tive or developmental energy or of 'determiners' by repeated regeneration but from changes in the non-regenerating part associated with age. In another place there is a discussion of the possibility that there may be an effect upon the rate of developmental processes in the organism as a whole due to continued regeneration of a part. This is studied particularly in connection with the effect of regeneration upon rate of metamorphosis in Amphibia.

Regeneration studies in general and those on successive regeneration in particular make it improbable that there is a definite number of cell regenerations between the fertilized egg and the end product, the differentiated cell. The possibility that certain cells may remain in an early cell generation can not be wholly excluded as an explanation of at least part of first regeneration phenomena. Under suitable stimulation such cells may be postulated to take up development where it has left off. The definite descriptions of de-differentiations of cells as well as other facts of regeneration argue against this conclusion. The view that there can be no such definite number of cell generations is strengthened by the facts of successive regeneration. It does not seem probable that embryonic cells of an early cell generation can be held in reserve through repeated regenerations.

The explanation of regeneration by the theory of duplicate sets of determiners meets difficulties in undiminished successive regenerations. The greater the number of repeated regenerations the greater the difficulties of explanation on this basis. Of course the difficulty does not hold for .the hypothesis that every cell or nearly every cell contains a full set of determiners.

The earlier appearance of the maximum rate in the second than in the first regeneration may be due to the more rapid progress of the cells in the early cell migration period alone or it may be due to the acceleration of the whole developmental cycle.

The full data will be published in the *University of Illinois Biological Monographs.*

THE GEOLOGIC RÔLE OF PHOSPHORUS

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Phosphorus appears in nature in many forms and in many situations. Its numerous transformations, however, follow an orderly sequence. In a broad way, the changes form a cycle but since the path of change divides here and there, the element really progresses through a series of subordinate cycles all having a common beginning and capable of being brought eventually to a common end.

Omitting the rare meteorites, we find the primary source of phosphorus in magma (molten lava). Almost all magmatic rocks, whether they solidify in the interior of the earth or are poured out upon its surface, contain this element. According to Clarke,[1] the average igneous rock of the world contains 0.29% of P_2O_5. The proportion is somewhat greater in the basic rocks, such as gabbro and the peridotites; and in the peripheral portions of certain magnetite ore bodies, which are believed to be merely ultrabasic segregations from a less basic magma, the quantity of P_2O_5 may exceed 10%. In these rocks the phosphorus almost invariably appears in the form of the mineral apatite, a compound of tricalcium phosphate with calcium fluoride or chloride.

The hot solutions and vapors emitted by subterranean bodies of magma, especially during the progress of crystallization, permeate the adjacent rocks, and, through the crystallization of their constituents upon the walls of fissures, are believed to form the veins known as 'pegmatites.' In rare instances pegmatites contain noteworthy quantities of apatite—generally in large crystals. Some of the Norwegian apatite deposits are probably of this origin.

There is another type of phosphatic veins which is even rarer than the pegmatitic variety, although locally in central Spain there are important deposits of this kind. These are the fibrous veins consisting not of apatite, but of the minerals staffelite or dahllite—hydrous calcium carbo-phosphates[2] containing about 38% of P_2O_5. These veins traverse quartzite, slate and limestone, but have a suggestive association with intrusions of granite. While their origin is not known, it may be suggested that they will eventually prove to have crystallized from magmatic solutions at a considerable distance from the parent intrusion and at a comparatively low temperature. Certain even rarer primary deposits containing phosphorus minerals may be neglected in this brief sketch.

At and near the surface of the earth, and under favorable climatic conditions, rocks of all kinds are subject to chemical decomposition. One of the chief agents of this process is ground water containing carbonic acid and other solvent substances. In this weak solution apatite and the hydrous phosphates such as dahllite dissolve somewhat readily, as compared with most other common minerals, although much less rapidly than calcite ($CaCO_3$).

The dissolved portion circulates through the rocks and is disposed of in several ways. Much of it is absorbed by plants and thus vicariously by animals, but returns again to the soil after the death of the organism, if not before. A very large part either immediately or eventually joins the streams and finds its way to the ocean, suffering on the way certain minor losses which may be passed over here.

Of the vast quantities of dissolved mineral matter delivered to the ocean annually by streams, it is estimated that nearly $\frac{1}{2}$ of 1% (0.45%) consists of phosphoric acid. Using the best available figures for the amount of water reaching the ocean, we may calculate that if the phosphatic material in the form of tricalcium phosphate were loaded into standard railroad cars it would fill a train stretching continuously from New York to Seattle and would be from 7 to 12 times as great as the world's total production of phosphate rock in 1911. Nevertheless so great is the volume of the oceans, and so vast the area of their floors, that if all of this material were converted into phosphatic minerals and deposited uniformly over the bottom of the sea, it would serve to form annually a layer less than $\frac{1}{5}$ mm. thick. Of the phosphorus poured into the sea, so large a proportion is utilized by living things that the net working balance dissolved in oceanic water at present averages less than 0.005%, expressed as P_2O_5, or about $\frac{1}{6}$% of the salts dissolved. This seemingly represents the most diffuse state reached by phosphorus in the course of its complex migrations. Its subsequent transformations, now to be described, generally tend toward ever greater concentration almost until the cycle is closed upon itself.

Soluble phosphates are absorbed by the myriads of oceanic plants. In some measure they become chemically linked in organic compounds but for the most part they probably remain as salts or ions. Living diatoms and other algae contain in both of these states $\frac{1}{10}$ to $\frac{2}{10}$% of P_2O_5. These organic substances containing phosphorus are devoured by an all but infinite variety of aquatic animals, each of which is in its turn liable to a similar fate. This endless process of devouring is recognized even in the ancient Chinese proverb to the effect that "the big fish eat the little fish, and the little fish eat the shrimp, and the shrimps eat the mud." In the individual animal, the phosphorus forms a constituent of its tissues, cells, liquids, and in some groups also its teeth, bones, shells and other hard parts.

There are at least two ways in which the phosphorus may escape from this oceanic cycle. The organisms of the sea may be eaten by land animals, chief of which are the birds, or the phosphorus may be fixed among the solid deposits on the sea bottom and eventually buried beneath the accumulating sediments. The second of these processes will be considered first.

At somewhat rare intervals, marine animals are killed in enormous numbers by sudden changes in temperature, by volcanic eruptions, submarine earthquakes, and other catastrophes. The carcasses of such animals generally float; but some may come to rest upon the sea bottom. In either event the omnipresent forces of decay rapidly convert the carcasses to soluble form and thus return their constituents to the oceanic solution before they are deeply buried. It is conceivable that, under the most favorable circumstances, a layer of bones and teeth might be left on the sea floor; but at best the reality of fixation in this manner is doubtful.

As an incident to the normal life of vast numbers of organisms both on the sea bottom and in its upper waters, shells and pellets of solid excrement are incessantly falling to the sea bottom. Dredging operations have shown that in many places the latter material forms an appreciable part of the bottom sediments[3] and in a few places the sediment has been found to consist almost entirely of such pellets, especially those of holothurians, marine worms, and echinoids. Under normal conditions, this material is devoured by the various scavengers of the sea bottom, and any portion that may be left is fermented by bacteria. Insofar as this action prevails, phosphorus cannot well become a solid part of the sediment deposited on the sea floor.

Under conditions probably anaërobic but not yet well understood, a quite different process may operate. The organic refuse fermented by bacteria in the absence of free oxygen yields such compounds as hydrocarbons, carbon dioxide, hydrogen sulphide and ammonia. Under favorable chemical conditions the phosphoric acid also liberated will react with various substances, particularly lime salts. With the latter it produces the mineral collophanite, a hydrous calcium carbo-phosphate.[4] Where calcareous shells lie on the sea bottom, they become phosphatized. Even organic matter such as excretory pellets, pieces of wood, and other non-calcareous materials, are altered in this way. Bones which initially contained about 58% calcium phosphate are still further phosphatized until that percentage rises to 85 or more. In addition, the collophanite forms little round grains resembling the oolitic grains common in certain limestones. It is also deposited as a cement between the particles of all kinds, thus producing hard nodules or even continuous solid beds of phosphate rock. At the same time, probably by the influence of carbonic acid evolved during the decay of the organic matter, lime carbonate is dissolved. Many facts indicate that in these situations only the phosphatic mineral is stable, even though lime carbonate shells may at the time be falling from the surface to the bottom of the sea. In such a phosphatic deposit the content of phosphorus pentoxide may range from less than one to at least 36%. Sediments of this type, subsequently lifted above the sea, have become the rare but locally voluminous source of our most important commercial phosphates, or have served as a necessary antecedent for the later formation of such deposits.

Reference has already been made to the fact that through the agency of birds and other animals of the land, phosphorus may escape from the cycle of changes in the ocean. Upon islands where they are out of reach of predaceous mammals, sea-birds congregate in extraordinary numbers, and the amount of excrement annually deposited by them on the surface of these islands is large.

In moist regions bacterial fermentation decomposes this material and the soluble resultants are removed by rain water so rapidly that little residue is left. On those islands, however, which are situated in the dry trade-wind belts, this process is almost inoperative, and hence the guano accumulates from year to year. The dry guano—before subsequent alterations have taken place—contains as much as 28% P_2O_5, plus organic matter. During moist seasons, transient though they may be, the guano is subject to fermentation by microörganisms such as the bacteria, with the result that the nitrogenous matter is largely converted into ammonia, and is lost. The occasional rains dissolve out some of the soluble phosphates and most of the nitrates, leaving a residue of solid 'stone guano' containing as much as 39% of P_2O_5, largely in the form of hydrous acid and basic calcium phosphates.

The solutions derived from the guano above sink downward through the underlying rocks, and produce characteristic alterations in them. If the subjacent terrane be limestone, it is slowly converted into a mass of calcium phosphate, in which the minerals collophanite and stafellite (?) are the characteristic forms. Observations on the islands in the Indian Ocean indicate that coralline limestone has been changed in recent times at the rate of 2 or 3 feet in twenty years.[5] In the laboratory, a coral skeleton became 60% phosphatized in only two months.[6] On volcanic cones, even such refractory igneous rocks as andesite have been converted superficially into a mass of aluminum and iron phosphates.

These processes of alteration near the surface of the earth affect not only the guano deposits, but also the marine sediments which contain phosphatic minerals. Some of the Cretaceous chalk deposits of Belgium, which it appears originally contained from 1 to 4% of P_2O_5, have been converted by the differential leaching of lime-carbonate by carbonated waters into much thinner beds, in which the proportion of P_2O_5 has arisen to more than 30%. As in the case of guano, more or less of the lime phosphate is dissolved along with the lime carbonate, and sinking down through subjacent limestones, converts them into secondary beds of phosphate rock. Our important Florida deposits (the hard rock variety) are believed by Sellards[7] to have originated in this manner. Other examples of the same type are probably to be found in the limestone plateau of southern France, some of the phosphates of central Tennessee, and many other regions.

Phosphatic deposits of any of the types already described may be buried to great depths and there be subjected not only to great vertical pressures but to the even more intense horizontal strains that accompany mountain folding. In harmony with the well established principle that most rocks tend to recrystallize under these conditions, the phosphatic rocks are probably reorganized. The hydrous minerals characteristic of the surface must become dehydrated, and there is also a tendency for carbonic acid to be driven off. As a result, beds which originally consisted of the hydrous carbo-phosphates—collophanite, dahllite and others—are believed to pass over into pure apatite, in which the proportion of P_2O_5 may rise to nearly 43%—the maximum attainable. Although none of the known apatitic deposits have thus far been proved to have originated in this way, it is more than probable that illustrations of this type exist. It has been suggested that the rich apatitic beds associated with the Grenville marbles and gneisses near Ottawa, Canada, are really the highly anamorphosed representatives of phosphatic sediments once deposited on the surface of the land or sea bottom.

There is no obvious reason why deeply buried layers of phosphate rock invaded by fluid lava from below should not be dissolved by the latter, diffused through its mass, and eventually crystallize as apatite disseminated through the resulting igneous rock. Insofar as this occurs it closes the cycle, for the phosphorus is thus brought back to its original condition, albeit after untold ages of migration and transformation in the surficial portion of the earth.

[1] Clarke, F. W., Data of Geochemistry, *Bull. U. S. Geol. Survey,* No. 616, p. 27 (1916).

[2] According to A. Lacroix, *Mineralogie de la France,* v. 4, pp. 555 et seq.

[3] Murray, Sir. J., and Philippi, E., *Wissensch. Ergeb. der Deutschen Tiefsee Exped.,* Bd. X, Lf. 4, (1905) (Carl Chun, editor).

[4] Lacroix, A., *Mineralogie de la France,* v. 4.

[5] Willis, J. L., *Ottawa Naturalist,* 6, 18 (1892).

[6] Collet, L. W., *Proc. R. Soc. Edinburgh* 25: 882.

[7] Sellards, E. H., *Florida Geol. Survey, 5th Ann. Rept.,* pp. 37–66 (1913).