Garrand Corp. (1974), (3) Bauer and Dunning (1979), and (4) Gulbrandsen and Krier (1980). The common factor of all four of these studies, as was pointed out earlier, was that the preponderance of data on which all four were based were the earlier U.S Geological Survey stratigraphic and geologic map reports (fig. 7). However, areas of coverage (fig. 8), methodology of resource assessments, and resource parameters varied substantially between estimates so that no two can be compared directly. Each is discussed in this report.

SERVICE AND COFFMAN ESTIMATES

The major portion of phosphate lands in southeastern Idaho was assessed by Service (1966), which included all of the phosphate districts except for that portion of the Snake River district, which was included by Coffman and Service in a later volume (1967) of the series that covered Wyoming and Utah. Thus, between the two volumes, all of the phosphate resources of Idaho of any importance were covered (fig. 8). A few deposits of Permian phosphate are known in central Idaho, but stratigraphic and mapping studies have shown them to be insignificant. The active mining areas were not included in the Service and Coffman studies.

The limits to grade classes used by Service and Coffman conformed to earlier limits, and they were as follows:

Acid-grade	greater than 31 percent P_2O_5
Furnace-grade	24–31 percent P_2O_5
Beneficiation-grade	18–24 percent P_2O_5
Low-grade shale	10–18 percent P_2O_5

Service and Coffman did not use a minimum thickness for minable phosphate rock beds in southeastern Idaho, apparently because the economic zones of the phosphate beds there occur in excess of minimum mining thickness so that the problem never arises. However, in the fringe areas where economically minable zones thin greatly, a minimum thickness of 3 feet was used, in conformity with earlier studies.

The quality limits of the phosphate rock in Idaho also were not explicitly defined by Service and Coffman, probably because the rock in the minable zones generally contains smaller amounts than required of calcium or magnesium carbonate and iron and aluminum oxides.

Service and Coffman considered only the phosphate resource available by surface mining methods and the resource above and within 100 feet below entry level (fig. 9). Service did not explicitly state whether or not his surface resources are included in resources above and within 100 feet below entry level, and it can only be assumed that they are not from his discussion of them (Service, 1966, p. 10). The criteria for determining surface resources were not specified by Service other than to say that "reserves are based on economic mining depth, amount of overburden and favorable waste to ore ratio." This lack of definition makes it impossible to accurately compare his estimates of surface minable resources with other estimates of surface resources.

Finally, the estimates of Service and Coffman for Idaho do not take into account phosphate rock spoiled by tectonic structural crushing or thinning, or breaking of beds by faulting into such small blocks that they would be unsuitable for mining. Their estimates are not based on detailed correlations of phosphate beds and thus lack geologic control. No allowance was made for the effect of lowering of grade in unweathered, underground resources below that indicated from the sample data, which were almost exclusively collected from weathered surface rock. No documentation of calculations was published. For these reasons, the Service and Coffman estimates are difficult to evaluate and to compare with other estimates.

The Idaho resources of Service and Coffman have only been determined in broad categories of the resource system used in this report. The resource can be regarded as identified in Idaho, due to the well-developed lateral continuity of the phosphate beds within phosphatic members. Only

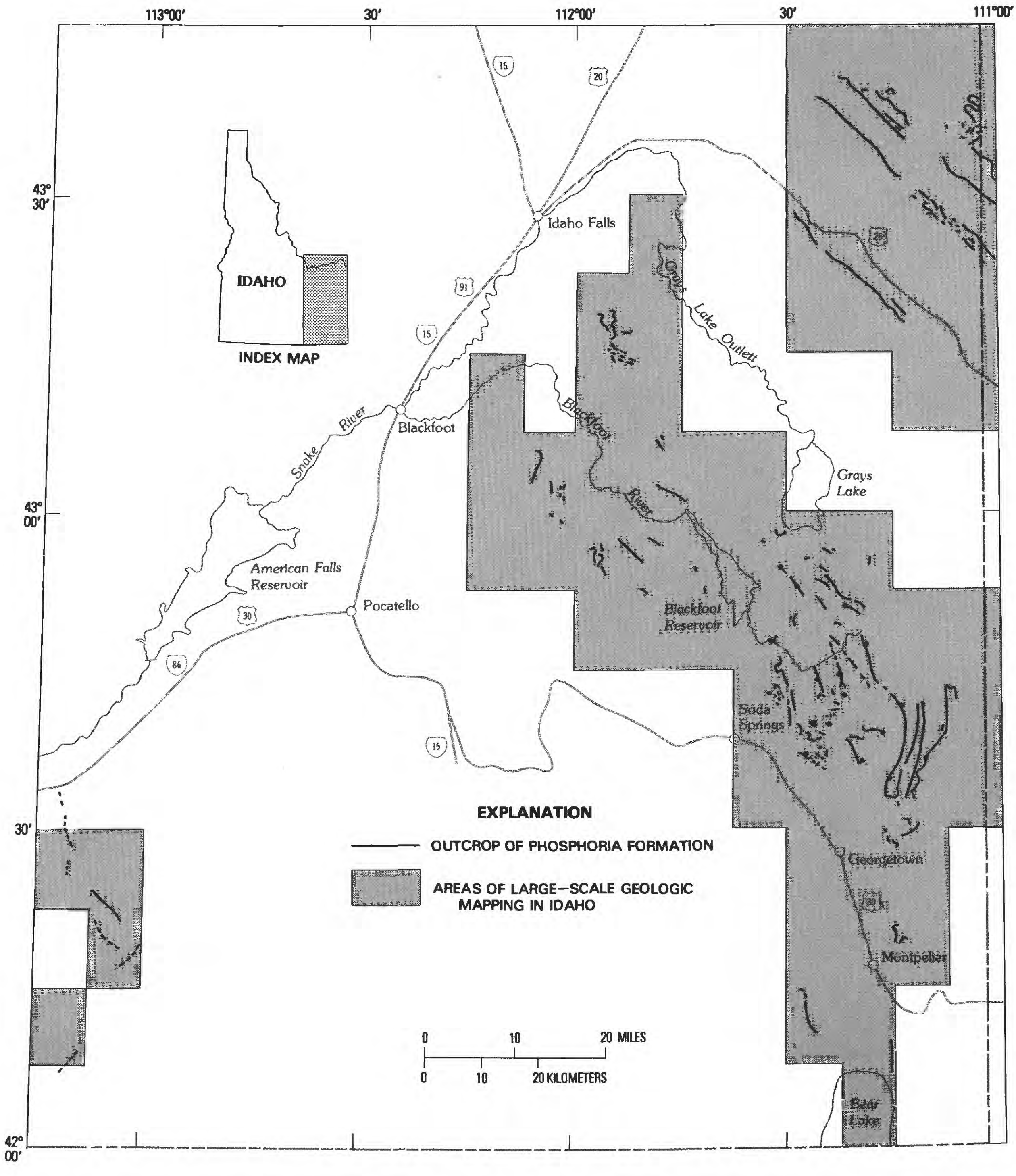

FIGURE 7.—Outcrops of the Permian Phosphoria Formation, sample localities, and areas of large scale geologic mapping in Idaho.

the surface minable resources greater than 18 percent P_2O_5 are considered to be economic. Because the Service and Coffman estimate is not of recoverable phosphate, this material must be considered an estimate of the reserve base and inferred reserve base. The average grade of all rock higher than 10 percent P_2O_5 is 22.4 percent P_2O_5, assuming that the average grades of each class are at

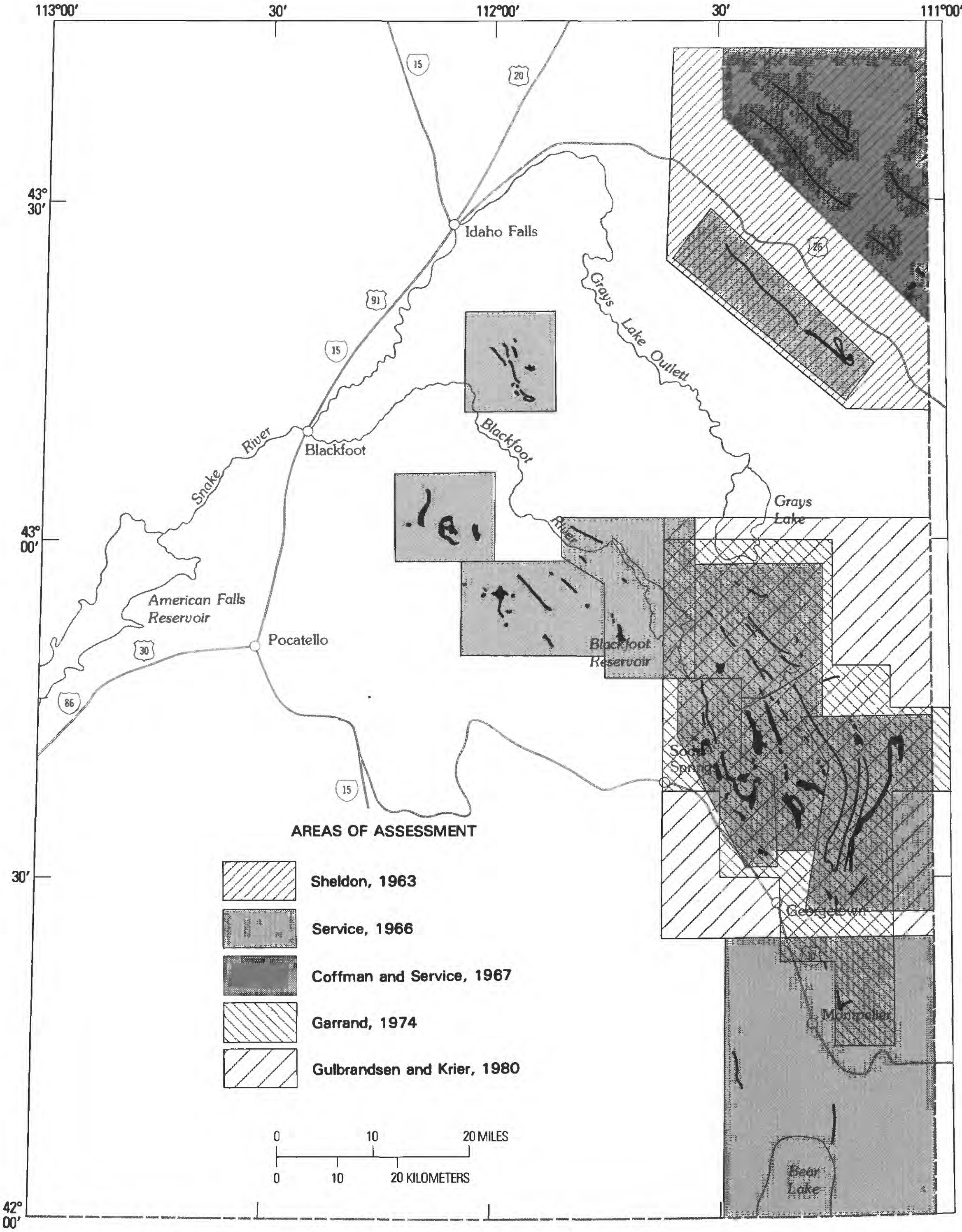

FIGURE 8.—Areas of phosphate resource assessment in Idaho.

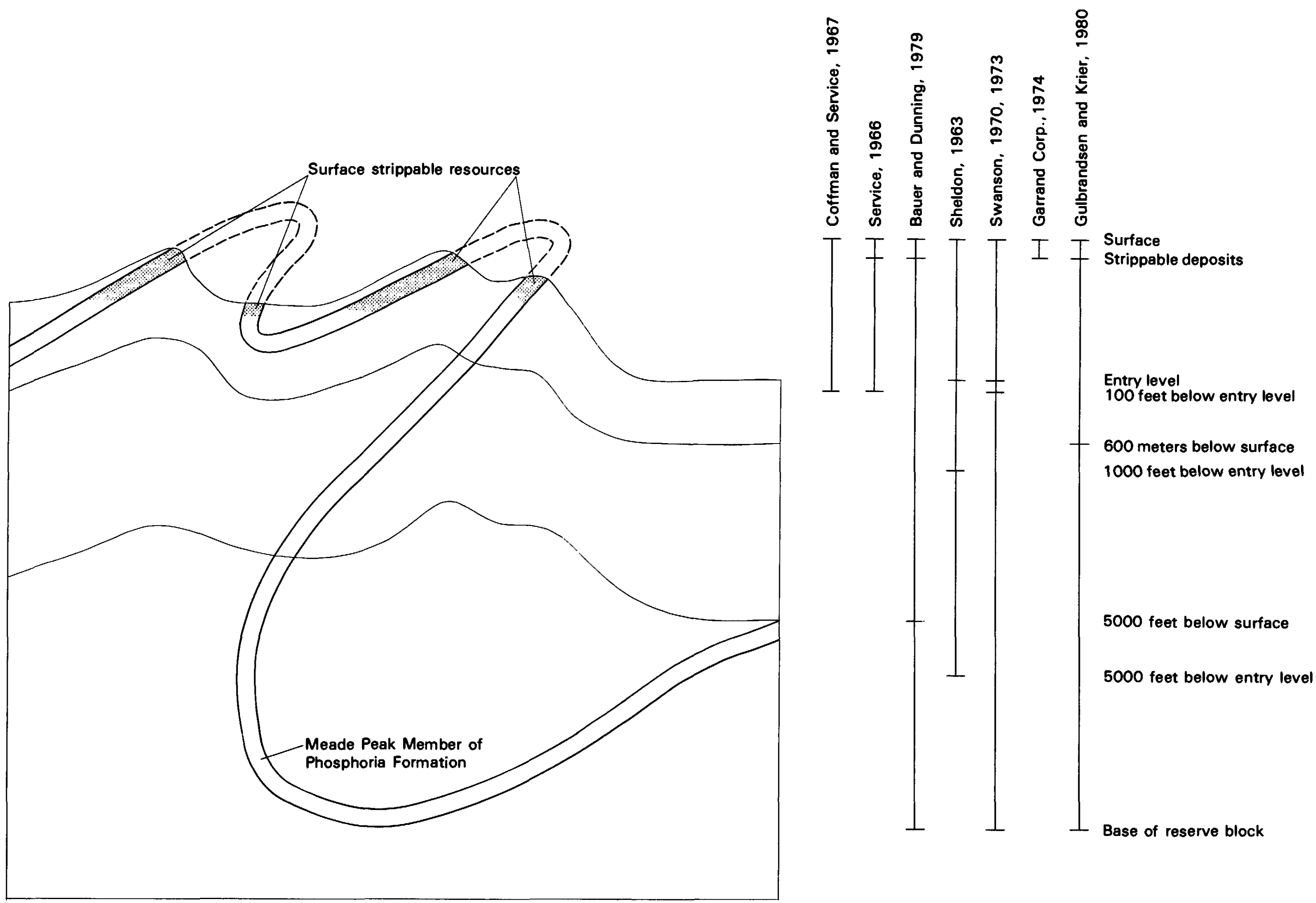

FIGURE 9.—Depth categories of Northwestern Phosphate Province.

the midpoint of the class; therefore, the phosphate between 10 and 18 percent P_2O_5 is included as subeconomic resource, because in the future, it could be blended with higher grade rock and still keep the average grade greater than 18 percent. The phosphate rock resource in the subeconomic identified resource class also includes phosphate rock higher than 24 percent P_2O_5 that occurs underground in the region from entry level to 100 feet below that level.

GARRAND ESTIMATES

L. J. Garrand (Garrand Corp., 1974) assessed only the strippable resources (fig. 9) in the Soda Springs area of southeastern Idaho. This area (fig. 8) essentially corresponds with the Peale Mountains. It should be noted that the area of Garrand's assessment does not include the Fort Hall, Chesterfield, Blackfoot River Reservoir, Mount Taylor, Swan Valley, and Snake River Range districts that were included, except for active mines, in the Service and Coffman assessments. However, the Garrand assessment does include the most important part of the southeastern Idaho phosphate region.

Garrand did not use grade cutoffs to define the surface minable resources of the Soda Springs area. He selected 10 minable phosphate zones, calculated their average phosphate content, and broke these zones into high-, medium-, and low-grade deposits and waste. He then calculated the weighted phosphate grade for each category. His data were combined into the two categories shown in table 7. His high-, medium-, and low-grade ore corresponds more or less with the acid, furnace, and beneficiation grades of earlier workers.

Garrand calculated resources using the actual thicknesses of the defined mining units. Because all units were over the commonly used minimum minable thickness of 3 feet, no minimum thickness was explicitly defined but was implicit in the assessment. Garrand assumed that all of these units could be selectively mined. The actual thicknesses used in the resource assessments were mining (or

TABLE 7.—*Comparison of estimates of phosphate rock resources in Idaho*

[Resources in millions of metric tons; P_2O_5 in weight percent]

			Service (1966), Coffman and Service (1967)		Garrand Corp. (1974)		Bauer and Dunning (1979)		Gulbrandsen and Krier (1980)		Summary	
			Tons x10⁶	P_2O_5 (percent)	Tons x10⁶	P_2O_5 (percent)	Tons x10⁶	P_2O_5 (percent)	Tons x10⁶	P_2O_5 (percent)	Tons x10⁶	P_2O_5 (percent)
Strippable resources	Reserve and inferred reserve base		777	25.7	1,038	24.5	5,235	27.0	5,000	28.0	1,038+	24.5
	Sub-economic		308	14	681	24.5					4,197-	24.5
Underground resources	Subeconomic	Above entry level	2,401	29.3					9,800	27.7	2,401	27.7
		Below entry level to 1,000 ft below					111,805	24.6			7,397+	27.7
Material not regarded as a resource	1,000-5,000 ft below entry level								12,100	27.7	102,007	27.7
	Greater than 5,000 ft below entry level						177,650	27.1			177,650	27.7
Total							294,690		26,900		294,690	

vertical) thickness rather than stratigraphic thickness.

A depth criterion was not considered by Garrand to be as important as surface mining criteria and hence was not used. The mining depth was defined as "the distance down dip along the contact between the limestone beds (which underlie the phosphatic beds) and phosphatic beds, beginning at the point in depth for which mining is expected to take place." The surface mining criteria used instead of depth criteria were as follows: The stripping ratio was defined as the cubic yards of waste to tons of ore. It was taken as 3.5 to 1 for presently economically minable phosphate rock and as 9 to 1 to indicate phosphate rock which "ultimately may be mined from the area in the distant future." The maximum backslope on the mine pit was taken as 40°. Material that lies lower than 150 feet below water table was excluded.

Garrand's estimates exclude some areas because of their complex structure or the thinness of their phosphate-bearing beds, which would suggest complex structure. The geologic structure of the phosphate deposits was derived from a series of cross sections that were made from the existing geologic maps. All of his data, analyses, and calculations are presented in his report.

Garrand's resource assessment is the most detailed and meticulous made for the main phosphate field of Idaho. It superseded an earlier assessment made by Powell (1974), which was approximately of the same area and which used much the same approach.

For the present report, the high-, medium-, and low-grade phosphate resource delineated by Garrand with a less than 3.5 to 1 stripping ratio is taken to be equal to reserve base and inferred reserve base, because no attempt was made to assess the recoverability of the deposits even though some rock was excluded for structural and water table reasons. The phosphate in the Soda Springs area can all be assumed to be at least of the inferred category, but Garrand made no attempt to subdivide it. The additional resource of the same grade material available at a stripping ratio of 9 to 1 was taken to be subeconomic identified resource.

BAUER AND DUNNING ESTIMATES

Bauer and Dunning (1979) assessed the phosphate resources of the Northwestern Phosphate Province broken down by State. The phosphate resources of Idaho were estimated comprehensively for all of southeastern Idaho. The small deposits of south-central Idaho were not covered. The grade categories used by Bauer and Dunning were identical to those used by Service (1966). Thickness minima for phosphate resources were 1 foot for surface mining, 3 feet for underground mining of high-, medium-, and low-grade phosphate rock and 6 feet for submarginal shale and waste shale. Three depth categories were used: (1) resources potentially amenable to surface mining methods and resources amenable only to underground mining, which were broken into two subcategories, (2) below surface resources and less than 5,000 feet below surface, and (3) more than 5,000 feet below surface.

The surface minable criteria were a stripping ratio (cubic yards of waste per ton of phosphate ore) of 9 to 1. They pointed out that the then current ratio was about 5 to 1 and that the ratio of the three highest grade categories together was 8.4 to 1.

The methodology of calculation of resources used by Bauer and Dunning was generally the same as that used by previous workers. The data are fully referenced or displayed in the publication, and the methodology is documented. Resource blocks were set up and defined by the area of influence of stratigraphic data, depth of the phosphate bed, geologic boundaries, State boundaries, and quadrangle boundaries. For large areas of no information, isopach and isopleth maps were made for data essential for resource calculation and projected into the areas of no information. Geologic maps, structure contour maps, structure sections, oil well tests, and stratigraphic information were used in these projections. The bias of resource estimates derived from the use of weathered, surface-sample analytical data was compensated for by using different specific gravities for calculating tonnages of unweathered rock of the various grades. This compensation corrects only for tonnage and not for grade categories, which are overestimated in the higher grades. No structurally spoiled rock was excluded.

The Bauer and Dunning estimates were categorized for this report as follows: The surface resources greater than 18 percent P_2O_5 were taken to be estimates of the combined categories of identified economic, marginally economic, and subeconomic resources, because the 9 to 1 stripping ratio was used and because no rock was excluded due to tectonic spoilage. The underground resources were included in their estimates of rock greater than 18 percent P_2O_5 (the actual grade of this category was greater than 24 percent) below-the-surface deposits and above a plane 5,000 feet below the surface, which would include rock that is subeconomic as defined in this study as well as phosphate rock that is not regarded as a resource. Thus, no clear definition of subeconomic resources of phosphate rock can be made. The Bauer and Dunning estimates of rock more than 5,000 feet below the surface are given in table 7 and are deposits not regarded as a resource in the frame of reference of the present report.

GULBRANDSEN AND KRIER ESTIMATES

Gulbrandsen and Krier (1980) assessed the phosphate resources of the Soda Springs area in southeastern Idaho in 1980. This area approximately corresponds to that assessed by Garrand (Garrand Corp., 1974). (See fig. 8.)

The primary concern of the Gulbrandsen and Krier assessment was the grade of underground rock, which has never been adequately sampled to make direct estimates, but which must be estimated from the sampling done on surface rocks. They analyzed the grade distribution of surface phosphate rocks from about 18 sections, and on the basis of two measured underground sections at mines, they made estimates of the grade of the unsampled underground rock. They discovered that the grade distribution of both surface and underground phosphatic rocks was bimodal with a distinct natural break at 20 percent P_2O_5. They calculated the resources of the rock with greater than 20 percent P_2O_5. Because the zones of this rock occur in natural units of large enough thickness that their minability was no problem, no thickness criteria were used.

The depth classes of the resource used were (1) surface resources, (2) underground resources down to 600 m below the surface, and (3) underground resources 600 m or more below the surface (fig. 9). The surface resources were defined as those underlying outcrops of the Phosphoria Formation.

The Gulbrandsen and Krier estimates were categorized for this study in the following way: The surface resources would include rock with stripping ratios as large as 9 to 1 and would fall in the grade class with the P_2O_5 value greater than 24 percent and therefore are classed as identified resources of all categories. The underground resources are greater than 24 percent P_2O_5 and also are within 600 m of the surface, which is approximately equivalent to 1,000 feet below entry level. The Gulbrandsen and Krier estimates are difficult to compare precisely with the other estimates for reasons of difference of class parameters.

SUMMARY OF ESTIMATES

It is possible to derive a composite estimate of all the resource classes of phosphate rock in Idaho from the existing estimates. The classes are shown in the summary column in table 7.

No one has attempted to differentiate demonstrated resources from inferred resources, so all resources must be reported simply as identified. In the fringe areas of the main phosphate district of Idaho, data become sparse enough and stratigraphic correlations become uncertain enough that some of the resources probably should be classed as hypothetical resources of the unidentified class. However, these resources are certainly minor in comparison with those of the main districts of southeastern Idaho and can be included in identified resources for the present study.

Strippable resources of the economic and marginally economic classes make up the reserve base and the inferred reserve base and have been best estimated by Garrand (Garrand Corp., 1974). However, he did not estimate the strippable reserve base of Idaho other than in the Soda Springs area so that his estimates are minimal. The strippable identified resource for all of Idaho was estimated by Bauer and Dunning (1979), and by subtracting the reserve base and inferred base estimates of Garrand, a maximum estimate of the subeconomic identified strippable resources is obtained. The grade of the strippable resource is about 24.5 percent P_2O_5 based on Garrand's work, which used minable units.

The underground resources, which are all subeconomic identified resources, can be broken into those above entry level and those below entry to 1,000 feet below entry level. The estimates of Service (1966) of the phosphate rock containing more than 24 percent P_2O_5 give the former. When that is subtracted from the Gulbrandsen and Krier estimate of the resource from the surface to 600 m below the surface, a crude minimal estimate of the resource from entry level to 1,000 feet below entry level is obtained. This is quite crude because the

Gulbrandsen and Krier estimate is only for the Soda Springs area; whereas, the Service estimates are for all of Idaho. Also, the Gulbrandsen and Krier plane that is 600 m below the surface is only a very crude approximation of the plane 1,000 feet below entry level.

Thus, Idaho phosphate reserve base and inferred reserve base consist of at least 1,038 million tons of phosphate rock that averages about 24.5 percent P_2O_5. Of this resource, only a fraction will be recoverable due to spoilage of the rock by folding and faulting. The subeconomic identified resources of Idaho consist partly of strippable rock and partly of underground rock. The strippable rock amounts to less than 4,197 million tons and averages about 24.5 percent P_2O_5. It also would be only partially recoverable. The underground portion of subeconomic resources amounts to about 9,798 million tons of rock averaging about 27.7 percent P_2O_5. Of this, 25 percent is above entry level, where it could be mined with gravity stoping, and 75 percent is below entry level, where it would have to be raised a maximum of 1,000 feet. Much phosphate rock exists below this, but in the foreseeable future, it seems unlikely that the energy costs of raising the rock more than 1,000 feet would allow its economic recovery.

These composite estimates leave much to be desired, as they are not entirely compatible. However, without a major new effort to assess the resource, they are the best available, and they do give a general idea of the magnitude of phosphate resources of Idaho.

MONTANA

Two estimates have been made of phosphate resources in Montana based on the complete data set. They are Swanson (1970, 1973) and Bauer and Dunning (1979) (table 8). Popoff and Service (1965) made estimates based on Swanson's unpublished information for southwestern Montana, and their central-western Montana data were obtained from the very early literature on the subject, which was completely superseded by Swanson's work.

SWANSON ESTIMATES

The two works of Swanson (1970, 1973) present the basic stratigraphic and chemical analytical data on the phosphate resources of southwestern and central-western Montana (fig. 10), studies that include all of the known phosphate areas in Montana. Phosphate resources were reported in the following classes: plus 31 percent P_2O_5, plus 24 percent, and plus 18 percent. In addition, the actual phosphate percentage was given for each class. The resources included only phosphate beds greater than 3 feet in thickness and were calculated above entry level, the first 100 feet below entry level, and the total block (fig. 9). The methodology of resource assessment was carefully and explicitly defined (Swanson, 1970). The resource blocks were conservatively defined and objectively presented in maps showing structure, contours, and faults.

Swanson's resource estimates are interpreted in this study as follows: The phosphate deposits containing more than 24 percent P_2O_5 and occurring above entry level are classed simply as resources, as they fall primarily in the identified class but also in the hypothetical class, and they include economic and marginally economic surface deposits, as well as subeconomic surface and underground deposits. The rock that contains more than 24 percent P_2O_5 and lies beneath entry level is a subeconomic resource down to 1,000 feet below entry level, and material that is more than 1,000 feet below entry level is not considered as a resource. Thus, the boundaries selected by Swanson for reporting phosphate resources do not conform to the boundaries adopted for this report, and his estimates cannot be broken down further than the general category of resources, with one large portion of phosphate rock containing both subeconomic resources and material not considered as a resource.

BAUER AND DUNNING ESTIMATES

The Bauer and Dunning estimates (1979) for Montana cover the same area as the Swanson estimates but divide the deposits into surface deposits, underground deposits, and deep underground deposits, as discussed under the section on the Idaho resources. Their estimate is interpreted in this study as follows: The strippable surface deposits are simply resources as they are based on a stripping ratio of 9 to 1. Also, they include deposits that would probably be classed as hypothetical as well as inferred. The deposits occurring below the surface deposits down to a depth of 5,000 feet below the surface include both subeconomic underground resources and underground deposits not considered a resource. No further breakdown can be made.

TABLE 8.—*Comparison of phosphate rock resources in Montana*

[In millions of metric tons]

<table>
<tr><th colspan="3" rowspan="2"></th><th colspan="2">Swanson (1970, 1973)</th><th colspan="2">Bauer and Dunning (1979)</th><th colspan="2">Best estimates (those used in this report)</th></tr>
<tr><th>Tons x10^6</th><th>P_2O_5 (percent)</th><th>Tons x10^6</th><th>P_2O_5 (percent)</th><th>Tons x10^6</th><th>P_2O_5 (percent)</th></tr>
<tr><td rowspan="2">Strippable resources</td><td colspan="2">Reserve and inferred reserve base</td><td rowspan="3">437</td><td rowspan="3">27.1</td><td rowspan="2">608</td><td rowspan="2">24.3</td><td rowspan="2">608</td><td rowspan="2">24.3</td></tr>
<tr><td colspan="2">Sub-economic</td></tr>
<tr><td rowspan="2">Underground resources</td><td rowspan="2">Subeconomic</td><td>Above entry level</td><td rowspan="3">9,755</td><td rowspan="3">27.8</td><td rowspan="3">9,755</td><td rowspan="3">27.8</td></tr>
<tr><td>Below entry level to 1,000 ft</td><td rowspan="3">7,168</td><td rowspan="3">26.9</td></tr>
<tr><td rowspan="2">Material not regarded as a resource</td><td colspan="2">1,000–5,000 ft below entry level</td></tr>
<tr><td colspan="2">Greater than 5,000 ft below entry level</td><td>6,714</td><td>29.0</td><td>6,714</td><td>29.0</td></tr>
</table>

SUMMARY OF ESTIMATES

The phosphate resources of Montana reported in the Swanson and the Bauer and Dunning reports cannot be very well classified according to the criteria used in this report. The Bauer and Dunning estimate of surface resources of 608 million tons of phosphate rock containing 24.3 percent P_2O_5 is the best estimate of combined economic, marginally economic, and subeconomic strippable resources. Their underground phosphate rock estimate of 9,755 million tons of phosphate rock containing 27.8 percent P_2O_5 includes both subeconomic resources and material that is not considered as a resource. Their deep underground deposits also cannot be considered a resource. The two estimates cannot be used to make a composite resource estimate as was done for the Idaho resources; however, the Bauer and Dunning estimate is the best for this report. It should be noted that the Bauer and Dunning estimates of total phosphate rock in the combined resource blocks of Montana are larger than the Swanson estimates for Montana. However, the difference is caused by more liberal boundaries of the resource blocks in the Bauer and Dunning study. Thus, the Bauer and Dunning estimate of 16,469 million tons of underground phosphate rock (combined underground and deep underground) include a large amount of hypothetical rock; whereas, the Swanson estimates are primarily made up of inferred rock. A

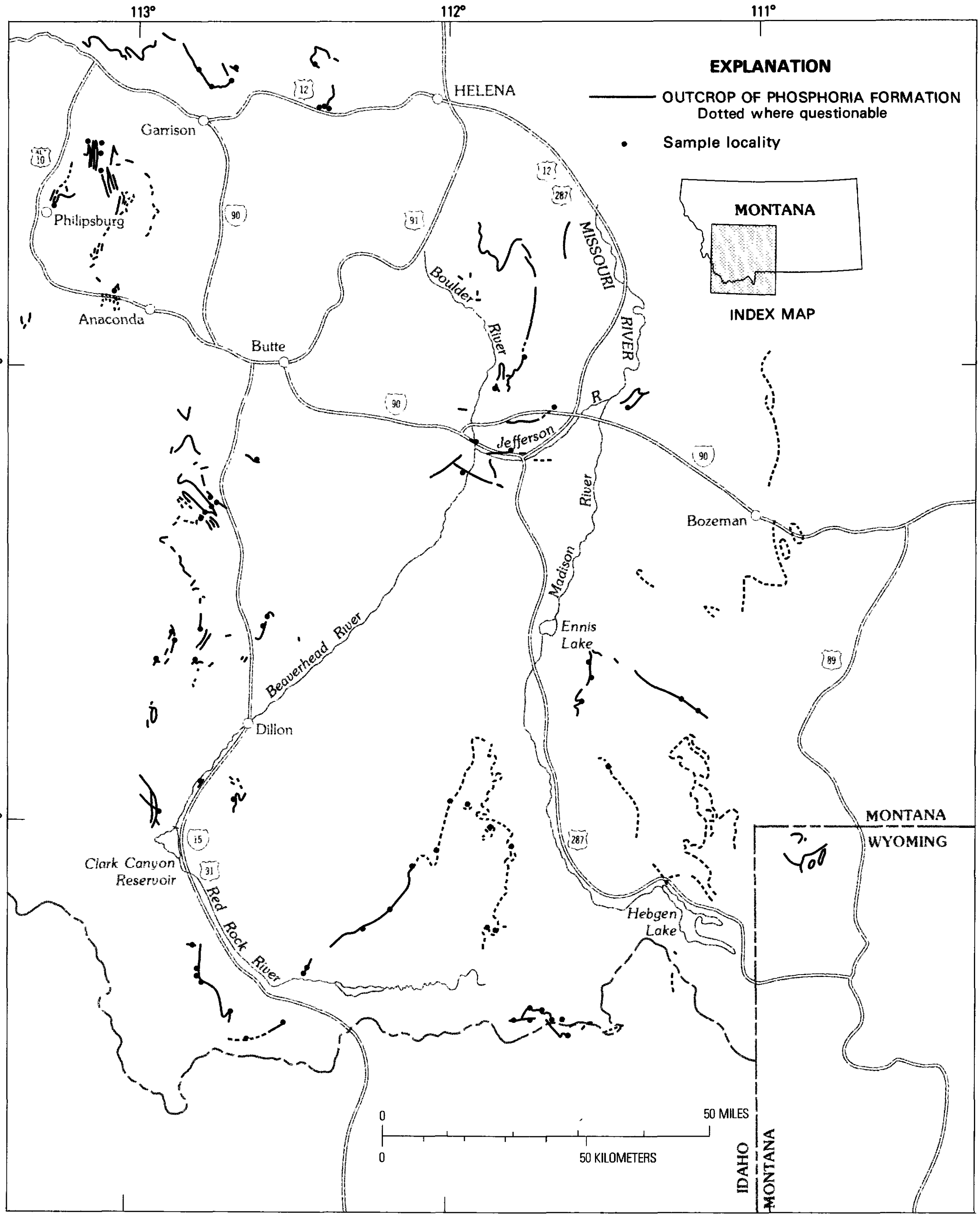

FIGURE 10.—Phosphate rock outcrops and sample localities in Montana.

difference between the two estimates that is hard to account for is that the Bauer and Dunning estimate of surface resources is larger than the Swanson estimate of rock above entry level. This problem could only be resolved by an extremely detailed comparison of the two estimates, which is beyond the scope of this study. The difference, at any rate, does not involve a major amount of phosphate resources.

WYOMING

Three resource assessments have been made of Wyoming (table 9, fig. 11). Sheldon (1963) assessed the phosphate resources in northwestern Wyoming, exclusive of the westernmost ranges. Coffman and Service (1967) assessed the area of Wyoming not covered by Sheldon. Finally, Bauer and Dunning (1979) reassessed the complete State.

SHELDON ESTIMATES

Sheldon (1963) presented the basic stratigraphic and chemical analytic data on the resources of northwestern Wyoming exclusive of the Salt River, Sublette, and Tump Ranges of Wyoming. His methodology and class boundaries were standard, and he presented the estimates of acid, furnace, and beneficiation grades of phosphate rock. By depth, the classes were broken down into

TABLE 9.—*Comparison of phosphate rock resources in Wyoming*

[In millions of metric tons]

<table>
<tr><th colspan="3" rowspan="2"></th><th colspan="2">Sheldon (1963), Coffman and Service (1967)</th><th colspan="2">Bauer and Dunning (1979)</th><th colspan="2">Best estimates (those used in this report)</th></tr>
<tr><th>Tons x10^6</th><th>P_2O_5 (percent)</th><th>Tons x10^6</th><th>P_2O_5 (percent)</th><th>Tons x10^6</th><th>P_2O_5 (percent)</th></tr>
<tr><td rowspan="2">Strippable resources</td><td colspan="2">Reserve and inferred reserve base</td><td rowspan="3">1,470</td><td rowspan="3">28.2</td><td rowspan="2">924</td><td rowspan="2">23.4</td><td rowspan="2">924</td><td rowspan="2">23.4</td></tr>
<tr><td colspan="2">Subeconomic</td></tr>
<tr><td rowspan="2">Underground resources</td><td rowspan="2">Subeconomic</td><td>Above entry level</td><td rowspan="3">20,163</td><td rowspan="3">27.5</td><td>1,165</td><td>28.2</td></tr>
<tr><td>Below entry level to 1,000 ft</td><td>767+</td><td>28.2</td><td>767+</td><td>28.2</td></tr>
<tr><td rowspan="2">Material not regarded as a resource</td><td colspan="2">1,000–5,000 ft below level</td><td>2,048</td><td>28.2</td><td>2,048
inf.
16,182</td><td>28.2

27.5</td></tr>
<tr><td colspan="2">Greater than 5,000 ft below entry level</td><td></td><td></td><td>129,760</td><td>27.3</td><td>129,760</td><td>27.3</td></tr>
</table>

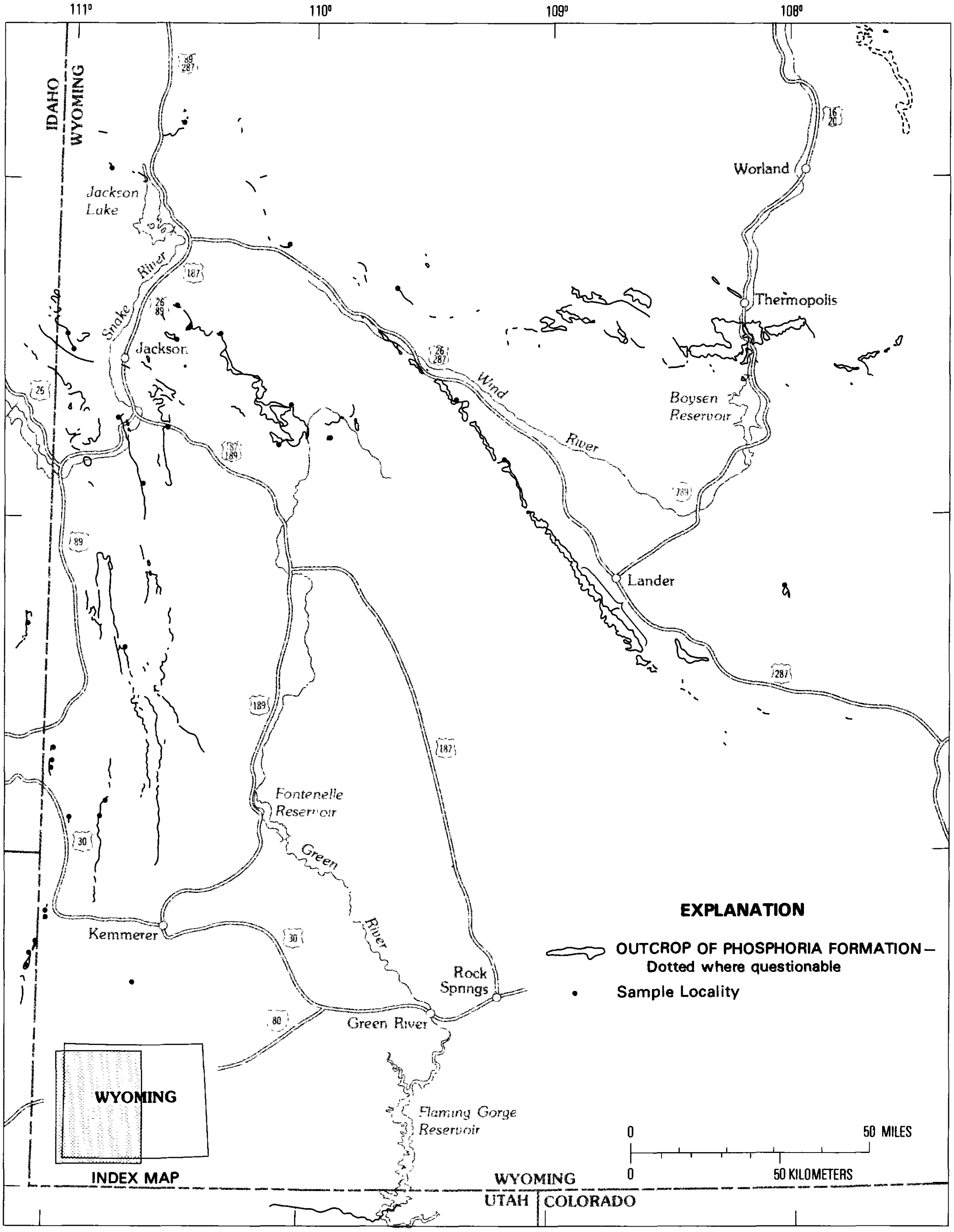

FIGURE 11.—Phosphate rock outcrops and sample localities in Wyoming. Compiled and modified from Sheldon (1963).

above entry level, entry level down to 1,000 feet below entry level, and from 1,000 to 5,000 feet below entry level (fig. 9). Thus, the rock below 5,000 feet below entry level was not estimated. His grade classes greater than 24 percent P_2O_5 and higher than 1,000 feet below entry level constitute subeconomic phosphate resources. However, the portion above entry level would include surface-reserve-base and inferred-reserve-base resources.

COFFMAN AND SERVICE ESTIMATES

The Coffman and Service (1967) assessment covered that part of Wyoming not covered by Sheldon. The comments on the Coffman and Service assessment made in the section on Montana phosphate resources apply to this section on Wyoming resources.

BAUER AND DUNNING ESTIMATES

The Bauer and Dunning assessment (1979) covered all of Wyoming and has been commented on earlier.

SUMMARY OF ESTIMATES

A composite of the estimates can be made from the three assessments (table 9). The Bauer and Dunning (1979) estimates of surface resources of 924 million tons of phosphate rock containing 23.4 percent P_2O_5 are interpreted as identified and some hypothetical resources of all economic classes. The difference between the Bauer and Dunning (1979) estimates of surface resources greater than 24 percent P_2O_5 (not shown in table 9) and the Sheldon (1963) and Coffman and Service (1967) estimates of resources above entry level give the underground resources above entry level. The Sheldon (1963) estimate of phosphate resources from entry level down to 1,000 feet below entry level is minimal because the westernmost ranges are excluded, and the Coffman and Service (1967) estimates did not cover this depth class. The Bauer and Dunning (1979) estimate of underground rock down to 5,000 feet below the surface, after subtracting the resources above entry level and below entry level down to 1,000 feet below entry level, approximately gives the total rock between 1,000 and 5,000 feet below the surface. The approximation is due to the difference between the planes 1,000 feet below the surface and 1,000 feet below entry level. By subtracting the Sheldon (1963) estimate of rock between 1,000 and 5,000 feet below entry level, which is for the most part inferred, from this, a rough estimate of the hypothetical rock is obtained. The rock deeper than 5,000 feet below the surface is given by Bauer and Dunning (1979).

UTAH

Three resource assessments have been published for Utah (table 10; fig. 12) and are those by Coffman and Service (1967), geologists of Dames and Moore, Inc. (1978), and Bauer and Dunning (1979).

COFFMAN AND SERVICE ESTIMATES

Coffman and Service (1967) assessed the phosphate resources of all of northern Utah east of Salt Lake Valley. Thus, the small deposits of western Utah were not included. The comments on the Coffman and Service (1967) assessment made on Montana phosphate resources apply to this section on Utah resources.

DAMES AND MOORE, INC., ESTIMATES

The estimates of phosphate resources made by Dames and Moore (1978) geologists covered the same region as the Coffman and Service (1967) estimates, and in fact they used the Coffman and Service (1967) estimates. They updated the Coffman and Service (1967) estimates and extensively analyzed the economic and technologic factors for phosphate production, concluding that underground mining would not be economic in the foreseeable future.

BAUER AND DUNNING ESTIMATES

The Bauer and Dunning assessment (1979) covered the same area of Utah as the two previous assessments. The parameters and methodology of the study have been discussed on page 29.

UNPUBLISHED VERNAL AREA ESTIMATES

The phosphate deposits near Vernal, Utah, on the southeast flank of the Uinta Range have been included in the estimates by Dames and Moore, Inc., and by Bauer and Dunning discussed in the last section; however, recent operations have shown them to be much larger than reported. Stauffer Chemical Company and Chevron Resources have indicated that the strippable reserves of phosphate rock are of the order of 500–700 million tons of rock (W. F. Stowasser, personal commun., 1981). The ore bed is about 20 feet thick and averages about 20 percent P_2O_5. Bauer and Dunning estimated 275 million tons for the Vernal area, and the difference presumably is due to use of a different stripping ratio by indus-

TABLE 10.—*Comparison of phosphate rock resources in Utah*

[In millions of metric tons]

		Coffman and Service (1967)		Dames and Moore, Inc. (1978)		Bauer and Dunning (1979)		Best estimates (those used in this report)	
		Tons $x10^6$	P_2O_5 (percent)	Tons $x10^6$	P_2O_5 (percent)	Tons $x10^6$	P_2O_5 (percent)	Tons $x10^6$	P_2O_5 (percent)
Strippable resources	Reserve and inferred reserve base							[1]600	
Strippable resources	Subeconomic	268	28.1	32	28	529	24.9	[1]254	24.9
Underground resources, Subeconomic	Above entry level			236	28			38	28.1
Underground resources, Subeconomic	Below entry level to 1,000 ft					5,716	27.5	5,679	27.5
Material not regarded as a resource	1,000-5000 ft below entry level								
Material not regarded as a resource	Greater than 5,000 ft below entry level					63,675	30.1	63,675	30

[1] Corrected for industry reserve estimate of 600 million tons reserve in Vernal area.

try than by Bauer and Dunning. If the Utah estimates of Bauer and Dunning are increased to account for the average of this larger estimate of strippable deposits (600 million tons) of the Vernal area, they become 854 million tons, and this revised figure is used for the Bauer and Dunning estimates.

SUMMARY OF ESTIMATES

The three sets of resource estimates are all based on essentially the same set of data, that is, that of the U.S. Geological Survey. Each assessment used different resource boundaries, but when assembled together, they can be put into a single, consistent set of resource estimates (table 10). Strippable resources of both the reserve and inferred reserve bases and the subeconomic categories were estimated by Bauer and Dunning (1979) as 529 million tons of rock greater than 18 percent P_2O_5. This compares to 32 million tons of subeconomic strippable resources estimated by Dames and Moore, Inc. (1978), who must have used a smaller stripping ratio. However, the revised figure of 854 million tons is used in this report. If the Coffman and Service (1967) estimate of 268 million tons of resources greater than 24 percent P_2O_5 above 100 feet below entry level is

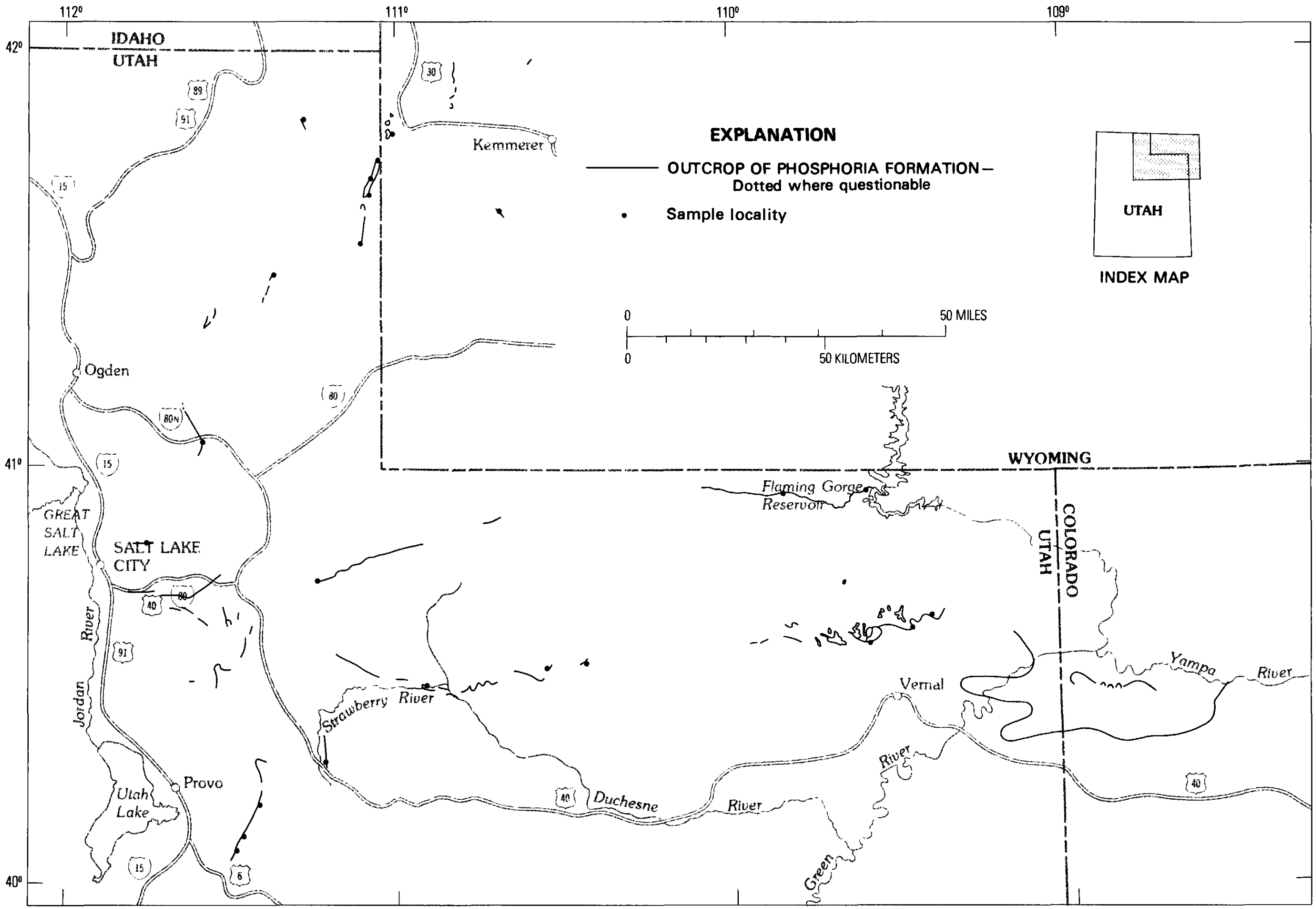

FIGURE 12.—Phosphate rock outcrops and sample localities in Utah. Recompiled and modified from Clabaugh (1946).

correct, and if Bauer and Dunning's 1979 estimate of 230 million tons of strippable rock greater than 24 percent P_2O_5 is subtracted from it, the subeconomic undergound resources above 100 feet below entry level would be 38 million tons. Subeconomic resources below this down to 1,000 feet below entry level are not possible to derive, but down to 5,000 feet below entry level are 5,679 million tons, using the Bauer and Dunning 1979 estimate and deducting the material above 100 feet below entry level. Tonnage of phosphate rock deeper than 5,000 feet below the surface is given by Bauer and Dunning (1979).

NORTHWESTERN UNITED STATES

The phosphate resource classes of the States of Idaho, Montana, Wyoming, and Utah cannot be added owing to different class boundaries. However, by apportioning, where necessary, the resource categories according to the ratios obtained in Idaho, an approximation of all of the resource categories can be obtained. These approximations, rounded to two figures, are shown in table 11, along with the average grade of the phosphate rock. This shows that more than 1,600 million tons of strippable economic reserve and inferred reserve base existed before mining began. It is difficult to say how much of the reserve base and inferred reserve base will actually be minable, but tectonic structural spoilage will probably be significant. If only half is minable, then 800 million tons would constitute the reserve. Approximately 140 million tons of phosphate rock have been mined since the inception of mining to 1980, and 8,117,000 tons was mined in 1979. Thus, about 660 million tons of reserve might be available for the

TABLE 11.—*Phosphate rock resources of the Northwestern Phosphate Field*

[In million of metric tons]

			Tons $x10^6$	P_2O_5 (percent)
Strippable resources	Reserve and inferred reserve base		1,600+	24
	Subeconomic		6,000-	24
Underground resources	Subeconomic	Above entry level	4,000	28
		Below entry level to 1,000 ft	13,000	28
Material not regarded as a resource	1,000-5,000 ft below entry level		130,000	28
	Greater than 5,000 ft below entry level		377,000	28

TABLE 12.—*Other phosphate rock resources, United States*

Rock unit and location. Description.	Estimated resources (metric tons)
Precambrian	
Marquette Range Supergroup, Michigan. Dense, black phosphate pebbles in quartzite Base of Proterozoic.	$20x10^6$ (25 percent P_2O_5).
Spokane Formation, Belt Supergroup, Montana. Phosphate pellets in very thin beds.	Very small.
Ocoee Supergroup, Tennessee. Phosphate pellets in black shale and sandstone. Beds up to 1.3 m thick, up to 35 percent P_2O_5.	No concrete data, individual deposits small--about $1x10^5$ tons (about 25 percent P_2O_5).
Cambrian	
Dunderberg Shale, Nevada. Thin beds (max. = 50 cm., about 20 percent P_2O_5), wide distribution.	No data. Total resource may be large but reserves nil.
Milton Dolomite, Vermont. Intraformational breccia zone about 1.5 m thick may contain 5 percent P_2O_5	$10x10^6$ (20-25 percent P_2O_5).
Ordovician	
Several formations, Nevada. Shale, limestone, dolomite, with phosphate pellets and nodules. 10 percent P_2O_5, maximum, thin beds.	No data, probably very small in individual deposits.
Maquoketa Shale, Iowa, Wisconsin, Illinois. Sandy phosphorite and phosphatic dolomite. Beds up to 1.5 m, and up to 15 percent P_2O_5.	$8x10^6$ (15 percent (P_2O_5 amenable to open pit mining near Dubuque. Total resources much larger.
Cason shale, Arkansas. Phosphatic shale, beds about 1 m, and up to 20 percent P_2O_5.	$20x10^6$.
Decorah Formation and Galena Dolomite, Minnesota. Very thin beds (lag gravels at unconformity).	Very small.
Nashville Group, Tennessee. Hermitage, Bigby, Cannon, and Catheys Limestones of Nashville Group and Leipers Limestone. Phosphatic limestone, average about 5 percent P_2O_5. Extends south into Limestone County, Alabama.	3 to $5x10^9$ tons of phosphate in these limestones (20 percent P_2O_5).
Lexington Limestone, Kentucky. Phosphatic limestone, same as in Tennessee but not as extensive	No tonnage data; may be about 1/5th of Tennessee.
Maravillas Chert, Texas. Phosphatic nodules in shale: nodules, 23 percent P_2O_5 - shale 1 percent P_2O_5.	No data--small?

TABLE 12.—*Other phosphate rock resources, United States*—Continued

Rock unit and location. Description.	Estimated resources (metric tons)
Silurian	
Red Mountain Formation, Alabama. Oolitic iron-ore deposits contain phosphate. When iron ores are treated by Bessemer process a "basic slag" containing about 8 percent P_2O_5 is formed. Phosphate is available to plants, good fertilizer.	No data.
Unnamed formation, Nevada. Dolomite, very thin beds (about 6 cm) contain up to 5 percent P_2O_5.	No data, very small.
Devonian and Mississippian	
Devonian Chattanooga and New Albany Shales and Mississippian Maury Formation. Alabama, Georgia, Tennessee, Kentucky, Ohio, Indiana, Arkansas, Oklahoma. Sparse phosphate nodules in black shale. Nodules contain up to 30 percent P_2O_5; black shale 2-3 percent P_2O_5.	Tonnages have never been totaled, but because of very large outcrop area, the resource is very large.
Devonian Hardin Sandstone Member of Chattanooga Shale, Tennessee. part of Chattanooga. So called "blue rock." Thin beds 1 m, up to 25 percent P_2O_5.	$80x10^6$ (20 percent P_2O_5) may be Basal greater.
Devonian Sylamore Sandstone Member of Chattanooga Shale, Shale Arkansas, Oklahoma. Basal Devonian, contains minor phosphate pellets or nodules. No data on grade, beds thin.	No data, very small.
Devonian Oriskany Sandstone. New York, Pennsylvania, Virginia. Basal bed of Oriskany in these states contains thin phosphorite bed, up to 25 percent P_2O_5.	No data, small.
Mississippian and younger Paleozoic	
Mississippian Brazer Limestone, Utah. Basal member, phosphorite up to 2 m thick, as much as 33 percent P_2O_5.	$800x10^6$ (20 percent P_2O_5).
Mississippian to Permian Lisburne Group, Alaska. Black shale, calcareous phosphorite, 4 m thick 16 percent P_2O_5.	$300x10^6$ (16 percent P_2O_5).
Mississippian Fayetteville Shale, Arkansas Low P_2O_5 content, but individual, thin beds contain as much as 35 percent P_2O_5.	No data. Could be large 2-5 percent P_2O_5.

future. At a linear rate of increase of production of 245,000 tons of rock a year, the rough average rate of increase from 1964 to 1980, these 660 million tons would be exhausted in about the year 2018. At that point, an additional subeconomic resource of 6,000 million tons of strippable resources and 4,000 million tons of underground resources above entry level would be available for mining if technology had been developed to economically mine it.

OTHER PHOSPHATE PROVINCES

Phosphate occurrences are known in the central interior of the United States from Texas in the south to Iowa and Wisconsin in the north, and in rocks that range in age from Ordovician through

TABLE 12.—*Other phosphate rock resources, United States*—Continued

Rock unit and location. Description.	Estimated resources (metric tons)
Mississippian and Pennsylvanian	
Several Pennsylvanian formations, eastern Kansas, and Oklahoma, and western Missouri. Coarse phosphate nodules in interbedded black shale and limestone. Nodules up to 30 percent P_2O_5 shale 2-3 percent P_2O_5.	No data large in total.
Pennsylvanian Macoupin Limestone, St. David Limestone Member, Cohn Coal Member, and Brereton Limestone Member, Illinois. Sparse phosphate pellets and nodules in interbedded shale and limestone.	No data.
Mississippian Pitkin and Pennsylvanian Hale Formations, Arkansas. Lenticular calcareous phosphorite at base of Hale Formation. Range from 0-7 m thick, up to 25 percent P_2O_5.	$5x10^6$ (20 percent P_2O_5) (measured), total greater.
Morrowan rocks, Texas. Sandy phosphorite at base, may be lag gravel.	$40x10^3$. Very small (20 percent P_2O_5).
Triassic	
Shublik Formation, Alaska. Black shaly phosphorite near base is 3-7 m thick and up to 35 percent P_2O_5 average = 12 percent.	$5,000x10^6$ (12 percent P_2O_5).
Cretaceous	
Several formations, Alabama, Georgia, Mississippi. Phosphate pellets in chalk, marl, and limestone. Phosphate pellets up to 30 percent P_2O_5, total rock 2-3 percent P_2O_5.	No data. Tons per acre very low, but total, because of because of large areal extent, large.
Several formations, Texas, Colorado, North Dakota, South Dakota, California, same as above.	Do.
Eocene	
Castle Hayne Formation, North Carolina. Phosphate and glauconite in fossiliferous limestone. Total P_2O_5, about 2 percent, nodules may be up to 20 percent.	No data, small.
Tallahatta Formation, Georgia. Phosphate pellets in sand. No analytical data. Phosphate pellets may be reworked from erosion of Cretaceous phosphate occurrences.	Do.
Midway and Claiborne Groups; Weches Greensand, Texas. Phosphate pellets in sand, limestone, glauconitic sand (greensand). Pellets up to 30 percent, individual, thin beds (50 cm) contain up to 10 percent P_2O_5.	No data. Tons per acre low, total tons probably large.
Eocene and Oligocene	
Cooper Marl, South Carolina. Sparse phosphate pellets in marl. P_2O_5 content of pellets up to 25 percent, but total rock contains only 1-2 percent P_2O_5.	No data, large (?).

TABLE 12.—*Other phosphate rock resources, United States*—Continued

Rock unit and location. Description.	Estimated resources (metric tons)
Miocene	
Monterey Formation, California. Thick sequence of shale, siliceous shale, and phosphorite, but low (5-10 percent) in P_2O_5 content. Mining may not be possible because of environmental restrictions.	Very large, hundreds of millions.
Pleistocene and Holocene Reworked and secondary deposits	
"River Pebble" (Florida and Georgia). Coarse phosphate gravels, as bars and in flood plains along streams that are draining phosphate terranes. Low phosphate contact because of leaching by acid waters.	$50x10^6$ (25 percent P_2O_5).
"Hardrock" (Florida and south Georgia) "Whiterock" (Tennessee). Phosphate, in solution, derived from acid leaching of phosphorite, is precipitated on, or replaces underlying limestone. Very high P_2O_5 content, very irregular deposits. Reworking after formation results in channel-like deposits (only in Florida).	Small in individual deposits, total may be large.
Brown-rock deposits, Alabama, Kentucky. High-grade phosphate residum left after acid weathering of phosphatic limestone. Deposits are erratic in distribution and individual deposits tend to be small.	Small (15 percent P_2O_5).
"Landrock" and "River rock" Charleston area, South Carolina. Reworked from Miocene (Hawthorn?) phosphorite in Pleistocene and Holocene. Small, erratic, low-grade deposits.	Small.
Offshore deposits	
Sea floor nodules, Pacific Coast. Coarse-phosphate nodules on sea floor have been forming since Miocene. Resources may be large but tonnage per unit area is small. Nodules are high in P_2O_5.	Large.

Tertiary. Deposits are being mined presently only in Tennessee.

TENNESSEE

The brown-rock deposits of Tennessee are associated with the Nashville dome. The phosphate was deposited in rocks of Middle Ordovician age and is in the form of pellets and phosphatized fossil gastropods. The rocks are phosphatic only on the western flank of the Nashville dome. The phosphatic limestones have been weathered in modern time, carbonate has been removed, and the phosphate is concentrated as a residual deposit. The deposits are covered by thin phosphatic soil and are economic because they are flat lying, poorly consolidated, and shallow. Reserves are only a few score millions of tons.

Mining is at the rate of a few million tons per year, and at the current rate, the reserves will be depleted sometime in the 1990's.

OTHER AREAS

A number of other small deposits are known throughout the United States and are listed in table 12, along with rough estimates of their magnitude.

SUMMARY OF U.S. PHOSPHATE RESOURCES

About 7 billion tons of phosphate concentrate that are economically or marginally economically feasible to mine and beneficiate by use of today's technology and prices are available for mining (table 13). Three-quarters of this resource occurs in Florida, and the rest is split about evenly between North Carolina and Idaho. This resource is being depleted by mining and will be exhausted in the next century; of course, the exact time of exhaustion is dependent on the rate of extraction.

In addition to these available resources, there exist an additional 24 billion tons of phosphate deposits classed as subeconomic resource, which are presently unavailable because mining and processing costs are too high relative to today's phosphate prices. Most of this subeconomic resource has been identified in the Northwestern Phosphate District of Idaho and adjacent States, where it consists of rock that must be mined by underground methods rather than by strip mining. Not only is the cost of underground mining higher than that of strip mining, but the rock has a different quality from rock now being mined and will require a different processing technology. Such a technology has not yet been developed.

More than 16 billion tons of additional phosphate deposits probably exist but are not listed here because of insufficient drilling information. They are classed as undiscovered and are hypothesized to occur in the southeastern Coastal Plain province, particularly in Florida, North Carolina, and the shallow Atlantic offshore areas of the Blake Plateau, North Carolina, and the Savannah River, where detailed drilling is necessary to prove their tonnage and grade.

FUTURE TRENDS AND PROBLEMS

The United States phosphate industry will have to undergo major changes early in the next century if it is to continue to supply phosphate to domestic and world markets to meet projected demand. The present available reserve will be depleted, and the industry will have to turn to resources that are presently uneconomic to mine or unavailable. Several technologic opportunities exist that may make this possible. Valuable byproducts could be obtained, including uranium, vanadium, chromium, rare earths, and fluorine, and the value of these byproducts is sufficient to affect the economics of phosphate mining. The western underground phosphorites, in addition, contain significant quantities of organic matter, which constitutes an energy supply that could help alleviate processing costs. Large amounts of ammonium-

TABLE 13.—*Phosphate rock resources of the United States*

[In millions of metric tons of phosphate product or phosphate rock]

	Identified recoverable resources			Hypothetical resources	Remarks
	Economic	Marginal	Subeconomic		
Florida	3,700	1,470	430	5,000+	Recoverable.
North Carolina		1,000		8,000	Mostly economic.
Georgia		(1,000)			Unavailable due to environmental restrictions.
Northwestern U.S.	1,600-	23,000			Pre-mining resources in ground recoverable is considerably less.
Total U.S.	7,000-	23,430	15,000+		Georgia resources not included.
Additional identified rock not considered a resource			500,000		Occurs in northwestern field at depths too great for mining in foreseeable future.

rich feldspar (Gulbrandsen, 1974) presently are being mined as waste in phosphate mining in Idaho, and research on this material, which contains $(NH_4)_2O$ in amounts up to 6 percent, might show that it could be utilized as special nitrogen fertilizer. Bore-hole hydraulic mining and slurry extraction hold some promise for mining the deeper subeconomic phosphate rock in the southeastern Atlantic Coast province. According to M. E. Zellars and J. M. Williams (written commun., 1979) the costs of dredge mining of offshore phosphate deposits may be equal to projected onshore mining costs, in the late 1980's or early 1990's.

The phosphate resources that the Nation must turn to in the future are not well known. In the southeastern Atlantic Coastal Plain districts, only about a third of the resource has been explored to the point that its quantity and quality can be measured. The undiscovered portion promises to be large, and its quality will probably be similar to that of the identified deposits, but much uncertainty still exists. A similar situation exists for Idaho and the adjacent States. Although the deposits in the Northwestern United States are much more regular in geologic occurrence so that their existence and quantity can be better estimated, their quality is only poorly known. The rock that will have to be mined if the province is to continue to contribute to the Nation's phosphate supply is deep under the ground, and samples cannot be obtained without drilling. Meaningful research on processing technology to produce both phosphate and byproducts cannot be undertaken until the quality of the rock is better known.

The important phosphate resources of the Nation occur in areas where the land is needed for such uses as citrus groves, suburban development, forestry, and recreation. Much phosphate land is presently unavailable for exploitation because of these alternate uses. In addition, the effect of phosphate mining and processing on water, air, and land quality is significant, and considerable effort, much of which has been successful, has been made to prevent mining. These problems for phosphate development will have to be resolved if the Nation's phosphate resources are to be used to their full potential.

GLOSSARY

Back Slope. The back slope of a mine pit is the slope of the pit after mining the ore bed.

Economic. This term implies that profitable extraction or production under defined investment assumptions has been established, analytically demonstrated, or assumed with reasonable certainty.

Entry Level. The level of the entry to the mine that is used as a haulage road. The lowest entry level is where the ore bed intersects the lowest stream level and is the entry level which maximizes the amount of ore that can be mined by gravity stoping, which minimizes the energy costs of moving ore out of the mine.

Identified Recoverable Resources. Those phosphate resources whose tonnage and grade have been determined by drilling and chemical analysis and in which the phosphate product can be recovered using existent technology.

Inferred Reserve Base. The inplace part of an identified resource from which inferred reserves are estimated. Quantitative estimates are based largely on knowledge of the geologic character of a deposit and for which there may be no samples or measurements. The estimates are based on an assumed continuity beyond the reserve base for which there is geologic evidence.

Marginal Reserves. That part of the reserve base which, at the time of determination, borders on being economically producible. Its essential characteristic is economic uncertainty. Included are resources that would be producible given postulated changes in economic technologic factors.

Matrix. Term used by phosphate companies in Florida and North Carolina to designate the potentially minable material.

Phosphate Product. Deposits in the Atlantic Coastal Plain must be beneficiated. This is done by washing, screening, and froth flotation. The flotation concentrate (size range 0.1–1 mm) is a phosphate product. In the Florida deposits, the fraction greater than 1 mm, called pebble, is also a phosphate product.

Reserve Base. That part of an identified resource that meets specified minimum physical and chemical criteria related to current mining and production practices, including those for grade, quality, thickness, and depth. The reserve base is the inplace, demonstrated (measured plus indicated) resource from which reserves are estimated. It may encompass those parts of the resources that have a reasonable potential for becoming economically available within planning horizons beyond those that assume proven technology and current economics. The reserve base includes those resources that are currently economic (reserves), marginally economic (marginal reserves), and some of those that are current subeconomic (subeconomic resources). The term "geologic reserve" has been applied by others generally to the reserve-base category, but it also may include the inferred-reserve-base category; it is not a part of this classification system.

Reserves. That part of the reserve base which could be economically extracted or produced at the time of determination. The term "reserves" need not signify that extraction facilities are in place and operative. Reserves include only recoverable materials; thus, terms such as "extractable reserves" and "recoverable reserves" are redundant and are not a part of this classification system.

Restricted Resources or Reserves. That part of any resource or reserve category that is restricted from extraction by laws or regulations. For example, restricted reserves meet all the requirements of reserves except that they are restricted from extraction by laws or regulations.

Subeconomic Resources. The part of identified resources that does not meet the economic criteria of reserves and marginal reserves.

Undiscovered Resources. Resources, the existence of which are only postulated, comprising deposits that are separate from identified resources. Undiscovered resources may be postulated in deposits of such grade and physical location as to render them economic, marginally economic, or subeconomic. To reflect varying degrees of geologic certainty, undiscovered resources may be divided into two parts:

Hypothetical Resources. Undiscovered resources that are similar to known mineral bodies and that may be reasonably expected to exist in the same producing district or region under analogous geologic conditions. If exploration confirms their existence and reveals enough information about their quality, grade, and quantity, they will be reclassified as identified resources.

Speculative Resources. Undiscovered resources that may occur either in known types of deposits in favorable geologic settings where mineral discoveries have not been made or in types of deposits as yet unrecognized for their economic potential. If exploration confirms their existence and reveals enough information about their quantity, grade, and quality, they will be reclassified as identified resources.

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