THE SIGNIFICANCE OF RED COLOR IN SEDIMENTS.

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The many articles with some variant of the above title which have recently appeared indicate the widespread interest in this as yet unsolved problem. Having taught for many years that red beds indicate moist rather than arid conditions at the place of accumulation, I wish to add my contribution to the small but growing list of papers in which this theory is upheld.

Red color in rocks is generally due to the presence of a ferric compound of iron, and it has usually been assumed that it is the oxide, hematite (Fe_2O_3). It is a question, however, whether the coloring matter may not be in reality, a red hydroxide. In view of the importance of the deductions which follow from a correct evaluation of the meaning of red color, it seems worth while to review the rôle of iron in the sediments in the light of recent work on the chemistry of oxides and hydroxides of that metal.

With the exception of aluminum, iron is the most abundant and widely distributed metal in the rocks of the earth's crust, occurring chiefly in the complex silicates which are the most easily decomposed constituents of igneous rocks. It also occurs as the oxides magnetite and ilmenite, which are not so easily attacked. Biotite, amphiboles, pyroxenes, olivine and chlorite probably furnish the greater part of the iron which goes into solution.

SOLUTION OF THE IRON.

During the process of weathering, the complex silicates are broken down by the action of various acids and alkalies. The acids are partly of inorganic, partly of organic nature, but very largely the result of organic processes. Carbonic acid is usually considered the most important single solvent. A small part of this is derived from the atmosphere, but much more from the decay of organic matter. It is well known that nearly all minerals are slightly soluble in water containing carbon dioxide, and such action alone would account in time for the freeing of considerable amounts of iron. The presence in decaying organic matter, however, of microorganisms such as bacteria, yeasts, and molds, results in the production of many organic acids, such as butyric, formic, lactic, acetic, citric, tartaric and propionic.

The action of organic acids on the minerals, and in some cases the work of specific bacteria, produces small amounts of other inorganic acids, particularly nitrous and sulphuric. A step in the process of the formation of nitrous acid is the production of considerable quantities of ammonia, an important factor in solution, since alkaline carbonates are thus formed.

As a result of the action of the various solvents in the soil, iron goes into solution in two forms; a large part of it as the bicarbonate and a lesser portion as organic compounds whose nature does not appear to be definitely known.

FATE OF THE CARBONATE.

Since the carbonate is soluble only in the presence of an excess of CO_2, such solutions are carried very short distances. On coming to the surface or otherwise losing carbon dioxide and returning to the presence of oxygen, the ferrous bicarbonate is immediately changed into the amorphous form of ferric hydroxide commonly called limonite. This material will, according to circumstances: (a) remain in the soil; (b), be deposited near the source; or (c) be transported in suspension to some other locality.

FATE OF THE SOLUBLE ORGANIC COMPOUNDS.

Very little is known about the organic compounds of iron, but it is known that some rivers carry an appreciable amount of the metal in solution. Thus, according to Clarke[1] the Dan and Roanoke Rivers of Virginia, the Neuse and Cape Fear of North Carolina, and the Flint River of Georgia all carry iron which, calculated as Fe_2O_3, makes up from 1.74 to 2.88 per cent of their total dissolved solids. Clarke also quotes analyses made by Harrison and Reid of waters in rivers of British Guiana, in which the iron, presumably in organic compounds, amounts, when calculated as Fe_2O_3, to from 6.18 to 15.78 per cent of the total solids carried in solution. Looking over the various analyses tabulated by Clarke, it will be noted

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[1] The Data of Geochemistry, U. S. Geol. Sur., Bull. 770, chapt. 3, 1924.

that the rivers containing an appreciable percentage of iron are those of fertile districts, and chiefly in warm regions. The rivers of the arid regions show only traces of iron.

Harder[2] has explained in some detail how the iron-depositing bacteria attack both organic and inorganic compounds of iron in solution, and cause the precipitation of ferric hydroxide and ferrous sulphide. He summarizes the processes in the following words: "According to present knowledge it may be said that, as regards physiologic activities, three principal varieties of these bacteria exist—(1) those which precipitate ferric hydroxide from solutions of ferrous bicarbonate and use the carbon dioxide liberated and the energy produced during oxidation for their life processes, (2) those which do not require ferrous bicarbonate for their life processes, but which cause the deposition of ferric hydroxide when either inorganic or organic iron salts are present, and (3) those which attack organic iron salts, using the organic acid radicle as food and precipitating ferric hydroxide, or basic ferric salts which are gradually changed to ferric hydroxide."

Iron-depositing bacteria appear to live in fresh water only, but seem to be of universal distribution in that medium. Consequently the greater part of the iron in solution as an organic compound probably shares the fate of that carried as a bicarbonate, and is precipitated before it has traveled far. Some iron in solution does reach the sea, but apparently not in greater amounts than is necessary for the support of organic life there. In fact, the supply of available iron may to some extent control the amount of marine vegetation. The ferric hydroxide deposited through the action of bacteria may appear as a deposit composed chiefly of limonite, but is more often seen as a stain on grains of clastic rocks.

ACCUMULATION OF FERRIC HYDROXIDE.

The greatest concentration of ferric hydroxide is in the regolith, and it appears that climatic control is a factor in its accumulation there, for it is chiefly in tropical and semitropical regions that laterites and laterite-like materials occur. As Glinka[3] points out, it is in warm regions of "optimal

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[2] Iron-Depositing Bacteria and their Geologic Relations, U. S. Geol. Sur., Prof. paper 113, 1919.

[3] Die Typen der Bodenbildung, Berlin, 1914.

moistening" that bacterial decay is so rapid as to balance the production of organic matter, leaving little residium of humus to enter the soils. The growth of vegetation is so great that the water is held or transpired, and the soil does not become water-logged. Under these conditions the soil waters become alkaline (Robinson[4]), and leach out silica, leaving the hydroxides of iron and aluminum as the ultimate products of a very thorough decomposition of the rocks. Under favorable circumstances such decomposition goes on to considerable depths. The upper part of the regolith is red or orange-red, whereas at depths of from one to fifty feet the color gradually changes to yellow.

In moist temperate and arctic regions vegetation is also abundant, but in the cooler climate the action of putrefactive bacteria and other organisms is less rapid, and entirely inhibited for a part of the year. As a result, cellulose, which does not decay rapidly, tends to accumulate and remains as humus in the soil. In humid temperate climates, because of less evaporation, the soils are more moist than in the humid tropics. This results in poorer aeration and slower decomposition of the plant residues. Decomposition is of an anaerobic nature, and leads to the formation of an acid type of soil water, which removes iron and aluminum rather than silica (Robinson). The downward movement of water in such a region produces a surficial zone of leaching from which the iron is constantly being removed. Robinson has called this the zone of eluviation. If the material is carried down to the permanent water table, carbonates of iron are apt to be formed in such regions, since the ground water is usually deficient in oxygen and rich in carbon dioxide.

If, however, the soil is porous and rather well oxygenated, ferric hydroxide is often formed in what Robinson has named the zone of illuviation, that is, the zone at which the fine-grained material carried down from above is dropped by the descending waters. At this horizon "hard-pan" cemented by red or yellow ferric hydroxide is often found. Such features are often to be noted in the accumulations of fluvio-glacial sand in New England, and there is at the present time an especially good exposure of a red "hard-pan" along the highway from Boston to Springfield about a mile east of Warren, Mass. Other instructive examples of the same sort of action

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[4] Pedology as a Branch of Geology, Geol. Mag., 61, 444-455, 1924.

can be seen at many places on Cape Cod, particularly among the old sand dunes of Orleans and Truro. The dunes are now covered with three or four inches of humus, beneath which is a layer, a few inches to two feet in thickness, of a glistening white, pure quartz sand. Below the white stratum, the body of the dune consists of sand which is stained in various tones of yellow, much of it shading to orange, and in a few places thin layers of red hard-pan may be seen. The sand as it came from the sea contained small particles of ferro-magnesian minerals which have now been leached out of the layer beneath the soil. The products of the leaching have not been in sufficient quantity to turn the sand red, but under exceptional conditions such action might take place. The distal end of the Cape shows the results of processes acting in a desert situated in a temperate, humid region. Very likely the similar pale orange and reddish sands of the Sahara and other deserts were formed during periods of a more humid climate.

In arid and semi-arid regions, little decomposition takes place, so that little solution of iron can be accomplished. Observation shows that red and yellow are seldom seen in the soils of such localities, unless the country rock itself happens to be of those colors.

Black soils do, however, accumulate to some extent under semi-arid climates, since the vegetation grows rapidly during the wet season, and decay is checked in the dry months which follow. Under these conditions some leaching occurs, but evaporation is so great that the moisture is drawn upward, and a calcareous hard-pan is formed relatively near the surface. No red soil seems to be forming under these conditions.

As is well known, water from higher regions often underlies the surface of arid and semi-arid regions, and at places the water-table is sufficiently close to the surface to allow an upward migration by capillarity, if the grain of the material is not too coarse. Under such conditions the water is evaporated at and near the surface, and the sands may be stained by the oxidation of the dissolved iron thus precipitated. Instances of this sort are, however, rare.

RED AND YELLOW COLORS.

Unfortunately, knowledge of the chemistry of iron oxides and hydroxides is not as yet far enough advanced to give any satisfactory explanation as to why some formations containing much iron are red, whereas others are yellow. It has been the general assumption that the former were colored by hematite, and the latter by limonite, but I do not know that there is any definite proof that such is the case. The assumption has been based, of course, on the fact that there was formerly supposed to be a more or less continuous series of hydroxides from limnite, $Fe_2O_3.3H_2O$, to turgite, $Fe_2O_3.\frac{1}{2}H_2O$, and then a passage to hematite, Fe_2O_3, with, theoretically, no water. The hydroxides containing from 6 or 7% to 28 or 30% of water are yellow, whereas turgite with 4 to 6% and hematite are red. The process of turning red was therefore supposed to be one of dehydration. It is true that with enough heat and enough pressure the yellow hydroxide can be turned red, but not at any temperatures or pressures encountered either at the surface of the earth or at any depths at which any of the red sediments have been buried (Posnjak and Merwin[5]). Observation alone shows the futility of appealing to deep burial, for in the Triassic sandstone of New Jersey, estimated to have a thickness of approximately three or four miles, the upper layers, never deeply buried nor acted upon by orogenic forces, are just as red as those at the base.

Neither has heat derived from the sun anything to do with the process, for the red material at the zone of illuviation beneath the surface in temperate and cold regions is just as red as the superficial layers in the tropics.

Another suggestion, first, I believe, put forward by Crosby,[6] has been looked upon with considerable favor, although it has been neither proved nor disproved. This is, that dehydration is a gradual process, which will take place provided time enough elapses. Barrell advocated this idea particularly, and believed that many of the red sediments when accumulated were colored yellow by limonite, and that in the course of time, dehydration had taken place, so that the color is now red.

This idea is attractive, both from the standpoint of what is known about the chemistry of the hydroxides of iron, and from what may be learned from observation of the sedimentary rocks, but it is confronted with some difficulties. It has long been known that "limonite" when first formed contains 28 to 30% of water, which on standing is reduced to 14%. Posnjak and Merwin in their recent careful study of the

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[5] The Hydrated Ferric Oxides, this Journal, **47**, 311-348, 1919.

[6] On the Contrast in Color of the Soils of High and Low Latitudes, Am. Geol., **8**, 72-81, 1891.

hydroxides of iron, found that in most of the so-called species, the water was not chemically combined but loosely held. They did, however, show that goethite and lepidocrocite were definite mineralogical species, ferric monohydrates ($Fe_2O_3.H_2O$), with definite chemical and physical properties, which did not change within wide limits of temperature and pressure. They also showed rather conclusively that turgite did not arise from a dehydration of the ferric monohydrate, but that it was probably a solid solution of the latter with hematite. They did not, however, categorically deny the possibility of slow dehydration, given plenty of time. There are also the facts, difficult to explain, that many ancient sediments rich in ferric iron are not red, and that red sediments are being formed at the present day. We seem here to be confronted with the same lack of chemical evidence that makes it so difficult for us to understand the devolitization of compounds of carbon, and the formation of dolomite.

Posnjak and Merwin therefore came to the conclusion that the red hydroxides are formed by different chemical reactions from those which produce yellow ones, an opinion previously put forward by others.

It was long ago shown that yellow and red hydroxides of iron could be formed artificially, although never in crystalline form. Solutions of ferric chloride and ferric nitrate when treated with sodium, potassium or ammonium hydroxides, give precipitates of red colloidal ferric hydroxide. Solutions of ferrous salts when treated with alkaline hydroxides give precipitates of light bluish green ferrous hydroxide which upon oxidation changes to yellow ferric hydroxide. Yellow ferric hydroxide is also formed by oxidation and hydration of ferrous carbonate and in the rusting of metallic iron.

It does not appear that anyone has followed up the thought inherent in these facts, but I should like to put forward the suggestion that the coloring matter in sediments may be formed in much the same way as are the synthetic hydroxides. As is well known, ammonium hydroxide is formed in the putrefaction of organic matter; nitrifying bacteria work this into nitrites, and they are followed by another group of bacteria which change the nitrites into nitrates. In the meantime more ammonium hydroxide is being produced, so that, in the soil, it is entirely possible that ferric nitrate is produced, and then changed to red ferric hydroxide as is done in the test-tube. Under such conditions a part of the iron in solution would be precipitated as red material. Other and probably larger portions of the iron would be carried downward as the soluble bicarbonate and remain as such in the zone of ground water, to be later oxidized to the yellow limonite. If such action took place, one could understand both the layering of red and yellow hydroxides in the tropics, where the superficial soil-waters are alkaline, and the thinness of the zone of red hydroxides beneath the surface in temperate and cold, moist regions.

Another view is possible, but difficult to apply to the sediments. Holden[7] has pointed out that hydrous ferric oxide prepared from $FeCl_3$ varies in color from pale yellow to dark red according to the concentration. This is in accordance with the common observation brought to my attention by one of my students, that railroad rails after a shower turn yellow, but as rusting proceeds, shortly become reddish. MacCarthy,[8] in a recent paper, applies this to the sediments and states: "That iron-yellows may be merely a more dilute phase of the orange-reds obtained with ferric hydroxide may easily be shown with a spectroscope."

The fact that many yellow sediments contain more ferric iron than red ones of the same grain, makes it doubtful if this explanation is of universal application, and although an orange-red ferric hydroxide may on dilution show a yellow color, it does not follow that a yellow one, on concentration, would necessarily become red. The stain on the sands of Cape Cod, mentioned above, does, however, seem to show that their yellow is a dilute form of orange-red.

FERRIC HYDROXIDE IN THE SEDIMENTS.

From what has been stated above, it appears that a *sine qua non* for the accumulation of considerable quantities of ferric hydroxide, either red or yellow, is the weathering of rocks through long periods of time under warm and moist conditions. The amount of such material on the continents to-day in tropical and subtropical regions is almost inconceivably vast, and a great deal of it is being transported and redeposited. In

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[7] The Color of Three Varieties of Quartz, Am. Mineralogist, 8, 117, 1923.

[8] Colors Produced by Iron in Minerals and the Sediments, this Journal, 12, 17-36, 1926.

the regolith the hydroxide occurs in part as a coating on other minerals, also as free particles of minute size, and apparently, in a colloidal condition.

When transported by streams, the larger part is at least temporarily deposited in alluvial fans or flood plains on the continent. When carried to the sea by rivers it is deposited wherever muds of the finest grain collect, that is, in estuaries, lagoons, and on the continental slopes. These are also the collecting places of the fine-grained, decaying organic matter, and of the resultant hydrocarbons and carbohydrates. The hydroxides of iron come therefore into contact with substances greedy for oxygen, in a medium, mud, which is notably deficient in that gas. Under such conditions it is believed that a reducing action goes on, and that the iron is reduced to a ferrous state. Observations indicate that such action does take place, as Dawson[9] long ago showed in the case of the harbor at Pictou, Nova Scotia, where the red sediment brought in by the rivers accumulates as a gray mud. The same thing has been noted in places off the mouth of the Amazon, and the red muds of the Tennessee do not give their color to the deposits of the lower Mississippi. There must, however, be considerable amounts of organic material if all the ferric hydroxide brought to the sea is to be reduced.

Where organic material is deficient in quantity, red deposits will be formed. There are at the present day, according to Murray and Hjort,[10] large areas where red clay is accumulating off the coasts of tropical eastern South America, western Africa, and China.

There is also a question as to just how great an extent the reduction of iron from the ferric to the ferrous condition is actually accomplished. Analyses of the blue clay, which is much more commonly found on continental slopes than the red, as collected by Clarke (1, 509, 510) show large amounts of ferric iron. Ferric hydroxide is not easily attacked, and it may be that in some instances the oxygen is not really removed, but that the color is masked by the organic matter. (See also MacCarthy.[8])

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[9] On the Colouring Matter of Red Sandstones and Greyish and White Beds Associated with them, Quart. Jour. Geol. Soc. London, 5, 25-30, 1849.

[10] The Depths of the Ocean, 1912.

DEPOSITION ON THE CONTINENTS.

Unfortunately there are no localities known to me where great amounts of red sediments are accumulating on land at the present time, a fact which may have an especial significance in the interpretation of the ancient deposits. This phase of deposition can therefore be discussed only briefly, and from a wholly theoretical standpoint. Ordinarily subaerial accumulations would be formed under the same climatic conditions as those which produced the regolith. It is possible, however, that the material might be carried far enough to enter the zone of another climate. It is still more probable that the residual material might be eroded and redeposited long after its formation, and under very different geographical and climatic conditions.

Since the red and yellow hydroxides are layered in the regolith, the red above the yellow, the denudation of such material naturally carries off more of the red than the yellow. The red color therefore predominates in the mixture, and the material transported is red. It is, therefore, necessary to speak of the latter color only in connection with deposition.

EFFECT OF ARID CONDITIONS.

If the red sands, silts, and clays were brought to and deposited in an arid region, where the streams spread out and lose themselves in their fans, the ultimate appearance would be governed by mechanical and not chemical conditions. Through the sorting action of the rivers there would be separation of the finer grains, which picked up by the winds would probably be transported considerable distances. The ultimate fate of such material would depend upon location, topography, and persistence in direction of the wind. The dust might be dispersed, or it might be accumulated in such a loess-like deposit as the Vernon red shale of the upper Silurian of western New York. The silt and coarser material, up to sizes of from 1 to 2 mm., would also be wind-blown, rounded, pitted, deprived of the red stain, and accumulated in dunes of the usual white or grayish white color. Locally, some portions of the accumulation might, if the dunes stayed long in one position, receive a second staining after the rounding had taken place.

EFFECT OF COOL, MOIST CONDITIONS.

As already stated, much humus accumulates in the soil when there is moisture enough to support vegetation and the climate is cool enough to check the action of bacteria over a considerable part of the year. Under such conditions leaching occurs, and also deoxidation, hence red sediments transported to such a region might have their color reduced to green or gray unless accumulation should be too rapid to allow plants to get a foothold. In such a region moisture could vary within large limits, as the grasses, sedges and mosses of semi-arid arctic regions seem to leave nearly as large a residuum of humus in the soil as do the products of the slower-growing forests. The red stain is not, however, easily or quickly removed, as may be seen by anyone who has occasion to pass over the red fluvio-glacial soils of some parts of the Connecticut Valley. These soils have supported vegetation since glacial times, and have been more or less intensively cultivated for nearly 300 years, but many of them are still notably red.

EFFECT OF WARM, MOIST CONDITIONS.

This subject has already been sufficiently discussed when reviewing the conditions under which hydroxides of iron accumulate. In regions with such climates production of vegetable material is rapid, yet organic decay is equally favored by the continuous work of the numerous bacteria, fungi and other agents. As a result humus does not accumulate, and observation shows that even tropical forests exist on red soils which are not leached. Red sediments might therefore accumulate either slowly or rapidly under such conditions.

EFFECT OF CONDITIONS OF SEASONAL, DEFICIENT RAINFALL.

Under conditions of semi-aridity with the annual precipitation falling within limited periods, a sparce, or in places, even a luxuriant vegetation springs up, the greater part withering and dying as the dry season advances. Under such conditions, because dryness checks bacterial action, a small amount of humus collects in the soil, but whether enough to have any reducing action on red clastic deposits is not clear. If red sediments could be transported into such a region rapidly, they would undoubtedly remain red for the most part, unless the material brought in during the wet season were sufficient to overwhelm the established vegetation. In that case the plants would not readily regain a foothold, and the area would be transformed into a real desert. If the deposition were slow, a thin layer each year, there would probably be enough humus and production of acids by roots to remove a good deal of the red color.

SUMMARY.

Red residual deposits accumulate in tropical and sub-tropical regions where there is enough moisture to insure a good cover of vegetation. To accumulate a considerable quantity of such material requires a long period during which erosion is not particularly active. Debris removed from such a regolith may be deposited without loss of color in any region provided it accumulates rapidly enough. It is least apt to remain red in arid or other desert regions where there is little or no vegetation to hold the deposits in place, and in cold, moist regions where, due to abundance of humus, much leaching occurs. Somewhat more favorable for the retention of red color is a semi-arid region, but since plants do not quickly get a foothold in such a situation, a rapid influx of sediments would probably cause a more or less continuously barren surface, on which the wind would have full play. More favorable would be a cool, moist region with abundant vegetation, and sufficient rapidity of influx of sediments to prevent the accumulation of large quantities of humus. Last and best of the terrestrial locations are those with a warm, humid climate, where bacterial action is rapid and humus does not readily accumulate.

Red beds may be formed in the sea likewise if the influx of material is rapid enough to introduce more ferric iron than the organic matter present will reduce. That such has been the case at times is shown by the fact that some of the Palaeozoic red sandstones contain marine fossils near the base even though they may become non-marine, or at least unfossiliferous in the upper portion. Instances are the red Juniata sandstone of south-central Pennsylvania, the Bays sandstone of south-western Virginia, and the Moccasin sandstone of eastern Tennessee.

Under conditions of rapid removal from the land the smallest of the red grains may be abundant enough to give a red color to a truly marine limestone formed some distance from shore. The Orthoceras limestone of Sweden is, in places, as at Kinnekulle, a deep cherry red, abundantly fossiliferous limestone. The coloring matter appears to be *terra rosa,* derived from the decomposition of Cambrian limestone in south-eastern Sweden. In this country there are similar red limestones such as the Tellico and Moccasin of eastern Tennessee, which owe their color to particles of the finest size, washed out by marine action from the deposits nearer the shore.

When the ferric hydroxide is brought into the sea less rapidly, much of it may be reduced with the formation of ferrous carbonate and pyrite, which may later become oxidized, to form the yellow limonite. Thus it is possible to cross the red Upper Devonian non-marine strata of the eastern Catskills to the rusty yellow marine strata of equivalent age in the vicinity of Oneonta. The yellow of these rocks is, however, only surficial, and beneath the surface they are "blue," a color due, according to MacCarthy's recent and very important paper,[8] to a mixture of ferrous and ferric compounds with the former equal to or somewhat predominant over the latter.

The significance of red color in sediments appears to be the rapidity of accumulation. Since they are derived from a region long stable, red beds usually indicate movement of the earth's surface. The climatic conditions under which particular examples were deposited cannot be judged from the color alone but must be deduced from other lines of evidence.

Two topics, selected from the many whose explanation involves the interpretation of red color, are briefly discussed in the pages which follow.

THE NEWARK GROUP.

The strata of the Newark Group of eastern North America may be taken as a good example of a red formation. The conditions under which they were deposited have often been discussed, and the present general concensus of opinion is that the accumulation is comparable to that in the elongate, semi-arid valleys of southwestern California. Dorsey[11] has recently challenged this view, and, I believe, rightly.

There is a general agreement about some parts of the history of the Newark, at least so far as the outcrops in Massa-

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[11] The Origin of the Color of Red Beds, Jour. Geol., 34, 131-143, 1926.

chusetts, Connecticut and New Jersey are concerned, and these may be summarized briefly.

After the end of the Palaeozoic, and before the beginning of the deposition of the Newark, the Appalachian region had been reduced practically to a peneplane, and the igneous and metamorphic rocks of the roots of the mountains were at the surface. The gradient of the streams had become low, the period of active erosion had long since passed, and chemical weathering under warm, moist conditions had produced a very thick blanket of red and yellow residual soil over the land. Beneath the clay, hydration had loosened up the rocks into small fragments, and the regolith, as is usual, contained many boulder-like masses of the less easily weathered rocks, such as vein-quartz, quartzite, etc.

After the formation of the peneplane with its residual deposits there was a regional elevation accompanied by faulting along a line more or less coincident with the present eastern border of the Triassic rocks. There was also, very probably, an approximately parallel zone of faulting along the western side, producing a graben whose bottom was above sea level, but some hundreds of feet at least below the general surface of the area. Into this valley the drainage of the adjacent region naturally fell, and sediments began to accumulate rapidly. Throughout Newark time, the floor of the graben continued to sink, or the adjacent land to rise, or both, till approximately 10,000 feet of sediments had accumulated in the Connecticut Valley and twice that amount in New Jersey.

As to the conditions under which they were deposited, there is difference of opinion. Those who believe that the Newark sediments were accumulated under semi-arid conditions point out that the advent of a dryer climate would (a) reduce the cover of vegetation and allow rapid erosion of the residual material on the highlands, (b) prevent the inclusion of much vegetable matter in the sediments, and so prevent reduction of the red color, (c) that the presence of fresh feldspar in the arkose indicates absence of moisture, (d) that the absence of skeletal remains and plants from the strata indicate semi-arid conditions, and (e) that the necessity for water led to bipedality among the dinosaurs.

The present writer would interpret the evidence somewhat as follows: The absence of any proof of the formation of mountains to intercept moisture-bearing winds indicates that there is no reason to postulate a change in climate in the late Triassic, and the climate of the graben must have been that of the general region. The presence of great quantities of sediments in the valley indicates that great quantities of water poured into it. Since neither marine, estuarine, nor extensive lacustrine beds were accumulated, the valley must have been well drained by a longitudinal river. That the rivers in the valley were of the permanent and not intermittent type is indicated by the many species of fish, found at 15 localities in Massachusetts and Connecticut, as well as in New Jersey, the presence of Unios, and the almost total absence of evidence of eolian action, either in bedding or in rounding or pitting of grains. The very retention of the red stain on the grains is indicative of moist and not semi-arid conditions, for the color would have been destroyed if subjected to eolian action.

That the sediments accumulated rather rapidly is indicated by the presence of coarse conglomerates and consolidated screes near the margins of the valley, indicating a considerable break in slope along this line, the presence of large barren mud-flats on which the dinosaurs left their footprints, and which also show impressions of raindrops, shrinkage cracks, and trails of invertebrates, and by the abundance of relatively fresh feldspar. The presence of this mineral can not possibly be used as evidence of aridity. Feldspar decays at the source of supply, not at the place of burial, unless by weathering after subsequent erosion. It is admitted that the feldspar came from the same region which supplied the red coloring matter, and it is evident that it is the material from deep down in the zone of weathering, pried out from its matrix by deep-zone hydration. That it was transported only a short distance and buried quickly accounts for its comparative freshness.

That vegetation was plentiful both on the highlands and in the valley during the accumulation is indicated both by the nature of such identifiable remains as have been found, and by the indirect evidence of black shale and abundance of animal life. The presence of ginkgos, cycads and ferns indicate that the climate was not semi-arid. Hollow casts, carbonized remains, and impressions of trunks, branches and twigs of trees have been found at numerous localities. Where they are most common the strata have usually lost the red color. Considerable patches of black shale at various localities in Massachusetts and Connecticut and many hundreds of feet of carbonaceous sediments in New Jersey, to say nothing of the Triassic coal of Virginia and North Carolina, attest the local abundance of vegetation. Perhaps most important of all is the abundance of evidence of the presence of vertebrated animals. Lull has summarized the present information about the life of the Triassic of the Connecticut valley and states that there are approximately a hundred species of vertebrates now known from tracks or skeletal remains. Among these there are some phytosaurs, remotely related to the living crocodiles, some amphibians of salamandrine form, very possibly stegocephalians, and a great many dinosaurs, most of them carnivores. Now it is obvious that the carnivores could not have fed entirely upon each other, hence a large herbivorous population, very much larger than the flesh-eating one, is indicated, and these animals must have been abundant because of the abundance of vegetation. A semi-arid region could not have supported the population indicated by the footprints in the Connecticut valley, and it is very unlikely that so narrow a valley had one climate and the adjacent highlands, which were not mountains, another.

The relative rarity of vegetal and skeletal remains in the sandstones is probably to be ascribed to the coarse textures of the sediments and their accumulation in fans subaerially, which permitted decay to go on rapidly even after burial. This, added to the warmth and moisture which facilitated active bacterial action, caused a rapid disappearance of both animal and vegetable matter.

If these sediments were accumulated under warm and moist conditions, we would not, as indicated above, have any reason to expect a great amount of reduction in color. The arguments derived from the nature of the sediments and their fossil contents lead us to believe that they were formed under warm and moist climate, rather than a semi-arid one. A further suggestion is that the rivers pouring into the valley probably carried as much iron in the organic state as does the Amazon at present (approximately 7% of the total solids in solution). This iron, released by bacterial action in the presence of decaying vegetation, might have added to the red stain on the sediments in the valley.

The abundance of carnivores was probably as great an incentive to the acquirement of bipedality in running as would be the necessity of travel for water.

ORIGIN OF AIR-BREATHING VERTEBRATES.

It will be remembered that Barrell's[12] explanation of the origin of the air-breathing habits which led to the emancipation of the ancestors of terrestrial vertebrates from the thrall of the aquatic habitat was involved with his theory of the accumulation of red sediments under semi-arid conditions. The fouling and final drying of the bodies of water occupied by the fringe-finned ganoids is supposed to have caused the more vigorous among them to have developed lungs by gulping air, and the use of the fins in crawling to have produced modifications which in time led to the structure of the typical vertebrate limb.

If the red beds of the early Devonian, the supposed site of this important episode in the drama of life, were really accumulated under warm and moist conditions, we must change the accent somewhat, although the key and tempo remain the same. The important factor in Barrell's scheme was the evanescent nature of the aquatic habitat, and such a *situs* is supplied by any alluvial fan, under any climatic condition. Streams are constantly changing their courses on them, pools and swamps are formed in which the waters are renewed by periodic overflow from the main channels, and in these any trapped animals would be subjected to the same process of gradual exhaustion of the oxygen as under semi-arid conditions.

There are also certain advantages to be gained from the explanation under the conditions now postulated. Where extreme fouling or actual drying out takes place, as in the homes of the lung-fishes of the southern hemisphere, the animals hibernate for a part of the year, and sloth rather than progressiveness is encouraged. Fishes inhabiting the constantly changing waters of a fan would doubtless often be routed from their homes by sudden changes in channel, to be left flopping about in very shallow water as the streams spread out over some flat. Those best able to travel by means of fins might win their way to a deeper pool, and so a premium was put on activity and the weak and unlucky weeded out. The instinct for overland migrations to other and fresher waters

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[12] Influence of Silurian-Devonian Climates on the Rise of Air-Breathing Vertebrates, Bull. Geol. Soc. Am., 27, 387-436, 1916.

may early have been developed under these precarious conditions of life. Food, too, would have been more abundant and the supply more constant under moist and warm than under semi-arid conditions. Further, with a greater supply of vegetable matter, fouling by decay would occur more readily.

And last, and most important, amphibians and water have been connected throughout their entire history. They constantly return to it to breed, except, of course, in some very specialized groups of the race, and no theory of their origin is satisfactory which requires their expulsion from it entirely.

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