



Phosphate Mineral Reactivity and Global Sustainability

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Phosphorus is a unique element. It is the limiting nutrient controlling biological productivity in many terrestrial and marine environments. When in excess, however, dissolved phosphate leads to uncontrollable biological growth and water-quality problems through a process called eutrophication. The use of phosphate minerals and their products as fertilizers has increased tremendously global food production; it would not be possible to feed the current world population without phosphate fertilizers. Yet phosphate is a limited global resource; current estimates suggest economic phosphorus supply may be severely depleted over the next 100 years. Nevertheless, mineralogists and geochemists have invested little time investigating phosphate mineral stability, reactivity, and transformations. This issue attempts to bring phosphates to the forefront of our scientific endeavours.

KEYWORDS: phosphate minerals, eutrophication, apatite, fertilizer production, global sustainability

INTRODUCTION

This thematic issue provides an overview of biotic and abiotic reactions involving phosphate minerals and discusses the consequences of these reactions for global sustainability. It is motivated by the importance of the role phosphate minerals play in natural and industrial processes. Phosphorus (P) is the 11th most abundant element in the lithosphere. It occurs as an oxyanion (phosphate, PO_4^{3-}) under the conditions prevailing on Earth, commonly as a constituent of either an inorganic mineral phase or an organic molecule. Phosphorus is a major constituent of deoxyribonucleic acid (DNA), ribonucleic acid (RNA), adenosine diphosphate (ADP), and adenosine triphosphate (ATP). Phosphorus is required for life to occur. Reactions at phosphate mineral surfaces play a major role in making fertilizers work (Becker 1989). As part of our bones, phosphate minerals keep us upright (Mann et al. 1989; Driessens and Verbeeck 1990) and, as the main component of our teeth, they enable us to chew our food (LeGeros 1991). Phosphate minerals provide an effective way to remediate metal-contaminated waters (Xu et al. 1994; Chen et al. 1997) and contribute to materials/medical technologies, such as bioceramics (Hench and Wilson 1993), and to medicine (Aoki 1991). Moreover, phosphate minerals are currently being considered both as possible additives to backfill for confinement of nuclear

waste (Perrone et al. 2002) and as potential actinide and iodine storage hosts (e.g. Boyer et al. 1998; Guy et al. 2002; Chairat et al. 2006).

Human activities have seriously impacted the natural cycling of phosphorus on Earth, not unlike that of carbon although one that is far less understood and discussed. Gabriel Filippelli presents in this issue the scale and significance of these effects (Filippelli 2008). Phosphorus is also recycled constantly at a far smaller scale within soils; as discussed in this issue by David Manning, this cycle has also been disrupted by humans, mostly as a result of agriculture (Manning 2008). Simon Parsons and Jennifer

Smith outline how phosphate minerals may hold the key to solving a major modern challenge: treatment strategies for removing nutrients from wastewaters before their release into the environment (Parsons and Smith 2008). Jill Pasteris and co-authors explore how evolution has optimised phosphate minerals to form the hard parts of mammalian anatomy (Pasteris et al. 2008). Finally, Eric Oelkers and Jean-Marc Montel provide a mechanistic approach to the contribution that phosphate mineral reactivity can make to nuclear waste disposal (Oelkers and Montel 2008). All these topics require some basic understanding of the behaviour of natural phosphate, which is summarized below.

THE MAJOR PHOSPHATE MINERALS

Huminicki and Hawthorne (2002) tabulated the names, chemical formulae and lattice parameters of nearly 400 phosphate compounds, but relatively few such compounds control phosphate concentrations in natural systems. The names, compositions and photos of selected minerals are presented in TABLE 1 and FIGURE 1. The most abundant phosphates on Earth are the apatite group minerals, $\text{Ca}_5(\text{PO}_4)_3(\text{F},\text{OH},\text{Cl})$. Of these, fluorapatite, usually called simply apatite, is the most abundant. It is present in almost all igneous rocks, typically comprising 0.1 to 1 volume percent (vol%), though in some cases it may be significantly higher. Apatite occurs in both thermally and regionally metamorphosed rocks and reflects the phosphorus composition of the original rock. In sedimentary rocks, apatite occurs as a detrital mineral and as a primary chemical precipitate. Some extensive sedimentary deposits contain up to 80% apatite and are locally interbedded with limestone. Such deposits, called phosphorites, are commonly exploited as phosphate ore. Much of the phosphate in these deposits is formed directly from P-rich aqueous solutions via diagenetic and

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biochemical processes in the sediments, although significant phosphorus deposits can originate from skeletons and guano. Apatite minerals also form the hard parts of many living organisms. Hydroxylapatite makes up 65 to 70% of mammal bones, the remainder being mostly organic compounds (Turek and Buckwattler 1994). The apatite crystal structure is very accommodating, allowing the incorporation of nearly half of the elements in the periodic table. Thus apatite serves as a repository for minor and trace elements in rocks (Hughes and Rakovan 2002).

The heavy-metal phosphate minerals monazite, xenotime and rhabdophane are widely distributed as microcrystals in crystalline and sedimentary rocks. Monazite occurs as an accessory mineral in granitic rocks and as large crystals in

pegmatites. Because monazite and xenotime are resistant to weathering (e.g. Oelkers and Poitrasson 2002), they can be concentrated in stream and beach sands. Together with apatite, they are a major source of rare earth elements (REE), uranium and thorium. As such they play a significant role in U–Th–Pb dating of rocks and minerals (Parrish 1990). These minerals have served as thorium and uranium ores and their solubility controls to a large degree the REE signature of natural waters (cf. Johannesson et al. 1995; Köhler et al. 2005). The low solubility and slow dissolution rates of the anhydrous heavy-metal phosphates have led many to propose their use in radioactive waste storage (Sales et al. 1983).

Many phosphate minerals are popular with collectors and are used in jewellery. Perhaps the phosphate mineral best known to the general public is turquoise, an opaque, blue-green mineral, prized as a gem for thousands of years because of its unique color. Autunite is one of the more attractive radioactive minerals. Its green and yellow colour, fluorescence and crystal aggregates that resemble inflated mica books make this distinctive mineral very popular with collectors. Wavellite, with its classical radiating, globular crystal habit, is another sought-after phosphate mineral.

AVAILABILITY IN NATURAL WATERS

Phosphorus is an essential nutrient for all life forms and a key element in many physiological and biochemical processes. It is taken up by most living organisms from natural waters, but its dissolved concentration is limited by the low solubility of phosphate minerals. An estimate of the solubility of metal phosphate minerals is presented in FIGURE 2. In natural waters with pH > 6, apatite is the least soluble species, whereas in more acidic waters, variscite and strengite may limit phosphate availability. The concentration of aqueous phosphate in equilibrium with these minerals also varies dramatically with pH. At extremely low pH, aqueous phosphate in equilibrium with strengite can reach 100 ppm, but

TABLE 1 SELECTED PHOSPHATE MINERALS

Mineral	Chemical Formula ¹
Apatite (fluorapatite)	$\text{Ca}_5(\text{PO}_4)_3\text{F}$
Autunite	$\text{Ca}(\text{UO}_2)_2(\text{PO}_4)_2 \cdot 10\text{--}12\text{H}_2\text{O}$
Chlorapatite	$\text{Ca}_5(\text{PO}_4)_3\text{Cl}$
Hydroxylapatite	$\text{Ca}_5(\text{PO}_4)_3\text{OH}$
Monazite	$(\text{REE,U,Th})\text{PO}_4$
Pyromorphite	$\text{Pb}_5(\text{PO}_4)_3\text{Cl}$
Rhabdophane	$(\text{REE})\text{PO}_4 \cdot \text{H}_2\text{O}$
Strengite	$\text{FePO}_4 \cdot 2\text{H}_2\text{O}$
Turquoise	$\text{CuAl}_6(\text{PO}_4)_4(\text{OH})_8 \cdot 4\text{H}_2\text{O}$
Variscite	$\text{AlPO}_4 \cdot 2\text{H}_2\text{O}$
Vivianite	$\text{Fe}_3(\text{PO}_4)_2 \cdot 8\text{H}_2\text{O}$
Wavellite	$\text{Al}_3(\text{PO}_4)_2(\text{OH})_3 \cdot 5\text{H}_2\text{O}$
Xenotime	$(\text{Y,REE})\text{PO}_4$

¹ REE stands for rare earth elements

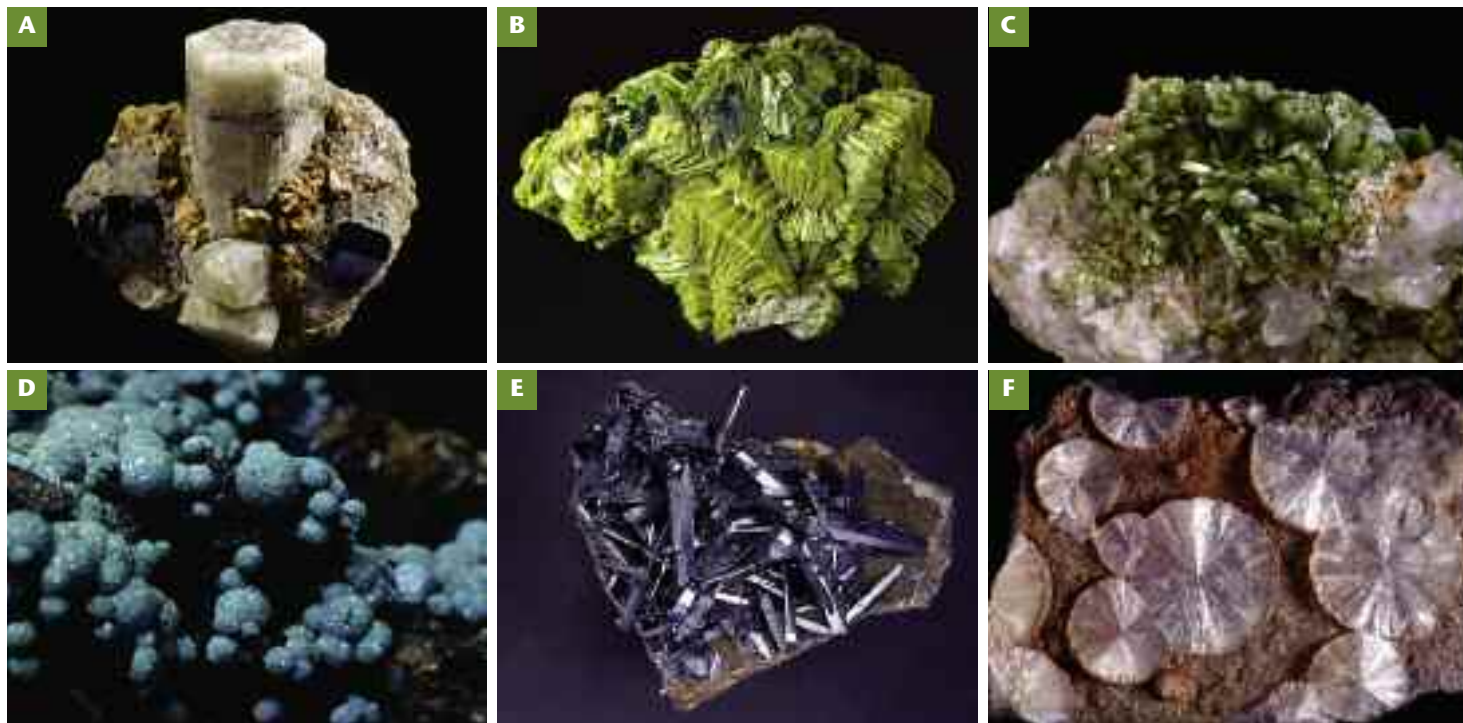


FIGURE 1 Images of selected phosphate minerals: (A) apatite, Wolley Farm, Devon, UK; (B) autunite, Spokane Co., Washington, USA; (C) pyromorphite, Wheal Alfred Phillack, Cornwall, UK; (D) turquoise,

West Phoenix Mine, Linkinhorne, Cornwall; (E) vivianite, Blackbird mine, Lemhi Co., Idaho, USA; (F) wavellite, Trenice, near Horovice, Bohemia, Czech Republic. COPYRIGHT NHM PICTURE LIBRARY

at near-neutral conditions, the concentration of phosphate in equilibrium with variscite and apatite ranges from 1 to 40 ppb. At high pH, phosphate in equilibrium with apatite becomes even less soluble. As a result of its low solubility, phosphorus is the critical limiting element for animal and plant productivity in most environments on Earth's surface. Historically this limitation was overcome by recycling manure, but more recently, phosphate-rich fertilizers have been used to dramatically increase global agricultural productivity, greatly increasing dependence on phosphate production.

In response to the low concentration of phosphate in natural waters, some microorganisms have developed methods to enhance phosphate liberation from minerals (e.g. Newman 2001). Such processes have been shown to modify reaction rates at mineral surfaces (e.g. Hutchens et al. 2006). The ability of microorganisms to exploit minerals for essential elements may define which environments can sustain life, both on Earth and on other planets, and they have likely played a role in the origin of life itself.

PHOSPHATE CONCENTRATIONS: ESSENTIAL AND TOXIC

Although phosphorus is critical for life, excess phosphorus causes environmental destruction in both fresh and marine ecosystems. Overabundance in natural waters results from phosphate fertilizers, human sewage, and detergents. Because phosphorus is often the limiting nutrient for plant growth, an oversupply can trigger rapid growth of aquatic plants and algae (Smith et al. 1999). The organic mat that forms blocks sunlight. When the nutrients are depleted and the plants or algal blooms die, they are decomposed aerobically by bacteria. This releases phosphorus but depletes the dissolved oxygen in the water. In the dark, O_2 -depleted water, plankton and fish die, destroying the food chain. The overall process is called eutrophication. An example of a eutrophic river is shown in FIGURE 3.

Although a concentration of 0.08 to 0.10 mg/L orthophosphate (PO_4^{3-}) may trigger periodic blooms, long-term eutrophication is usually prevented if total phosphorus and orthophosphate levels are below 0.5 mg/L and 0.05 mg/L, respectively (Dunne and Leopold 1978). To minimize eutrophication risk and limit algal growth, the U.S. Environmental Protection Agency water quality criteria require that phosphate not exceed 0.05 mg/L if streams discharge into lakes or reservoirs, 0.025 mg/L within a lake or reservoir, and 0.1 mg/L in streams or flowing waters not discharging into lakes or reservoirs (U.S. Environmental Protection Agency 1986).

GLOBAL PHOSPHATE MINERAL RESOURCES

Phosphate rock is the only economic source of phosphorus for production of fertilizers and chemicals. About 80% of world phosphate production is derived from deposits of sedimentary marine origin. About 17% comes from igneous rocks and their weathering derivatives and the remainder comes from residual sedimentary and guano deposits. In sedimentary deposits, the main phosphate mineral is microcrystalline carbonate-fluorapatite (formerly known as francolite), which occurs in association with a variety of accessory minerals and impurities (McClellan and Van Kauwenbergh 1990).

Economically produced ore typically contains 20–30% P_2O_5 . Like natural phosphate minerals, phosphate rock is sparingly soluble, and fertilizer production requires creating a more soluble form. In the typical treatment, sulfuric acid

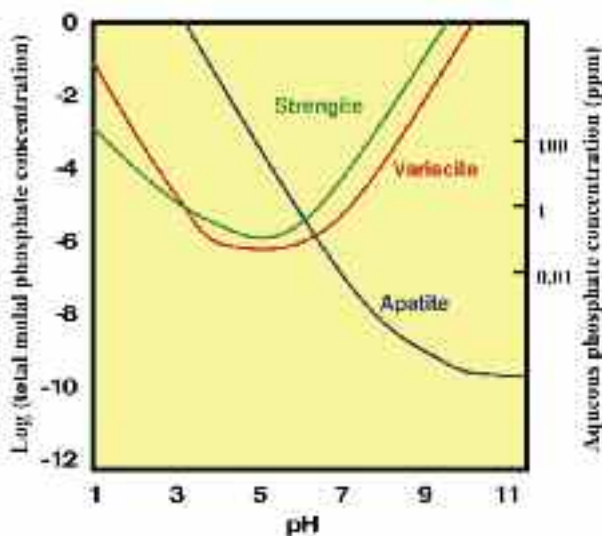


FIGURE 2 Solubility of mineral species that control aqueous phosphate concentration at 25°C as a function of pH (after Stumm and Morgan 1996). The calculations assume equilibrium with $Al(OH)_3$ and $\alpha-FeOOH$ and concentrations of aqueous Ca and F fixed at 0.01 and 0.0001 molal, respectively.



FIGURE 3 The eutrophic Verdoubre River near Les Gorges de Gouleyrous in southern France. PHOTO BY TERESA RONCAL-HERRERO

is used to produce phosphoric acid, the basic material for production. More than 90% of the phosphate rock mined in the United States is used for making fertilizer.

A summary of global phosphate production is provided in TABLE 2. The United States, China and Morocco collectively produce more than 60% of global supplies. The United States is the leading exporter of fertilizers, accounting for approximately 45% of global exports (Prud'homme 2005), but US dominance of the export market is currently declining as a result of competition from other countries. It is interesting that there are no major phosphate deposits in Europe. Global production of phosphate rock (FIG. 4) increased dramatically during the last century to meet the demands of agriculture. Production peaked during the mid-1980s, in part as a response to global concerns about eutrophication. The price of phosphate ore remained close to \$20–30 (inflation adjusted) per metric ton over much of the past century (FIG. 5).

TABLE 2 PHOSPHATE ROCK PRODUCTION AND RESOURCES FOR 2005 (Jasinski 2006)

Country	Production (thousands of metric tons P ₂ O ₅)	Resources (millions of metric tons of phosphate rock)
Australia	550	1200
Brazil	2200	370
Canada	380	200
China	9130	13,000
Egypt	800	760
Israel	880	800
Jordan	2060	1700
Morocco	8300	21,000
Russia	4000	1000
South Africa	1000	2500
Syria	1050	800
Togo	368	60
Tunisia	2400	600
United States	10,500	3400
Other countries	2482	2610
Total	46,100	50,000

Estimates of the future of global resources

Because most phosphate is used for fertilizer, estimates of the duration of global phosphate reserves are linked to estimates of future agricultural needs and efficiency. Increased life expectancy, decreased child mortality and improved farming methods, which have increased food production, have led to exponential world population growth over the last 150 years, raising our numbers from 1 billion to 6 billion by the beginning of this century. Currently, world population is growing by 1.5% per year. Although difficult to estimate accurately, UN population projections suggest a decrease in this rate, such that the population will remain roughly constant at 10 billion after 2050 (United Nations 1998). Agricultural production and phosphate consumption may, however, increase faster than global population. As the world becomes richer, increased demand for meat, dairy products and other 'higher quality' foodstuffs will modify existing consumption patterns. Thus, global phosphate demand may increase by as much as 2–2.5% annually over the next several decades. Such estimates suggest that half the global phosphate resources will be consumed during the next 60 to 70 years. This depletion will set off a progressive increase in prices, as extraction and processing costs rise and as countries holding deposits become conscious of their value. Decreased agricultural production, because of dwindling fertilizer availability, could have grave consequences for society in the future.

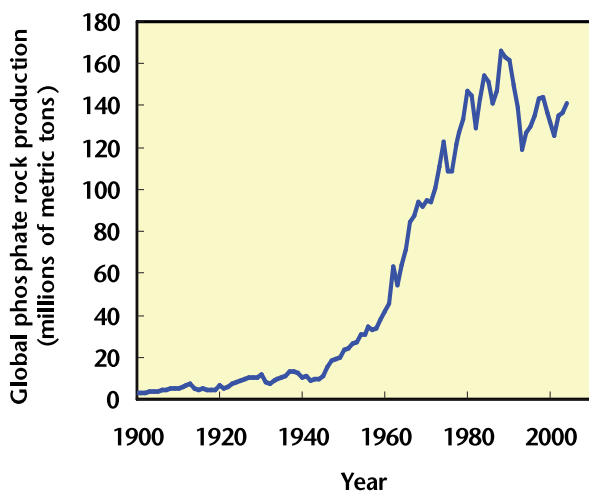


FIGURE 4 Global phosphate production (U.S. Geological Survey 2007)

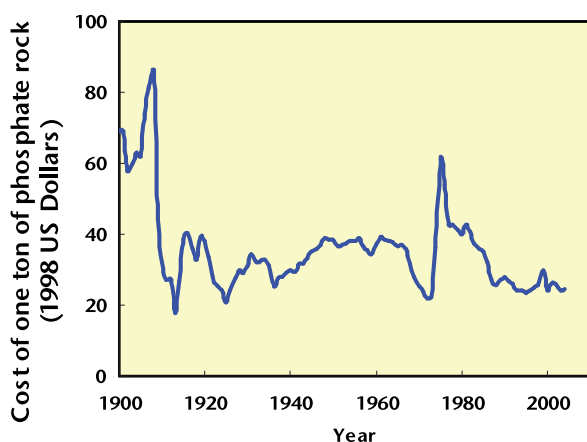


FIGURE 5 Cost of phosphate rock from 1900 to 2005 in constant 1998 US dollars (U.S. Geological Survey 2007)

CHALLENGES FOR EARTH SCIENTISTS

One of the obvious roles for Earth scientists is to improve our ability to limit the mobilization of phosphorus from agricultural and other human sources to natural waters where it causes eutrophication. This may be achieved by developing 'designer' fertilizers with formulations that allow better control of the rate of phosphorus release. Alternatively, if methods are developed to recycle phosphorus from waste forms (e.g. sewage sludge and effluents), it may be possible to use current resources more effectively and conserve the limited global phosphate reserves (Valsami-Jones 2004). Another area of active research is finding ways to take advantage of the low solubility of many metal phosphate minerals, such as pyromorphite and actinide phosphates, to design better methods to immobilize toxic and radioactive waste (cf. Valsami-Jones et al. 1998).

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REFERENCES

- Aoki H (1991) Science and Medical Application of Hydroxyapatite. Japanese Association of Apatite Science, Tokyo, 542 pp
- Becker P (1989) Phosphates and Phosphoric Acid: Raw Materials, Technology and Economics of the Wet Process, 2nd edition. Fertiliser Science and Technology Series, vol 6, Dekker, New York, 760 pp
- Boyer L, Savariault J-M, Carpena J, Lacout J-L. (1998) A neodymium-substituted britholite compound. Acta Crystallographica C54: 1057-1059
- Chairat C, Oelkers EH, Schott J, Lartigue J-E (2006) An experimental study of the dissolution rates of Nd-britholite, an apatite-structured actinide-bearing waste storage host analogue. Journal of Nuclear Materials 354: 14-27
- Chen X, Wright JV, Conca JL, Peurrung LM (1997) Effects of pH on heavy metal sorption on mineral apatite. Environmental Science & Technology 31: 624-631
- Driessens FCM, Verbeeck RMH (1990) Biominerals. CRC Press, Boca Raton, Florida, 440 pp
- Dunne T, Leopold LB (1978) Water in Environmental Planning. W.H. Freeman and Company, New York, 818 pp
- Filippelli GM (2008) The global phosphorus cycle: Past, present, and future. Elements 4: 89-95
- Guy C, Audubert F, Lartigue J-E, Latrille C, Advocat T, Fillet C (2002) New conditioning for long-lived radionuclides. Comptes Rendus Physique 3: 827-837
- Hench LL, Wilson J (eds) (1993) An Introduction to Bioceramics. World Scientific, Singapore, 386 pp
- Hughes JM, Rakovan J (2002) The crystal structure of apatite, $\text{Ca}_5(\text{PO}_4)_3(\text{F}, \text{OH}, \text{Cl})$. In: Kohn MJ, Rakovan J, Hughes JM (eds) Phosphates: Geochemical, Geobiological, and Materials Importance. Reviews in Mineralogy & Geochemistry 48, pp 1-12
- Huminicki DMC, Hawthorne FC (2002) The crystal chemistry of the phosphate minerals. In: Kohn MJ, Rakovan J, Hughes JM (eds) Phosphates: Geochemical, Geobiological, and Materials Importance. Reviews in Mineralogy & Geochemistry 48, pp 123-253
- Hutchens E, Valsami-Jones E, Harouiya N, Chairat C, Oelkers EH, McEldoney S (2006) An experimental investigation of the effect of *Bacillus megaterium* on apatite dissolution. Geomicrobiology Journal 23: 177-182
- Jasinski SM (2006) Phosphate Rock. In: 2006 Minerals Yearbook. United States Geological Survey, Reston, http://minerals.usgs.gov/minerals/pubs/commodity/phosphate_rock/myb1-2006-phosp.pdf
- Johannesson KH, Lyons WB, Stetzenbach KJ, Byrne RH (1995) The solubility control of rare earth elements in natural terrestrial waters and the significance of PO_4^{3-} and CO_3^{2-} in limiting dissolved rare earth concentrations: A review of recent information. Aquatic Geochemistry 1: 157-173
- Köhler SJ, Harouiya N, Chairat C, Oelkers EH (2005) Experimental studies of REE fractionation during water-mineral interactions: REE release rates during apatite dissolution from pH 2.8 to 9.2. Chemical Geology 222: 168-182
- LeGeros RZ (1991) Calcium Phosphates in Oral Biology and Medicine. Karger, New York, 200 pp
- Mann S, Webb J, Williams RJP (1989) Biomineralization: Chemical and Biochemical Perspectives. Weinheim, New York, 541 pp
- Manning DAC (2008) Phosphate minerals, environmental pollution and sustainable agriculture. Elements 4: 105-108
- McClellan GH, Van Kauwenbergh S (1990) Mineralogy of sedimentary apatites. In: Notholt AJG, Jarvis I (eds) Phosphorite Research and Development. Geological Society Special Publication 52: 23-31
- Newman DK (2001) How bacteria respire minerals. Science 292: 1312-1313
- Oelkers EH, Montel J-M (2008) Phosphates and nuclear waste storage. Elements 4: 113-116
- Oelkers EH, Poitras F (2002) An experimental study of the dissolution stoichiometry and rates of a natural monazite as a function of temperature from 50 to 230 °C and pH from 1.5 to 10. Chemical Geology 191: 73-87
- Parrish RR (1990) U-Pb dating of monazite and its application to geological problems. Canadian Journal of Earth Science 27: 1431-1450
- Parsons SA, Smith JA (2008) Phosphorus removal and recovery from municipal wastewaters. Elements 4: 109-112
- Pasteris JD, Wopenka B, Valsami-Jones E (2008) Bone and tooth mineralization: Why apatite? Elements 4: 97-104
- Perrone J, Fourest B, Giffaut E (2002) Surface characterization of synthetic and mineral carbonate fluorapatites. Journal of Colloid and Interface Science 249: 441-452
- Prud'homme M (2005) Global fertilizer supply and trade in 2005-2006. In: 31st Proceedings of the International Fertilizer Industry Association, Sevilla, Spain, November 14-17, 2005
- Sales BC, White CW, Boatner LA (1983) A comparison of the corrosion characteristics of synthetic monazite and borosilicate glass containing simulated nuclear waste glass. Nuclear Chemistry and Waste Management 4: 281-289
- Smith VH, Tilman GD, Nekola JC (1999) Eutrophication: impacts of excess nutrient inputs on freshwater, marine, and terrestrial ecosystems. Environmental Pollution 100: 179-196
- Stumm W, Morgan JJ (1996) Aquatic Chemistry, Chemical Equilibria and Rates in Natural Waters, 3rd edition. John Wiley & Sons Inc., New York, 1022 pp
- Turek SL, Buckwatler JA (1994) Orthopaedics: Principles and Applications, 5th edition. Lippincott Williams & Wilkins, 768 pp
- United Nations (1998) World Population Projections, www.un.org/esa/population/publications/sixbillion/sixbillion.htm
- U.S. Environmental Protection Agency (1986) Quality criteria for use, 1986: U.S. Environmental Protection Agency Report 440 14-86-001
- U.S. Geological Survey (2007) Phosphorus statistics. In: Kelly TD, Mantos GR (compilers) Historic Statistics for Mineral and Mineral Commodities in the United States. U.S. Geological Survey Data Series 140
- Valsami-Jones E (ed) (2004) Phosphorus in Environmental Technology: Principles and Applications. IWA Publishing, London, 656 pp
- Valsami-Jones E, Ragnarsdottir KV, Putnis A, Bosbach D, Kemp AJ, Cressey G (1998) The dissolution of apatite in the presence of aqueous metal cations at pH 2-7. Chemical Geology 151: 215-233
- Xu Y, Schwartz FW, Traina SJ (1994) Sorption of Zn^{2+} and Cd^{2+} on hydroxyapatite surfaces. Environmental Science & Technology 28: 1472-1480 ■

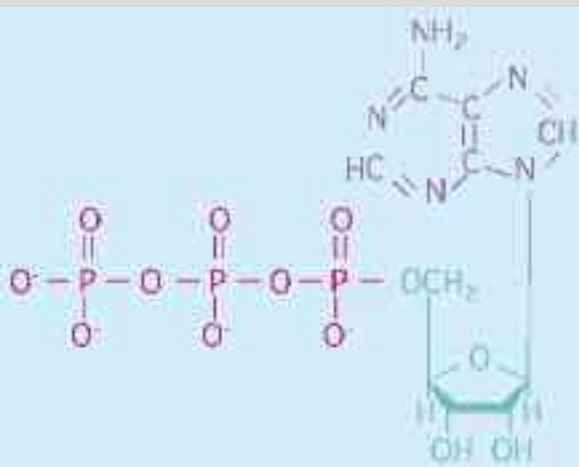
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Adenosine triphosphate (ATP) is probably the most important phosphate compound of all. It is the universal energy "currency" for all known life forms. ATP and its reaction products provide or store energy for all organism activity. The reaction takes place within the cell and is responsible for a range of functions, including metabolism, DNA synthesis, and cellular motility.

ATP consists of a central sugar molecule, ribose (which also happens to be the foundation for DNA) (green in the figure) bounded to a base, adenine (purple), on one side (adenine plus ribose = adenosine) and to three phosphate groups on the other (red). The three phosphate atoms are the key to ATP's worth. The bonds between P and O are very strong, so when the end phosphate is released by the activity of an enzyme, the cell gains a lot of energy. The adenosine diphosphate (ADP) that is produced can further react, losing a second phosphate, releasing more energy, and leaving adenosine monophosphate, AMP.


When the cell needs to store energy gained from food or sunlight, reverse reactions reattach two phosphate groups. This molecular "rechargeable battery" is essential for life, explaining



why phosphate supply is critical. In order to ensure a ready reservoir, vertebrates have developed a storage system that doubles as the skeleton's building material. In bones, we carry around our emergency stockpile of phosphorus.



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