World Phosphate Rock Reserves and Resources

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by

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Foreword

Today's heightened global awareness of food security and environmental issues offers new opportunities for institutions such as IFDC and the world fertilizer industry to contribute to future agricultural sustainability and the alleviation of hunger and poverty, while minimizing losses of nutrients to watersheds and oceans. Efficient fertilizer use that minimizes losses while maximizing utilization is one of the main themes of several initiatives implemented under IFDC's Strategic Framework: 2009-2013.

Information circulating on the Internet and in conventional literature for several years has suggested that phosphate rock reserves are dwindling. This is a critical issue because phosphorus (from phosphate rock) is one of the three key elements needed for optimum plant growth (along with nitrogen and potassium). Information gathered over the years at IFDC, preliminary literature research and contacts within the world phosphate fertilizer industry suggested an independent estimate of world phosphate rock reserves and resources was needed, since major efforts in this area concluded 15-20 years ago.

This study was conducted as part of IFDC's Strategic Framework: 2009-2013 primarily using publicly available information and documents. Funding for this initiative was provided solely by the U.S. Agency for International Development (USAID). It was recognized early on that this study would result in a preliminary estimate. This report constitutes Phase I of a two-phase program. Phase II will involve developing a more definitive global phosphate rock reserve and resource estimate through the Virtual Fertilizer Research Center (VFRC), an initiative of IFDC. Hopefully, phosphate rock producers, geologic surveys and mining departments, university personnel and other stakeholders will take an active role in participating in this effort.

Amit H. Roy
President and CEO

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Acronyms and Abbreviations

BPL	Bone Phosphate of Lime (1 percent P_2O_5 = 2.185 percent BPL)
$CaCO_3$	The common formula for calcite
$CaMg[CO_3]_2$	The common formula for dolomite
CPECs	Centrally Planned Economy Countries
DAP	Diammonium Phosphate
DCFROR	Discounted Cash Flow Rate of Return
DNPM	Departamento Nacional de Produção Mineral
DPRA	Development and Planning Research Associates Inc.
ENMC	El Nasr Mining Company
FIPR	Florida Institute of Phosphate Research
f.o.b.	Free on Board
FSU	Former Soviet Union
GDP	Gross Domestic Product
Gecopham	General Company of Phosphate and Mines
GSI	Geological Survey of Israel
ICS	Société des Industries Chimiques du Senegal
IFA	International Fertilizer Industry Association
IGCP	International Geological Correlation Programme
IOE	Institute of Ecology
IPL	Incitec Pivot Limited
MAP	Monoammonium Phosphate
MECs	Market Economy Countries
MgO	Magnesium Oxide
mmt	million metric tons
MOP	Muriate of Potash
mt	metric tons
NFDC	National Fertilizer Development Center
OCP	Office Chérifien des Phosphates
SSP	Single Superphosphate
STN	Scientific and Technical Information Network
TSP	Triple Superphosphate
TVA	Tennessee Valley Authority
UNESCO	United Nations Educational, Scientific, and Cultural Organization
UNIDO	United Nations Industrial Development Organization
USBM	United States Bureau of Mines
USGS	United States Geological Survey
VFRC	Virtual Fertilizer Research Center
WPA	Wet Process Phosphoric Acid

World Phosphate Rock Reserves and Resources

Executive Summary

The amount of remaining phosphate rock reserves and resources worldwide has become an issue of speculation. It has been hypothesized that phosphorus (phosphate rock) production will "peak" in 2033-2034 and then production will unavoidably decrease as the reserves are depleted. Because phosphorus is one of the three elements critical to plant growth, dire consequences for world agricultural production and food security are linked to "peak phosphate."

This study reviewed phosphate rock reserve and resource literature, past world reserve and resource estimates and the methodology used to perform reserve and resource estimates. The study is not a totally comprehensive analysis; it primarily focuses on the countries listed by the United States Geological Survey (USGS) in the Mineral Commodity Summaries series. The available literature was used to prepare a preliminary estimate of world reserves and resources.

The literature review indicates the use of the terms "reserve" and "resource" are not consistent on a worldwide basis. There is a great deal of published data available on phosphate rock deposits prior to 1990. Since then, however, there is a limited amount of detailed information on world phosphate rock reserves and resources available in conventional scientific literature. Useful information was located on websites, in trade magazines, papers presented at conferences and in papers or reports that have limited distribution and are generally not catalogued on commercial literature databases.

The search for phosphate rock deposits became a global effort in the 20th century as demand for phosphate rock increased. Development of deposits further intensified in the 1950s and 1960s. World production peaked in 1987-1988 and then again in 2008 at over 160 million metric tons (mmt) of product. Phosphate rock mining has evolved over time and worldwide it relies on high volume and advanced technology using mainly open-pit mining methods and advanced transportation systems to move hundreds of millions of tons of overburden to produce hundreds of millions of tons of ore that are beneficiated to produce approximately 160 mmt of phosphate rock concentrate per year. Concentrate of suitable grade and chemical quality is then used to produce phosphoric acid, the basis of many fertilizer and non-fertilizer products.

Previous estimates of phosphate rock reserves range from 15,000 mmt to over 1,000,000 mmt, while estimates of phosphate rock resources range from about 91,000 mmt to over 1,000,000 mmt. Using the available literature, the reserves of various countries were assessed in terms of reserves of concentrate. The IFDC estimate of worldwide reserve is approximately 60,000 mmt of concentrate. The IFDC estimate of world phosphate rock resources is approximately 290,000 mmt. This figure includes the unprocessed ore of the IFDC reserve estimate. If estimates of potential phosphate rock resources are included, the total world resources of phosphate rock may be about 460,000 mmt. This resource estimate does not include estimates of phosphate reserves/resources from every country or known phosphate rock deposit in the world. Many countries are rather incompletely explored. In addition, there are many small phosphate deposits in the countries listed, as well as in other countries. These deposits were not included in this study.

Based on the data gathered, collated and analyzed for this report, there is no indication that a "peak phosphorus" event will occur in 20-25 years. IFDC estimates of world phosphate rock reserves and resources indicate that phosphate rock of suitable quality to produce phosphoric acid will be available far into the future. Based on the data reviewed, and assuming current rates of production, phosphate rock concentrate reserves to produce fertilizer will be available for the next 300-400 years.

It should be stressed that reserves are only proven or established over a planning horizon based on the amount of concentrate needed for a number of years. Reserves are not established on an infinite planning horizon. The world reserve of phosphate rock is a dynamic figure. The cost of phosphate rock is going to increase as lower-cost phosphate rock deposits are mined out and mining companies have to move more overburden, process lower grade ores, open

new mines, employ increasingly expensive technology and use additional raw materials and processing media (such as water) to produce concentrates. When the price of phosphate concentrates increase, deposits that were marginally economic may become viable and new deposits will be opened. Some of these deposits may be in challenging environments and alternative mining methods will also be developed and used. The utilization of underground mining methods may become attractive in many countries if the price of phosphate rock is high enough. Vertical integration of phosphate rock mining and processing has occurred at numerous sites around the world over the past few decades. Vertical integration of phosphate rock mining and processing may be a necessary component to compete in the world phosphate fertilizer market when new deposits are developed.

It must be stressed that this study contains a preliminary estimate of world reserves and resources. A collaborative effort by phosphate rock producers, government agencies, international organizations and academia will be required to make a more complete and accurate estimate of world phosphate rock reserves and resources. These stakeholders also should be involved in phosphate fertilizer production or use initiatives that may influence individual government or global economic, environmental and/or food security policies.

No matter how much phosphate rock exists, it is a non-renewable resource. The amount of this resource that can be produced is based on its value to the current world agricultural system and for other uses. There should be a global effort to more effectively mine and process reserves/resources of phosphate rock and to utilize phosphate fertilizer and phosphate-containing waste as efficiently as possible, while keeping nutrients out of watersheds and the oceans. All of these efforts must be tempered and explored realizing that only those techniques or processes that are logistically, technically and economically feasible are likely to be adopted.

World Phosphate Rock Reserves and Resources

Introduction

During the last decade, there have been numerous published articles, presentations and Internet postings concerning a looming scarcity of phosphate rock. Examples include: Rosemarin (2004); Rosemarin et al. (2009); Cordell, Dragert and White (2009); de Haes et al. (2009); Vaccari (2009); and articles referenced within these sources. Some of this material indicates that the phosphate rock reserves/resources of the Earth will be exhausted in the next century with a peak in phosphorus production occurring in 2033-2034. Essentially, all these articles reference U.S. Geological Survey (USGS) Mineral Commodity Summaries for phosphate rock reserve and reserve base tonnage data.

In general, phosphate rock reserves are materials that can be economically produced at the present time using existing technology. Phosphate rock resources include reserves and any other materials of interest that are not reserves. A reserve base is a portion of the resource from which future reserves may be developed. In a subsequent section of this report, these terms are discussed in greater detail.

This is not the first time there has been concern over depleting phosphate resources. Pittman (1990) pointed out that in the early part of the 20th century, conservationists in the United States promoted a ban on foreign sales of phosphate rock. Subsequently, resources on public lands in the western United States were removed from public entry. In 1971 the Institute of Ecology (IOE) in Chicago published the results of a workshop which indicated the known world reserves of phosphate rock might be exhausted in 90-130 years. This report precipitated several articles and estimates of world phosphate rock reserves and resources and may have fueled the vast amount of research done in this area in the 1970s and 1980s. Using United States Bureau of Mines (USBM) and USGS data, Herring and Fantel (1993) modeled depletion of known world phosphate rock reserves and the reserve base and concluded that the known reserves would be depleted in 50 years, and the remainder of the reserve base would be depleted within the next 100 years.

In order to explore this issue, IFDC initiated a two-phase study. Phase I, and this report, explore the following elements:

- Review the literature and evaluate past and current world phosphate rock reserve/resource estimates.
- Review existing methodologies of estimating world phosphate rock reserves and resources.
- Evaluate current methods of phosphate mining, beneficiation and P_2O_5 recovery in mining and processing.
- Make a preliminary estimate of world reserves and resources.

Phase I was conducted primarily using publicly available information and documents. No confidential information was used in the production of this document. This report was not envisioned as a definitive analysis. Phase II is envisioned as a collaborative effort among phosphate rock producers, government agencies, international organizations and academia to better estimate world phosphate rock reserves and resources.

Phosphate rock resources that may not be mentioned or elaborated on in other reports due to environmental factors or other issues will be mentioned in this report. This report does not attempt to promote the development of these resources, but merely acknowledges the existence of these phosphate rock resources.

Phosphate rock and fertilizer grade is almost universally expressed by those in this field as phosphate pentoxide (P_2O_5). Most countries express the phosphorus content of fertilizers as P_2O_5. This will be the convention of this report. Phosphate rock grade is often listed in trade publications as BPL, referring to “bone phosphate of lime,” the common name for tricalcium phosphate. Early workers believed tricalcium phosphate was the chief constituent of phosphate rock. These commercial terms are widely used and the following conversion factors are included for reference purposes:

$P_2O_5 = 0.4576 \times BPL$

$BPL = 2.1852 \times P_2O_5$

$P = 0.1997 \times BPL$

The Manufacture of Phosphate Fertilizers

At the present time, nearly all phosphate fertilizers are manufactured from naturally occurring phosphorus-containing minerals. Bone meal, guano and other natural organic phosphate sources are of only minor commercial importance today because of the higher cost per unit of nutrient, and the potential supply is only a tiny fraction of the amount of the raw material needed to produce the amount of phosphate-based fertilizers used in world agriculture.

The phosphate content of phosphate rock, in the form of the mineral apatite, is not readily available to plants. Phosphate rock generally must be treated to convert the phosphate to water-soluble or plant-available forms. There are several methods to process phosphate rock into fertilizers (Figure 1). For more detailed information on the manufacturing of fertilizers, see the *Fertilizer Manual* (United Nations Industrial Development Organization [UNIDO] and IFDC, 1998) and Van Kauwenbergh (2006).

International Fertilizer Industry Association (IFA) estimates (Prud'homme, 2009) indicate world processed phosphate fertilizer capacity in 2008 was 70 million metric tons (mmt) of product with the potential to reach 89 mmt in 2013. Globally, diammonium phosphate (DAP), monoammonium phosphate (MAP) and triple superphosphate (TSP) account for half of phosphate-based fertilizer applications. IFA predicts that most of the growth in phosphate fertilizer demand during the next five years will be met by high analysis phosphate fertilizers, notably DAP and nitrogen (N), phosphorus (P) and potassium (K) – known as NPK – compounds and, to some extent, MAP and TSP. Over the next five years, IFA estimates about 40 new units to produce MAP, DAP and TSP will be constructed in 10 countries. High analysis phosphate fertilizer products can be transported more economically on a per-nutrient basis compared with lower analysis phosphate fertilizers. For example, an 18-46-0 DAP product, purely on a P_2O_5 basis, carries about 2.5 times (46/18) more P_2O_5 payload than an 18 percent P_2O_5 single superphosphate (SSP).

Currently, about 72 percent (Nyiri, 2010) to 75 percent (Prud'homme, 2010a) of the phosphate rock

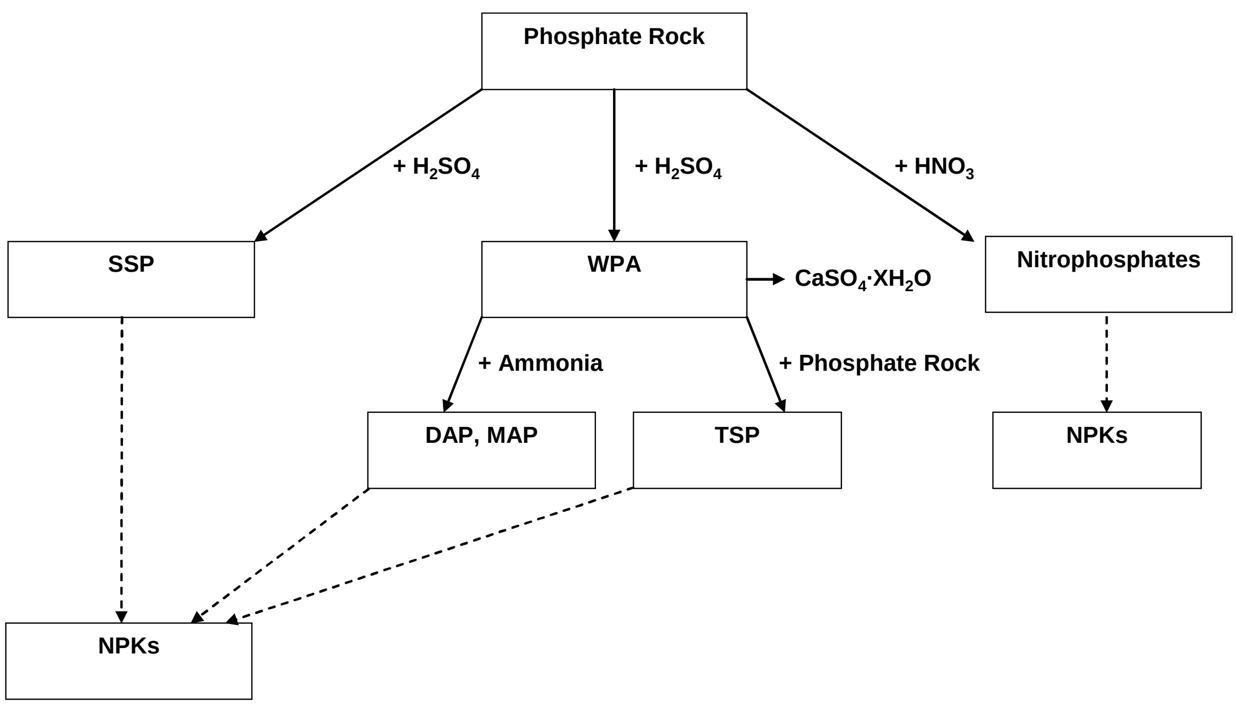


Figure 1. Relationship of Phosphate Rock and Phosphate Fertilizers

produced in the world is used to produce phosphoric acid by the wet process, an essential precursor to these high analysis fertilizers. Nyiri (2010) indicates 28 percent of world phosphate rock production is used for SSP (12 percent), TSP (2 percent, excludes acid) and other P_2O_5 products (14 percent). Prud'homme (2010b) estimated that 18 percent of the total P_2O_5 currently produced is for industrial uses and 82 percent is used for fertilizer. Secondary processing losses range from 2 percent to 15 percent and a global weighted average is 5 percent.

In order to produce DAP at the worldwide accepted commercial grade (18-46-0), phosphoric acid with a suitably low impurities content must be used. Depending on the minor elemental contents (mainly iron, aluminum and magnesium), several phosphate compounds may form in the process which are not citrate soluble and/or are not available to bond with ammonia. Most notably, the world standard nitrogen grade of 18 percent for DAP may not be reached if the phosphoric acid is not suitable. There are several engineering options to deal with this issue that are beyond the scope of this paper. The most suitable option, and probably least expensive, is the use of phosphate rocks that have a relatively low and suitable level of impurities to manufacture wet process phosphoric acid (WPA). For an overview of the complexities of producing WPA, see Becker (1989).

Phosphate Rock Characteristics, Mining and Beneficiation

Geology and Mineralogy of Phosphate Rock

"Phosphate rock" is an imprecise term that includes both unprocessed rocks and beneficiated concentrates. Nearly all phosphate fertilizer production is based on phosphate rock containing some form of the mineral apatite. There are two main types of phosphate rock deposits – sedimentary and igneous. Sedimentary phosphate deposits are exploited to produce more than 80 percent of the total world production of phosphate rock. Igneous phosphate deposits are often associated with carbonatites and/or alkalic (silica deficient) intrusions. Igneous phosphate rock concentrates are produced from deposits that are mainly exploited in Russia, the Republic of South Africa, Brazil, Finland and Zimbabwe. Igneous phosphate ores are often low in grade (less than 5 percent P_2O_5), but can be upgraded to high-grade products (from about 35 percent to over 40 percent P_2O_5).

Sedimentary phosphate rocks occur throughout the geological time scale. Most sedimentary deposits were apparently formed in offshore marine conditions on continental shelves. They exhibit a wide range of chemical compositions and great variations in physical form. The most desirable sedimentary phosphate rocks contain distinct phosphate particles that can be separated from the unwanted gangue minerals. Insular deposits, a type of sedimentary deposit associated with oceanic islands (such as Nauru and Christmas Island), have been an important source of phosphate rock for more than 100 years; however, most of these deposits have been totally depleted or have short projected remaining lifetimes.

Depending on their origin (igneous or sedimentary), phosphate rocks have widely differing mineralogical, textural and chemical characteristics. Several cycles of deposition and reworking may have concentrated the phosphate, and weathering may have removed most of the carbonates from the near-the-surface portions of the deposits. Some igneous phosphate deposits, such as the Kola deposit in Russia, are hard-rock deposits; apatite crystals are found within a hard crystalline fabric of other igneous minerals. With intense weathering, the fabric of igneous phosphate rocks can be destroyed; soft soil-like residual deposits are produced. Sedimentary phosphate rocks can range from loose unconsolidated materials, to weakly cemented materials, to highly indurated rocks.

When phosphate rock deposits have been subjected to varying levels of burial and heat, profound mineralogical and textural changes can occur. Crystal growth occurs, and individual phosphate particles and cementing phases can become highly interlocked and difficult to separate. Sedimentary phosphate and igneous rocks that have been subjected to extremely deep burial (high pressure and perhaps shearing forces and/or heat) may be further categorized as a third type of phosphate rocks – metamorphic phosphate rocks.

Most sedimentary deposits contain varieties of carbonate-fluorapatite called francolite. Francolite is defined as an apatite that contains significant CO_2 with >1 percent fluorine (McConnell, 1938). McClellan and Lehr (1969), McClellan (1980), McClellan and Van Kauwenbergh (1990) and Van Kauwenbergh (1995) studied francolite in commercial phosphate rock concentrates and documented that the contents of Ca, Na, Mg, P_2O_5, CO_2 and F can adequately describe most francolites. Carbonate substitutes for phosphate in a 1:1 ratio. The maximum amount of substitution is between 6 percent and 7 percent CO_2. Sedimentary phosphate rocks containing the most highly carbonate-substituted apatites can only be beneficiated to maximum grades of 33-34 weight percent P_2O_5. Depending on the amount of carbonate substitution, the grade can increase to a maximum of about 42 weight percent P_2O_5 for sedimentary apatites with essentially no substitution.

The apatite associated with igneous source rocks may be of a primary magmatic, hydrothermal or secondary origin. Primary apatite from igneous sources may be of fluorapatite, hydroxylapatite or chlorapatite varieties. Pure apatites from igneous deposits contain slightly over 42 percent P_2O_5.

Mining and Beneficiation of Phosphate Rock

The generally quoted first commercial production of phosphate rock was in England in 1847 (Cathcart, 1980), and mining was undoubtedly by hand methods. Phosphate mining began in the United States in South Carolina in 1867. Platy phosphate rock beds were mined by hand and later by dredges; sorting was mainly by hand (Shepard, 1880).

Phosphate rock deposits were discovered in North and West Africa in the late 1800s. Exploitation of deposits in Algeria and Tunisia began prior to 1900. Production of phosphate rock began at many of the deposits in the North and West Africa region in the early to mid-20th century.

The most successful phosphate mining operations in the world generally involve high-volume removal of waste and ore, low or reasonable costs for upgrading, ore suitable for upgrading to prevailing market-grade specifications and large annual concentrate output in terms of hundreds of thousands to millions of tons per year. Successful export-oriented mining operations are also generally located within 200 kilometers of the coast and a port, or there is a well-developed transportation network to a port or markets. All of these operations work 24 hours per day, 365 days per year mining, processing or performing maintenance.

A wide variety of techniques and many types of equipment are used to mine and process phosphate rock. The methods and equipment used are very similar to methods and equipment used for coal mining. Phosphate rock is mined by both surface (open-cast or strip mining) and underground methods. Surface mining can take many forms – from manual methods employing picks and shovels to highly mechanized operations. Surface mining is the most utilized method by far for mining phosphate deposits. In high-volume applications, surface mining methods are typically less costly and are generally the preferred method when deposit geometry and other factors are favorable.

In large-scale surface phosphate rock mines, large electric walking draglines are often used to both strip soft overburden and mine relatively flat-lying soft phosphate beds. Typical bucket sizes may range from 40 m^3 to 70 m^3. The draglines must have a relatively flat and stable surface to work from and walk on. Bulldozers, dump trucks, graders, earthmovers, power shovels and various other equipment are used for site preparation and at some mines may also be used to mine thin phosphate rock beds.

Large bucket wheel excavators are very suitable for moving large volumes of material in open-pit operations when the overburden and ore are soft and relatively dry. The first several meters of overburden, containing tree roots and other debris, may be extracted using bulldozers, front-end loaders, power shovels and large dump trucks. In these types of operations, the overburden is often transferred to mined-out areas by conveyors and offloaded by transloaders. Bucket wheel excavators may also be used to mine ore zones.

There have been numerous underground phosphate rock mining operations in the world and, just as with surface mining, the methods used range from labor-intensive to highly mechanized. Conventional room and pillar methods can be used with the aid of short-wall drum shearers or continuous miners. Longwall techniques similar to the techniques used to mine coal also have been used.

In large-scale phosphate mines, ore or product may be moved by trucks, conveyor belts, as slurry in pipelines or by rail. The methods used depend upon the individual deposit, distances involved, availability of water and other factors.

Increasing world fertilizer demand in the 1960s and 1970s and the need for phosphate feedstocks stimulated efforts to develop techniques to upgrade low-grade ores and remove impurities. It is highly desirable, for both economic and technical reasons, to remove as much of these impurities as possible, thus increasing the apatite content and the grade of phosphate feedstocks and improving the chemical quality. Phosphate ores can be beneficiated by many methods, and usually a combination of methods is used.

In phosphate rock beneficiation, the availability of water is of prime importance and may dictate the process or processes used. The total lack of water or lack of freshwater availability may exclude deposits from development or restrict capacity. In areas where water availability is severely restricted, dry screening may be an effective way to produce pre-concentrates or concentrates if ore characteristics are suitable. Seawater or brackish water may be used for washing and size classification. Seawater may also be used for flotation. Where seawater or brackish water is used for beneficiation, a freshwater final rinse is needed to remove as much chloride as possible from the final concentrate. A high chloride content can lead to severe corrosion in further processing. In other areas of the world, freshwater availability is not as restricted. In Florida, from 8 to 15 tons of freshwater is used to produce each ton of phosphate rock; most of this water is recycled.

Fine-grained impurities can often be removed from phosphate ores by using combinations of comminution, scrubbing, water washing, screening and/or hydrocyclones. The disposal of fine ore constituents (slimes) can be problematic.

The beneficiation technique of froth flotation is widely used within the world phosphate rock industry. Froth flotation is generally employed with siliceous ores when other less expensive or less complicated techniques fail to produce phosphate concentrates suitable for chemical processing. Many other techniques are often employed to prepare the feed for froth flotation.

The removal of carbonates from phosphate rock has been the focus of significant research efforts. Several countries have large deposits of phosphate rock that contain significant amounts of calcite ($CaCO_3$) and dolomite ($CaMg[CO_3]_2$).

Calcination of phosphate ores to remove carbonates is expensive because of the high costs of energy. Calcination is practiced commercially at several phosphate rock mining operations around the world, mainly to improve final product quality by removing minor amounts of carbonates and organic matter. Calcination is also used to remove carbonates where the cost of natural gas is very low.

Flotation of calcareous and dolomitic phosphate ores seems to be the most economically viable technical alternative. However, selective flotation of carbonates from phosphate is rather difficult due to the similarity in the physicochemical properties of carbonate and phosphate minerals. Carbonate/phosphate separation by flotation is used commercially in Finland and Brazil to treat igneous phosphate rocks. The production of well-consolidated and highly indurated sedimentary ores may require mining and beneficiation techniques resembling those typically used for hard igneous phosphate ores. Carbonate-containing sedimentary phosphate ores are mined and beneficiated by flotation in India and China. These sedimentary deposits in India and China are Cambrian or older in age, have been subjected to varying degrees of heat and pressure and may be considered metamorphic phosphate rocks.

Despite the fact that significant research has been conducted on the selective flotation of carbonate-containing sedimentary phosphate ores, flotation had not been widely adopted commercially for the treatment of relatively unconsolidated calcite- or dolomite-containing sedimentary phosphate ores. Both direct and reverse phosphate and carbonate flotation techniques have been tested for effectiveness in upgrading sedimentary phosphate ores with high free carbonate contents. Flotation has been used to treat phosphate ores from the Vernal, Utah, deposit since the 1980s. Ore from the Al-Jalamid Deposit in Saudi Arabia, scheduled for startup in 2010-2011, also will be treated by flotation to remove carbonates.

The principal market specification relating to the P_2O_5 content (grade) of phosphate rock is not a reliable indicator of the potential quality of phosphate fertilizer produced by a particular process, nor is it an indicator of the similarity of equivalent grade phosphate rocks from different sources. In general, lower P_2O_5 means higher impurity contents. Lower P_2O_5 content results in lower yields, and high impurity contents result in more processing problems and higher costs.

Commercial phosphate rocks vary in grade from over 37 percent P_2O_5 (80 BPL) to less than 25 percent P_2O_5 (60 BPL). International trade generally involves higher grade phosphate rock. It is important to realize that higher P_2O_5 content translates to lower impurity content. Increased P_2O_5 content in concentrates results in increased yields per ton of material shipped, handled and processed. Lower impurity content generally results in increased reaction efficiencies, fewer processing problems and less waste. In general, higher P_2O_5 concentrates command higher prices. Processing of phosphate rocks containing less P_2O_5 and more impurities results in less product, higher processing costs and less potential profit.

In order for a phosphate rock to be suitable for a wide range of processing options, the R_2O_3 (Fe_2O_3 + Al_2O_3)/P_2O_5 ratio must generally be below approximately 0.10. The R_2O_3 + MgO/P_2O_5 ratio must generally be below 0.12. When phosphate rocks have impurity contents at or above these levels, problems can occur in processing, products may not dry properly or the products may contain phosphates that are not water-soluble. For a review of the effect of impurities on fertilizer processing, see Becker (1989) and Van Kauwenbergh (2006).

Florida and Morocco phosphate rock have long been standards in WPA production. However, in the last 20 years, it has been difficult to ammoniate phosphoric acid produced from Florida phosphate rock to commercial DAP grade (18-46-0). The impurity level in Florida phosphate rock has reached a point where iron, aluminum and other phosphates form in phosphoric acid production, reducing the phosphate available to combine with ammonia. For years, producers in Florida have had to add ammonium nitrate or urea in processing to make the 18 percent nitrogen grade of DAP. Phosphoric acid producers using Moroccan phosphate rock from the Khouribga area have not reported this problem.

Phosphate deposits were first discovered in Florida in the 1880s, both in what is known as the hard rock district and what later became known as the Land Pebble, or Central Florida district. For a history of Florida phosphate mining, see the Florida Institute of Phosphate Research (FIPR) website (http://www1.fipr.state.fl.us). Mining in Florida progressed through hand, mule and other methods until electricity and diesel power became available in the 1920s and 1930s. Large electric draglines are used today. The workable, or commercially viable, phosphate zone in Central Florida had an easily separable pebble (~greater than 1 mm) fraction. The entire zone was about one-third pebble, one-third sand and one-third clay-sized material. The development and implementation of flotation technology in the late 1920s and 1930s allowed the recovery of the sand-sized fraction of the phosphate particles. The Florida phosphate district area is a very water-rich area and water is used to initially wash the ore, transport the ore to the beneficiation plant and further wash and treat the ore. Much of the water is recycled. Good mining recovery of the desired ore zone in Florida is approximately 95 percent.

In Florida and at other deposits around the world, open-pit mining is in a single pass configuration. The dragline strips overburden, placing it in a previously mined area. The same dragline also mines the ore. Draglines are operated as multiple units in the mines. While one dragline is stripping overburden, another dragline is mining ore and sending the ore to the beneficiation plant. No secondary handling of overburden is required in this mode except in land reclamation.

Good mining recovery using open-pit methods in other parts of the world should be approximately 95 percent. Using smaller-scale equipment to mine distinct beds may even allow higher recovery. If mining conditions are difficult or the operators are inexperienced, recovery rates can be lower. Prud’homme (2010b) recently indicated an average of 82 percent for mining recovery with a global sample equating to 93 percent of world phosphate production with two-thirds of the producers operating above the weighted average ratios. The details of this study were not available, and a definition of mining recovery was not given. Prud’homme (2010a) indicates that the average of 82 percent mining recovery only includes the recovery of the targeted ore zone.

Phosphate rock production in Morocco began in 1922 using underground methods. Full-scale, open-pit mining began in the mid-1950s. Underground mining ceased in the mid-1990s near Khouribga but is still being used at Youssoufia according to the Office Chérifien des Phosphates (OCP) website (www.ocpgroup.ma). There are many underground mining methods. If a room and pillar configuration is used, possibly 65-70 percent of the ore is removed leaving supporting pillars. If longwall techniques are used, recovery may be much higher, perhaps 85 percent.

In North African and Middle Eastern countries, early mining operations generally involved producing direct shipping ores or ore which required minimal beneficiation. Some losses may be incurred with drying and/or de-dusting. In many countries, water use is an issue. Dry screening is generally the first step in any upgrading. Ores may be further water washed. Dry cyclones or wet hydrocyclones may be used for separation depending on whether it is a dry or wet process. Calcination may be used to remove carbonates after the final screening or washing step. Flotation of phosphate rock was not introduced in Morocco until 1999-2000. Prior to the introduction of flotation, beds that could not be successfully upgraded by the beneficiation methods in use at the time were spoiled, possibly stockpiled or bypassed in mining. Similar methods were and are used in Jordan. Flotation was not employed in Jordan until 1997-98 and may be used on an intermittent basis. Flotation of phosphate rock was introduced in Syria in 2005.

In mines where several phosphate beds are being recovered, some of the overburden and interburden may undergo secondary transport to off-mine or mined-out areas. Large electric trucks are often employed in such mines. In Togo, large bucket wheel excavators, conveyor belt and transloaders move overburden to the edge of the mine area. Secondary transport of overburden or interburden adds costs to mining.

Relatively low-grade ores and concentrates prepared with minimal processing have been used to produce elemental phosphorus by the electric arc methods. In Tennessee, USA, small mine plots (in terms of hectares) were mined with small power shovels and draglines. The ore was trucked to beneficiation and processing plants, where it was washed and screened at approximately plus 45 µm to produce a concentrate at about 25 percent P_2O_5. The material was then used to produce elemental phosphorus mainly for chemical applications. Low-grade phosphate rock formed the basis of the elemental phosphorus industry of Kazakhstan. Worldwide, much of this production by electric arc methods has been closed down due to various factors including energy costs, environmental issues and competition from lower cost purified WPA. However, there is still significant production of thermal acid in the People's Republic of China and a few other locations.

Phosphate rock mining and beneficiation methods used around the world generally attempt to maximize the recovery of commercially usable product. This does not necessarily mean all the resource is recovered. For example, mining in Florida is terminated generally at a hard dolomitic layer located at the bottom of the phosphate-bearing unit. There may be several meters of phosphate rock resource below the dolomitic layer that, when processed to concentrate, contain dolomite, and the magnesium (MgO) content is too high for processing to phosphoric acid and DAP in Florida processing plants. The FIPR website points out that much of today's reserves are left in the ground because the dolomite, which contains magnesium, causes problems in phosphoric acid production.

There may be significant P_2O_5 losses associated with the type of ore that was mined in the Central Florida district. DeVoto and Stevens (1979) point out that up to 40-50 percent of the P_2O_5 was lost in the clay fraction or sand tailings. These P_2O_5 losses include very fine material that could not be separated from clays. Some of these P_2O_5 losses are not in the form of the mineral apatite but may be in the form of secondary iron and aluminum phosphate minerals. The presence of these minerals in phosphate concentrates may be very detrimental when processing to fertilizers. As mining has progressed to the south in Florida, the character of the ore zones has changed and the P_2O_5 losses currently experienced may be different.

P_2O_5 losses in mining and processing occur all over the world (Table 1) (Fantel et al., 1988). Phosphate rock beneficiation technology has not changed significantly in the last 25 years and beneficiation recovery has probably not improved substantially. Please note that the rock grade mentioned in the table is the grade of the phosphate rock feed to the beneficiation plant and does not include mining losses. The figure of 79 percent recovery for the southeastern United States should be viewed with skepticism. This figure probably includes data from North Carolina operations, which mine a different ore type than Central Florida. Also, this recovery figure may be for material after the initial washing and removal of pebble and slimes.

Table 1. Phosphate Recovery From Producing Mines by Region[a] (Adapted From Fantel et al., 1988)

Region	Feed Grade	Product Grade	Recovery of P_2O_5	Loss of P_2O_5
	(% P_2O_5)	(% P_2O_5)	(%)	(%)
North America				
Southeast United States	10.9	30.4	79.0	21.0
Western United States	22.2	31.2	71.3	28.7
South America	9.6	33.8	58.6	41.4
North Africa	26.0	32.2	69.8	30.2
West Africa	27.1	33.3	40.5	59.5
Middle East	24.7	31.4	71.4	28.6

a. See original text for definitions of terms. Feed grade, product grade and recovery are weighted averages for all deposits in the region.

Based on Table 1, recovery of P_2O_5 in beneficiation ranges from 40.5 percent to 79.0 percent, with an average of 65 percent. The South American figure of 58.6 percent P_2O_5 recovery was derived mostly from the processing of residuum over igneous deposits and the hard rock igneous deposits themselves. The North African and Middle Eastern producers were dry and wet screening sedimentary ores at the time and their recovery was about 70 percent. The West African producers, at that time, were Senegal and Togo. Togo ore was washed with seawater and separated using hydrocyclones. Senegal ore was washed and floated.

It must be recognized that the figures in Table 1 are only the feed materials sent to the mill. Portions of deposits that cannot be effectively treated, beds that are too thin to effectively mine or other material that may never be mined or sent to the beneficiation plant are not taken into account.

Similar to phosphate products, the cost to transport phosphate rock on a P_2O_5 basis to processing plants is a significant factor in the overall economics. Higher analysis phosphate rock simply costs less, on a P_2O_5 basis, to handle and transport long distances. The processing of relatively low-grade phosphate rock concentrates (less than 28 percent P_2O_5) to WPA and high analysis fertilizers became more and more commonplace in the world phosphate industry in the late 1970s and 1980s. In Florida, lower grade concentrates that were not suitable for export were increasingly utilized in Florida processing plants. This provided an outlet for phosphate rock reserves that might not have been mined or processed in the past. Export of phosphate rock from the United States began to decline in the early 1990s and essentially ceased in the early to mid-2000s. Practically all the phosphate rock mined in Florida is used to produce value-added products.

Relatively low-grade phosphate rock is treated by an undisclosed dry minimal beneficiation process to produce a relatively low-grade (~23 percent P_2O_5) concentrate at the mine associated with the IPL operations in Queensland. The main impurity is SiO_2 and the low content of other impurities allows production of WPA and ultimately MAP and DAP on the site. Mining and beneficiation with minimal transport of the concentrate and the vertically integrated fertilizer processing plant are factors that make this operation economically viable. This is also an example of a phosphate rock that is almost directly processed with minimal P_2O_5 losses.

Detailed data and in-depth analysis would be required to fully assess P_2O_5 recovery and losses from phosphate deposits that are currently being produced. Current detailed data are simply not readily available. Recovery at many operations has probably been improved.

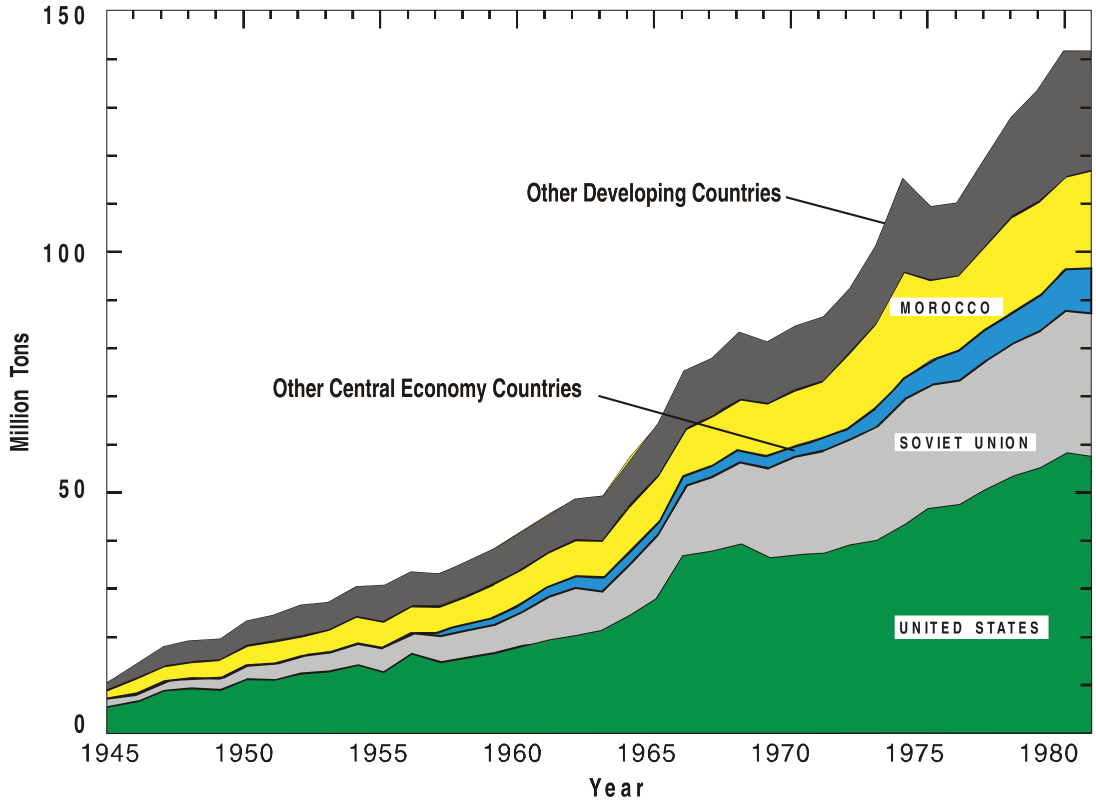
Phosphate rock producers typically strive to maximize recovery and minimize losses. It should be recognized that the best available technology is not often proven and implemented immediately. Investments in technology and processing plants are based upon assessments of risk and consideration of service lifetimes, maintenance, operational and other costs. Reinvestments in new technology, and possibly improved recovery, must usually be economically justified. Also, in a less-than-perfect real world, pressure to provide required amounts of feed for a fertilizer plant, day-to-day operational issues, technical issues, budgetary considerations and a myriad of human factors may contribute to falling short of optimal recovery for phosphate rock producers.

Vertical integration of phosphate rock mining and processing has occurred at numerous other sites around the world, particularly in North America, North Africa and the Middle East. Vertical integration of phosphate rock mining and processing provides several advantages to integrated producers including potential savings in transportation and handling, improved consistency and continuity of supply, potentially higher overall P_2O_5 recovery and potentially higher overall return on investment.

World Phosphate Rock Production

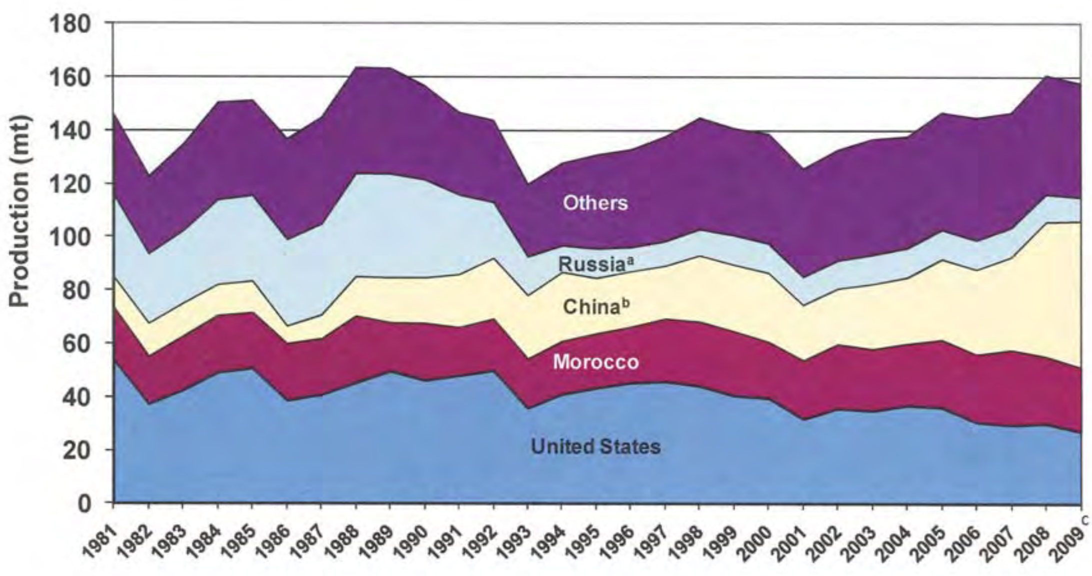
As previously mentioned, the first commercial phosphate rock production in 1847. World production increased to 5,000 metric tons (mt) in 1850, 10,000 mt in 1853, over 100,000 mt in 1865, over 1 mmt in 1885, over 10 mmt in 1928 and over 100 mmt in 1974. In the mid-1970s, one estimate indicated that phosphate rock production would be about 300 mmt by the year 2000 (Anonymous, 1976).

In 1945 total world concentrate tonnage was just over 10 mmt (Figure 2). Growth in phosphate concentrate production seems to have increased linearly to about the mid-1960s, reaching a level of about 50 mmt; an abrupt increase in the growth rate then occurred. However, in the 1980s and into the early 1990s, phosphate rock demand growth stagnated and production was reduced accordingly (Figure 3). Production seemed to level off at a world production rate of around 150-160 mmt prior to the breakup of the Soviet Union (1990/91). According to USBM (1984-95), in 1988 the following nations accounted for 74.8 percent of world phosphate



Source: Krauss et al. (1984).

Figure 2. World Mine Production of Phosphate Concentrate, 1945-1981



a. 1992-1997 Former Soviet Union data includes Kazakhstan, Uzbekistan and Russia data; 1998-2008 FSU data includes Russia only.
b. Official People's Republic of China data.
c. Year 2009 estimated.

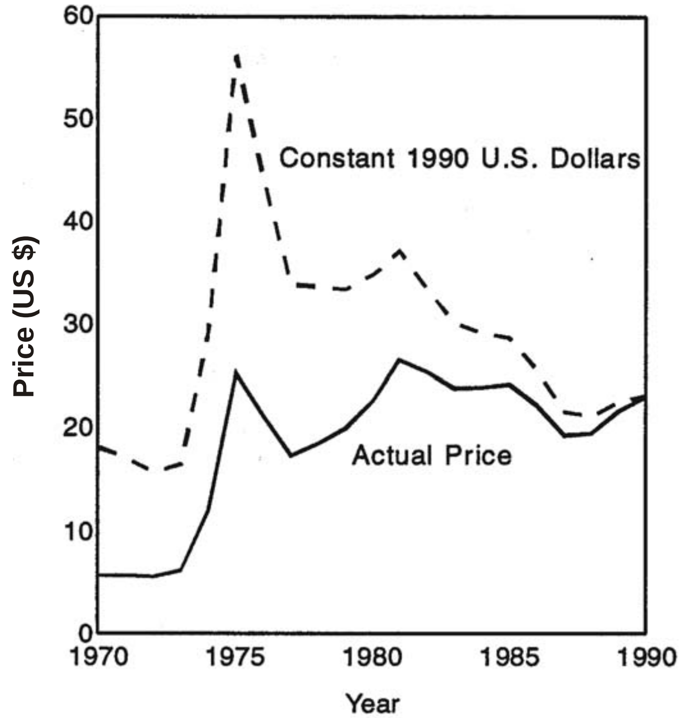
Source: Compiled from USBM, 1984-1995; USGS, 1996-2010.

Figure 3. World Phosphate Rock Production, 1981-2009

rock production: United States (28.0 percent); former Soviet Union (FSU) (21.2 percent); Morocco and Western Sahara (15.4 percent); and the People's Republic of China (PRC) (10.2 percent).

With the advent of significant social changes in the FSU and associated economic disruption, FSU production decreased significantly. This was due mainly to decreased internal demand. World production reached a low point in 1993 due mainly to reduced production from the FSU but also due to reduced production from the United States. World production reached a high point in 1998, then dropped to a low point in 2001. Production steadily rose again until 2008 when it surpassed 160 mmt (USBM, 1984-1995; USGS, 1996-2010) for the first time in 19 years. According to USGS (1996-2010), the PRC (31.5 percent), the United States (18.7 percent), Morocco and Western Sahara (15.5 percent) and Russia (6.4 percent) accounted for 72.1 percent of world phosphate rock production in 2008.

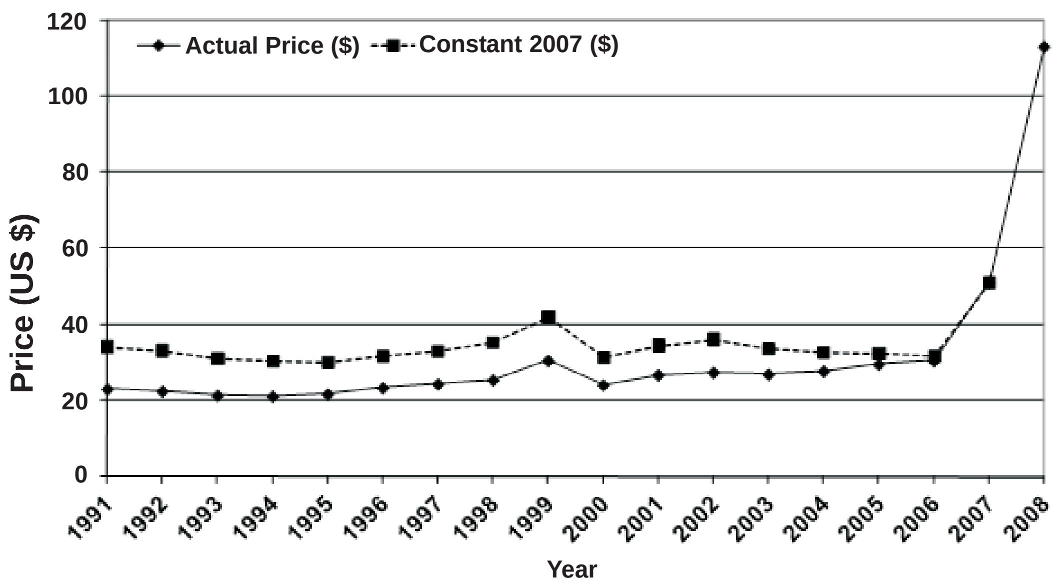
Traditionally, phosphate rock has been a relatively low-cost bulk commodity. Since the phosphate rock shortage of 1975, the price of U.S. phosphate rock in constant dollars steadily declined with some minor recovery in 1980 and 1981 and in 1990 and 1991 (Figure 4); however, prices dropped from 1992 to 1995 (Figure 5). In general, world phosphate rock prices have behaved



(Average annual U.S. producer domestic and export price, f.o.b. mine)

Source: Stowasser (1991).

Figure 4. Time-Price Relationships for Phosphate Rock, 1970-1990



(Average annual U.S. producer domestic and export price, f.o.b. mine)

Source: USBM (1984-1995); USGS (1996-2009).

Figure 5. Time-Price Relationships for Phosphate Rock, 1991-2007[a]

a. Based on Producer Price Index, International Financial Statistics Yearbook (International Monetary Fund, 2008).

similarly to U.S. phosphate rock prices. In 1993 and 1994 world phosphate rock prices dropped to 20-year lows (Mew, 1994; Anonymous, 1994).

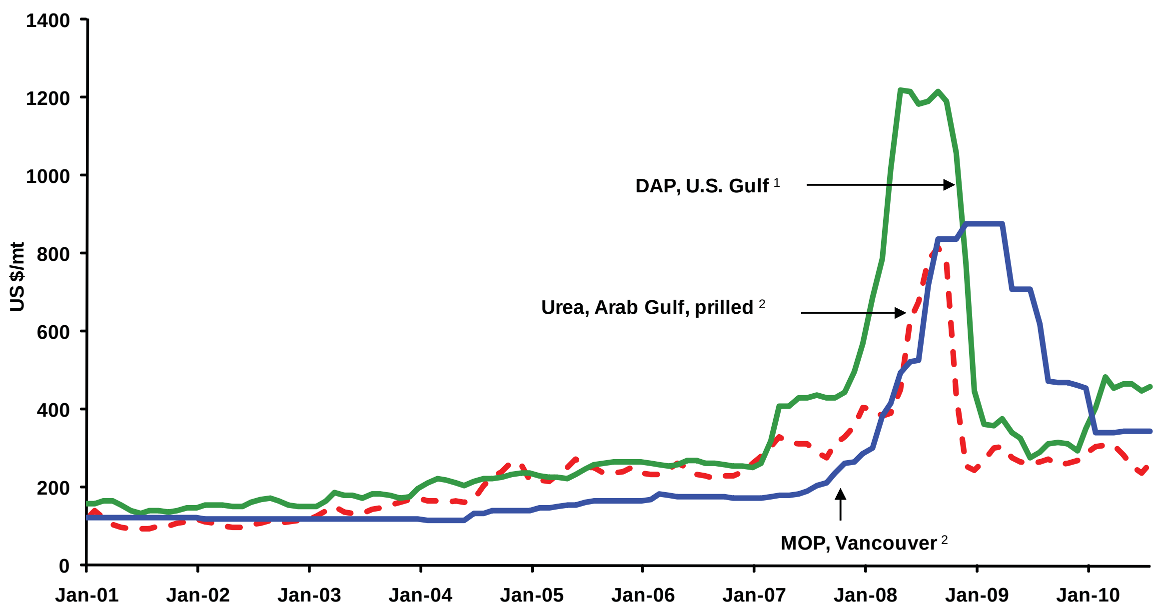
From 1994/95 to 1999, the price of U.S. phosphate rock steadily increased. In 2000, U.S. phosphate rock prices dropped over $8.00/ton; some recovery was seen in 2001. U.S. phosphate rock prices peaked in 2002 and decreased in 2003 and 2004. In 2005 phosphate rock prices began to rise again.

Phosphate rock prices began to rise very significantly in 2007 when phosphate fertilizer prices began to rise (Figure 6). In June 2007, phosphate rock from North Africa was listed for US $42-$46/ton and Jordan phosphate rock (70-74 BPL) could be obtained for US $43-$51/ton (Figures 7a and 7b). Between July and December 2007, North Africa phosphate rock could be obtained for US $68-$75/ton.

In late 2007, the cost of phosphate and other fertilizers began to rise sharply. Between January and June 2008, North Africa phosphate rock was listed at US $150-$400/ton and Jordan phosphate rock (70-74 BPL) was listed at US $200-$300/ton. In October 2008, fertilizer prices began to fall precipitously. The January 5, 2009, issue of *Green Markets* indicated North Africa phosphate rock could be obtained for US $400-$500/ton and Jordan (70-74 BPL) was listed as US $300/ton. On March 18, 2010, North Africa phosphate rock was listed at US $105-$110/ton and Jordan phosphate rock was listed at US $80-$90/ton.

A significant factor in future world phosphate rock production, and ultimately fertilizer production, is the projected U.S. phosphate rock mine capacity (Figure 8). Jasinski (2005) has pointed out reserves in Florida could be depleted by 60 percent by 2030 and totally depleted in 50 years. Jasinski indicated new processing technology may slow reserve depletion. It should be pointed out that the analysis by Jasinski (2005) was based on reserves as defined by the industry and the USGS at that time.

Additional capacity must be developed to replace the production from Florida. OCP (Feytis, 2010) has announced the opening of four new mines to produce an additional 20 mmt/year, increasing the current production capacity from about 25 mmt/year to 45-50 mmt/year. The total investment in the mines is reported to be US $1.68 billion.



1. Derived from *Green Markets*. 2. Derived from *FMB Weekly*.

World fertilizer prices doubled in 2007 and reached all-time highs in April 2008. But prices began dropping dramatically in October and November, 2008. FOB = free on board (average price, with buyer paying freight and insurance, to destination port). DAP = diammonium phosphate. MOP = muriate of potash.

Graph by IFDC

Figure 6. Fertilizer Prices (f.o.b., bulk), Monthly Averages, January 2001-July 2010

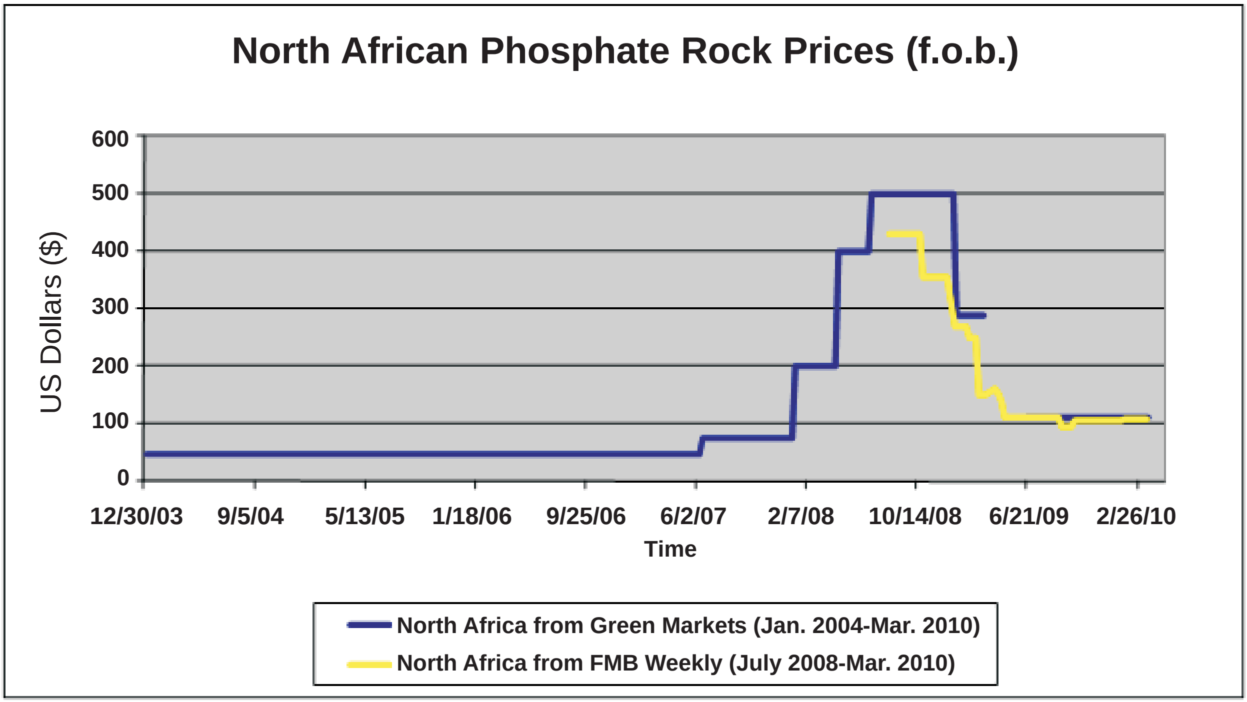


Figure 7a. North African Phosphate Rock Prices

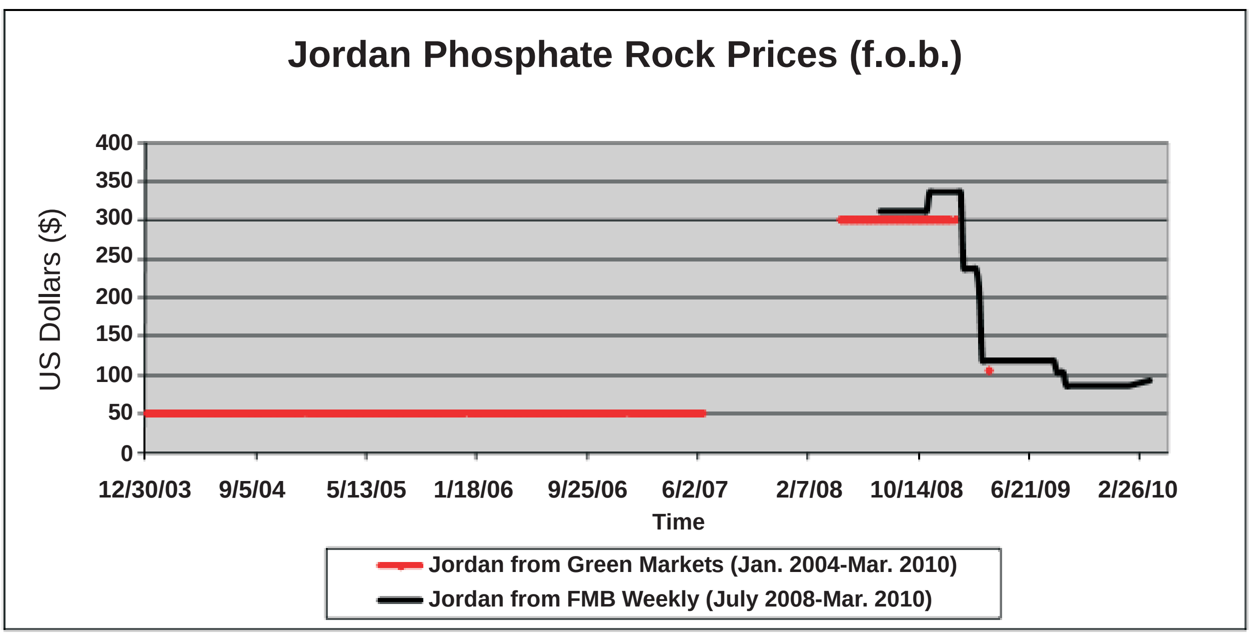


Figure 7b. Jordan Phosphate Rock Prices

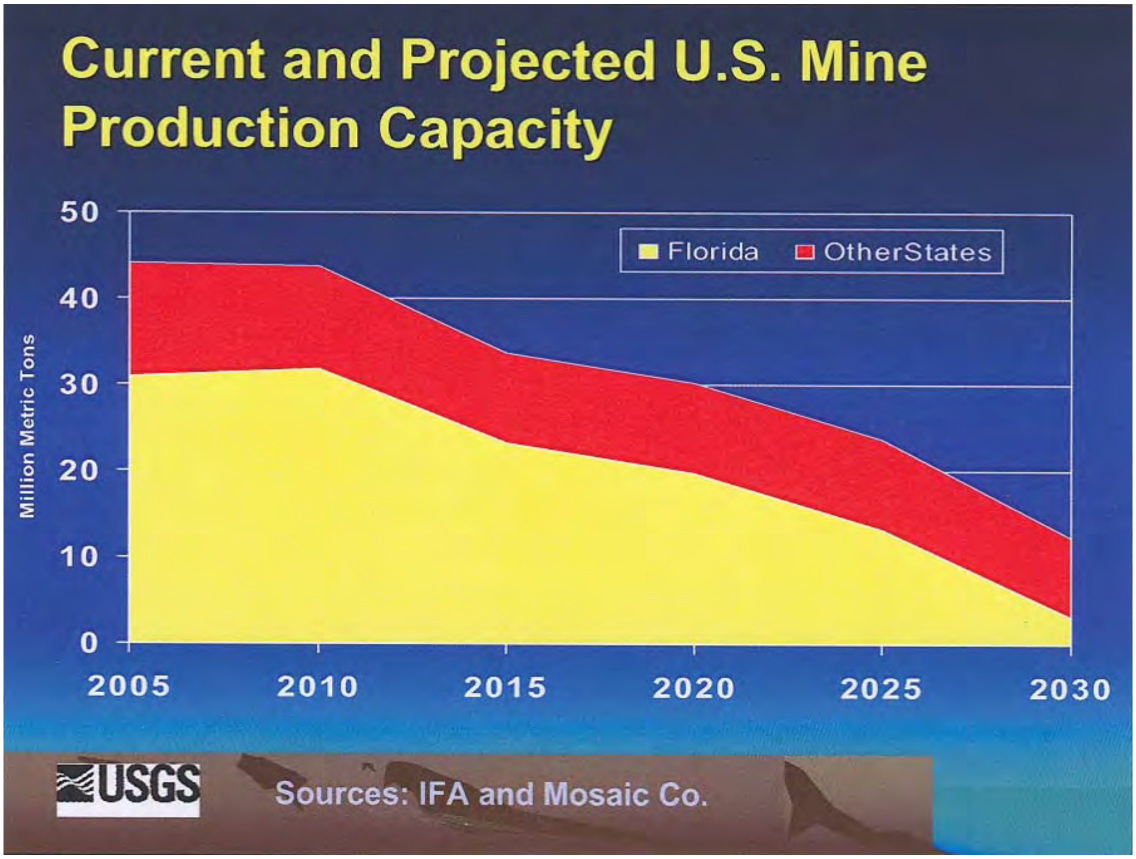


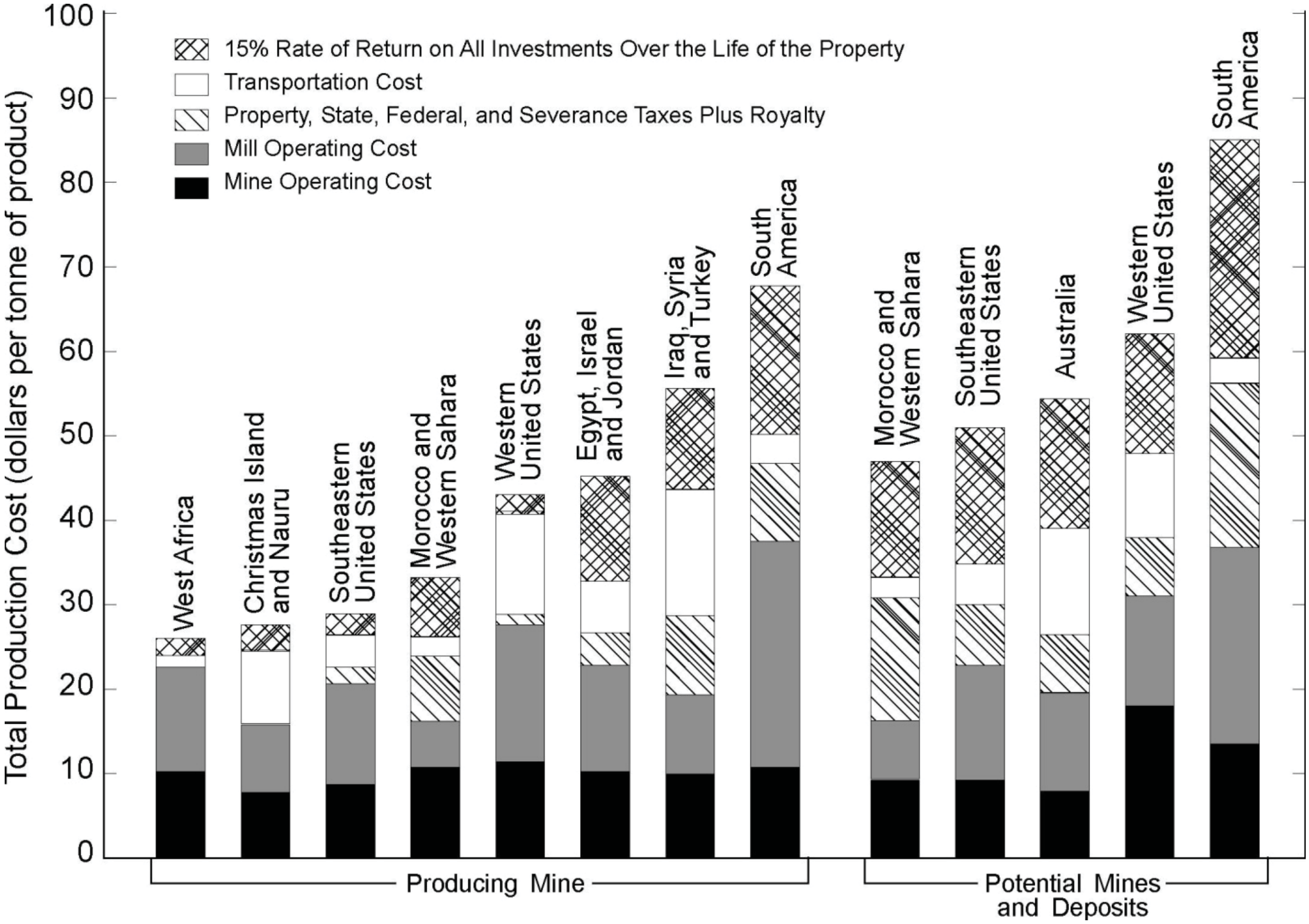
Figure 8. Current and Projected U.S. Mine Production Capacity (Jasinski, 2005)

In 1985, Fantel, Peterson and Stowasser indicated phosphate rock production costs would rise substantially when new mines and deposits were developed to replace depleted deposits (Figure 9). The costs indicated in Figure 9 are from the early 1980s and are not appropriate today. However, the relative costs between producing mines and potential mines and deposits should be relatively appropriate as they were all calculated on the same basis. Costs which may have changed between the localities considered since the Fantel, Peterson and Stowasser (1985) evaluation may include those influenced by technology changes, costs of permitting and the costs of satisfying environmentally related regulations and requirements.

In 1988, Fantel et al. indicated that development of phosphate rock properties in the late 1990s to replace existing capacity would require price increases of 20-50 percent to break even. To earn a 15 percent rate of return on investment, Fantel et al. (1988) indicated prices must rise to nearly double the current level, which was US $24-$29/mt at the time. There were several downturns in the world phosphate industry in the 1990s and early 2000s and the need for replacement capacity was not apparent until 2007 and 2008, when phosphate rock was in limited supply. Doubling the costs given by Fantel et al. (1988) and multiplying by a gross domestic product (GDP) deflator of 1.77 to account for the changing value of money between 1988 and 2010 indicates the price of phosphate rock from new deposits and mines must be about US $85-$103/mt.

Literature Research and Information Concerning Phosphate Rock Reserves and Resources

IFDC geologists, beneficiation engineers, chemical engineers and other scientists have systematically collected phosphate rock reserve and resource, beneficiation and processing data since the inception of the Center in 1974. IFDC also acquired numerous documents and reports concerning phosphate rock characteristics from the Tennessee Valley Authority (TVA) National Fertilizer Development Center (NFDC) staff, and IFDC acquired most of the holdings of the TVA library in Muscle Shoals, Alabama. Published literature and reports are located within the IFDC library and in dedicated files that are maintained by individual staff members.



Source: Fantel et al. (1985).

Figure 9. Estimated Production Costs for Selected World Phosphate Surface Mines and Deposits

Literature searches were conducted through the use of the Scientific and Technical Information Network (STN), a computer-based system. STN is jointly operated by CAS and FIZ Karlsruhe worldwide and operated in Japan by the Japan Association for International Chemical Information (JAICI). For more information, see the CAS website (www.cas.org).

The Chemical Abstracts (CAplus) and Georef (geologic information files) were the main files searched. Repetitive searches using the keywords “phosphate rock” and (phosphate) “reserves” or “resources” or “deposits,” and perturbations of similar terms, for a 20-year time period from 1989 to 2009 typically turned up 30-150 titles. STN research personnel were enlisted in the searches with similar results. Many of the titles found in the 20-year search period were from Notholt, Sheldon and Davidson, 1989, Volume 2 of *Phosphate Deposits of the World*, Phosphate Rock Resources (a collection of 93 chapters). This volume is an outgrowth of Project 156 – Phosphorites supported by IGCP under the aegis of the International Union of Geological Sciences and the United Nations Educational, Scientific, and Cultural Organization (UNESCO). Most of this literature was already in the possession of IFDC.

There are numerous reports on phosphate deposits that are simply not in the public domain or may have very limited distribution. These reports would include studies of specific deposits performed by contractors or mining companies and in-house reports of activities by mining companies or geologic surveys. Periodically, some of the larger consulting or engineering companies have offered studies and projections on phosphate rock on a subscription basis. Sometimes such reports are available if you actually visit a specific geologic survey or Ministry of Mines office. Often, the existence of such reports seems to be a well-kept secret. Similarly, at times the World Bank and other entities have funded studies related to loans for phosphate rock mining operations; these reports are also practically impossible to obtain by the public.

In general, detailed publicly available information concerning phosphate rock reserves and resources published since the early 1990s is very limited in traditional literature. Phosphate rock reserve/resource estimate figures sometimes can be found in trade magazines such as *Fertilizer International*. Articles in magazines are generally not catalogued in commercial reference databases. The Internet sites of geologic surveys in phosphate rock-producing countries may be sources of information. If phosphate rock-producing companies have an Internet site, there may be information on reserves and resources, particularly if it is a company with publicly traded stock. Companies formed to promote the development of phosphate deposits typically list reserve and resource estimates as a part of promotional literature. One of the main sources of information in the last 10 years is the IFA website (www.fertilizer.org) and the publicly available papers from various IFA fertilizer conferences. *The Mining Journal* produced an Annual Review until approximately six to seven years ago that had pertinent information on phosphate deposits. With some notable exceptions, as will be documented in this report, most of the detailed and general phosphate rock reserve and resource estimates were produced before the early 1990s.

From the 1950s to the mid-1980s, USGS and USBM engaged in numerous studies of the phosphate deposits of the United States and the world. USGS engaged in geologic surveys of phosphate rock-bearing areas and conducted exploratory drilling programs. Methodologies for reserve and resource classification were developed, and detailed studies were conducted both by these agencies and contractors. In September 1995 the U.S. Congress voted to close USBM, and by March 1996 layoffs (approximately 1,000 employees) and the transfer of functions to other agencies were complete. The "Mineral Industry Surveys," "Mineral Commodity Summaries" and "Minerals Yearbook" were transferred to USGS and remain available at the USGS website. Prior to this period and during the 1990s, USGS was also dealing with program and personnel adjustments.

USGS has been, and is, the U.S. federal agency generally responsible for the determination of U.S. phosphate rock resources. USGS geologists typically have also gathered data on phosphate deposits around the world. Prior to closure, USBM used USGS data, and data obtained from other sources, to determine world reserves and the reserve base by applying a methodical evaluation procedure and an economic assessment. For an example of this, see Fantel et al. (1988). Until 1993-94, the USBM defined phosphate rock reserves as material that could be produced at less than US $40/ton. That included capital, operating expenses, taxes, royalties, miscellaneous costs and a 15 percent rate of return on investment, f.o.b. The term "reserve base" was used for the phosphate rock that could be produced for less than US $100/ton using the same evaluation criteria.

The last time USBM published a cost for phosphate rock of less than $40/mt was in the phosphate rock section of the 1994 Mineral Commodities Summaries for 1993 data. In 2010 USGS discontinued publishing figures for the reserve base and only publishes reserve figures for all commodities. For a description of the terminology used by USGS, see the Introduction of the 2010 Mineral Commodities Summaries (USGS, 1996-2010). USGS uses official government data when possible, but uses other sources if there are no alternatives.

Examples of phosphate rock reserve or reserve base calculations in literature from other countries at the level of materials publicly available in the United States are practically unknown. Confidential studies of specific phosphate deposits to determine reserves examined by the author from Canadian, French, German, Romanian, British, U.S. and other sources typically use methodology similar to that used by USBM. The level of detail will vary depending on the effort and amount of funds expended on the analysis. Often such studies are performed in several stages.

Data from various sources for phosphate rock reserves and resources can range from very concise to broad calculations based on many assumptions. Some of the studies indicate confidential information was obtained from producers and other sources. Data in these studies are often composited to mask the source and then the data is analyzed. Often, reserve and resource figures are quoted without references in an article. The next time these figures are found in the literature, phosphate rock reserve and resource figures are then quoted with a reference.

In reviewing this report, the reader may get the impression that much of this material is rather dated. However, this is the best information the author could locate that could be made available to the public. If the phosphate rock resources identified and estimated in the older literature have not been mined, these resources are still available.

Resource/Reserve Classification for Phosphate Rock

In 1976, USGS and USBM staff developed a common classification and nomenclature that was published as U.S. Geological Survey Bulletin 1450-A (USGS, 1976). A revision, *Principles of a Resource/ Reserve Classification for Minerals* (USGS, 1980), was published as Geological Survey Circular 831 in 1980. The agencies recognized that known resources should be classified from two standpoints: (1) purely geologic or physical/chemical characteristics – such as grade, quality, tonnage, thickness and depth of the material in place; and (2) profitability analyses based on the costs of extracting and marketing the material in a given economy at a given time (Figures 10 and 11). Please refer to the original USGS publication for exact definitions and guidelines for classification of minerals. There are other guides for reserve/resource determinations (JORC, 2004; SME, 2007; CIM, 2008; PERC, 2008; US SEC, 2007) for various regions of the world and countries. These guides use similar terminology. These guides provide criteria for reserve/resource classification for professional purposes or for purposes of using resource/ reserve information in publicly available media used for investment decisions.

The following are some simplified definitions of the USGS/USBM classification system applied to phosphate rock.

- ***Resource*** – A concentration of naturally occurring phosphate material in such a form or amount that economic extraction of a product is currently or potentially feasible. Resources are divided into many categories depending on the amount of pertinent information available to define the amount of material potentially available and if it is economic, marginally economic or sub-economic to exploit these resources.
- ***Reserve Base*** – The part of an identified resource that meets minimum criteria related to current mining and production practices including grade, quality, thickness and depth.
- ***Reserves*** – The part of the reserve base which can be economically extracted or produced at the time of the determination. This may be termed marginal, inferred or inferred marginal reserves. This does not signify that the extraction facilities are in place or functional.
- ***Economic*** – Profitable extraction or production under defined investment assumptions has been established, analytically demonstrated or assumed with reasonable certainty.

This system appears to be logical, well thought out and explained. At face value, this system appears to be

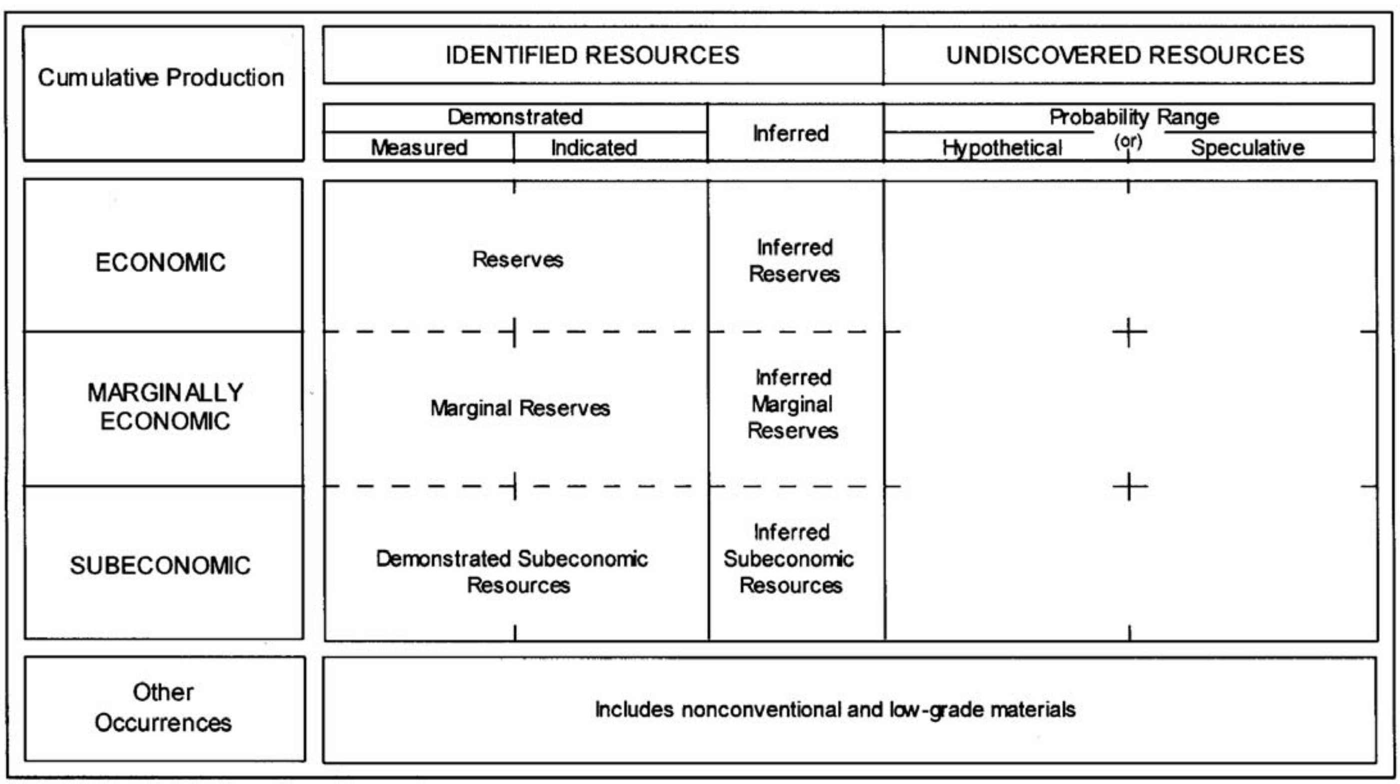


Figure 10. Major Elements of USBM and USGS Mineral-Resource Classification, Excluding *Reserve Base* and *Inferred Reserve Base*

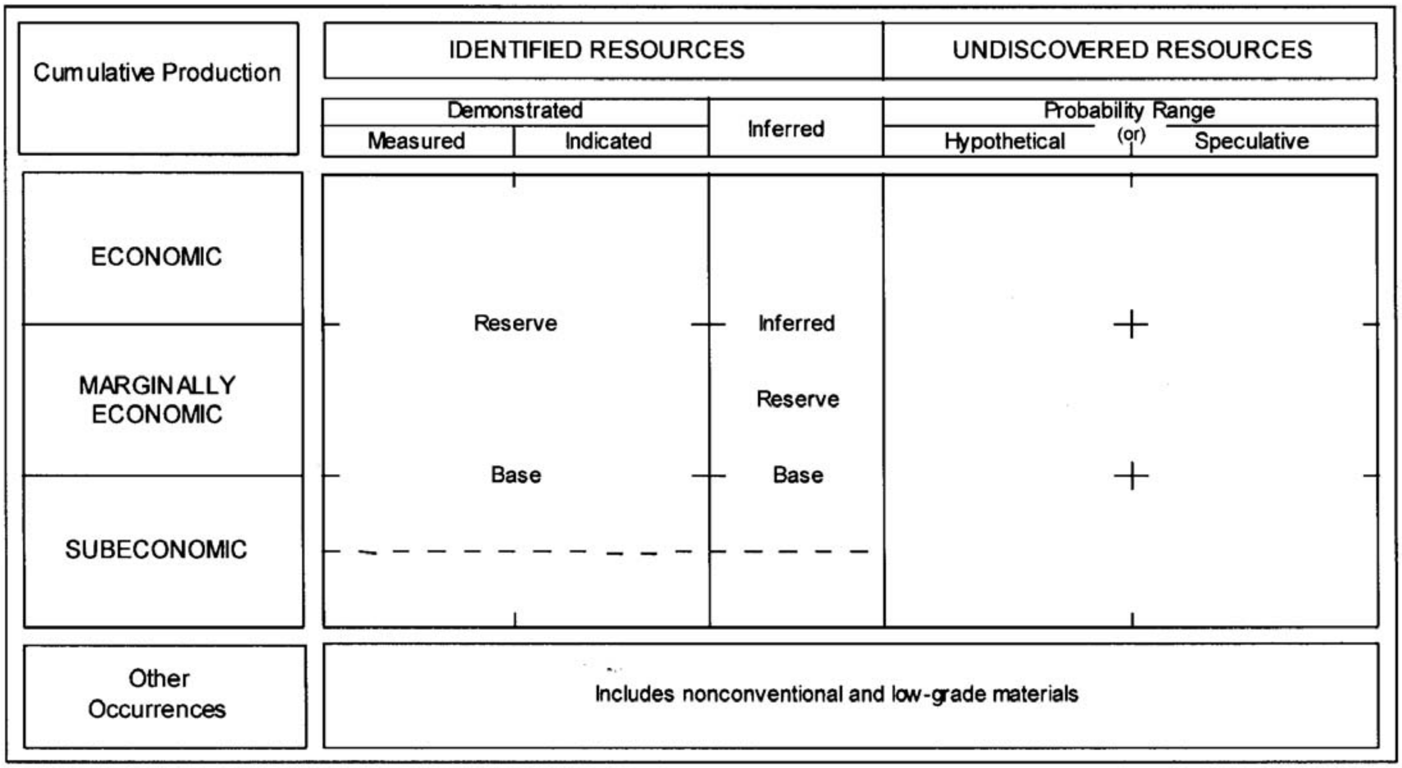


Figure 11. ***Reserve Base*** **and** ***Inferred Reserve Base*** **Classification Categories of USBM and USGS**

straightforward. However, such a system requires a considerable amount of data to initiate and then to maintain. Under such a system and in order for a geologic survey or other organization or individual to make estimates, information often must be provided by mining companies. This information generally must be presented in aggregated forms by any organization publishing these data. Detailed analysis of these data cannot be provided if it compromises a company's strategic position or, if publicly traded, influences its stock price.

In reality, the terms reserves and resources are used in a very erratic fashion in the traditional phosphate rock literature or from other information sources. Under the USGS system, reserves are included in the resource determinations. In the definitions, it is not clear if the reserves should be included in the resources as recoverable product or material in situ. The USGS/USBM system does not take mining losses or ore dilution into account. Poorly defined terms such as "proved," "measured," "identified," "geologic" and others are both applied to resources and reserves in the general literature.

In the last 20 to 30 years, numerous other factors have assumed increasing importance affecting the classification of reserves. These include legal factors; exploitation must be compatible with local, national or international agreements on ownership and environmental restrictions. Environmental issues include obtaining permits. Permits may involve satisfying regulatory requirements at several levels of government. Legal challenges may be posed by governmental bodies or non-governmental organizations. Permitting and resolving challenges to mining may be very time-consuming and costly to resolve. Reclamation after mining must be planned and accounted for in any mine plan. For a perspective on the socio-cultural and institutional drivers and constraints to mineral supply, see Brown (2002). All of these factors must be taken into account in classifying phosphate rock or other deposits as reserves.

Typically, insufficient data are presented in traditional and other literature to objectively evaluate if the reported reserves are indeed economically producible. Reserves may be reported as tons of producible product at an average P_2O_5, ore in the ground at an average P_2O_5 or as cubic meters (m^3) of ore. Resource estimates may include an average P_2O_5 content, or they may not. Often, broad-scale phosphate resource estimates do not include the original sources of these data.

After a phosphate deposit is located and the deposit is being developed, boreholes for samples are drilled on regular grids. In the exploration stage, borehole locations may be very widely spaced (kilometers apart). Chemical analyses of borehole intervals in the initial stages of development are usually rather limited and may be designed to ensure the beds or body of material is apatitic phosphate rock that is potentially commercial. The P_2O_5 contents for a bed or a sequence of beds are usually determined over an area. If development proceeds, at some point laboratory beneficiation work is performed and eventually larger scale samples are taken (usually by pitting) for pilot plant-scale work to verify the yield of concentrate from the ore and suitability of phosphate rock concentrates for processing to fertilizer or other products. In most areas of the world, to establish “proven” reserves, boreholes and samples are drilled on approximately 100-m centers. Samples from selected intervals may be processed in laboratory scale to simulate commercial-scale beneficiation. Boreholes may be more widely spaced for other reserve categories if the beds are uniform in thickness, composition and processing characteristics.

Phosphate mines, beneficiation facilities and downstream fertilizer processing plants are usually designed for a 20- to 30-year working life or longer. Individual mines, mining tracts, production panels or ore bodies must have the reserves to support such facilities over their working life or beyond.

Extensions of existing mines or development of new mines and related infrastructure may require capital investment in terms of hundreds of millions to billions of U.S. dollars. Investment may require bank lending and/or joint ventures or partnerships. Consultants are often employed in these instances to monitor studies and assess the results of investment studies. Substantial investment is generally involved and this usually requires proper justification and significant documentation. It must be proven that there is sufficient ore that can be upgraded to suitable product for at least the term of the loan and/or the productive lifespan of the mine. For an overview of the assessment of fertilizer projects, see Van Kauwenbergh (2006). Considerable time and money must be spent in developing sound assessments of technical and economic feasibility.

All companies engaged in phosphate rock production must have estimates of reserves in terms of product for some foreseeable future if they are to be sustainable. Companies requiring public disclosure by law usually provide reserve estimates in terms of product or estimates that might be recalculated in terms of phosphate rock product. However, much of the time the phosphate rock reserves indicated by various sources are not very straightforward. The reader should bear this in mind during the examination of this report.

In this report the following simplified definitions will be used.

- ***Reserves*** – Phosphate rock that can be economically produced at the time of the determination using existing technology; reported as tons of recoverable concentrate.
- ***Resources*** – Phosphate rock of any grade, including reserves, that may be produced at some time in the future; reported as tonnage and grade in situ.

It cannot be stressed enough that only a fraction of the phosphate rock resources are technically and economically suitable for production at any point in time. Technology changes and production costs fluctuate over time.

Markets for various commodities are generally first established near historic sources. As the demand and use of a commodity becomes established and grows, the search for more deposits widens. The search for phosphate rock deposits certainly became global in the early to mid-20th century. As the global market for fertilizers and concurrently the market for phosphate rock developed, the most suitable and/or favorable known deposits were developed. These deposits, or portions of these deposits, were amenable technologically and economically to development at the time and tended to be near ports or markets. Many of these deposits produced direct shipping product or ore that could be beneficiated by relatively simple methods. Generally, the highest grade material was near the surface. Over time, technology progressed; mining and beneficiation treatment became more complex. Production of phosphate rock was and is being conducted on an increasingly larger scale.

If the price of any final product commodity goes up, the amount of money that can be invested to mine and money spent to produce the commodity can be increased. When this happens, mining companies can go deeper in the earth to obtain the raw material and can invest more to enrich lower grade ores. The implementation of suitable technologies in mining or beneficiation, or increasing the scale of operations, can result in reclassifying deposits or portions of deposits that are considered resources to the reserve category. As prices increase, deposits which were economically marginal or projected to be unprofitable can become reserves (i.e., economically marginal deposits become suitable for profitable investment).

Previous World Phosphate Rock Reserve and Resource Estimates

This section does not attempt to list, point out the merits of or critique every world phosphate rock resource and reserve estimate. This section only attempts to list some of the more significant phosphate resource and reserve estimates made since about 1970, and the basis on which these studies were performed. As indicated in a previous section, bear in mind the use and meaning of the terminology “reserves” and “resources,” and associated modifiers, by various authors is highly variable.

The increasing use of phosphate rock for phosphate fertilizer and the publication by the IOE (1971) apparently motivated several individuals and institutions to examine the issue of phosphate reserves and resources. The original IOE document listed about 23,000 mmt of phosphate rock available as reserves. Emigh (1972) pointed out the inconsistencies in the IOE report with respect to other sources of information and reviewed potential world resources of phosphate rock concluding with an estimated reserve of approximately 1,200,000 mmt. The Emigh estimate (1971) did not include many countries now known to have significant phosphate rock reserves and resources including Algeria, Jordan, Morocco, People’s Republic of China, Peru, Syria and Tunisia.

Wells (1975) performed a mineral resource analysis based on the IOE data, revised IOE data, the data of Emigh and on the basis of other assumptions. Wells used various resource estimates, population growth modeling, estimates of fertilizer use and potential costs of production to explore various scenarios. The analysis conducted by Wells indicated the IOE report conclusions were wrong. The Wells report (1975) used a reserve figure of approximately 180,000 mmt of P for calculations; this translates to 530,000 mmt of phosphate rock at 30 percent P_2O_5. Wells’ calculated world phosphate rock reserve exhaustion times were more on the order of thousands of years.

Notholt (1975) discussed world phosphate rock production at a time when it was still rapidly increasing. Notholt indicated estimates of world phosphate rock resources vary considerably but the estimates generally indicated between 100,000 mmt and 150,000 mmt. At that time Notholt noted 40,000 mmt of phosphate rock reserves in Morocco at up to 32 percent P_2O_5. Notholt indicated there were about 7,200 mmt of reserves in the United States at 30 percent P_2O_5 and about 49,000 mmt of resources at 24 percent P_2O_5. Notholt (1975) did not tabulate total world figures. In 1975, Notholt recognized there were phosphate rock resources in the People’s Republic of China but did not list any figures.

A summary of phosphate resources of the United States and the free world (as it was known in this time period) from DeVoto and Stevens (1979) is given in Table 2. The figures from the original tables were converted to metric tons. This was actually a study concerned with uranium recovery from the phosphate resources of the United States and the rest of the free world, and it was conducted for the U.S. Department of Energy. The phosphate resources of the United States are examined in great detail, while the resources of the rest of the free world are reviewed generally. This study was performed with the cooperation of the U.S. phosphate industry; 24 individual companies are listed in the acknowledgments of the study. Richard C. Fountain and Associates, Winter Haven, Florida, conducted the study on the southeastern United States. C.W. Bauer and C.P. Dunning conducted the analysis of the U.S. Western Phosphate Field. G.E. Rouse examined other uraniferous phosphate resources of the United States. G.D. Emigh summarized the data on the phosphate resources of the rest of the free world.

Phosphate resources were identified and then further classified by several criteria. Total phosphate resources were calculated for districts, states or countries with a typical P_2O_5 content. For the southeastern United States, a 50-65 percent P_2O_5 recovery factor was applied to the resource determination depending on the district to arrive at the potentially minable product. A beneficiation recovery factor of 1.6 tons of ore to produce 1 ton of concentrate was applied to the U.S. Western Phosphate Field. Recovery factors for the rest of the free world deposits were apparently calculated from individual deposit data and aggregated for individual countries. Mining recovery factors were applied depending on the district and/or mining method. Lands not available for mining were subtracted from the available resources. Please see the footnotes for Table 2 and the original text for details.

The estimated phosphate rock resources of the southeastern United States in the DeVoto and Stevens study (1979) were reduced from approximately 150,000 mmt to 18,000 mmt of recoverable product at 30 percent P_2O_5 (approximately 12 percent of the estimated resource). The phosphate rock resources of the U.S. Western Phosphate Field were reduced from approximately 900,000 mmt to 200,000 mmt of recoverable

Table 2. Summary of Phosphate Resources of the Free World Adapted From DeVoto and Stevens (1979)

Area	Phosphate Resource	Typical P_2O_5 Content of Phosphate Resource	Potentially Mineable Phosphate Product (~30% P_2O_5)[a]	Estimated Recoverable Phosphate Product (~30% P_2O_5)[b]
	(mmt)	(%)	(mmt)	(mmt)
United States				
Southeastern				
Central Florida	8,854	15-18	1,576	1,024
Southern Extension	23,454	10-15	4,612	2,767
North Florida-South Georgia	17,336	8-10	2,930	1,600
Eastern Florida	23,215	8-16	4,025	2,415
Eastern Georgia-South Carolina	16,492	4-15	3,147	1,621
North Carolina	65,100	8-18	13,686	8,554
Others	247	16-23	131	63
Subtotal	154,699		30,107	18,044
Western Phosphate Field				
Idaho	294,748[c, d]	24-26	184,217[d]	76,269
Utah	140,141[c, d]	24-26	87,275[d]	31,907
Wyoming	260,882[c, d]	24-26	162,185[d]	61,142
Montana	52,894[c, d]	22-24	32,533[d]	14,228
Subtotal	748,665		466,209	183,545
Other[e]	8,538	12-28	2,048[d]	1,023
Total United States	911,902		498,364	202,612
Rest of Free World				
Algeria	998	25	635	476
Australia	3,629	17	1,451	1,089
Brazil	1,996	5-14	383	287
Egypt	1,492	20-26	907	680
Iraq	2,141	18	699	525
Jordan	14,515	15-33	3,629	2,722
Mexico	46,439	3-27	5,020	3,765
Morocco	79,832	25-34	54,431	40,823
Peru	9,072	8-12	2,722	2,041
South Africa	95,527[f]	7-16	46,058	3,266
Syria	816	19-28	490	367
Tunisia	1,179	26-30	826	619
Western Sahara	9,979	31-33	6,713	5,025
Others	4,482	13-30	1,664	1,250
Total, Rest of Free World	272,097		125,627	62,945
Total, All of Free World	1,183,999		623,991	265,557

a. Includes the phosphate product (of approximately 30 percent P_2O_5 content) that could be producible from the total phosphate resource, without accounting for a mining recovery factor, but accounting for an unavailability factor. In the United States, resources unavailable for mining development because of federal land classifications, cultural features or other environmental factors are included in the total phosphate resource column but are excluded from the potentially minable phosphate product column. Only the federal land classifications listed on page 218 of DeVoto and Stevens (1979) are specifically used here for resource exclusion purposes. (In other words, only the portion of RARE II lands recommended for wilderness designation are considered unavailable for purposes of this table.)
b. Average mining recovery factors generally of 50-75 percent for surface minable resources, depending on the district, 50 percent for underground resources to a depth of 5,000 feet and sub-ocean resources, and 35 percent for deep underground (greater than 5,000 foot depth) resources have been applied to the “Potentially Minable Phosphate Product” to determine this “Estimated Recoverable Phosphate Product.”
c. Includes ore-grade ($\geq$18.0 percent P_2O_5) resources in all resource depth categories.
d. A beneficiation recovery factor of 1.6:1, the operating experience in the Western Phosphate Field, has been applied to the phosphate resources in order to obtain the potentially minable phosphate product. In other words, 1.6 tons of phosphate resource must be mined and beneficiated to produce 1.0 ton of approximately 32 percent P_2O_5 product.
e. Includes all other marine phosphorites of the United States, but not any of the monazite placer or igneous apatite deposits, because of their clear lack of economic viability.
f. The offshore phosphorites off South Africa, which are lithified to a great extent, are considered to be not minable with current technology.

product at 30 percent P_2O_5 (approximately 22 percent of the estimated resource). The total for the rest of the free world was reduced from about 270,000 mmt to 63,000 mmt (approximately 23 percent of the estimated resource). Overall, all of the free world resources were estimated at about 1,200,000 mmt. Recoverable product was estimated at about 266,000 mmt at 30 percent P_2O_5 (approximately 22 percent of the original estimated resources).

The DeVoto and Stevens report indicates that the United States had the largest phosphate rock resources in the free world, based primarily on the phosphate resources of the Western Phosphate Field. For Morocco, the paper indicated approximately 80,000 mmt of resources, which translated to about 41,000 mmt of recoverable product. The report indicated there was not enough prospecting data to make any accurate estimates of quantities in Morocco. In the text of the report, it is mentioned that one data source indicated as much as 60,000 mmt of product could be available from Morocco.

Chapter 4 of the DeVoto and Stevens report lists other phosphate resources of the United States. The conclusion was that the igneous apatite deposits are small or low grade. One of the most interesting of the sedimentary deposits is in the Brooks Range of Alaska (6,000 mmt); however, most of this resource lies in the Arctic National Wildlife Refuge. The DeVoto and Stevens (1979) work indicates exploration for phosphate resources in the rest of the free world at that time was in its infancy. The report contains no data for Centrally Planned Economy Countries (CPECs) or countries other than those listed in Table 2.

Cathcart (1980) divided world phosphate rock resources and reserves into marine phosphorite (Table 3a), apatite of igneous origin (Table 3b) and deposits derived from guano. Cathcart (1980) expressed reserves and resources in terms of at least 30 percent P_2O_5. Tonnage figures for reserves from the literature apparently were converted to product based on P_2O_5 contents. It appears Cathcart did not consider mining or processing losses. Reserves were material that could be produced at a profit using “today’s” prices and technology. Resources included reserves and were considered deposits of reasonably known extent and grade but were not profitable to produce.

The phosphorite and igneous apatite reserves and resources determined by Cathcart (1980) are summarized in Table 3c. Cathcart (1980) indicated there were 35,000 mmt of at least 30 percent P_2O_5 phosphate rock resources in Morocco and 15,000 mmt in Western Sahara; combined reserves of both localities are given as 6,600 mmt. The total resources of the United States are given as 13,000 mmt, of which 7,600 mmt were considered reserves. In *Geological Survey Circular 888* a few years later, Cathcart, Sheldon and Gulbranson (1984) indicated total U.S. identified recoverable resources were 7,000 mmt, 23,430 mmt and 15,000 mmt in the economic, marginal and subeconomic categories, respectively, for a total of 45,430 mmt. Chinese resources at that time were considered 1,000 mmt with 100 mmt as reserves. Compared with the DeVoto and Stevens (1979) study, the Cathcart estimate seems very conservative. Cathcart indicated the reserve basis for the IOE study of 1971 was obviously in error.

In 1980 British Sulphur Corporation published the Fourth Edition of *World Survey of Phosphate Deposits* (Mew, 1980). This is an invaluable source of information concerning phosphate rock deposits listing reserves, resources and other data. In 1987, British Sulphur published the Fifth Edition of *Phosphate Deposits of the World* (Savage, 1987). This was the last edition of this series; it did not contain a summation of world reserves and resources.

Demonstrated world phosphate resources as of January 1985, according to Fantel et al. (1988), are summarized in Table 4. *USBM Information Circular 9187* was an in-depth analysis using information from many sources, including generally available literature, the Bureau of Mines Minerals Availability System (see Spangenberg, Carey and Takosky, 1983) and contracts with Zellars-Williams Inc., Lakeland, Florida, and the British Sulphur Corporation. USBM investigated resources, costs, capacities, market relationships and the short- and long-run supply of phosphate rock and phosphoric acid.

The base case was 1985. The quality and grade of phosphate ore resources were evaluated based on physical and technical conditions that affect production for each deposit. Two hundred and six deposits in 30 market economy countries were evaluated. Capital investment and operating costs for appropriate mining and beneficiation methods were evaluated for each mine or deposit. Company-provided data were used when possible. However, when costs were not available, many cost-operating parameters were estimated using a USBM cost-estimating system. A cash flow analysis of each operation was performed to determine the total cost of each mine, or deposit, production life as determined by estimates of capacity and demonstrated resources and the tonnage of product that could be produced at specific production levels.

Table 3a. World Phosphate Reserves and Resources of Marine Phosphorite (in mmt of Material Containing at Least 30% P_2O_5), Adapted From Cathcart (1980)

Location	Reserves	Resources
	(mmt)	(mmt)
North Africa		
Algeria	500	600
Morocco	5,000	35,000
Tunisia	500	800
West Africa		
Angola	20	100
Senegal (Taiba)	100	1,000
(Thies)	90	2,000
Western Sahara	1,600	15,000
Togo	100	200
Middle East		
Egypt	800	2,000
Iran	30	100
Iraq	60	600
Israel	100	200
Jordan	100	200
Saudi Arabia		1,000
Syria	400	400
Turkey		300
Europe		
USSR (Kazakhstan)	250	250
(Karatau)	700	700
(Aldan, Yakut)	500	2,000
Other (France, Belgium, Germany)	15	30
Asia		
Australia	500	1,500
China	100	1,000
India	70	200
Mongolia	250	700
North Vietnam	100	400
Pakistan		150
North America		
Mexico (Baja)		1,000
(Zacatecas)		140
United States		
(Eastern)	1,600	6,000
(Western)	6,000	7,000
South America		
Brazil (Bambui)	200	500
(Olinda)		20
Colombia		600
Peru (Sechura)		6,100
Venezuela	20	20
Totals	19,705	87,810

Table 3b. World Phosphate Reserves, Resources and Production of Apatite of Igneous Origin (in mmt of Material Containing at Least 30% P_2O_5), Adapted From Cathcart (1980)

Location	Reserves	Resources
	(mmt)	(mmt)
Kola Peninsula, USSR	400	400
Phalaborwa, South Africa	100	1,300
Brazil (Carbonatites)		
Araxa	50	50
Jacupiranga	12	
Catalao	75	75
Tapira	100	150
Others		500
Eastern Uganda	40	160
Finland	50	100
North Korea	5	30
Southern Rhodesia-Dorowa	10	10
Canada	–	40
Others	10	30
Totals	852	2,845

Table 3c. Cathcart (1980) Summary

Type	Reserves	Resources
	(mmt)	(mmt)
Marine phosphorite[a]	19,705	87,810
Igneous	852	2,845
Total	20,557	90,655

a. Marine phosphorite is assumed to be sedimentary phosphate rock of marine origin.

U.S. phosphate deposits had to meet the technological criteria representing then-current U.S. industry standards. This included ore tonnage in a radius from the center of the deposit, minimum grade of ore and concentrate, minimum bed thickness, maximum overburden-to-ore ratios and a maximum MgO content for Florida deposits (less than 1.0 percent MgO). Western U.S. phosphate deposits were only evaluated above entry-adit level.

Foreign deposits had to meet defined criteria. Producing properties accounting for 85 percent of each producing country were evaluated. Developing and explored deposits were evaluated where the demonstrated reserve-resource quality met the lower limits of producing deposits. Past producing deposits were evaluated when the reserve-resource quality met the quality of producing deposits.

Data were aggregated for producers and areas in North America, South America, North Africa, West Africa and the Middle East. Operating costs, recovery of capital and 0 percent discounted cash flow rate of return (DCFROR) and a 15 percent DCFROR were evaluated. Total costs were plotted for market economy countries (MECs), the United States and North Africa to determine the total recoverable phosphate rock at various cost levels.

Data from MEC countries indicated about 35,000 mmt of recoverable rock could be produced at less than US $100/ton. There were no economic data for CPECs. Recoverable rock product from the CPECs brought the total to 37,000 mmt.

At that time, 82 percent of the recoverable phosphate rock (1,300 mmt) that was estimated to be

Table 4. Summary of World Demonstrated Phosphate Resources as of January 1985, Adapted From Fantel et al., 1988

Region and Country	In Situ Ore Tonnage	In Situ Grade	Recoverable Rock Product	Rock Product Grade
	(10^6 mt)	(wt % P_2O_5)	(10^6 mt)	(wt % P_2O_5)
MECs:				
North America:				
Canada and Mexico	[a]	[a]	199	34
United States	26,625	9	6,104	30
Total			6,303	
South America:				
Brazil	[a]	[a]	387	34
Colombia, Peru and Venezuela	2,613	10	415	30
Total			802	
East Africa: Uganda	186	12	35	42
North Africa:				
Algeria and Tunisia	1,247	22	545	31
Morocco and Western Sahara	39,005	28	21,559	31
Total			22,104	
Southern Africa:				
Angola and Zimbabwe	39	16	11	34
Republic of South Africa	21,426	6	2,544	37
Total			2,555	
West Africa:				
Senegal and Togo	834	27	237	34
Middle East:				
Egypt	1,755	26	1,006	28
Iraq, Saudi Arabia and Turkey	739	21	304	32
Israel	357	26	190	32
Jordan	1,169	26	511	33
Syria	447	24	204	30
Total			2,215	
Oceania:				
Australia and Christmas Island	1,588	18	611	33
Nauru	22	38	14	39
Total			625	
Europe: Finland	1,120	6	114	37
Asia: India, Pakistan and Sri Lanka	107	25	65	32
Total MECs			35,055	
CPECs[b]				
China	337	26	208	28
USSR	[a]	[a]	1,333	33
Total CPECs			1,541	
Total World			36,596	

a. In situ tonnage and grades are not totaled or averaged because deposits of different geologic types have been combined (e.g., igneous and sedimentary).

b. Values have not been updated from previous world study; they remain as of January 1981.

produced for less than $30/ton was from the United States. Fantel et al. (1988) indicated much of the competing phosphate rock from existing mines in Morocco (which were indicated to have sufficient resources to last well into the next century) can be produced for under US $40/mt.

It should be noted that the Fantel et al. (1988) analysis was on the basis of 1985 data. At that time, they indicated there were about 39,000 mmt of ore in Morocco and Western Sahara from which it was estimated approximately 22,000 mmt of recoverable rock product could be obtained. The study included producing mines in the Khouribga and Youssoufia districts and non-producing deposits in these areas and the Meskala district. At roughly the same time, OCP (1989), on the basis of 1985 data, indicated identified phosphate rock resources were 26,800 mmt (at greater than 25 percent P_2O_5) at Khouribga, 8,020 mmt (at greater than 22.9 percent P_2O_5) at Youssoufia, 20,480 mmt (at greater than 20.6 percent P_2O_5) at Meskala and 950 mmt (at greater than 31.1 percent P_2O_5) at Bu Craa. OCP (1989) indicated that at the time only 31 percent of the Khouribga deposit area was explored and only 18 percent of the Ganntour deposit area was explored. No figure was given for the coverage of exploration in the Meskala area. The grades and bed thickness given by OCP for the Khouribga and Youssoufia districts indicate they probably only included beds that could be mined and washed to produce product.

Tables 5a through 5h incorporate data from Notholt, Sheldon and Davidson (1989), *Phosphate Rock Resources of the Phosphate Deposits of the World*. These tables are synopsis tables from the introductory sections

Table 5a. World Phosphate Resources Summarized From Notholt, Sheldon and Davidson (1989) – Identified Phosphate Resources in North America

Age/Country	Resources	Average P_2O_5
	(mmt)	(%)
Neogene-Quaternary		
United States		
Florida	5,600	30+[a]
Georgia	1,000	30+[a]
North Carolina	9,000	30[a]
North Carolina[b]	2,000	30+[a]
California[c]	600	5+
Mexico	1,100	4+
Palaeogene		
Mexico	900	14
Jurassic		
Mexico	154	16
Triassic		
United States		
Alaska	5,700	12
Permian		
United States		
Western Phosphate Field	7,600	24
Carboniferous		
United States		
Alaska	300	16
Utah	800	20
Precambrian		
Canada[d]	245	26
Total		
Rock	34,999	24
P_2O_5	8,288	

a. Phosphate concentrate.
b. Blake Plateau (Charleston Bump).
c. Excludes 122 million tons averaging 17 percent P_2O_5 on Continental Borderland.
d. Igneous, Cargill and Martison complexes.

Table 5b. World Phosphate Resources Summarized From Notholt, Sheldon and Davidson (1989) – Identified Phosphate Resources in South America

Age/Country	Resources	Average P_2O_5
	(mmt)	(%)
Neogene-Quaternary		
Brazil[a,b]	1,906	10
Peru		
Sechura	1,453[c]	31[d]
Chile	374	9
Venezuela	45	23
Cretaceous		
Brazil[a,e]	286	5
Colombia	744	21
Venezuela	208[f]	20
Precambrian		
Brazil	227	13
Total		
Rock	5,243	18
P_2O_5	931	

a. Igneous.
b. Leached residuum derived from complexes of Cretaceous age: Anitapolis, Araxa, Catalao I, Ipanema and Tapira.
c. Proved resources total 350 million tons with 31 percent P_2O_5, as concentrate.
d. Phosphate concentrate.
e. Jacupiranga and Anitapolis complexes.
f. Proved resources.

for continents and regions of the world. The USSR and Mongolian People's Republic were treated separately. The introductory sections for each section appear to incorporate data from various chapters in the book and data from the authors' files. The phosphate rock tonnage is described as identified resources and gives an average P_2O_5 content. In the original text, appropriate footnotes are given for specific deposits. The deposits are generally broken down by age of deposit (sedimentary deposits) or emplacement time (igneous deposits).

The following are cursory comments on the tables derived from Notholt, Sheldon and Davidson (1989). Table 5a recognizes U.S. resources are typically given as concentrate or 30 percent-plus P_2O_5. In Table 5c, Moroccan resources are listed as approximately 56,000 mmt at 28 percent P_2O_5, apparently based on Chapter 47 (OCP, 1989). The calculation for the P_2O_5 content is not apparent. Saudi Arabian resources are listed as about 8,000 mmt in Table 5d based on Chapter 52 (Riddler, Van Eck and Farasini, 1989). This is one of the first instances in the literature that data were available on these Saudi Arabian resources.

In Table 5f, Chinese resources are reported as 4,000 mmt at 22 percent P_2O_5 and 8,000 mmt at 25 percent P_2O_5. The section listing the resources of the PRC references an article by Li (1986) found in Volume I of the *IGCP Project 156 – Phosphorites* series. There are no data on resources in Li (1986). There was an IGCP workshop and seminar in the PRC in 1982; this may have been the source of these data. This is one of the first instances in the literature that any information recognizing significant phosphate rock resources in the PRC was acknowledged.

Data from the various chapters in Notholt, Sheldon and Davidson (1989) are summarized in Table 5i. The total world resources are approximately 163,000 mmt at 22.5 percent P_2O_5 according to this tabulation.

The world reserve and resource estimates of the various authors vary widely. Most of these studies rely on secondary and tertiary data to estimate reserves and resources. Authors with geology backgrounds tend to optimistically describe phosphate deposits in broad terms. Mining engineers, geologists with economics and

Table 5c. World Phosphate Resources Summarized From Notholt, Sheldon and Davidson (1989) – Identified Phosphate Resources in Africa

Age/Country	Resources	Average P_2O_5
	(mmt)	(%)
Neogene-Quaternary		
Senegal	50[a]	29
South Africa		
Cape Province	100	6
Agulhas Bank[b]	1,400	10
Tanzania[c]	10	20
Uganda[d]	230	13
Eocene		
Algeria	500	24
Guinea Bissau	112	30
Mali[e]	12	25
Mauritania	100	20
Morocco	56,250[f]	28
Senegal	65	31
Togo	100	36[g]
Tunisia	3,000	16
Cretaceous		
Egypt	3,000[h]	22
Tanzania[a]	125	5.5
Zambia[a,i]	207	2.5
Zimbabwe[a]	100	7
Precambrian		
Burkina Faso	60	25
Burundi[a]	40	5.6
Mozambique[a]	155	9
Niger[j]	100	26
South Africa[a]	1,300	7
Total		
Rock	67,016	26
P_2O_5	17,419	

a. Igneous.
b. Ocean floor deposit. Extrapolated from a reported 140 million tons P_2O_5 and assuming an average of 10 percent P_2O_5.
c. Guano-derived phosphorite.
d. Leached residuum, Cretaceous Sukulu Carbonatite.
e. Tamaguilel deposit.
f. Includes the Bu Craa deposit, Western Sahara.
g. Marketable phosphate concentrate.
h. Proved reserves: 1,508 million tons averaging 23 percent P_2O_5.
i. Kaluwe Carbonatite only.
j. Tapoa deposit.

Table 5d. World Phosphate Resources Summarized From Notholt, Sheldon and Davidson (1989) – Identified Phosphate Resources in the Middle East

Age/Country	Resources	Average P_2O_5
	(mmt)	(%)
Palaeocene-Oligocene		
Iran	165	20
Iraq	4,050	22
Saudi Arabia	3,600	20
Syria	414	4
Upper Cretaceous		
Israel	1,000[a]	26
Jordan	1,574[b]	28
Saudi Arabia	4,280	20
Syria	643[c]	25
Devonian		
Iran	46	15
Cambrian		
Iran	30	12
Total		
Rock	15,642	21
P_2O_5	3,392	

a. Proved resources: 380 million tons averaging 27 percent P_2O_5.
b. Proved resources: 1,010 million tons averaging about 28 percent P_2O_5.
c. Proved resources: 60 million tons averaging 26 percent P_2O_5.

Table 5e. World Phosphate Resources Summarized From Notholt, Sheldon and Davidson (1989) – Identified Phosphate Resources in Europe

Age/Country	Resources	Average P_2O_5
	(mmt)	(%)
Miocene		
Italy	60	11
Cretaceous		
Belgium	60	9
Greece	29	15
Turkey	309	13
Permo-Carboniferous		
Norway[a]	70	8
Turkey[a]	20	9
Ordovician		
Yugoslavia	40	12
Devonian		
Finland[a,b]	110	17
Precambrian		
Finland[a]	470	5
Total		
Rock	1,168	7
P_2O_5	77	

a. Igneous.
b. Leached residuum associated with carbonatite.

Table 5f. World Phosphate Resources Summarized From Notholt, Sheldon and Davidson (1989) – Identified Phosphate Resources in Asia

Age/Country	Resources (mmt)	Average P_2O_5 (%)
Oligocene		
Pakistan[a]	200	5
Cambrian		
China	4,000[b]	22
India	45[c]	17
Pakistan	22	17
Vietnam	1,400[d]	23
Precambrian		
China	8,000[b]	25
India	132	23
Korea (D.R.)	88	13
Sri Lanka[a,e]	60[f]	38
Total		
Rock	13,947	24
P_2O_5	3,289	

a. Igneous.
b. Resource category not reported. Likely to include possible (hypothetical) resources.
c. High-grade portion: 10 million tons averaging 20 percent P_2O_5.
d. Proved: 100 million tons averaging 35 percent P_2O_5.
e. Leached residuum associated with carbonatite.
f. Proved: 30 million tons averaging 38 percent P_2O_5.

Table 5g. World Phosphate Resources Summarized From Notholt, Sheldon and Davidson (1989) – Identified Phosphate Rock Resources in the USSR and the Mongolian People's Republic (MPR)

Age/Deposit	Resources[a] (mmt)	Average P_2O_5 (%)
Palaeogene		
Kisil Kum	2,600	24
Cretaceous-Jurassic		
European USSR[b]	2,000	20
Devonian		
Khibiny[c]	4,000	15
Kovdor[c,d]	700	7
Ordovician		
Baltic Basin	6,500	10
Proterozoic-Cambrian		
Karatau Basin	3,000	23
Oshurkov[c]	500	5
Seligdar[c]	300	7
Khubsugul (MPR)	432	21
South Siberian		
Belka	274	10
Kharanur	300	11
Ukha Gol	483	11
Telek[e]	180	14
Total		
Rock	21,269	12
P_2O_5	969	

a. Estimated on best available data. Totals may include hypothetical (as yet undiscovered) resources.
b. Includes Aktyubinsk Basin, northwestern Kazakhstan.
c. Igneous.
d. Iron ore.
e. Leached residuum.

Table 5h. World Phosphate Resources Summarized From Notholt, Sheldon and Davidson (1989) – Phosphate Resources in Australia, New Zealand and Oceania

Age/Country	Resources	Average P_2O_5
	(mmt)	(%)
Neogene-Quaternary		
Australia		
Christmas Island[a]	214[b]	28
Mt. Weld[c]	250	18
French Polynesia		
Mataiva	24	38
Nauru[a]	15	39
New Zealand		
Chatham Rise	100[d]	22
Cambrian		
Australia		
Georgina Basin	3,352	17
Total		
Rock	3,955	18
P_2O_5	712	

a. Insular guano-derived phosphate.
b. Mostly as aluminium phosphate ore.
c. Leached residuum associated with carbonatite.
d. Extrapolated figure based on delineated reserve of 25 million tons over 380 km^2.

Table 5i. World Summary From Notholt, Sheldon and Davidson (1989) (Tables 5a-h)

Continent/Region	Resources	Average P_2O_5
	(mmt rock)	(%)
North America	34,999	24
South America	5,243	18
Africa	67,016	26
Middle East	15,642	21
Europe	1,168	7
Asia	13,947	24
USSR and MPR	21,269	12
Australia, New Zealand and Oceania	3,955	18
Total	163,239	22.5

engineering training, and mixed discipline teams of geologists, mining engineers and cost estimators evaluate deposits in greater detail. Great detail and cash flow analysis is required to categorize an undeveloped phosphate deposit as a reserve. Great detail and economic analysis is required to plan a mine, beneficiation plant and supporting infrastructure to ultimately provide phosphate rock concentrate to a processing facility or to an external market.

Current World Phosphate Rock Reserve and Resource Estimates

Phosphate rock reserves as published by the USGS and USBM in Mineral Commodity Summaries for 1989-2010 for the United States, USSR (transitioning to Russia), the PRC, South Africa, Morocco and Western Sahara and Jordan are illustrated in Figure 12. These are six of the top producers and holders of reserves over the last 20 years. According to Figure 12, U.S. reserves have essentially remained constant over the last 20 years at or a little over 1,000 mmt. U.S. producers prove reserves in about a 10- to 20-year timeframe in advance of production and in conjunction with new mine development. New mines are generally developed from a production core area as relatively continuous blocks of land. This is due to several factors including environmental aspects (permitting), logistical considerations and costs including personnel, acquisition, land classification and taxes. Permitting a mine in the United States may take 5-10 years.

USSR/Russian reserves plummeted to approximately 200 mmt after the changes in the Soviet Union and only Russian data were listed as reserves. There was essentially no data concerning the PRC until the early 1990s. In approximately 2003, official PRC government data were provided to USGS (Jasinski, 2010). For several years, the PRC appeared to have the largest phosphate rock reserves in the world. The Chinese reserve figures were revised in 2009 and 2010.

South African reserves remained constant at 2,500 mmt until 1999, when they were revised to 1,500 mmt. There have been no changes to South African reserves from 1999 to 2010. Moroccan reserves were 7,000 mmt in 1988 and 1990. Reserves then were

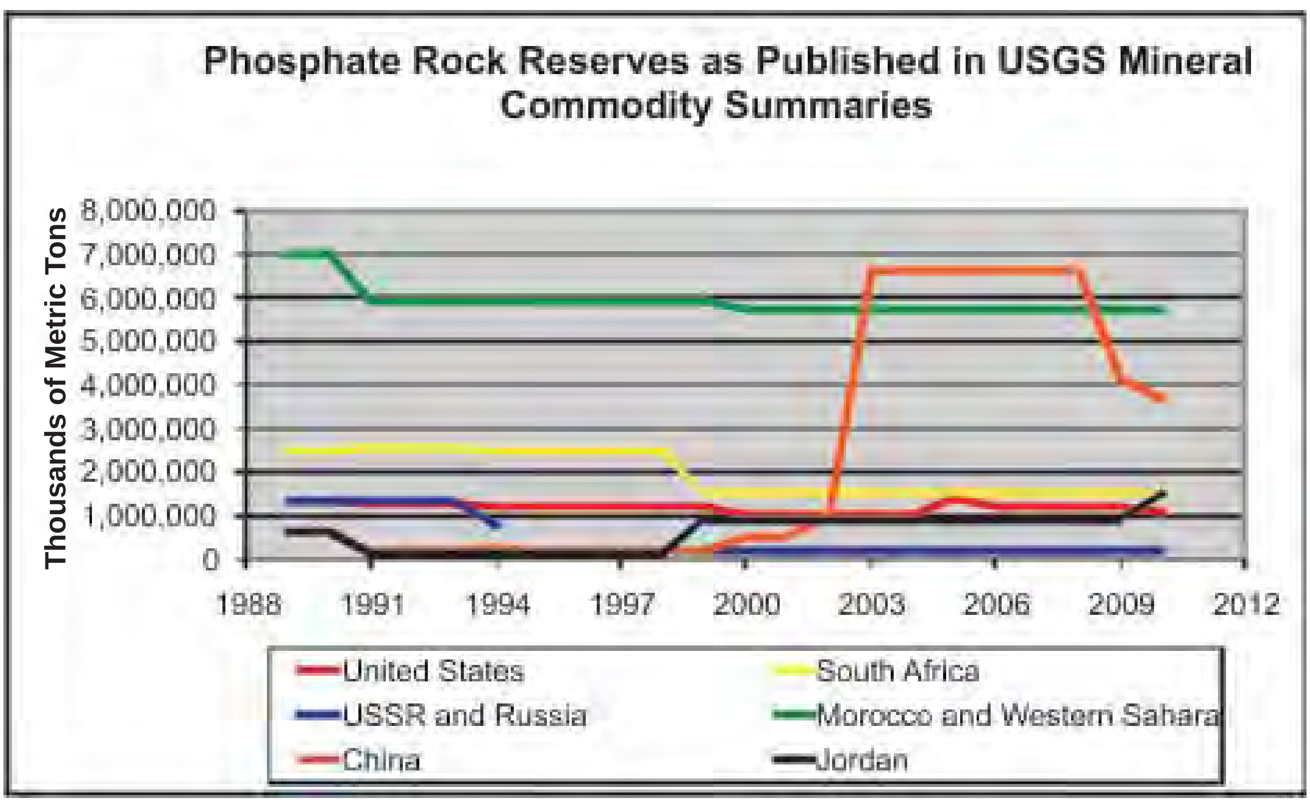


Figure 12. Phosphate Rock Reserves as Published in USGS Mineral Commodity Summaries (1989-2010)

revised to below 6,000 mmt until 1999 at which time they were revised to 5,700 mmt, where they remain today. Jordanian reserves were downgraded to 90 mmt in 1990 and stayed at that level until 1999, when they were revised to 900 mmt. This appears to be related to the development of the Eshidiya Mine. Jordanian reserves were revised to 1,500 mmt in 2010.

Production, reserves and reserve base data of the USGS Mineral Commodity Summary for 2008 released in January 2009 are given in Table 6. This was the last year the reserve base figures were published. As previously mentioned, 1993 was the last time USBM indicated that a cost of $40/ton was applied to reserves – and one of the criteria for the reserve base was phosphate rock producible for less than $100/ton.

Deposits derived from guano have been depleted for the most part and are not considered in this IFDC report. The exploitation of bird or bat guano usually involves disturbing bat or bird rookeries, involves a few hundred thousand tons of material (according to Cathcart, 1980) and will not be considered here. Secondary iron and aluminum phosphate deposits considered by Cathcart (1980) and other authors also will not be considered in this IFDC report.

World production and world reserves according to USGS as published in 2010 are given in Table 7. This data is compared and contrasted to the reserve and resource estimates developed as a result of this study.

The reserve and resource estimates in this study are based on limited information of varying quality. Estimates of the concentrate available from specific deposits are often based on ore-to-concentrate ratios, or ratios of concentration, found in the literature or based on run of mine ore and beneficiation plant capacities. When these ratios are found in the literature, the exact nature or source of the data used to derive these ratios is generally not given. These ratios may or may not be from in-place ore to concentrate or from mined ore to concentrate. For the purposes of this evaluation, these ratios are sufficiently accurate. When appropriate, a five percent loss of ore was assumed during mining. A figure of 95 percent recovery may or may not be appropriate. However, this

Table 6. USGS Phosphate Rock Mineral Commodity Summary, January 2009, Reserves and Reserve Base (USBM, 1988-1995; USGS, 1996-2010)

Country	Mine Production		Reserves[b]	Reserve Base[b]
	2007	2008[a]		
	(x 1,000)			
Australia	2,200	2,300	82,000	1,200,000
Brazil	6,000	6,000	260,000	370,000
Canada	700	800	25,000	200,000
China	45,400	50,000	4,100,000	10,000,000
Egypt	2,200	3,000	100,000	760,000
Israel	3,100	3,100	180,000	800,000
Jordan	5,540	5,500	900,000	1,700,000
Morocco and Western Sahara	27,000	28,000	5,700,000	21,000,000
Russia	11,000	11,000	200,000	1,000,000
Senegal	600	600	50,000	160,000
South Africa	2,560	2,400	1,500,000	2,500,000
Syria	3,700	3,700	100,000	800,000
Togo	800	800	30,000	60,000
Tunisia	7,800	7,800	100,000	600,000
United States	29,700	30,900	1,200,000	3,400,000
Other countries	8,110	10,800	890,000	2,200,000
World total (rounded)	156,000	167,000	15,000,000	47,000,000

a. Estimated.
b. See original publication for exact definition of terms.

Table 7. USGS Phosphate Rock and Mineral Commodity Summary, January 2010, Mine Production (2008, 2009) Reserves. IFDC Reserve and Resource Estimate

Country	Mine Production 2008	Mine Production 2009[d]	USGS 2010 Reserves[a]	IFDC Reserves[b] (Product)	IFDC Resources[c]
	(mmt)				
United States	30.20	27.20	1,100	1,800	49,000
Australia	2.80	2.50	82	82	3,500
Brazil	6.20	6.00	260	400	2,800
Canada	0.95	0.90	15	5	130
China	50.70	55.00	3,700	3,700	16,800
Egypt	3.00	3.30	100	51	3,400
Israel	3.09	3.00	180	220	1,600
Jordan	6.27	6.00	1,500	900	1,800
Morocco	25.00	24.00	5,700	51,000	170,000[e]
Russia	10.40	9.00	200	500	4,300
Senegal	0.70	0.00	80	50	250
South Africa	2.29	2.30	1,500	230	7,700
Syria	3.22	3.00	100	250	2,000
Togo	0.80	0.80	60	34	1,000
Tunisia	8.00	7.00	100	85	1,200
Other countries	7.44	7.00	950	600[f]	22,000[g]
World total (rounded)	161.00	158.00	16,000	60,000	290,000

a. See original publication for exact definition of terms.
b. Reserves as usable or marketable product. See text for details.
c. Resources as unprocessed phosphate rock of varying grades or concentrate. See text for details.
d. Estimated.
e. Including hypothetical resources based on the area limits of the deposits, Morocco resources may be approximately 340,000 mmt
f. Includes data from Algeria, Finland, Peru and Saudi Arabia (Al-Jalamid).
g. Includes data from Algeria, Angola, Finland, Kazakhstan, Peru and Saudi Arabia.

is usually achievable according to numerous mine managers and phosphate rock mining consultants and is typically a goal in most open-pit operations around the world. In evaluating underground operations, it was assumed the terminology "recoverable ore" indicated mining losses and ore left for support were not included in the reserve figures.

References concerning each deposit were critically evaluated to determine if the tonnage listed as reserves was indeed reserves as recoverable concentrate (product) or reserves as ore, or if the tonnage listed as reserves was indeed resources. In some cases, it was obvious that data should be reclassified. In some cases, classification of the data was rather subjective, and when this was done, the justification for this is mentioned in the description for each country.

In order to evaluate reserve data, reserves were calculated to a common basis, if necessary. That is, IFDC reserve data (Table 7) are listed in terms of million metric tons (mmt) of recoverable concentrate. The analysis was focused on the countries that have been recently listed by USGS and other countries for which reserve data were available or data were available that could be recalculated in terms of tons of concentrate.

The USGS does not indicate an average P_2O_5 grade for the phosphate rock reserves of countries listed in compilations. This is generally because the average grade of phosphate rock may or may not be listed in official or other information available concerning deposits. If a phosphate rock grade or grades is listed in some type of literature concerned with reserves, it might be for a typical ore, several types of ore, a typical concentrate product or several grades of concentrate product. This paper also does not list the grades of reserves or resources in Table 7. Grades of phosphate rock resources, ores and concentrates can be found in the individual country sections and references within. The IFDC reserve data should be viewed as the tonnage of producible concentrate at the grade or grades typically produced for the deposits in the listed countries.

Resource estimates are more speculative than reserve estimates. Resource estimates are given in terms of unprocessed phosphate rock. Phosphate rock resource data was not recalculated to terms of tons of recoverable concentrate product as there are little or no criteria available for most deposits.

Practically no data are available in the generally available literature to ascertain current production costs and if the reported reserves or a portion of the reported reserves are actually economically producible. As mentioned in the World Phosphate Rock Production section, phosphate rock prices may have reached a new plateau at US $80-$110/ton depending on the source. The criteria of US $40/ton for phosphate rock reserves and US $100/ton for the reserve base are 15-20 years out of date and simply inappropriate.

Australia

USGS (2010) indicates the phosphate rock reserves of Australia are 82 mmt.

The economic demonstrated resources of Australia, as indicated by the terminology of the Australian Atlas of Mineral Resources, Mines and Processing Centers (2009), are 82 mmt. This is the reserve associated with the mine feeding the IPL phosphoric acid and ammonium phosphate plant in Queensland. Australian resources are estimated at 3,500 mmt (Cook, 1989). All other printed data or data available indicate all other Australian deposits are considered resources.

Brazil

USGS (2010) indicates the phosphate rock reserves of Brazil are 260 mmt.

The Departamento Nacional de Produção Mineral, Brazil (DNPM, 2010) indicates the reserves of phosphate rock in Brazil are 260 mmt at 100 percent P_2O_5. Based on data from Notholt, Sheldon and Davidson (1989) and Damasceno (1989), it is estimated that 11 mmt of the quoted total P_2O_5 reserve is sedimentary phosphate rock. This would indicate about 250 mmt P_2O_5 of the reserve figure is igneous rock. Production of sedimentary phosphate rock in Brazil appears to be minor and most of the production is igneous phosphate rock used for production of high analysis fertilizer. Igneous phosphate rock resources in Brazil average about 10.4 percent P_2O_5. The amount of igneous ore is calculated to be about 2,600 mmt. Data in Gurmendi (2009) indicate the concentrate-to-ore ratio of these deposits is 1:6.1 with an average P_2O_5 content of about 36 percent P_2O_5. Assuming 95 percent mining recovery, this translates to about 400 mmt of concentrate from the igneous deposits. The sedimentary phosphate rock deposits of Brazil do not appear to be suitable for upgrading to produce quality concentrates and are not considered a reserve for purposes of this paper.

Total IFDC-estimated phosphate rock resources of Brazil are the igneous sources (2,600 mmt) and 230 mmt of resources associated with the Rocinha Mine for a total resource of 2,800 mmt. Notholt, Sheldon and Davidson (1989) reported the total phosphate rock resources of Brazil were about 2,400 mmt at 5-13 percent P_2O_5.

Canada

Canadian reserves are based on an Agrium prospectus (2009) and are rounded to 5 mmt as product; the reserves of the Kapuskasing Mine. Agrium has indicated they are looking for additional reserves in the area. Canadian resources are based on the Kapuskasing reserves and the resource data for the Martison Project (Phoscan, 2009) at 125 mmt. These are igneous rocks located in central Canada.

Egypt

USGS (2010) indicates Egyptian reserves are 100 mmt.

The El Nasr Mining Company (ENMC) apparently controls all the reserves and resources of the Sabaiya area (east and west), the eastern desert and the Red Sea coastal area. ENMC (El Nasr Mining Company, 2010) develops reserves in advance of mining. West Sabaiya reserves are indicated as 24 mmt of ore. East Sabaiya reserves are indicated as 55 mmt of ore. The ore is dry or wet screened depending on the area. The typical ore-to-product ratio is 1.6. On this basis, the concentrate reserves of the West Sabaiya area are 15 mmt at about 27 percent P_2O_5. The reserves of concentrate for the East Sabaiya area are 34 mmt at about 29-30 percent P_2O_5. The reserves of phosphate rock from the Red Sea area are nearly exhausted. ENMC lists 1.6 mmt at a minimum of 27 percent P_2O_5 as reserves. Concentrate from the Red Sea has been marketed for direct application. The concentrate from West Sabaiya is marketed in Egypt. Concentrate from East Sabaiya is exported.

ENMC indicates there are 5.0 mmt of resources in the Red Sea area, 710 mmt of resources in the West Sabaiya area and 1,647 mmt of resources in the East Sabaiya area. The other significant Egyptian phosphate rock reserve/resource is in the Western Desert. Schröter (1989) indicates the experimental mine at Abu Tartur has been operational since 1984. As commercial production has not been proven, the phosphate rock in the area is considered to be resources. Issawi (1989) indicates 988 mmt at 23 percent P_2O_5 is available in the area.

The IFDC reserve estimate for Egypt is approximately 51 mmt product. Resources are estimated at 3,400 mmt of phosphate rock in situ. ENMC will undoubtedly prove more reserves in advance of mining in the Eastern Desert in the future.

Israel

USGS (2010) indicates there are 200 mmt of phosphate rock reserves in Israel.

The Geological Survey of Israel (GSI) (2010) indicates that 220 mmt of the known phosphate resources of Israel are marketable. The use of the term marketable indicates the 220 mmt is economic product. Ore-to-product ratios for Israeli phosphate ores appear to be about 1.6. The marketable phosphate rock product reserves might be about 130 mmt if the 220 mmt is actually ore. The P_2O_5 content of the marketable product is about 32 percent. GSI and Negev Phosphates Ltd. participated in a national phosphate rock survey involving 1,900 boreholes and 120,000 samples; 20 deposits were identified. The total phosphate rock resources of Israel are considered to be 1,600 mmt at 20.0-35.5 percent P_2O_5.

Jordan

USGS (2010) indicates Jordanian reserves are 1,500 mmt. The Jordan Phosphate Mines (2010) website indicates there are 1,459 mmt of ore reserves associated with the three operating mines (Eshidiya, Al Hassa and Al Abiad). This estimate is based on a well-defined ore assessment program.

There are three phosphate ore beds at Eshidiya. Beds A1 and A3 require processing. Bed A2 is direct shipping material which may be processed to remove fine dust. Bed thickness data found in Jallad, Abu Murrey and Sadaqah (1989) indicate Beds A1, A2 and A3 account for 25 percent, 44 percent and 31 percent of the ore, respectively. Data found in Goshen, Amara and Dabbas (1998) indicates the ore-to-product ratio of Bed A1 is 2.8 without flotation and 2.6 with partial flotation. The Bed A3 ore-to-product ratio is 3.0. Based on 95 percent mining recovery, bed thickness data, ore-to-product ratios and total ore reserves at Eshidiya of approximately 1,300 mmt, approximately 800 mmt of concentrate at over 30 percent P_2O_5 is the estimated reserve as product.

Jordan Phosphate Mines (2010) indicates there are 32 mmt of ore reserves at Al Hassa and 106 mmt of ore reserves at Al Abiad. Data in Fantel et al. (1988) indicate an ore-to-concentrate ratio of 1.6 for the deposits. Applying a 95 percent recovery factor and assuming the 1.6 ore-to-product ratio, the concentrate reserves at Al Hassa and Al Abiad are estimated at 19 mmt and 63 mmt, respectively.

Total phosphate concentrate reserves for the three mines in Jordan are estimated at approximately 900 mmt. The phosphate reserves of Jordan may eventually prove to be much larger. Reserves are mainly established on the Eshidiya Mine and at a production rate of 6-10 mmt/year are sufficient for the next 90-150 years.

Total Jordanian resources include the ore estimates from the three mining areas (1,300 mmt) and the Wadi El-Yabis structure in northwest Jordan (Mikbel and Abed, 1985). This area contains 370 mmt at 26.5 percent P_2O_5 and these are termed estimated reserves. Total phosphate rock resources of Jordan are estimated at approximately 1,800 mmt. This is probably a relatively low estimate of the phosphate rock resources of Jordan. The Jordan Natural Resource Authority (2010) estimates phosphate formations underlie approximately 60 percent of the surface area of Jordan.

Morocco

USGS (2010) indicates the phosphate rock reserves of Morocco are 5,700 mmt.

Phosphate deposits in Morocco occur in three areas – the Khouribga area (Oulad Abdoun Plateau), the Ganntour area (Youssoufia area) and the Meskala area. OCP operates the mine near Láyoune-Bu Craa. Exploitable phosphate beds were deposited in the Upper Cretaceous, Paleocene and Eocene eras in northwest Africa.

The phosphate rock resources of Morocco are extremely large and apparently still incompletely explored. In British Sulphur's *World Survey of Phosphate Deposits* (Savage, 1987), it was indicated that identified minable reserves were placed by OCP in 1984 at "56.25 billion tonnes." In view of the incomplete exploration, it was speculated total resources may approach 140 billion tons.

In 1989 OCP (1989) indicated 36 percent of the area of the Khouribga deposits was explored and ore resources were 26,800 mmt. At that time OCP indicated only 18 percent of the Ganntour (Youssoufia) deposit was explored and ore resources were 8,020 mmt. The ore resources of the Meskala and Bu Craa deposits were 20,480 mmt and 950 mmt, respectively. Total resources amounted to approximately 56,000 mmt.

Gharbi (1998) indicated the identified reserves of the Khouribga region were 37,370 mm^3 and the surface area of the deposit was 45 percent explored. The identified reserves of the Ganntour region (Youssoufia-Benguér region) were 30,750 mm^3; 30 percent of the area was explored. The identified reserves of the Meskala region were 15,000 mm^3 and Bu Craa (Oued Eddabab) identified reserves were 1,000 mm^3.

A factor of 2.0 tons/m^3 was used to convert the identified reserves of the deposits to phosphate rock tonnage. Data in OCP (1989) and Gharbi (1998) indicate the uppermost beds in the Khouribga region contain about 36 percent of the total phosphate rock thickness in the section and Bed 3 makes up about 64 percent. A mining recovery factor of 95 percent was used. A 1.8 ore-to-concentrate ratio (appropriate for Moroccan phosphate rock that is washed and screened) (based on Fantel et al. 1988 data) was used for the upper beds. An ore-to-concentrate ratio of 3.3 was used for Bed 2, which must be treated by flotation; this ratio was derived from averaging the ore-to-concentrate ratios of similar ores treated by flotation. A portion of the Khouribga product is treated by calcination. The effects of calcination on recovery are not known and not accounted for in this study. The estimated approximate amount for concentrate production in the area since 1985 (380 mmt) was subtracted from the total. The IFDC-estimated amount of reserves remaining in the Khouribga area is approximately 28,000 mmt.

For the Ganntour region deposit, a factor of 2.0 tons/m^3 and a mining recovery factor of 95 percent were used; it was assumed all the mining in the area would eventually be open-pit mining. Examination of the geologic sections in OCP (1989) and Gharbi (1998) indicates about 30 percent of the thickness of the phosphate rock in the section could be treated by simple screening and 70 percent would have to be treated by flotation. A washing and flotation unit was installed at Youssoufia in 2005. Some of the ore from the area may be treated by calcination. An ore-to-product ratio of 1.7 (Fantel et al., 1988) was used for the washed material and an ore-to-product ratio of 3.3 was used for the remaining material that must be treated by washing and flotation. The approximate production from the area since 1985 (200 mmt of product) was subtracted from the total. The IFDC-estimated reserves as product from the Ganntour area are approximately 22,000 mmt.

Gharbi (1998) indicated the identified reserves of the Meskala area were 15,900 mm^3 of ore. While the deposits of this area were explored in the 1970s and 1980s, no development has occurred. OCP has recently announced the opening of four new mines (Feytis, 2010); none of these mines are based on the Meskala area deposits. For the purposes of this study, the Meskala deposit phosphate rock is considered a resource, not as a reserve.

Gharbi (1998) indicated the identified ore reserves of the Bu Craa deposit were 1,000 mm^3. At 2.0 tons/m^3, this is 2,000 mmt of phosphate ore. Assuming 95 percent recovery, a 1.7 ore-to-product ratio (Fantel et al., 1988) and subtracting 50 mmt production, the remaining reserve as product is estimated at 1,100 mmt.

The identified reserves of the Khouribga, Ganntour and Bu Craa regions, or deposits, as calculated in this study are approximately 51,000 mmt as product. It is not known if all of this phosphate rock is truly producible at today's costs and prices. There is no data to assess mining costs. Also, as mining proceeds into the Plateau des Phosphates, the ore may contain more carbonate, requiring additional processing. All of this phosphate rock, with the addition of the estimate for the Meskala deposit, are considered identified resources. The identified resources of the three regions and the Meskala region are approximately 170,000 mmt. If the known phosphate-bearing areas of the Khouribga and Ganntour regions that have not been explored contain phosphate rock that is similar in thickness and in other properties to the existing reserves are considered, the combined identified resources and hypothetical resources of the four areas are estimated as approximately 340,000 mmt.

People's Republic of China (PRC)

Very limited data are available concerning Chinese reserves. It must be stressed that the data available on Chinese phosphate rock deposits are generally presented with limited information upon which critical assessments of reserves, resources, mining losses or overall recovery can be made. As previously mentioned, according to the USGS, for several years the PRC appeared to have the largest phosphate rock reserves in the world. USGS (2010) currently lists 3,700 mmt of reserves for the PRC. This figure appears to have been obtained from Li, Ying and Zhong (2006) and was verified by a USGS country representative through government contacts (Jasinski, 2009). In the paper by Li, Ying and Zhong, this figure is indicated to be 100 percent of the "standard ore" at 30 percent P_2O_5 from the five southern provinces of the PRC. For lack of better information, this figure is listed as the Chinese reserves. The amount of this standard ore that is producible is not known.

Fountain (1999) indicates the PRC had reserves of 40,000 mmt; this is obviously a resource figure. Li, Ying and Zhong (2006) indicate “ensured resource reserves” at 16,800 mmt; this figure includes 4,100 mmt of basic reserves and 12,700 mmt of resource. For lack of better information, 16,800 mmt is used as a resource figure.

The Li, Ying and Zhong (2006) article indicates the average recovery of the phosphate resource is 60.8 percent and the recovery rate at small mines is about 30 percent. There is no indication if this is mining recovery or overall recovery. There were 511 phosphate mines in the PRC at the time and only 31 were large- to middle-sized operations. Large- to middle-sized was not defined in the article.

The Li, Ying and Zhong (2006) article indicates the average grade of minable ore was 23 percent P_2O_5. Direct shipping phosphate ore (Grade I, greater than or equal to 30 P_2O_5) is indicated to be 6.4 percent of the resource. Phosphate rock described as simple or no flotation (Grade II, 24-30 percent P_2O_5) is indicated to be 7.4 percent of the resource. Grade III (14-27 percent P_2O_5) is 72.9 percent of the resource and Grade IV (3-14 percent P_2O_5) is 13.3 percent.

It is suggested that phosphate rock mining in the PRC is probably focused on what is described as Grade I and Grade II ore. Of a total resource of 16,800 mmt, this is approximately 2,300 mmt; only a portion of this ore is likely recoverable.

Russia

The USGS reserve estimate for Russia is 200 mmt.

Reserve and resource estimates in this report for the Kola region and the Kovdor complex are based on Federov (2003) and Khangaldyan (2005). As open pits are becoming exhausted in the Kola area, mining has been moving underground. Recoverable ore reserves under the control of the Russian company Apatit include six deposits worked with four mines at 1,600 mmt. The use of the terminology recoverable reserves implies these figures include ore losses that must be left in place to provide roof support and any other mining losses. Production data indicate an ore-to-product ratio of 3.15. Subtracting production from 2004 to 2009 indicates reserves of 465 mmt concentrate. Concentrates from these mines in Russia typically assay at 38-39 percent P_2O_5. Ore reserves at the Kovdor Complex appear to be about 50 mmt. This ore provides about two-thirds of production, while the rest of the concentrate is derived from iron ore tailings. Concentrate reserves from Kovdor are calculated as 11 mmt of product.

According to the *Mining Journal* (2007), JSC Acron acquired the ore reserves of the Oleny Ruchei deposit of 355 mmt at 13 percent P_2O_5 in an auction in late 2006. No other information was obtained concerning the deposit, and this 355 mmt is considered a resource in this report.

The 10 deposits under Apatit control are indicated to contain 3,600 mmt of recoverable reserves (Khangaldyan, 2005). This is unprocessed ore and is considered a resource. The reserves, as ore, are within this category.

Activities at the Kingisepp Mine are believed to have stopped in July 2006. This is a sedimentary phosphate rock deposit of Ordovician age. There may be 250 mmt of potential ore remaining in the area at 6.6 percent P_2O_5. This ore is considered a resource.

Reserves of phosphate rock concentrate in Russia include the Kola (Apatit) and Kovdor reserves and are estimated to be approximately 500 mmt. Russian phosphate rock resources include the unprocessed phosphate rock of the Kingisepp, Apatit (Kola), JC Acron (Kola) and Kovdor deposits at 4,300 mmt.

Senegal

USGS lists 80 mmt as reserves for Senegal.

At the Taiba Mine, the mining equipment of the Société des Industries Chimiques du Senegal (ICS) was moved from the Keur Mor Fall area to the Tobene area in October 2003. The ore is washed, sized and subjected to flotation. Maximum production is about 1.8 mmt/year. At the time of the move, ICS indicated the new reserves would ensure production for 20-30 years and probably 50 years (Van Kauwenbergh, 2006). At that time, ICS indicated reserves were 54 mmt at 31-37 percent P_2O_5.

High P_2O_5 losses are associated with washing and floating Taiba ore. Fantel et al. (1988) indicate feed ore at 26.9 percent P_2O_5 is processed to concentrate at 33.4 percent P_2O_5 with an ore-to-product ratio of 4.3.

The reserve of 54 mmt has a P_2O_5 content corresponding to the P_2O_5 content of Taiba concentrates analyzed at IFDC. At a production rate of 1.8 mmt/year, the 54 mmt reserve will suffice for exactly 30 years. The 90 mmt at 13-37 percent P_2O_5 appears to be additional material. Using an ore-to-product ratio of 4.3 and the 1.8

mmt/year production rate, the additional resources would last about 21 years. In 2009 ICS indicated reserves of 60-70 mmt. The estimate corresponds to the amount of concentrate available from the 2003 estimates of reserves and resources.

Approximately 25 mmt of marketable product at 34 percent P_2O_5 is available in the Pire Goureye area (McClellan and Notholt, 1986) and 40 mmt is available from the Matam area.

Subtracting production since the 2003 estimate, the phosphate rock concentrate reserves of Senegal appear to be about 50 mmt. The resources of the Taiba, Matam and Pire Goureye deposits are estimated at about 250 mmt.

It is suggested that exploration in Senegal is rather incomplete. It appears that ICS has the proven reserves for a 20- to 30-year time period. The map in Savage (1987) indicates there is more ore to the north of the Keur Mor Fall area. The Pire Goureye deposit may not have been completely explored. This estimate does not include the aluminophosphate resources in the Thies area or the small amount of conventional ore associated with this deposit (2 mmt).

South Africa

USGS (2010) lists 1,500 mmt as reserves for South Africa.

The Foskor annual report (2009) lists reserves (proved, probable and stockpiles) as 1,624 mmt at 6.89 percent P_2O_5. Resources are considered separately. Resources (measured, indicated and inferred plus the Phalaborwa Mining Company active tailings dam) are 6,023 mmt at 6.54 percent P_2O_5.

Data in Savage (1987) indicates the ore-to-concentrate ratio at Phalaborwa was about 6.7. Unconfirmed data indicate the ratio may vary from 5 to 7. Assuming mining losses at 5 percent and a 6.7 ore-to-concentrate ratio, reserves are about 230 mmt at 36.5-39.5 percent P_2O_5.

While there are numerous occurrences and small deposits of phosphate rock in South Africa, only the Phalaborwa deposit is considered in this report as reserves and resources. Total resources at Phalaborwa include the listed resources (6,024 mmt at 6.54 percent P_2O_5) plus the reserves as ore (1,624 mmt) for total resources of approximately 7,700 mmt.

It is prudent to point out that Birch (1990) indicated there are 5,500 mmt of phosphate rock at 16 percent P_2O_5 offshore on the Agatha Bank and 3,500 mmt at 16 percent P_2O_5 offshore on the Western Margin.

Syria

USGS (2010) indicates there are 100 mmt of reserves in Syria.

Data in Atfeh (1989) indicates there were 573 mmt of reserves at 23.9 percent P_2O_5 in the area known as the Eastern Block in 1981. Atfeh (1989) also indicated there were 39 mmt at 28 percent P_2O_5 in the Khneifiss area. Two screening plants are located in the Eastern area with an average ore-to-concentrate ratio of 1.8 to produce concentrate at 29-30 percent P_2O_5. The Khneifiss plant utilized a 31 percent P_2O_5 feed to produce a 33 percent P_2O_5 product at an average ore-to-concentrate ratio of 1.5.

The General Company of Phosphate and Mines (Gecopham) website (Gecopham, 2010) indicates prior to 2005 about 30 percent of the product came from Khneifiss and 70 percent came from the Eastern A and Eastern B plants. Gecopham appears to have installed a flotation plant in 2005 to increase capacity.

Assuming 95 percent mining recovery, a 1.8 ore-to-concentrate ratio and subtracting 52 mmt of production, the Eastern Block reserves are estimated at 250 mmt of product. Assuming 95 percent mining recovery, a 1.5 ore-to-product ratio and subtracting 22 mmt, the Khneifiss reserves are estimated at 3 mmt. Total Syrian reserves as concentrate are therefore estimated at approximately 250 mmt of concentrate.

Gecopham (2010) indicates phosphate rock resources in Syria are in excess of 2,000 mmt. One of the larger deposits in Syria has an average P_2O_5 content of about 19 percent (Atfeh, 1989). Utilizing such deposits will probably require the use of flotation technology.

Togo

USGS (2010) indicates there are 60 mmt of reserves in Togo.

A letter from the Ministry of Mines and Energy in Togo to IFDC indicates that as of July 2007 there were 37 mmt of reserves as product producible from 82 mmt of ore remaining in the Hahotoé-Akoumapé deposit. Togo concentrates were guaranteed at one time to be a minimum of 35 percent P_2O_5. Subtracting 3 mmt as product from 2007-2009 indicates a remaining reserve of 34 mmt. The letter from the Ministry of Mines and

Energy indicates there are 500 mmt of concentrate available from carbonate-containing phosphate formations. Palut (2004) indicates phosphate rock resources of more than 1,000 mmt from lower grade carbonate phosphate. IFDC conducted beneficiation tests on the carbonate bed (CSC) in the early 1980s (Van Kauwenbergh, 2007). A beneficiation pilot plant was constructed near the main beneficiation plant at Kpemé in the late 1980s for test work on this ore. Details of the results of beneficiation studies have not been made generally available. For the purposes of this study, the phosphate rock resources of Togo will be considered as 1,000 mmt of unprocessed phosphate rock.

Tunisia

USGS (2010) estimates there are 100 mmt of phosphate rock reserves in Tunisia.

Making a Tunisian reserve estimate is very difficult as information is very limited. The Tunisian deposits have been mined by several underground methods and surface methods, and ores range from direct shipping grade to materials which are dry or wet screened.

Tunisian reserves of what is apparently ore are listed by Anonymous (1982) as 495 mmt. Processing data in Anonymous (1982) indicate the ore-to-concentrate ratio for 10 deposits that were being produced at that time was approximately 1.8. It is assumed the mining method is accounted for in the reserve estimate. Subtracting 1981-2009 production as ore from the Anonymous (1982) reserve estimate indicates about 85 mmt of concentrate remaining in Tunisia.

Tunisian resource estimates are mainly focused on the Sra Ouertane deposit. Estimates of resources have ranged from 2,500 mmt (Anon, 1982; Svoboda, 1989) to 1,100 mmt at 12-15 percent P_2O_5 (Savage, 1987). The official government announcement and an international prequalification tender (Tunisian Ministry of Industry and Technology, 2010) indicate estimated reserves of 1,000 mmt of ore. Tunisian resources are assumed to be the resources of Sra Ouertane plus the 153 mmt of ore associated with reserves identified in this report for a total of approximately 1,200 mmt.

United States

The USGS (2010) indicates U.S. reserves are 1,100 mmt. It appears the USGS and the USBM have been reporting U.S. phosphate rock reserves in terms of tons of producible concentrate since at least the early 1980s.

U.S. reserve data were compiled from the Form 10-K filed by each U.S. phosphate rock producer (Mosaic, 2009; CF Industries, 2009; PCS, 2009). The estimate for PCS includes 408 mmt of reserves in North Carolina on which PCS has an option. A Short Form Base Prospectus from Agrium (Agrium, 2009) indicated the company's reserves. Reserves of the current Monsanto phosphate mine in Idaho was based on *Green Markets* (2009) information. J.R. Simplot is a private company and does not file a 10-K. J.R. Simplot reserves in Idaho were based on concentrate requirements for their phosphate plant in Pocatello and projected permitted mine lifetimes as indicated on the J.R. Simplot website. The estimate of the J.R. Simplot reserves near Vernal, Utah, was based on an industry estimate (Cathcart, Sheldon and Gulbranson, 1984) of 600 mmt at a stripping ratio of less than 3:1, assuming 95 percent recovery, applying an ore-to-concentrate ratio of 2.0 to adjust to 285 mmt and then subtracting 36 mmt of concentrate approximately produced since the reserve estimate. The Vernal, Utah, reserve estimate is a total of approximately 250 mmt of product at ~30 percent P_2O_5 remaining. The IFDC U.S. total reserve estimate is approximately 1,800 mmt of product.

The U.S. resource estimate for Florida is mainly based on Cathcart, Sheldon and Gulbranson (1984). This is the last comprehensive overall study of the phosphate rock resources of the United States. This study incorporated the work of Bauer and Dunning (1979), Fountain and Hayes (1979), Mayberry (1981), Zellars and Williams (1978) and the work of USGS. Total Florida identified resources (5,600 mmt) and hypothetical resources (5,000 mmt) were 11,000 mmt at 29 percent P_2O_5. From this total, all the resources of Central District (800 mmt), one-half of the North Florida economic identified resources (450 mmt), all of the Central Florida marginally subeconomic resources (30 mmt) and 1,000 mmt of the identified economic resources from South and East Florida (~3,000 mmt) were subtracted. It is assumed the remaining reserves of Florida (700 mmt) are within the remaining resource. The total remaining phosphate rock resource for Florida is then estimated to be approximately 8,500 mmt.

Fountain and Hayes (1979) and Cathcart, Sheldon and Gulbranson (1984) indicated there are 1,600 mmt of recoverable phosphate rock product on and offshore eastern Georgia from a resource of approximately 16,000 mmt at 4-15 percent P_2O_5. This resource was considered un-minable by Cathcart, Sheldon and Gulbranson (1985). In a study for USBM, Zellars and Williams (1978) indicated there were approximately 2,800 mmt of recoverable product at approximately 30 percent P_2O_5 available both onshore and offshore in Georgia; this figure is used in this report. A study by

Zellars and Williams (1979) released the next year assumed a distinct mining block that would contain about 150 mmt of recoverable flotation product at about 30 percent P_2O_5. This feasibility study indicated the operation described in the report would support royalties in excess of 5 percent of rock value price and possibly up to 10 percent of sales prices.

Western phosphate rock resources are estimated as phosphate rock to a level 305 meters below entry level (approximately 25,000 mmt) in the U.S. estimate (verified by Moyle and Piper, 2004). This is considerably less than the estimate of recoverable product found in DeVoto and Stevens (1979) of approximately 200,000 mmt.

Fountain and Hayes (1979) indicated there were about 8,500 mmt of phosphate rock at ~30 percent P_2O_5 from the North Carolina area. Cathcart, Sheldon and Gulbranson (1985) listed a similar figure (greater than 9,000 mmt). Development and Planning Research Associates Inc. (DPRA) (1987) conducted an economic feasibility study of mining the phosphate deposit offshore the North Carolina continental shelf. DPRA delineated an area for dredge mining with 130 mmt of recoverable phosphate concentrate. The borehole mining available resources were extremely large and, for purposes of that report, were considered limitless. The in situ resource estimate was approximately 100,000 mmt at 7.33 percent P_2O_5. The in-place concentrate (~30 percent P_2O_5) was estimated at about 21,000 mmt and with 50 percent recovery was considered about 10,000 mmt. Under the assumptions of the DPRA study (1987), both dredge and borehole mining showed a positive internal rate of return. It is impossible to determine how much of this resource is onshore or offshore and ultimately minable without more data.

Resources in Alaska, 5,000 mmt at 12 percent P_2O_5 (Cathcart, Sheldon and Gulbranson, 1985), have been added to the total. As indicated, most of this resource is located in the Arctic Wildlife Preserve.

The total U.S. resources are estimated by the criteria outlined in this study as approximately 49,000 mmt. If the figure of potentially recoverable phosphate product (~30 percent P_2O_5) given by DeVoto and Stevens (1979) (203,000 mmt) and the in-place amount of concentrate available by DPRA (1987) (21,000 mmt as in-place tons concentrate) are used for the resource estimate; the resource total could be much higher.

The phosphate rock reserves of the United States may evolve to include only that tonnage which can be obtained from lands or areas wherein the necessary permits for mining (or other activities) can be obtained, and legal challenges do not become logistically and economically overwhelming. If the reserves of such deposits should become unavailable, it is suggested they be considered resources as they may ultimately become available as economic, regulatory, legal and other criteria evolve over time.

One factor that has not been considered in this analysis is the recovery of phosphate from clay settling areas in Florida. At the present time, this is not technically or economically feasible. This material might be considered as a resource. However, there is no precedent to do this in phosphate rock reserve and resource studies.

Other Countries

USGS (2010) lists the reserves of Other Countries at 950 mmt.

The focus of the IFDC study was the main producers and holders of reserves/resources as listed by the USGS (2010). It is hoped an exhaustive list of reserves and resources can be developed in the next phase of this study. The list of Other Countries in the report is not an exhaustive compilation, but includes reserve and resource data that was available or could be estimated for deposits in Algeria, Angola, Finland, Kazakhstan, Peru and Saudi Arabia (Al-Jalamid).

Algeria has been a phosphate rock producer since the late 1800s (Savage, 1987). Current production is about 2 mmt/year. Data in Chabou-Mostefai and Flicoteaux (1989), an ore-to-product ratio of 1.75 (Fantel et al., 1988) and estimates of 1985-2009 production were used to calculate a remaining ore reserve of approximately 260 mmt. Resources of 2,000 mmt at Djebel Onk have been listed by FERPHOS (2010), the Algeria phosphate rock producer.

Concentrate reserves of approximately 130 mmt have been estimated for Angola/Cabinda (Van Kauwenbergh, 2006). The total resources of Angola/Cabinda are approximately 600 mmt.

Based on information found in Puustinen and Kauppinen (1989), Geological Survey of Finland (2010) and Newman (2009), the remaining concentrate reserves at the Siilinjarvi Mine may be on the order of 23 mmt at about 38 percent P_2O_5. Resources at the Sokli Igneous Complex are on the order of 310 mmt of weathered crust at 4.5 percent P_2O_5 and 110 mmt of ore at 16.5 percent P_2O_5. Total resources of product and ore in Finland are 330 mmt.

Resources of the Karatau Basin in Kazakhstan were reported by Levine (1997) as 2,600 mmt. Production in the basin was shut down in 1997. *Fertilizer Week* (2010) indicated resources of the Chilisai deposit were estimated by Sunkar Resources to be 475 mmt at 10.6 percent P_2O_5. Total Kazakhstan resources are estimated as 3,100 mmt.

Fertilizer International (2009) indicated reserves at Bayovar, Peru, were 100 mmt product at 30.5 percent P_2O_5. Savage (1987) indicated total resources of Peru at 10,000 mmt. The Bayovar Mine came on-stream in August 2010. The phosphate concentrate to be produced (3.9 mmt/year) has not yet been totally dedicated to any fertilizer producer. Mosaic (2010) has invested in the project and will take 35 percent of the total production.

Based on data in Neser (2004) and Maaden (2010), the reserves of concentrate at the new Al-Jalamid Mine are 93 mmt. Total resources in the area may be on the order of 500 mmt. Total Saudi Arabian resources in the Sirhan-Turayf Basin may be on the order of 7,800 mmt at 19.5 percent P_2O_5 (Riddler, Van Eck and Farasani, 1989).

Phosphate rock reserves of concentrate for Algeria, Angola, Finland, Peru and Saudi Arabia are estimated at approximately 600 mmt. The phosphate rock resources of these countries and Kazakhstan are estimated at 22,000 mmt.

Under the conditions of this analysis for each country considered in this study, world phosphate rock reserves as concentrate product are estimated at approximately 60,000 mmt (Table 7). World resources of unprocessed phosphate rock are estimated at approximately 290,000 mmt. If the hypothetical resources of Morocco are considered, the world resources of unprocessed phosphate rock may be on the order of 460,000 mmt.

Phosphate deposits in numerous other countries were not analyzed in this phase of the study due to time constraints and/or a lack of current data concerning reserves and resources. Numerous additional deposits will merit significant attention in any subsequent phase, including significant phosphate rock resources located offshore in the territorial waters of several countries.

Summary and Conclusions

The phosphate rock reserve and resource literature, past world reserve and resource estimates and the methodology of performing reserve and resource estimates were reviewed. Table 8 summarizes the results of several previous studies using the terminology of the original authors. Estimates of reserves range from 15,000 mmt to over 1,000,000 mmt. Estimates of resources range from about 91,000 mmt to over 1,000,000 mmt. Every study utilized a different methodology and criteria for what constitutes reserves or resources.

The literature review indicates the use of reserve and resource terminology is not consistent on a worldwide basis. The literature review indicates that prior to 1990, there was a wealth of literature available on phosphate rock deposits. At or about this point in time, literature on phosphate deposits becomes relatively limited. This roughly corresponds to the end of the IGCP Project 156 – Phosphorites. The third volume and last of the series was published in 1990; a fourth working group on “Cretaceous and Tertiary Phosphorites” never produced a publication before the 10-year project ended. In the early to mid-1990s, U.S. government organizations

Table 8. Past World Phosphate Rock Reserve and Resource Estimates Based on Author’s Terminology

	Phosphate Rock Resources	Estimated Recoverable Product	Reserves	Reserve Base
	(mmt)			
Emigh (1972)			1,200,000	
Wells (1975)			530,000 (30% P_2O_5)	
DeVoto and Stevens (1979)	1,200,000	266,000 (~30% P_2O_5)		
Cathcart (1980)	91,000		21,000 (≥ 30% P_2O_5)	
Fantel et al. (1988)		37,000		
Notholt, Sheldon and Davidson (1989)	163,000 (~22.5% P_2O_5)			
USGS (2009)			15,000[a]	47,000[b]

a. Originally described as phosphate rock that could be produced at less than US $40/ton.
b. Originally described as phosphate rock that could be produced at less than US $100/ton.

that devoted manpower and funding to mineral resource surveys were undergoing structural and personnel changes. USBM, the agency responsible for detailed cost estimation and economic feasibility studies on phosphate deposits, was closed in 1996.

There is limited current information on world phosphate rock reserves and resources available in the conventional scientific literature. Some information can be found on websites, in trade magazines, papers presented at conferences and in papers or reports that have limited distribution and are generally not catalogued on commercial literature databases.

The search for phosphate rock deposits became global in the 20th century. Deposit development intensified in the 1950s and 1960s. Production peaked in 1987-1988 and then again in 2008 at over 160 million tons of product. Phosphate rock from Florida, USA, was a processing standard and one of the lowest cost sources of P_2O_5 for many decades.

Phosphate rock mining has evolved over time, and worldwide it relies on high volume and advanced technology using open-pit mining methods and advanced transport systems. This process moves hundreds of millions of tons of overburden to produce hundreds of millions of tons of ore to produce on the order of 150-160 million tons of concentrate per year.

Beneficiation technology also has evolved. Flotation may be one of the final steps in a process and may be required after various washing and physical sizing steps to produce concentrates. While flotation technology was embraced in the United States in the 1920s and 1930s, flotation technology has only been embraced by North African and Middle Eastern producers to treat low-grade ores in the last 10-15 years. The availability of water may be a constraint to the use of flotation.

Concentrate of suitable grade and chemical quality is then used to produce phosphoric acid and DAP of world standard grade (18-46-0). Phosphate rock resources have been bypassed in mining due to the fact that concentrates could not be produced that were suitable for phosphoric acid for DAP production. Phosphate rock resources have also been bypassed or spoiled in mining due to the fact that the technology was not developed or available to process these materials into marketable products.

There is no viable practical process to mine and beneficiate phosphate rock that can recover all of the P_2O_5 usually indicated in resource and reserve estimates based on ore or potential ore. Detailed study usually indicates there are technical and/or economic limits to mining. There are losses in mining depending on the mining method and conditions. Typical losses of P_2O_5 generally run from 30 percent to over 50 percent in beneficiation. In beneficiation, recovery is inversely proportional to grade. Usually, high recovery results in a lower grade or quality product. Beneficiation to a higher grade or quality results in lower recovery.

The available literature was used to prepare a preliminary estimate of world reserves and resources. This was not a comprehensive analysis, but focused primarily on the countries listed by USGS in the 2010 Mineral Commodity Summaries.

Using the available literature, the reserves of various countries were assessed in terms of reserves of concentrate. The IFDC reserve estimate is approximately 60,000 mmt of concentrate. The largest discrepancy between this estimate and previous or other estimates is the amount of concentrate reserves available from Morocco (approximately 51,000 mmt). This magnitude of reserves for Morocco had been previously mentioned in the literature (DeVoto and Stevens, 1979; Savage, 1987). Previous reserve and resource studies typically indicate exploration was incomplete for Morocco and other North African or Middle Eastern producers. Exploration in Morocco apparently remains incomplete.

It should be stressed that these reserves were estimated based on the use of the terminology “reserves” in the literature. It should also be stressed that reserves are only proved or established over a planning horizon based on the amount of concentrate needed for a number of years. Reserves are not established on an infinite planning horizon. Reserves are established on the costs of production and price of suitable phosphate rock at considerable expense and with experienced manpower. Phosphate rock producers do not spend money documenting reserves they will not use for decades.

IFDC-estimated world phosphate rock resources are approximately 290,000 mmt. This figure includes the unprocessed ore of the reserve estimates. This figure includes data from the Khouribga, Ganntour and Meskala areas of Morocco; the Meskala area of Morocco was not included in the reserve estimate. All these resources of Morocco have been declared identified reserves in the literature. If hypothetical estimates of Moroccan phosphate rock resources are included, based on the total area indicated to be underlain by the deposits, total resources of Morocco may be about 340,000 mmt and the total world resources of phosphate rock may be about 460,000 mmt.

As mentioned in the text, this resource estimate did not include every country or phosphate rock deposit in the world. Many countries are rather incompletely explored, and there are many small phosphate deposits in the countries listed and other countries that were not included in this study.

Based on this world phosphate rock reserve estimate and the estimate of Moroccan reserves and resources, it appears phosphate rock of suitable quality to produce phosphoric acid will be available far into the future. Based on this reserve estimate, at current rates of production, phosphate rock reserves to produce fertilizer will be available for 300-400 years.

Currently, phosphate rock prices have increased to the US $80-$110 range. It is not known at what price point these prices will stabilize. However, predictions (Fantel et al., 1988) indicated another generation of mines to replace existing production would require significant investment and the price of phosphate rock from new deposits and mines must be on the order of US $85-$103 (in 2010 dollars).

There is no indication there is going to be a "peak phosphorus" event within the next 20-25 years. It appears production from Morocco and other countries will replace Florida production at an indeterminate time in the future. The world reserve of phosphate rock is not a static figure. The cost of phosphate rock is going to increase as the lower-cost phosphate rock deposits are mined out and producers have to move more overburden, process lower grade ores, open new mines and employ increasingly expensive technology and additional raw materials and processing media (such as water) to produce concentrates. When the prices of phosphate concentrates increase, deposits that were marginally economic may become viable. New deposits will be opened. Of particular interest are alternative mining methods such as borehole mining and developing new mines in challenging environments. The utilization of underground methods may become attractive in many countries if the price of phosphate rock is high enough.

Vertical integration of phosphate rock mining and processing has occurred at numerous sites worldwide. Such vertical integration may be a necessary component to compete in the world phosphate fertilizer market in the future.

This study provides a preliminary estimate of world reserves and resources. It should be stressed that this report was not envisioned as a definitive analysis. A collaborative effort by phosphate rock producers, government agencies, international organizations and academia will be required to make a more definitive current estimate of world phosphate rock reserves and resources. Without the support and experience of knowledgeable professionals in the phosphate rock and fertilizer industry and current data, realistic estimates cannot be made. A Phase II initiative has been envisioned to be similar to the IGCP Project 156 – Phosphorites, but with the objective to explore future world phosphate rock reserves and resources. The following suggestions and observations are offered.

- Common definitions of "reserve" and "resource" should be agreed upon. These definitions should be as simple as possible.
- Reserve estimates should be made in terms of tons of recoverable phosphate rock concentrate.
- Reserve estimates should be based on mine development data and/or a reasonable planning horizon.
- The term "reserve base" as used now should be discontinued unless definitive production cost criteria can be developed. The criteria of producible at less than $100/ton is not appropriate.
- Resource estimates should include material of any P_2O_5 grade that might be processed or utilized in the future.
- Phosphate producers and/or geologic surveys and mining departments in phosphate rock-producing countries need to take an active role in producing realistic reserve and resource estimates. In fact, it will not be possible to produce a worldwide reserve and resource estimate without the cooperation of these stakeholders in the appropriate countries.
- Phosphate rock producers and trade organizations need to be active stakeholders in any initiatives that may influence government policy, agricultural productivity and food security on a worldwide basis.

There is no substitute for phosphorus in agriculture – or indeed in life as we know it on Earth. Phosphate rock is a non-renewable resource. The amount of this resource that can be called reserves and produced is based on its value to the current world agricultural system and for other uses.

Efforts are needed to more effectively mine and process reserves/resources of phosphate rock and to utilize phosphate fertilizer and phosphate-containing waste as efficiently as possible. Keeping nutrients out of watersheds and the oceans is most desirable. All of these efforts must be tempered and explored realizing that only those techniques or processes that are logistically, technically and economically feasible are likely to be adopted.

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