Geology of Phosphate Rock in China: Distribution, Rock Type and Metallogenic Perspective

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Abstract

Phosphate rock (PR) is an important strategic material, providing the non-renewable elemental resource phosphorus (P). From the view of geosciences, PR can actually be seen as a special rock rich in the element P. Many studies have reported on PR distribution, but there is little predictive geological research from a metallogenic perspective on the causes of phosphate ore distribution. This paper reviews research on the origin and geological features of the mineralization distribution of phosphate ore resources in China, introduces the main types of P-containing rocks and/or deposits in China, and provides a good understanding of the mode of occurrence, geological setting and phosphogenesis of China's phosphate resources. It forms an invaluable aid to the search for, and exploitation of, new P resources in China.

Key words: China, geology, metallogenic perspective, phosphate resources, phosphate rock, rock type

1. Introduction

Phosphate rock (PR) is the only significant global resource that contains phosphorus (P). Phosphate rock is considered an important strategic resource, and is non-renewable. PR is a fossil resource, regenerated very slowly and requiring geological time spans for its regeneration. Once phosphate resources are mined and used, it will be difficult to get by with simple recycling of phosphorus. PR resources are age-old, their metallogenic conditions are extremely complicated, and they are characterized by non-renewability. In general, PR 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. Almost all countries in the world have many PR deposits, but only a few have the economic significance of large state-owned phosphate resources. According to recent statistical data (USGS, 2014), the annual world PR production capacity was projected to increase from 228 million tons in 2013 to about 260 million tons in 2017. The largest increases in capacity were expected from projects in Brazil, China, Morocco, Peru and Saudi Arabia. Other significant development projects were planned or in progress in Algeria, Australia, Canada, Kazakhstan, Namibia, Russia, Togo and Tunisia. Fillippelli (2008) has estimated that there is in total about 18 billion tons of PR available in high grade deposits, 25 billion tons of PR in low grade deposits and 50 billion tons of PR in ultra-low grade deposits. The largest sedimentary deposits are found in northern Africa, China, the Middle East and the United States. Significant igneous occurrences are found in Brazil, Canada, Finland, Russia and South Africa. Large phosphate resources have been identified on the continental shelves and seamounts in the Atlantic and Pacific oceans. The distribution of phosphate resources in these countries and regions is relatively concentrated, *e.g.*, the phosphate resources in only five provinces of China accounted for 76.3% of Chinese phosphate resources, in terms of quantity. The commercial deposits in the United States are all marine phosphorites that were formed under warm, tropical conditions in shallow plateau areas where upwelling water could collect. Over 70 percent of the U.S. reserve base is located in Florida and North Carolina (Stowasser and Fantel, 1985). There are also large phosphate deposits in some western states.

China has rich PR resources, and is one of the main P producing countries of the world. Its total PR resources are extremely large, but are unequally distributed geographically and a large proportion cannot be mined on an economic scale at present. It is important to find new P resources, and more important to understand where they can be found.

The world phosphate resource distribution is related to the origins of geological and natural environments. Although some studies exist on phosphate resource distribution (Arthur *et al.*, 2005; Chang *et al.*, 2010; Xue *et al.*, 2011; Wen, 2011), it is still worth looking at the geologist's research to get a good understanding of the modes of occurrence, geological settings and phosphogenesis of the world's phosphate resources. It forms an invaluable aid in the search for and exploitation of phosphate deposits. In this paper, based on basic theories on geological rock formation, we review the research on the origins and geological features of the mineralization distribution of phosphate ore resources from a geological perspective, introduce the main rock types of P rocks and/or deposits in China, and provide suggestive predictions for exploration in the search of new P resources.

2. Basic Geological Theories on Rock Formation

Geology refers to the nature and features of the earth. It comprises the study of the earth's material composition, structure, development history (including the earth sphere differentiation), physical properties, chemical properties, rock properties, mineral composition, rock occurrence, contact relationship, tectonic evolution history, biological evolution history, climate change history, mineral resource status and distribution, etc.

Stone, as we usually call it, is more properly called "rock" as a geo-scientific term. Rock is a natural output with a certain structure of mineral aggregates, and is made of crustal or upper mantle materials. Most rocks are composed of several kinds of minerals, such as granite (which includes orthoclase, quartz, biotite, etc.), while the rest type of rocks are of single mineral composition, such as marble which only includes calcite. Different types of rocks can be distinguished based on their luster, density and hardness, among other properties. A geode looks like a common rock on the outside, but when it is cut in half, a fantastic range of colors and shapes can be revealed. Several classes of rocks can also be grouped according to how they formed, giving us the categories of igneous, metamorphic and sedimentary rocks. Most characteristics of rocks depend on their constituent minerals (Pellant, 2002). The differences among them have to do with how they formed.

Igneous rocks are formed from magma or lava. They are tough, frozen melts with little texture or layering; in color, they consist of mostly black, white and/or gray minerals; and they may look like granite or lava. Igneous rocks can be classified according to their composition. This classification takes into particular account the relative proportions of silica, magnesium and iron minerals found in these types of rocks; their grain size (which reveals how fast they cooled); and their color. Rocks that contain silica, along with much quartz and feldspar, tend to have pale colors; those with low silica content have dark colors created by iron and magnesium-containing minerals, such as olivine, pyroxene and amphiboles. A rock's texture is determined by the configuration of its crystal grains.

Sedimentary rocks are formed from particles of sand, shells, pebbles and other fragments of material. Together, all these particles are called sediment. Gradually, the sediment accumulates in layers and over a long period of time hardens into rock. Generally, sedimentary rock is fairly soft and may break apart or crumble easily. You can often see sand, pebbles or stones in the rock, and it is usually the only type that contains fossils. Examples of this rock type include conglomerate and limestone. Sedimentary rocks can also form through the accumulation and lithification of organic remains. The most common example is coral reefs, which develop underwater, surrounding the coasts of many temperate seas. Many limestone rocks also originate this way; they are made of calcium carbonate (calcite) or calcium and magnesium (dolomite). Because of their porous consistency, they often serve as repositories for fossil fuels, which are also of organic origin. Other rocks, like coquina, form through the accumulation of fragments of marine shells, lithified over time as materials filled and cemented their interstices.

Metamorphic rocks form under the surface of the earth from the metamorphosis (change) that occurs due to intense heat and pressure (squeezing). Metamorphic rocks are tough, with straight or curved layers (foliation) of light and dark minerals, and they come in various colors, often glittery with mica. The rocks that result from these processes often have ribbon-like layers and may have shiny crystals, formed by minerals growing slowly over time on their surfaces.

PR is an imprecise term that describes naturally occurring geologic materials (minerals) that contain a relatively high concentration of P. The term PR is used to describe raw (unbeneficiated) phosphate ores, but may also be applied to beneficiated or concentrated products, and then, it can actually be seen as special rocks rich in P. Therefore, based on geological theory and modern metallogenic theory, starting from the geological tectonic environment and the actual situation of known deposits, through the analysis of existing PR characteristics, one can understand the principle of mineralization conditions of P ore. Taking this as the premise, we can carry on the explanation of P ore resources, by using the geological, geophysical, geochemical and other data from multiple disciplines, deepening the understanding of the geological and metallogenic regularity of P ore resources, and compile a comprehensive predictive information map system of mineral P ore resources. Further, we can analyze potential mineral resources and provide a prospecting evaluation to guide prospectors, giving them clear directions for practical exploration. This is of great significance to the expansion of mineral P resources.

3. The Main Characteristics of Phosphate Rock Resources in China

Marine sedimentary PR is the class of phosphate-resource-bearing rocks most widely distributed in the world. The world's largest sedimentary phosphate deposits are found in northern Africa, China, the Middle East and America. The second most common are igneous rock phosphate deposits, mainly found in Brazil, Canada, Russia and South Africa. In addition to those two kinds of PR, there are small amounts of guano phosphate deposits, mainly distributed on islands (USGS, 2014; Arthur, 2005). Van Kauwenbergh (2010) reported that PR occurs in both sedimentary and igneous deposits across the world (Fig. 1). Most (80% to 90%) of PR used to produce fertilizer is sedimentary in origin, and was deposited in ancient marine continental shelf environments. Sedimentary deposits, sometimes called phosphorites, originated throughout geologic time. Most PR is mined by open pit techniques, but a significant amount of deposits in China, Russia and other countries are extracted by underground mining.

Wen (2011) reported that marine sedimentary phosphorites constitute the main Chinese phosphate deposits, located mainly in the southwestern and southern regions. Metamorphic phosphate deposits are mainly distributed in Jiangsu, Anhui and Hubei provinces; magmatite-type apatite deposits are mainly distributed in the north; weathered secondary phosphate deposits are mainly distributed in Yunnan and Guizhou provinces; and guano phosphate deposits are distributed in Hainan Province. The important industrial P deposits in China are mainly sedimentary PR deposits, with metamorphic phosphorite deposits and magmatic apatite deposits of secondary importance (see Fig. 2). Calculations of proven reserves show sedimentary phosphorite to account for about

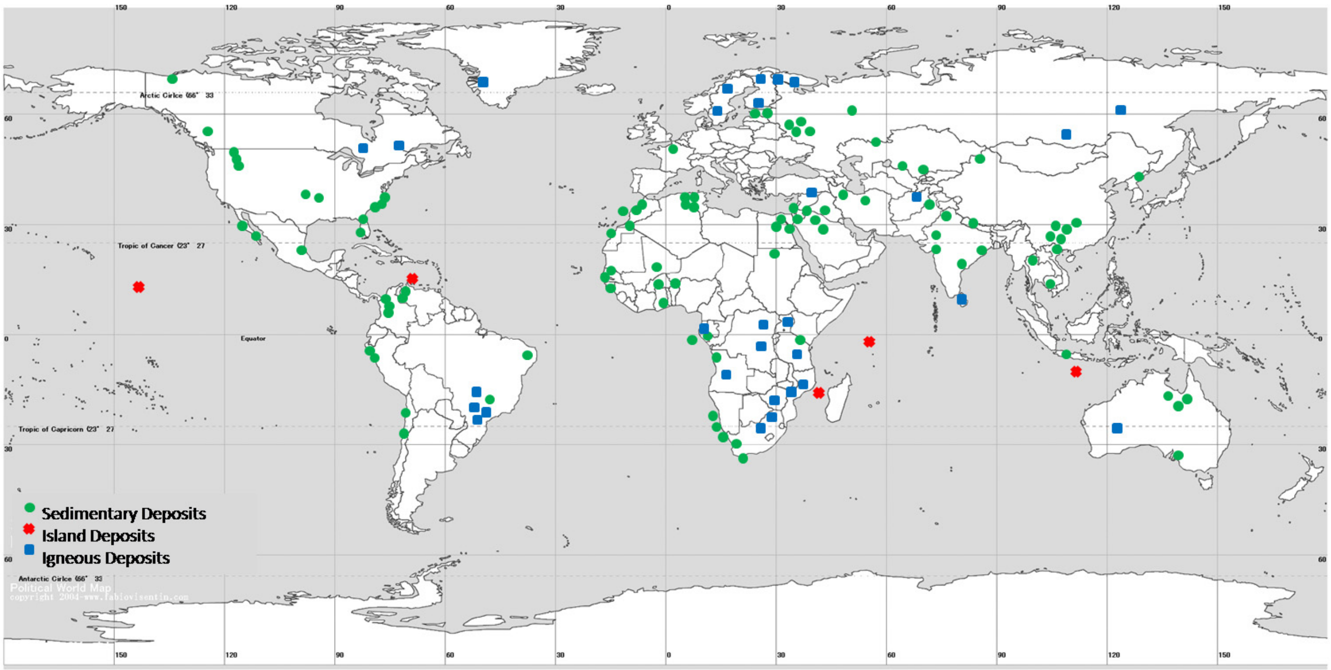

Fig. 1 World phosphate rock resources (Cooper *et al*. 2011).

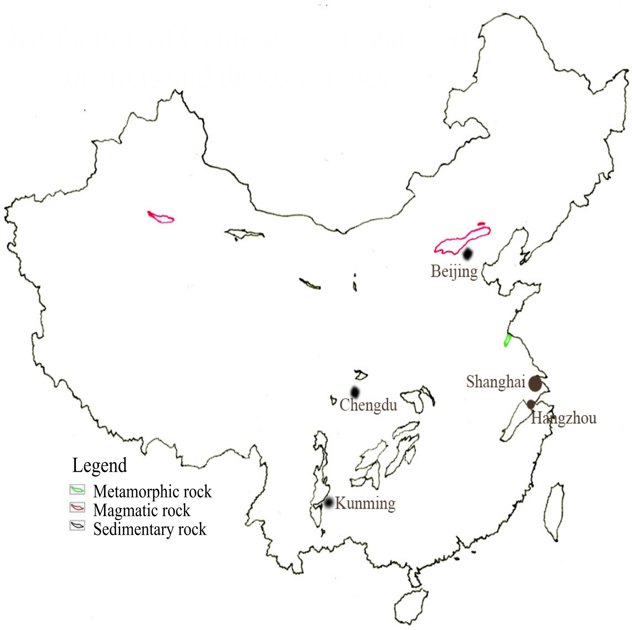

Fig. 2 Distribution map of districts with phosphorite concentrations and deposit types in China (Xue *et al*. 2011).

75.5% and metamorphic and magmatic apatite ore for about 24%, with guano PR and other types of phosphate ore accounting for only about 0.5%. The phosphate-bearing metallogenic rocks of China were formed in many geological ages. The most important industrial phosphate ore metallogenic rocks belong to the Sinian (Ediacaran) age and Cambrian period. According to statistics, the Sinian-Cambrian ages account for 51%, the Devonian period accounts for about 44%, and others accounted for 5% (Xue *et al*., 2011). Different ore types require different treatment processes. On this basis, PR mining methods can be divided into scrub-off-the-mud, re-selection, flotation, combined process re-maglev, roasting-digestion and electrostatic separation processes. A study on the genetic and industrial types of phosphorite ore deposits in China divided them into 114 deposit types. Sedimentary PR deposits, accounting for 95.5%, are the main type. The other important P ore deposit types include metamorphic phosphorite and magmatic apatite deposits. Based on a scheme dividing P ore districts in China, considering minerogenetic laws, tectonic background, lithofacies palaeogeography, and other factors, there are 22 P ore districts China. The most important P ore districts are found basically in 15 areas, including the main PR producing areas and potential areas, and show the basic characteristics of important rich P ore zones on the whole (Xue *et al*. 2011).

In metallogenic regularity and metallogenic modesl of PR, geological research scholars believe that bays are a favorable environment for the deposition of phosphate ore. The initial deposition and secondary enrichment of phosphorite ore is closely related to palaeogeographic position. It has been found that rich PR deposits are located in areas close to the centers of three secondary bays. The main direction to search for rich PR in the future should be in such areas. A regional metallogenic model is shown in Fig. 3 (Xue, *et al*. 2011), from which it can be understood that rich PR deposits are located in the eastern part of the continental shelf area. The results of many years of geological surveying and exploration show that China has great potential mineral P resources in the Yangtze paraplat-form area, northern margin of the Tarim Basin in Xinjiang, northern margin of the North China platform and the Haizhou Dawu area, in which resource prospects are very optimistic. This indication is inconsistent with Cramer's (2010) concluding remark: "Phosphate as a limiting resource is an important and specific constraint that plants have co-evolved with ever since making the transition to the terrestrial environment. There has been substantial progress in identifying how plants meet the challenge of acquiring and conserving this resource. However, the responses of plant species richness and plant production to P-limitation can only be understood when the interactions of this limitation with multiple other abiotic resources (*e.g*., N, water, light) and biotic interactions (*e.g*., competition, fire, herbivory) are taken into consideration."

According to Wen's master's degree thesis (Wen, 2011), China's PR can be divided into three types, sedimentary PR (exogenous deposits), apatite deposits and metamorphic PR (endogenous deposits). Different types of PR have different metallogenic regularity. The exogenous sedimentary phosphorite deposits occur mainly in Paleozoic and Neoproterozoic marine to coastal sedimentary layers. These kinds of deposits are large to extra-large scale. The deposits' ore zones can extend tens or hundreds of kilometers. This kind deposit, however, has characteristics of few areas with rich ore but many with

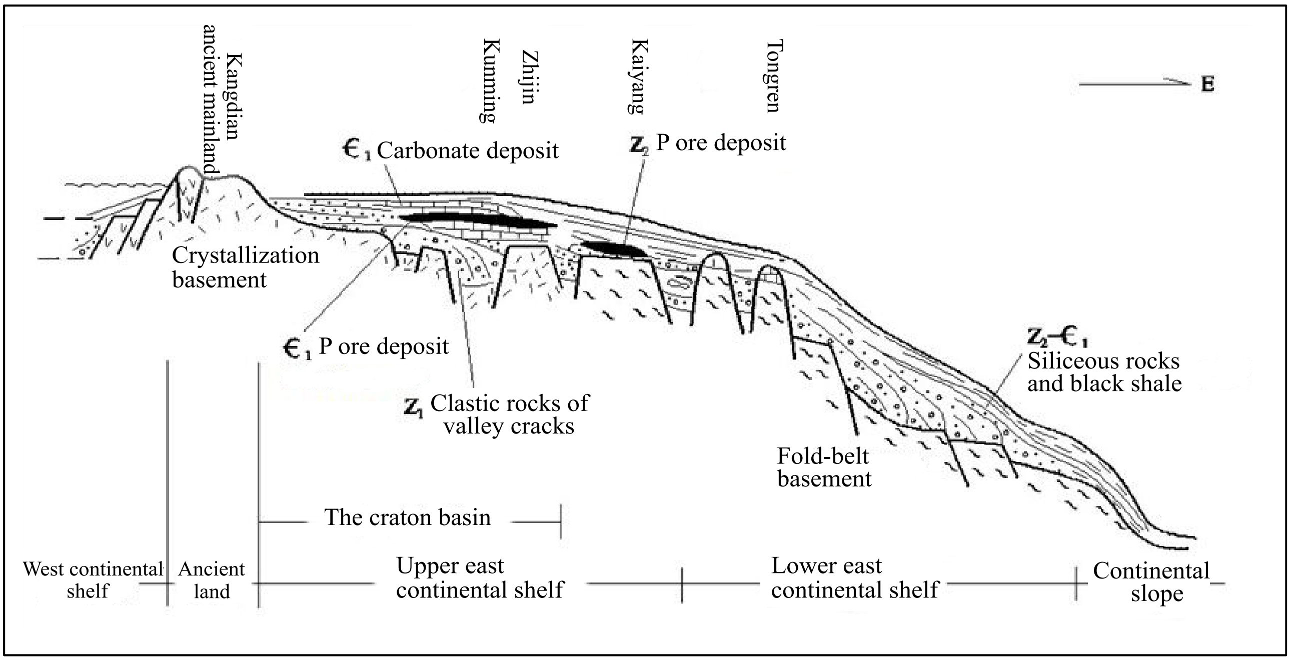

Fig. 3 Pattern chart of P deposit formation in southwest China.

poor ore, making ore processing easy part of the time, but more frequently difficult. In gently inclined rock deposits of carbonate-type PR deposits, sometimes there is a large-scale weathering belt, which is an important source of high quality rich phosphorus ore. Endogenous apatite deposits are formed mainly by magmatic fractionation or penetration effects. In such deposits, the apatite grains are large, the ore is mostly intergrown with magnetite (vanadium titanium), so mineral separation is easy, and it has good comprehensive utilization value. On the other hand, in such deposits, there are a few other kinds of rock deposited, the scale is small, the grade, variable, and they normally do not have industrial significance. Moreover, there are clues to the locations of carbonate-type apatite deposits formed from magmatic differentiation in China, so that would be where to search next for endogenous apatite deposits.

In accordance with original causes of formation, metamorphic phosphorite rock deposits can be divided into two sub-categories, sedimentary metamorphic and metamorphic metasomatic. Metamorphic phosphorite rock deposits formed mainly in metamorphosed rock layers from the Proterozoic and Archean eons, and their scale is larger. Compared with endogenous apatite deposits, the P content of this kind of apatite is richer, but the grain size is small. There are broad prospects for this kind of deposit.

4. Conclusion

By understanding the geological and metallogenic regularity of P ore rocks, we can compile a comprehensive prediction information map system of mineral P ore resources. Further, we can analyze potential mineral resources, conduct prospecting evaluations to guide prospectors, and provide clear directions for practical exploration.

Among phosphate resources, marine sedimentary PR is the most widely distributed class of rock in the world, and China is no exception. Marine sedimentary phosphorites are the main phosphate deposits in China, and are found mainly in the southwestern and southern regions. The most important industrial P rock deposits formed in those regions. Sedimentary PR deposits constitute the main type, with metamorphic phosphorite and magmatic apatite deposits coming second.

It has been found that rich PR is located in areas close to the centers of three secondary bays. The main direction to search for rich PR in the future should be in such regions.

Moreover, there are clues to the location of carbonate-type apatite deposits formed from magmatic differentiation in China, and that would be the next place to search for endogenous apatite deposits. In accordance with the original causes of formation, metamorphic phosphorite rock deposits can be divided into two subcategories, sedimentary metamorphic and metamorphic metasomatic. Metamorphic phosphorite rock deposits formed mainly in metamorphosed rock layers from the Proterozoic and Archean eons, and appear on a larger scale. Compared with endogenous apatite deposits, the P content of this kind of apatite is richer, but grain size is small. There are broad prospects of this kind of deposit. To explore this kind of P deposit or uncover new P resources in China, consideration must be given to the different types of P deposit formation, complex geological structures and technical conditions for mining.

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