ART. XXIII.—*The Decay of Rocks Geologically Considered*; by
T. STERRY HUNT, LL.D., F.R.S.

[Read before the National Academy of Sciences at Washington, April 17, 1883.]

CONTENTS OF SECTIONS.—1, 2. The supposed relation of rock-decay to climate; 3, Decomposition of silicated rocks; 4, 5, Studies of Pallas, Fournet, J. F. Dana, Webster, Blake; 6, Of Hartt in Brazil; 7, Of Shepard in Connecticut; 8, 9, Whitney, Pumpelly and Dawson on decay of limestones; 10, A sub-aërial process; 11, 12, Its antiquity and its relation to glacial erosion; 13, Decay in the Blue Ridge; Hunt, Burbank; 14, 15, Chemical significance of decay of aluminous silicates; 16, Analyses of decomposed feldspars; 17, 18, The question in relation to eozoic rocks; 19, Boulders in crystalline schists; 20, 21, Decayed gneiss of Hoosac Mountain; 22, Of the South Mountain, Penn.; 23, At Atlanta, Ga.; density of decayed rocks; 24–26, Cupriferous pyrites; its decay; iron and copper ores; 27–30, Limonites of the Appalachian valley; tertiary limonites (foot-note); 31–34, Lesley, Jackson, Frazer and Lyman on limonites; 35, 36, W. B. Rogers on formation and segregation of siderite; 37, 38, Limonites from serpentine of Staten Island; 39, Pumpelly on decay of petrosilex-porphry in Missouri; its pre-Cambrian antiquity; 40, Of gneisses in Wisconsin and Minnesota; White, Winchell and Irving; 41, Rock-decay in Sweden and in Scotland; 42, Post-Cambrian decay of igneous rocks; 44, 45, Decay of auriferous gravels in California; influence of carbonic acid; 46, Slight decay in post-glacial times; effects of changes of temperature (foot-note); 47–49, Pumpelly on the geological relations of rock-decay; 50–52, Studies of Reusch in Corsica; 53, Conclusions.

§ 1. The subject of the decay of rocks has not yet received from geologists all the attention which it merits, and there still appear to be misconceptions with regard to it which warrant us in reviewing some points in its history. Professor F. H. Storer,¹ in a recent notice of a suggestion of Nordenskiöld's as to the liberation of gems through the decay of the feldspathic rocks in which they are often contained, cites with approval the opinion of Professor Stubbs of Alabama that "the decomposition of these rocks in southern latitudes has proceeded much faster than with the same rocks in higher latitudes," a "condition which can be accounted for, to a large extent, by climatic influences." The cold and frost now prevailing in northern regions are supposed by him to retard the action of atmospheric waters, regarded as the chemical agent of this process of decay.² These views, implying that the process is one belonging to the present time, are accepted by Professor Storer, who writes of the "more active and thorough-going disintegration which occurs" in these southern regions.

§ 2. That the presence in the northern hemisphere of a mantle of softened material from the decay *in situ* of crystalline rocks is more common at the outcrops of these in low than in high latitudes, where it is often entirely absent, is a familiar fact; but it will, I think, be made evident that present climatic

¹ Science, for February 16, 1883, p. 29.

² Bernay's Hand-book of Alabama, 1878, p. 199.

differences have nothing to do with the fact that similar rocks are in one area covered with a thick layer of the products of decay, and in another are wholly destitute of it.

§ 3. The decay in question is well known to be due to a chemical change of which the predominant mineral silicates of the rock, chiefly feldspars and hornblende, are the subjects, and which results in the removal by solution of the protoxyd-bases, together with a great proportion of the combined silica, leaving essentially a residue of clay, mingled with quartz, garnet, magnetite and such other mineral species as resist the process of decomposition.

§ 4. A memoir, by Fournet, published in 1834,³ gives many facts regarding the early observations on rock-decay. Its author there describes the wide-spread decomposition of the granites near Pont-Gibaud in Auvergne, a change which Deribier de Cheissac had already shown to be anterior to the deposition of the Tertiary rocks. Fournet, moreover, noticed the similar decay of basalts, phonolites, trachytes, and even obsidians, and described the process of exfoliation by which were left rounded masses of undecayed rock. He cites in this connection the observations of Pallas, who, in his travels in Siberia (1768-1774), noticed hills "that seemed composed of masses heaped together, as it were rounded by decomposition." The view of Werner that the rounded form of masses such as these was due to original concentric structure, was rejected by Fournet.

§ 5. In 1818, Messrs. J. F. and S. L. Dana described a similar phenomenon in the decaying greenstones at Somerville, near Boston, Mass., where the rock was found to be converted by decay *in situ* into nodular masses presenting exfoliating concentric layers of differing degrees of decomposition. These masses rest upon each other, decayed matter filling the interstices.⁴ In 1825, T. W. Webster noticed the same example, and explained the formation of boulders by the exfoliation of the decayed greenstone.⁵ Again, in 1858, W. P. Blake described the production of rounded masses both of sandstone and of granite through disintegration. He explains how angular blocks, separated by joints admitting water to all sides, would be "attacked most rapidly on the angles, thus producing a succession of curved faces gradually approaching a sphere," and illustrates the process by figures. He described, moreover, the boulder-like masses of granite in Placer County, California, lying on an uneven surface of the same rock, "as due to the manner in which the rock decomposes, and not to

³ Ann. de Ch. et de Phys. [2] v, 225-256.

⁴ Mem. Amer. Acad. Sciences, 1st Series, iv, 201.

⁵ Boston Journ. Philos. and Arts, ii. 285.

abrasion." Like Fournet, he rejects the notion of an original concentric structure in the rock.⁶

§ 6. Hartt, in 1870, discussed the well-known examples of rock-decay found in Brazil, and called such rounded masses of rock as we have just described "boulders of decomposition." He moreover noted that the process of decay was there anterior to the supposed glacial action, which had worked over the material of the previously decomposed rocks.⁷ Lyell already, in 1849, had pointed out that the Tertiary clays and sands of the southern United States have been derived from the waste of the previously decayed crystalline rocks of the region;⁸ and as we have seen, the ante-Tertiary age of the decay in Auvergne had long before been recognized.

§ 7. The account given by Professor Charles Upham Shepard, in 1837, of the origin and mode of occurrence of the porcelain-clays of western Connecticut is remarkable for its exactness and perspicuity. That at New Milford is described as occurring "upon the western slope of an elevated range of granitic gneiss. . . . In many places the decomposition of the parent rock is so complete as to present the aspect of a secondary deposit; but the prevailing appearance is that of the rock altered in place through the decay of the feldspar and mica. Indeed, the same relative arrangement of the quartz and the altered feldspar is observed in the bed as is presented by these materials in the undecomposed rock. Veins and seams of a perfectly impalpable white clay traverse the rock in various directions, analogous to the veins of feldspar in the granite of the neighborhood." Of a pure white clay in the town of Kent, our author says, "It forms a vein many feet in width, cutting through quartz rock. It owes its origin to a graphic granite, which must have been free from mica." A similar vein of clay is described as occurring in the town of Cornwall, and as including frequent crystals of black tourmaline; the feldspar also being incompletely decomposed.⁹

§ 8. As showing that the process of sub-aerial decay is not confined to silicated rocks, it may be noted that J. D. Whitney described in 1862, the existence in the lead-region of Wisconsin of a layer of red clay and sand, mixed with chert, sometimes thirty feet in thickness, which he showed to be a residuum from the secular decay of several hundred feet of the impure Paleozoic limestones of the region.¹⁰ A like occurrence was afterwards, in 1873, described by Pumpelly, in southern Missouri, where such residuary deposits sometimes attain a thick-

⁶ Geol. Recon. of California, pp. 146, 286.

⁷ Scientific Results of a Journey in Brazil, pp. 28, 573.

⁸ Lyell: A Second Visit to the United States, ii, 28.

⁹ Shepard: Report of Geological Survey of Connecticut (1837), pp. 73-75.

¹⁰ Geology of Wisconsin, i, 121.

ness of 120 feet.¹¹ This process is evidently due to a simple solution of the carbonates of lime and magnesia in meteoric waters.

§ 9. A similar decay is conspicuous along the outcrop of the Auroral limestones and their associated schists in the Appalachian valley, as will be noticed farther on, in § 27, and may also be seen at several points in the Trenton limestone and the Utica shale of the St. Lawrence valley. One of these localities, described by Dr. J. W. Dawson, is at Les Eboulements, on the north shore of the St. Lawrence, below Quebec. Here, at the southwest base of the high Laurentide hills, the Post-pliocene clays, enclosing marine shells and large gneiss boulders, are found resting upon a mass of Utica slate, deprived of its calcareous matter, and so soft as to be readily mistaken for the newer clays of the region but for its stratification and its organic remains. This, according to Dawson, had been changed to a great depth by sub-aërial action previous to the period of submergence, during which it was covered with the boulder-clay.¹² Some facts connected with the decay of the Trenton limestone near Montreal will be mentioned in § 42.

§ 10. It may be said that with the exception of Darwin, who had observed the decay of rocks in Brazil and conjectured that the process might have been sub-marine, all observers have correctly regarded it as sub-aërial. The chemistry of the process was discussed, among others, by Fournet in the paper already cited, and later by Delesse in 1853;¹³ also very fully by Ebelmen, who considered the question of rock-decay in its relations to the atmosphere, in two memoirs in 1845 and 1847.¹⁴ The same subject was further considered at some length by the present writer in 1880.¹⁵

§ 11. Having thus briefly indicated some of the points in its history during the past century, we are prepared to notice in more detail the contributions made to the subject, considered in its geological bearings, during the last ten years. Previous to this, as we have seen, it had been recognized that the process of rock-decay had been in operation not only in pre-glacial but in pre-Tertiary times, and that the resulting material had been the source of Tertiary clays and sands, and even, in certain cases, of glacial drift and boulders.

§ 12. In a review of Hartt's volume on Brazil, in 1870, the present writer said: "The great wasting and wearing-away of crystalline rocks in former geological periods, of which we have

¹¹ Geological Survey of Missouri; Iron Ores and Coal Fields, p. 8.

¹² Dawson: Notes on the Post-pliocene Geology of Canada; from Canadian Naturalist, vol. vi, 1872.

¹³ Bull. Soc. Geol. de France, x. 256.

¹⁴ Annales des Mines [4], vii. and xiii.

¹⁵ This Journal, xix. 349; see also his Chem. and Geol. Essays, p. 100.

AM. JOUR. SCI.—THIRD SERIES, VOL. XXVI, NO. 153.—SEPT., 1883.

abundant evidence, is less difficult to understand, when we learn that rocks as hard as those of our New York Highlands become [are] even in our own time, under certain conditions so softened as to offer little more resistance to the eroding action of a torrent than an ordinary gravel-bed.¹⁶ Subsequently, in an account of some observations made in North Carolina among the rocks of the Blue Ridge, and presented to the Boston Society of Natural History, October 15, 1873, he expressed the belief that the decay of crystalline rocks was a process of great antiquity; that it had been universal; that the covering of decayed material now seen in the south at one time extended to the rocks of northern regions, from which it had been removed by erosion during successive ages, culminating in the Glacial period at the close of the Pliocene, since which time the chemical decomposition of the surface has been insignificant. From the products of this sub-aërial decay it was then maintained has been derived a great part of the sediments alike of Paleozoic, Mesozoic and Cenozoic times. The permeable nature of the surface-soil formed of highly inclined strata of decayed rocks, affording a natural subterranean drainage, explains, it was said, both the absence of lakes and the comparative permanency of the surface to be remarked in uneroded regions; showing that something more than ordinary aqueous agencies must have effected the removal of the decayed material.¹⁷

§ 13. This communication of mine was speedily followed by a paper published in the Proceedings of the Boston Society of Natural History for November 19, 1873, by the late Mr. L. S. Burbank, repeating and insisting upon the same conclusions, and, moreover, dwelling especially upon the process of decay (which he also had studied in North Carolina), as a preliminary to the formation of bowlders and glacial drift.

In accordance with the views thus expressed in 1870 and 1873, it was conceived that the power of the usual eroding agents, ice and water, would be inadequate to the removal of great areas of rock unless this had been previously softened by decay, and in a review of the subject by the present writer, in 1873, the conclusion was reached that the decomposition of rocks has been "*a necessary preliminary to glacial and erosive action, which removed already softened materials.*"¹⁸ Such erosion and denudation would, in accordance with this view, consist in the removal of previously decayed rocks, and the forms and outlines of the sculptured surface thereby exposed would be determined by the varying depths to which the process of sub-

¹⁶ The Nation, New York, Dec. 1, 1870.

¹⁷ Proc. Boston Soc. Nat. History, Oct. 15, 1873, and this Journal, vii, 60; also Proc. Amer. Assoc. Adv. Science for 1874, p. 39; and Hunt, Chem. and Geol. Essays, pp. 10, 250.

¹⁸ Harper's Annual Record of Science, etc., for 1873, p. xlviii.

aërial decomposition had already penetrated the once firm and solid rock. The basin-like depressions and the hillocks of the eroded surface, not less than the detached rounded masses or boulders, were thus, as the writer has ever since taught, the results of the previous process of rock-decay.

§ 14. I had long before this time been led to insist upon the evidences of a wide-spread decomposition of crystalline rocks in very early periods of geological history. In an essay, entitled *Some Points in Chemical Geology*, published in 1859,¹⁹ and another, on *The Chemistry of Metamorphic rocks*, in 1863,²⁰ both reprinted in my volume of *Chemical and Geological Essays*, I have pointed out the important part played by the protoxyd-bases liberated by the sub-aërial decay of feldspathic and hornblendic rocks. Starting from the conception of a primitive terrestrial crust consisting wholly of crystalline silicated rocks, we are forced to find in such a process of decay the source of all limestones and dolomites, which are derived from the carbonates of lime and magnesia generated either directly, during the process, from the bases previously existing in the state of silicates, or indirectly, by reactions between magnesian and alkaline carbonates formed during the decay, and the calcic salts of the early ocean. The chemical genesis of the lime carbonate must evidently precede its assimilation by organisms. It was, in fact, thus shown, as the result of a great number of observations, that fossil sea-waters (mineral waters), representing the ocean of Paleozoic and even of Mesozoic times, contained large proportions of calcic chloride, such as are required by this theory.²¹ The relations of these reactions when "this decay of alkaliferous silicates is sub-aërial," as set forth in 1859 and 1863, will be found discussed at length in the volume of essays above named on pages 23–31, and page 108.

§ 15. I further proceeded at that time to consider the proportions between the alkalies and the alumina in the various characteristic minerals of crystalline rocks, noting the decrease in the former which is seen when silicates like orthoclase and albite are compared with micas like muscovite, and with silicates like cyanite, pyrophyllite and staurolite. The conclusion was then reached that "the chemical and mineralogical constitution of different systems of rocks must vary with their antiquity," and that "it now remains to find in their comparative study a guide to their respective ages;" in which connection a comparison was then attempted between the older gneisses and the newer crystalline schists. A further application of this principle was essayed in 1878, when the progres-

¹⁹ *Geol. Journ.*, London, xv. 488–496.

²⁰ *Geol. Soc. Journ.*, Dublin, x. 85–95.

²¹ *Hunt: Chem. and Geol. Essays*, pp. 41, 108, 117–121.

sive elimination of the alkalis from the aluminiferous rocks of the eozoic groups was shown by comparing the mineralogical composition of the Laurentian with the Huronian, Montalban and Taconian crystalline schists.²²

§ 16. It should here be noted that decayed feldspars, even when these are reduced to the condition of clays, have not, in most cases, lost the whole of their alkalis. This is well illustrated in a series of analyses by Mr. E. T. Sweet, of the kaolinized granitic gneisses of Wisconsin, to be noticed farther on (§ 31). From these analyses it appears that the levigated clays from these decayed rocks still hold, in repeated examples, from two- to three-hundredths or more of alkalis, the potash predominating.²³

§ 17. It would follow from the considerations advanced above, that the decay of crystalline rocks is an indispensable preliminary to the formation of limestone, and that the earliest silicated rock must have contained no carbonates whatever. There are many reasons for doubting whether this veritable primary system is known to us, but it will be remembered that at the base of the Laurentian, as seen on the Ottawa River, there is a vast and unknown thickness of red and gray granitoid hornblendic gneiss, apparently destitute of limestones, and underlying the great series of somewhat similar gneisses interstratified with limestones with graphite, iron-oxyds and quartzites, which were, as early as 1847, described by the Canadian geological survey as "a separate group of metamorphic strata," characterized by these lithological differences. Logan, however, supposed the two groups to be conformable, and they were in 1854 both included under the common name of Laurentian (afterwards the Lower Laurentian of Logan).

In a subsequent review of the subject in 1878, I designated the lower as the Ottawa group, and the upper group as the Grenville series.²⁴ It was this latter group which had been carefully studied and mapped by Logan and his assistants, and which has served as the type of the Laurentian system. I have since, in a paper read before the American Association for the Advancement of Science, in 1879,²⁵ noticed the probable non-conformability of this Laurentian system with the underlying or pre-Laurentian gneiss, and the possible relations of the latter to the fundamental or Lewisian gneiss of Scotland, and the Bojian gneiss of Bavaria.

²² Second Geological Survey of Pa.: Azoic Rocks, Rep. E, p. 210.

²³ See for these, Irving on the Mineral Resources of Wisconsin, Proc. Amer. Inst. M. Engineers, vol. viii, p. 305. For other analyses, see Geo. H. Cook, Geol. Survey of New Jersey, Report on Clays, 1878.

²⁴ Azoic Rocks, pp. 64, 148, 154-156.

²⁵ The pre-Cambrian Rocks of Europe and America compared. Amer. Jour. Sci., xix, pp. 270, 275, 281; also Geol. Mag., Jan. 1882, p. 38, and Bull. Soc. Géol. de France, x, 26.

§ 18. The existence, in the Laurentian series, of limestones, not less than that of iron-ores and of graphite, pointing to the existence of land and of vegetation during the deposition of the Laurentian, forces us to conclude to a process of sub-aërial decay of the more ancient gneisses in that far-off period. Such a process must have been continued in later times to give the materials for the aluminiferous sediments of the newer eozoic groups, and we might therefore hope to find in the latter boulders or pebbles of more ancient gneisses, such as are met with among the products of sub-aërial decay in later deposits. Remarkable examples of such rounded masses, alike of Montalban, Huronian and Laurentian or pre-Laurentian types are found abundantly in the very ancient pre-Cambrian (Keweenawian), conglomerates on Lake Superior, as I have elsewhere described.²⁶ Not less striking examples of rounded masses of older gneisses occur in the Huronian series in many localities, particularly on Lake Temiscaming, where are great beds of conglomerate made up chiefly of gneiss boulders.²⁷ I have elsewhere noticed a specimen in my possession which shows a perfectly well-defined and rounded pebble of finely granular white limestone, measuring an inch in its greatest diameter, enclosed in a laminated hornblendic gneiss from Grafton County, New Hampshire. Slices cut from the specimen for the microscope show a strong adhesion between the limestone and the quartz and feldspar of the matrix, without however any evidence of chemical change at the contact.²⁸

§ 19. The rounded masses and pebbles of gneiss found abundantly in several localities imbedded in the pre-Cambrian micaceous schists of the Saxon Erzgebirge are not less remarkable examples of the same kind. I had in 1881 the opportunity of examining with Dr. Credner a large collection of these, which consist chiefly of types of various kinds of gneiss resembling those of the Laurentian series as seen in North America and in the Alps. These Saxon mica-schists, with their associated gneisses passing into granulites or leptynites, have all the characteristics of the Montalban or newer gneissic series of North America and of the Alps, to which I have elsewhere compared them in two communications²⁹ wherein are noticed the above-mentioned conglomerates, which had been previously studied in much detail by Sauer³⁰ in 1879. No one who sees these accumulations of rounded masses of gneiss and other crystalline rocks entering into conglomerates at the various horizons above named, can fail to be struck with their close resemblance with

²⁶ Hunt, *Azoic Rocks*, pp. 78, 230.

²⁷ *Geology of Canada*, 1863, p. 50.

²⁸ *Bull. Soc. Géol. de France*. [3] x, 27.

²⁹ *Geol. Magazine*, Jan. 1882, p. 39, and *Bull. Soc. Géol. de France*, x, 26.

³⁰ *Zeitschrift f. d. ges. Naturwiss*, Band lii.

those which are to be found either in the glacial or other modern deposits, or lying *in situ* as undecayed rounded masses in the midst of decomposed rocks. It is difficult to resist the conclusion that these rounded masses of the eozoic ages must have been formed under conditions not unlike those which gave rise to their more modern representatives.

§ 20. The various considerations above presented thus led the writer in 1873 to assign to the beginning of the process of rock-decay an antiquity compared with which the time that has elapsed since the drift-period is to be regarded as of short duration. It was, however, then suggested by him that a climate and atmospheric conditions unlike those of modern times might have favored the process in the earlier ages. Further evidence was soon forthcoming both of the former spread of this decay over northern regions and of its great antiquity.

In 1874 I was called to examine the condition of the great tunnel then recently opened through the Hoosac Mountain in western Massachusetts, my report on which was published by the General Court of the State;³¹ while a note on the observations therein made which have a bearing on the present inquiry, was presented to the American Institute of Mining Engineers in October, 1874.³²

§ 21. As there explained, the gneissic rock of Hoosac mountain, at the west end of the tunnel, 700 feet above the sea, is completely decayed, the feldspar being converted into kaolin for a distance of several hundred feet eastward along the line of the tunnel. The gneiss on the crest of the mountain, 2,000 feet above the sea, and on the eastern slope, on the contrary, wherever exposed, presents the rounded surfaces common throughout the region, often marked by glacial striæ, and without any appearance of decay. The softening and decomposition of the highly inclined strata of gneiss in the tunnel were described as complete for a distance of 600 feet from the west portal, where the floor of the tunnel is 200 feet from the surface, and were partial at 1,000 feet, where it is 230 feet below; while farther in, at 1,200 feet, an included bed of limonite, doubtless of epigenic origin, showed that the solvent and oxydizing action of atmospheric waters had penetrated to a depth of more than 300 feet from the present surface. At the western entrance to the tunnel the gneiss is immediately succeeded by the crystalline limestone and quartzite of the Taconian (Lower Taconic) series, the decayed rocks apparently coming from beneath the limestone. It was evident that this great mass of decayed gneiss at the western base of Hoosac Mountain is but a portion of a once wide-spread mantle of similar materials

³¹ House Document No. 9, 1875.

³² Proc. Amer. Inst. M. Engineers, iii, 187.

which has escaped the action that denuded and striated the surface of the other parts of the mountain.

§ 22. Numerous examples of similar remaining portions of decayed feldspathic rock have been observed farther southward, as in northwestern Connecticut (described in § 7), and among the Laurentian rocks of the South Mountain in Pennsylvania, north of the Schuylkill. One of these decayed portions, at Siesholtzville, Penn., was seen in 1875, where a bed of magnetite, at that time mined, was found to overlie at a high angle a mass of granitoid gneiss completely kaolinized, but apparently protected from erosion by the incumbent iron-ore.

In another example in the same region, about two miles south of Allentown, Penn., the Primal sandstone was found resting for a little distance on the Laurentian gneiss, here much decayed. Where this had been exposed in a recent cutting (in 1875) the reddish feldspathic rock, still retaining its color and its gneissic structure, though kaolinized, contained numerous "bowlders of decomposition," from three to twelve inches in diameter, consisting of undecayed gneiss, the laminated structure of which was clearly continuous with that seen in the enclosing decayed mass. These bowlders, still *in situ*, spheroidal in form, and often with pitted surfaces, are identical with those found in the drift near by, on the southeast slope of the hill, and are very different in outline from the half-angular forms of adjacent sandstone blocks. This gneiss rock, lying decayed in place, would, unless examined in fresh cuttings, be readily mistaken for the drift of the vicinity, which has evidently been derived from it.

§ 23. In my earlier notices of the decayed Montalban rocks of the Blue Ridge in North Carolina, I had described a mantle of from fifty to one hundred feet or more of decayed material, but this according to the late Professor W. B. Rogers, sometimes exceeds two hundred feet, a thickness approaching to that observed at the western base of Hoosac Mountain. I have since noticed the decay of the Montalban rocks near Atlanta in Georgia, where, with local exceptions of undecayed areas (as in Stone Mountain) the decomposition is more or less complete, in many places, to a depth of fifty feet. Here, as elsewhere, the more massive rocks include nuclear masses of undecayed material. The decayed highly hornblende gneiss of Atlanta, though still retaining considerable coherence, has lost about two-thirds of its weight, the specific gravity of unchanged portions being 2.97—3.08, while that of the decayed material is reduced to 1.20, and even, for some specimens, to less than 1.0.³³ The decomposed gneiss in this region is, in some cases, sufficiently coherent to furnish blocks for certain purposes of

³³ Azoic Rocks, p. 250.5

construction, such as the walls of rude chimneys, but at the surface it readily disintegrates, yielding a strong red soil, often used as a brick-clay. The decayed mica-schists of the Montalban series, which still retain their micaceous aspect, have been called hydro-mica schists, though distinct from those of the Taconian, with which they have been confounded.

§ 24. The relations of the large deposits of cupriferous iron-pyrites found in the rocks of the Blue Ridge, to the general process of decay, was discussed by the writer in 1873,³⁴ after a study of the copper-mines opened in Carroll Co., Va., in Ashe Co., N. C., and in Polk Co., Tenn.³⁴ These ore-deposits were described as in each case in rocks of the Montalban group—the newer gneisses and mica-schists—and as constituting veins or lenticular masses of posterior origin, consisting essentially of pyrite, pyrrhotine and chalcopyrite. The agent which kaolinized the enclosing rocks, also oxidized the sulphurets, removing the sulphur and the copper, and converting the residue into limonite, which, in a vertical lode in Ashe Co., N. C., was found to extend to depths of from forty to seventy feet. Beneath the oxidized portion is found in all cases the unchanged pyritous mass, seldom carrying more than four or five hundredths of copper. The limonites thus generated were for some years smelted for iron, both in Virginia and in Tennessee, before they were discovered to be *gossans* at the outcrops of cupriferous pyrites-lodes. Between the unchanged pyrites and the limonite there is often found in favorable conditions an accumulation known as black ore, consisting of imperfectly crystalline sulphurets, rich in copper, and sometimes approaching to bornite in composition, occasionally with red oxide and native copper, the whole doubtless reduced from the oxidized and dissolved copper brought from above.

§ 25. The crystalline Eozoic rocks of various ages in the more northern parts of the continent contain, as is well known, many deposits of cupriferous pyritous ores, both in veins and beds which, like the enclosing strata, are undecayed, showing that the process of oxidation, like that of kaolinization, has been a very gradual one, going back to remote ages. We have seen from the observations in the southern United States that the oxidation of the sulphids, their conversion into limonites, and the removal therefrom by solution of the copper went on *pari passu* with the decay of the including rocks, and hence preceded their erosion. The copper thus dissolved was, as I have suggested, again deposited in rocks at the time in process of formation. The chief part of the iron being left behind, a veritable concentration of the copper would thereby be effected,

³⁴ Proc. Amer. Inst. M. Engineers, ii, 123, and this Journal, vi, 305: see also Chem. and Geol. Essays, pp. 217, 250.

and we should expect to find it separated on reduction as rich sulphides, or as native copper. In accordance with this view, it was said in an essay on The Geognostical Relations of the Metals, in February, 1873,³⁵ that certain deposits of such copper-sulphids found chiefly in limestones, probably of Cambrian age (Quebec group), which, in the province of Quebec, as at Acton and Durham, lie along the northwest border of the crystalline Huronian belt, might be formed from "the results of oxidation of the cupriferous beds which abound in the crystalline schists of these mountains, from which the dissolved metal accumulated in basins at their foot," as suggested by Murchison with regard to the cupriferous Permian strata near the crystalline schists of the Ural Mountains. "To a like process," it was said, "we may perhaps ascribe the rich deposits of native copper in the Keweenaw amygdaloids and conglomerates which rest upon the ancient Huronian schists."

§ 26. The farther extension of this view to the Mesozoic sandstones of Connecticut, New Jersey and Pennsylvania, well known to be very often impregnated with copper disseminated in the form of sulphides, sometimes associated with organic remains, is obvious. It is to be noticed that the strata in question are generally deposited directly upon Eozoic rocks, from the ruins of which they were formed, and that these, in our hypothesis, furnished the dissolved copper from which the disseminated ores were derived. If this view be admitted we have farther and independent evidence that the decay of the Eozoic rocks, with that of their contained cupriferous sulphurets, was going on in that pre-Cambrian period in which the Keweenaw series was accumulated, and was still active in Mesozoic time.

§ 27. Not less striking examples of rock-decay are seen in the great Appalachian valley, of which Hoosac Mountain, the South Mountain and the Blue Ridge form parts of the eastern rim. Therein, as is well known, large quantities of limonite are mined, from New England to Alabama. This ore, as well as its accompanying manganese-oxide, is clearly of epigenic origin, and is, in most cases, still imbedded in ancient and highly inclined clayey strata derived from the sub-aërial decay *in situ* of the schists which accompany the dolomites and quartzites of the Primal and Auroral (Taconian) series. These ores have been formed by the transformation in place of included masses of pyrites and of carbonates of iron and manganese.³⁶ The evidences of the pyritic origin of many of these limonites is similar to that for those of the Blue Ridge (§ 24), namely, their association with unchanged pyrites. An example of this is seen in the so-called copperas mine at Breinigs-

³⁵ Proc. Amer. Inst. M. Engineers, i, 341.

³⁶ Azoic Rocks, pp. 201-203.

ville, near Trexlertown, Penn., long ago described by H. D. Rogers,³⁷ where large quantities of pyrites have been mined from the same openings which yield limonite, some of which I found still retaining the imitative forms of the adjacent pyrites, (from which Rogers had inferred a conversion of limonite into pyrites,) while the waters of the mine, like those of others in the region, were charged with sulphuric acid and with iron-sulphate. Another remarkable locality, where pyrites replaces the limonite in depth, was visible in 1875 at Seitzinger's mine, near Reading, Penn., and other similar cases are reported in the vicinity; while at Salona in the Nittany valley the association of pyrites with limonite at this same geological horizon has also been noticed.

§ 28. The association of siderite or iron-carbonate with the limonites of the Appalachian valley is well known east of the Hudson in New York and Massachusetts. This mineral is often manganesian and passes into nearly pure rhodocrosite. Examples of the association of siderite with limonite are also seen, among other localities, near Hackettstown, New Jersey, and near Hanover, York County, Pennsylvania. These carbonates, or at least the limonite and manganese-oxide derived from them, are found in close association with pyritous deposits, as we have seen near Trexlertown. In like manner pyrites and siderite as is well known, often occur side by side, in the coal-measures.

§ 29. I have elsewhere considered the change in siderite under the action of oxydizing atmospheric waters, which proceeds like that in feldspathic rocks, from without inwards, and is necessarily accompanied with considerable diminution of volume, which, in the conversion of a siderite of specific gravity 3.6 into a limonite of the same density, would equal 19.5 per cent.

“The evidences of this contraction may be seen in the structure of the limonite derived from siderite, which often forms a porous or spongy mass. In the case, however, of nodules or blocks of solid ore, the conversion beginning at the outside of the mass, an external layer of compact limonite is formed, and then another within this, and still another, till the change is complete. The void space resulting from contraction is then found between the layers, which are arranged like the coats of an onion; or sometimes wholly at the center, where a cavity will be formed, holding in many cases, more or less clay or sand, the impurities of the carbonate which have been separated in the process of conversion into limonite. In this way are formed the hollow masses sometimes known as bomb-shell ore, [which occasionally include nuclei of unchanged siderite.] Their structure

³⁷ *Geology of Pennsylvania*, i, 265.

will generally serve to distinguish the sideritic from the pyritic limonites.”³⁸

In the paper just quoted I have also considered the change of volume which should accompany the conversion of pyrites into limonite, a process generally complicated by the loss of a part of the iron as a soluble sulphate.

§ 30. Portions of the contorted and often highly inclined schistose strata enclosing the limonite ores in the Appalachian valley, are still found but partially decayed, and while some are converted to depths of 100 feet or more into white or variously colored clays, others retain more or less of their original texture. From the presence in some of these of considerable quantities of a hydrous micaceous mineral, having the composition of damourite, they have been called damourite-slates. There are many reasons for believing that these ancient rocks were thus folded and were decomposed before the deposition of the Trenton and Chazy limestones, which rest upon them in the outlying or western valleys of the Appalachian region, alike in Pennsylvania and in Alabama.³⁹

§ 31. Prof. Lesley, in discussing the history of the limonites of the Appalachian valley, has fallen into an error with regard to my view of their origin. Referring in 1876 to the opinions expressed in my paper of 1873, (already noticed in § 13), touching the decayed crystalline rocks of the Blue Ridge, that “the iron-oxide from these has been in great part dissolved out by subsequent processes, and was the source of the immense deposits of hydrous iron-ores” in question, he supposes me to “conjecture that the ores lying along the eastern edge of the Shenandoah valley had been washed into it from or across the Blue Ridge.” This Lesley properly qualifies as an “absurd conclusion;” since it does not explain the origin of the limonites found in the back or central valleys, a hundred miles or more to the west of the Blue Ridge; and declares that had R. S. M. Jackson continued his geological studies, “he would have published a satisfactory refutation of this surface-drainage theory of the brown hematites.”⁴⁰

³⁸ The Genesis of certain Iron Ores, read before the Amer. Assoc. Adv. Science, Boston, 1880: see *Canadian Naturalist*, for Dec. 1880, vol. ix, p. 434.

³⁹ The fact of the existence at various points in the Appalachian valley of beds of limonite interstratified in Tertiary clays with lignite, as at Brandon, Vermont, must not be overlooked. First recognized by Edward Hitchcock, and subsequently noticed by Lesley in 1864, the later observations of Prime, Lewis and others, show the presence of these ores and clays with lignites at various points in Pennsylvania and in Alabama, as well as in Vermont. These are but fragments of what were probably once extended deposits, and although of geological interest as resulting from resolution and re-arrangement in Tertiary time, of a portion of the ancient decayed strata of the valley, are of comparatively little economic importance. (See H. C. Lewis, Proc. Acad. Nat. Sci. Philadelphia, Oct. 27, 1879.

⁴⁰ Second Geol. Survey of Penn., Report A, p. 83.

§ 32. Those who have read what I had written on the subject previous to 1876, and especially my discussion of the origin of these ores in 1874,⁴¹ are aware that I have never advocated any such theory. I have, it is true, endeavored to find in the insoluble products of decay of these ancient crystalline rocks, the source not only of the clays and sands of the succeeding sediments, but of their contained iron, whether diffused or accumulated in ore-masses. I have, however, at the same time, always maintained that the ores associated with the so-called Primal and Auroral rocks of the Appalachian basin, like those of the higher horizons, up to the coal-measures inclusive, were deposits contemporaneous with the strata in which the valleys were subsequently excavated; and that save in some cases where, as in the Clinton beds, it was apparently deposited as peroxide, the iron was accumulated in the form of carbonate, and more rarely of sulphid; from the alteration of both of which, *in situ*, the limonites have been formed. This view, which as I then showed, was that advocated by C. U. Shepard, in 1837, for the limonites of western New England, was the same as that put forward in 1838, by R. S. M. Jackson himself, who maintained, as stated in the language of Prof. Lesley, "that the ore belonged to the stratified limestone beds themselves, and had been set free from them by chemical and mechanical decomposition." This history was clear to Dr. Persifor Frazer, who, having remarked that "the theory of alteration *in situ* of various iron-minerals resulting in the formation of many of these limonites, advanced by C. U. Shepard, and ably discussed and adopted by Dr. T. Sterry Hunt, cannot be disregarded in seeking the cause which produced these limonites," adds, "in 1838, and independently of Prof. Shepard's observations, Dr. R. S. M. Jackson reported to Prof. H. D. Rogers, substantially the same conclusion from the study of the limonites of Center and Huntingdon counties."⁴²

§ 33. This same view in fact was well stated by Lesley himself in 1864, when he said "the brown-hematite ore-deposits of Mount Alto follow the edge of the slates and sandy limestones," and are "but the residues of these beds after decomposition and dissolution; the honey-combed and altered edges" of the slates and limestones themselves, "after the lime has been washed out of them, and their carbonated and sulphuretted iron has been hydrated and peroxidized; the slates having formed the red and white clays." He further described at one locality of the region in question "an outcrop of almost unchanged blue carbonate of iron and lime, several feet thick * *

⁴¹ Proc. Amer. Institute Mining Engineers, iii, pp. 418-421.

⁴² Second Geological Survey of Penn., Report C, p. 143.

and evidently in part changing into honey-combed brown hematite ore."⁴³

§ 34. In 1867, Mr. Benjamin Smith Lyman, expressed similar views in his account of the limonites of Smyth County, Virginia, found lying below the limestones of No. II (Auroral), where many localities "show the ore unmistakably in regular beds conformable to the other rocks." He at the same time supposed that some of these ore-deposits are, like one noticed in Wythe County, Virginia, due to "the weathering of the upper part of a fissure-vein of iron-pyrites," but maintains that the ores, with such exceptions as this, were "deposited in regular beds of greater or less extent and thickness, at the same time with the other rocks," and from the presence in the limonite of occasional masses of carbonate of iron, concludes that it was originally deposited in this condition."⁴⁴

§ 35. But while it is apparent that the ores in question now found imbedded in clays resulting from the decomposition *in situ* of ancient schists, were previous to that decay enclosed therein as massive siderite, or pyrites, we must not overlook the evidences that in certain cases a process of segregation of diffused iron-oxide has played an important part, alike in ancient and in modern times, in the genesis of limonites. Setting aside, as not relevant to our present inquiry, the formation of bog iron-ores, and ochers, which are directly deposited from ferrous solutions by peroxidation and precipitation, we here recall the contribution to the theory of the origin of imbedded iron-ores made by the late William B. Rogers.

The ferrous carbonate found in the rocks of the coal-measures, has, as he has endeavored to show, been generated from diffused ferric oxide by a process of reduction, carbonation and solution, through waters charged with organic matters from vegetable decay; the carbonate of iron thus formed remaining in some cases diffused through the sediments, and in others becoming concentrated by accretion.⁴⁵

§ 36. This view is to be supplemented by the consideration that carbonated solutions of ferrous oxide formed as above (and often containing organic acids), may, by reacting with beds of carbonate of lime, effect a gradual replacement of the latter by carbonate of iron.⁴⁶ The transformation of diffused

⁴³ Amer. Philos. Soc. Proc., ix, p. 471-475.

⁴⁴ Proc. Amer. Assoc. Adv. Science, 1867, p. 114.

⁴⁵ Geological Survey of Penn., 1858, ii, 757.

⁴⁶ J. Ville found one liter of carbonated water at the ordinary pressure to hold in solution at 20° C. 1.142 grams of ferrous carbonate. and at 15° C. 1.390 grams. From these solutions neutral alkaline carbonates readily throw down the ferrous carbonate, themselves passing to the state of bicarbonates; and carbonates of lime and magnesia produce the same effect though more slowly. (C. Rendus de l'Acad. des Sciences, Oct., 1881, vol. xciii, p. 443.) The present writer found recently precipitated ferrous carbonate to be temporarily much more soluble, under the

ferric oxide in sediments into massive limonite imbedded therein, is thus a two-fold process, involving first, the intervention of reducing solutions converting the peroxide into ferrous carbonate, and the concentration of the latter; and second, the change of this latter, through peroxidation and hydratation, into limonite.

It is evident that the first stage of the process thus indicated by Rogers as taking place in sediments as yet unconsolidated, may also be set up in the disintegrated ferriferous materials resulting from the sub-aërial decay of rocks, and still undisturbed; that is to say, that the infiltration of waters holding dissolved organic matter may give rise in the decomposed mass to concretions of ferrous carbonate, which are subsequently changed into limonite. In this way, a concentration may be effected, through which rocks originally containing a small portion of diffused iron-oxide come to include masses of limonite. Illustrations of this process are sometimes seen in the decay of impure limestones or dolomites containing, as is often the case, some ferrous carbonate, in the residuum of which we find the iron accumulated in the shape of crusts or layers of limonite.

§ 37. An instructive example of an analogous process is seen in the limonite which on Staten Island, New York, is found imbedded in a layer of brownish earthy material, sometimes attaining a thickness of twelve feet, which rests immediately upon the serpentine-rock of the region, into which it graduates, and from the sub-aërial decay of which it has evidently been derived, the lower portion of the earthy matrix still preserving the peculiar jointed structure of the underlying serpentine. This decomposed material, though including botryoidal crusts, geodes and concretionary grains of limonite, with occasional druses of chalcedony and of quartz crystals, retains considerable coherence.

The source of this limonite seems to have been the iron-oxide liberated by the decay of the ferriferous serpentine, and the proportion of ore in the superjacent mass shows a direct relation to the color and apparent proportion of iron-silicate in the serpentine beneath. This limonite, which is now mined to a considerable extent, contains, as several analyses have shown, from one to two-hundredths of chromic oxide, which is also known to be present in small amount in the serpentine. An impure argillaceous specimen containing only 59·63 of ferric oxide yielded the writer 2·81 of chromic oxide in a condition readily soluble in chlorhydric acid.

§ 38. Dr. N. L. Britton, of the School of Mines of Columbia

above conditions, yielding supersaturated solutions, which inclose vessels spontaneously deposit, after many hours, a large part of the carbonate in a crystalline condition.

College, in whose company I lately had an opportunity of visiting this interesting locality, published in 1880 a geological map with sections and a description of Staten Island.⁴⁷ He therein shows that the earthy material in which the limonite is imbedded is confined to the tops of certain hills of serpentine, being absent alike from other similar hills adjacent, and from intervening valleys cut into the serpentine, and he has connected this distribution of the ore-bearing stratum with the facts of the local glaciation of the region, to which he has devoted much attention. It is I think evident that the decay of the serpentine, and the concentration in the residuum, of its iron in the form of limonite, was a process anterior to the glacial erosion, and that the ore-banks are areas of the decayed material which escaped this action.

§ 39. Turning now to the valley of the Mississippi, we find that Pumpelly in his geological survey of Missouri, showed in 1873 that the decay *in situ* of granitic rocks and of quartziferous porphyry has left great rounded blocks of these crystalline rocks, while the conversion of the porphyry into clay, and its subsequent removal, has liberated included veins or masses of crystalline hematite, giving rise to an accumulation of detrital iron-ore, such as, at the well-known Iron Mountain, forms a covering over the surface of the hill of porphyry. From the presence of stratified deposits of this detrital ore in the ancient Cambrian strata around the base of the hill, Pumpelly inferred that the decay of the porphyry was already complete to a considerable depth at this early period.⁴⁸ His observations and deductions were not known to me when, in the same year, I published my conclusions as to the great antiquity and the universality of the process of rock-decay.

§ 40. Proceeding from Missouri northward, we find that in Minnesota, as shown by C. A. White⁴⁹ in 1870, and by N. H. Winchell in 1874, the ancient granitoid rocks, when protected by Cretaceous strata, support a kaolinized layer of considerable thickness.⁵⁰ In Wisconsin, a similar condition of things is found beneath the Potsdam sandstone in the central part of the State, as described by Irving in 1876,⁵¹ in an essay which is a valuable contribution to the literature of kaolin, and contains many analyses of the decayed rocks of the region by Mr. E. T. Sweet, which have been already referred to, § 16. Further details of the same region and its kaolins, with analyses as before, were given by Irving in an essay in 1880 on the

⁴⁷ Annals New York Acad. Sciences, vol. ii. part 6.

⁴⁸ Geology of Missouri: Report on Iron Ores and Coal Fields. pp. 8-12.

⁴⁹ Geology of Iowa, i. 124.

⁵⁰ Second Annual Rep. Geol. Minnesota. pp. 162, 166, 207; also Hunt, Chem. and Geol. Essays, p. 250.

⁵¹ Trans. Wisconsin Academy, etc., iii. 13.

Mineral Resources of Wisconsin.⁵² In Jackson and Wood counties, where the crystalline (Laurentian) rocks are covered by a thin sheet of Potsdam sandstone, the river-valleys, cutting through this, expose the kaolin, which "occupies its original position, retaining sometimes the structure of the unaltered rock." This is derived from the decay *in situ* of certain bands, which passing downward, graduate into unaltered feldspathic rock. Save where this mantle of decayed material has been protected by the Paleozoic sandstone, the crystalline rocks are there seen for the most part in an undecayed condition, evidently, as Irving remarks, from the removal of the decayed material by "the denuding action of the drift." In some portions of the driftless area of this region the unprotected gneisses still retain their mantle of kaolinized material.

§ 41. From the facts before us, it is clear that the decay of the Eozoic crystalline rocks was already far advanced in pre-Cambrian times. I am informed that similar evidence is afforded in Sweden by the presence of decomposed rock beneath Cambrian strata. Prof. A. Geikie has moreover shown that the sculpturing of the gneiss rocks of western Scotland, a process which I have maintained to be dependent on previous sub-aërial decay, was effected before the deposition of the Cambrian sandstones, which there rest upon ancient *roches moutonnées*.⁵³

§ 42. It might be supposed, from their stability under ordinary atmospheric influences in regions protected by vegetation, that all such portions of decayed Eozoic rocks as still exist in driftless or in protected areas date from the dawn of Paleozoic time, did we not know that the same processes of decay have been active in subsequent ages, as is shown by the decay of eruptive rocks of later periods. An example of this, which shows at the same time the little progress made in the process of decay since the drift-period, is seen in Canada, at Montreal, where, to the south of Mount Royal, the nearly horizontal beds of the impure Trenton limestone are found in sheltered places, deeply decayed and porous from the removal of their carbonate of lime, and are moreover traversed by dykes of dolerite and other feldspathic rocks, themselves decayed to considerable depths; while near by, and especially to the north of the mountain, where glaciation did its work of removing alike decayed aqueous and igneous rocks, the eroded surfaces of both of these are found hard and comparatively unchanged beneath a thin layer of soil and vegetation, as described by J. W. Dawson.

Another instance is afforded by a dyke intersecting the

⁵² Proc. Amer. Inst. M. Engineers, viii, 103.

⁵³ Nature, August 26, 1880, p. 403.

Potsdam sandstone in this vicinity, which is found to be converted to a depth of twenty feet or more into a plastic highly aluminous clay, which, from the presence of portions of titanium and chromium is, we may conjecture, derived from a doleritic rock.⁵⁴

§ 43. Rigaud Mountain, an igneous mass rising through the Potsdam sandstone, and occupying several square miles on the south side of the Ottawa, near its confluence with the St. Lawrence, is probably of Paleozoic age, and consists in large part of a reddish granitoid orthoclase rock. Considerable areas of its surface, lying lower than the surrounding crests of the mountain, are covered to a depth of seven feet or more, in places, with well rounded bowlders from three to eighteen inches in diameter, consisting wholly of the rock of the mountain, with the exception of a few masses of sandstone. The plains so covered attain in their higher parts an elevation of about 280 feet above the Ottawa, but slope gently both to the south and the north. The bowlders are very rare on the north slope of the mountain, and at its northern base, but are abundant on the southern slope and in the low-lying clay-covered plains to the southward.⁵⁵ These well-rounded masses, spread over so much of the mountain are apparently bowlders of decomposition, still *in situ*, having escaped the denuding agents of the drift-period.

§ 44. Examples of more recent sub-aërial decay of crystalline rocks, under peculiarly favorable conditions, were in 1880 described independently by Jos. LeConte and myself, in the auriferous Pliocene gravel of California. The pebbles of feldspathic and hornblendic rocks occurring in the portions below drainage-level—the so-called *blue gravel*—are unaltered, while above that level the similar pebbles, exposed to the action of meteoric waters, are more or less completely kaolinized, exfoliating, becoming earthy in texture, rusty in color, and in some cases converted into a clayey mass. The pyrites so abundant in the blue gravel, has, in these upper portions, or so-called *red gravel*, been oxidized, and the accompanying lignites have been silicified, and often incrustated with crystallized quartz, from silica liberated in the process of rock-decay through the infiltration of surface-waters.⁵⁶

§ 45. To the porosity of the gravel, and the great amount of surface thus exposed, is to be added the influence of carbonic acid from the decaying lignite, the carbon of which is oxidized as the process of silicification goes on. The amount of carbonic dioxide in the air of certain drift-mines in these auriferous

⁵⁴ Report Geol. Survey of Canada, 1878-79, H., p. 7.

⁵⁵ Geology of Canada, p. 896.

⁵⁶ LeConte, this Journal, xix, 177; Hunt, *ibid*, xix, 371.

gravels is so great that candles will not burn therein. Mr. D. T. Hughes of San Francisco, a well-known mining engineer, to whose careful scientific observations I have been much indebted, informs me that in the case of a drift-mine 300 feet below the surface, in Table Mountain, Tuolumne Co., Cal., where the foulness of the air was especially remarked, he satisfied himself by appropriate tests of the presence in the air of a large proportion of carbonic-dioxide. If, as there is reason to suppose, the amount of this element in our atmosphere was somewhat greater in former ages than at present, we have in these gravels an illustration of its influence in promoting the decay of silicated rocks. It is not improbable that the sulphuric acid generated by the oxidation of the pyrites present in these gravels may also have aided in the process.

§ 46. The slight evidences of decomposition to be seen in the crystalline rocks of thoroughly glaciated regions, as well as in transported boulders, makes it probable that the seemingly rapid progress of decay, occasionally observed on exposure, of similar rocks in other regions, sometimes appealed to as evidence of a decomposition now going on, is really but the mechanical disintegration of masses already partially kaolinized in former ages. The crumbling of certain apparently unaltered granitoid rocks, in which the feldspar remains bright and hard, should be distinguished from that which follows chemical decomposition. Such disintegration, due apparently to changes of temperature⁵⁷ and the action of frost, is, however, important, and deserves farther study from the fact that materials apparently of similar origin enter into the composition of many derived rocks. Lava-flows are, it has been observed, subject to comparatively rapid sub-aërial decay, but these rock-surfaces differ widely in texture as well as in composition from most crystalline rocks.

§ 47. An essay by Professor Pumpelly on Secular Rock-Disintegration, read before the National Academy of Sciences in April, 1878,⁵⁸ is a very valuable contribution to the subject before us. He cites therein my conclusions as to the great antiquity and the universality of the process of rock-decay (to which his own observations in Missouri have contributed im-

⁵⁷ In this connection I venture to recall the attention of geologists to a phenomenon already described both by Dr. Shaler and myself, apparently due to superficial alternations of temperature on certain crystalline rocks, which have resulted in establishing in them, to a considerable depth, a series of rifts or divisional planes parallel to the present surface, which are well known to quarrymen. Instances of this abound; besides those noticed by me in this Journal for July, 1870 (vol. i, p. 89), may be mentioned the gneiss on the opposite slopes of Rolleston Hill, Fitchburg, Mass., and that of Stone Mountain near Atlanta, Ga.; also a remarkable example of comparatively thin horizontal plates at the outcrop of beds of nearly vertical micaceous gneiss in the vicinity of Worcester, Mass.

⁵⁸ This Journal, xvii, 133-144.

portant data) and also as to the final removal of decomposed material from northeastern America in the time of the glacial drift. He further notes the little attention hitherto given to the subject of sub-aërial decay, and points out its importance in connection with great problems in dynamical geology. The view that this process of rock-decay is "a necessary preliminary to glacial and erosive action, which removed already softened materials," receives from Professor Pumpelly an extended discussion and application. He proceeds to consider the removal and the re-arrangement of these softened materials by three different agencies. First, the encroachment of the sea upon a subsiding region of decayed rocks; second, the action of land-glaciers, in which he points out that the great mass of disintegrated and water-impregnated rock would become frozen, and included, as it were, in the glacier, sharing in its movements and forming thus a ground-moraine.⁵⁹

§ 48. To these modes, with which are to be included the ordinary action of rivers and floods, all acting on the peripheral areas of continents, he adds, for the central areas, removed from these agencies, and rendered desert by geographical conditions, the action of the winds. By these, the decayed rock, according to Pumpelly's extension of the ingenious hypothesis of Richt-hofen, will be separated into the fine material of the loess, on the one hand, and the sand and gravel of the desert steppes on the other. He thus explains the condition of the crystalline rocks in northern Asia, from which the decayed mantle has been removed not by glacial but by aërial agencies; while the similar rocks in southern Asia, as in Brazil and the southern United States, are still deeply covered with the products of their own decomposition.

§ 49. Pumpelly further remarks that the surface of the undecayed rock to be laid bare by erosion is necessarily an irregular one, the inequalities depending not upon its original differences in hardness, but upon its resistance to decay under the influence of atmospheric waters. The effect of fractures, joints, veins and dykes in the rock in favoring or retarding the action of this agent would be manifested by still further irregularities of the plane limiting the decomposition of the rock in depth.

⁵⁹ Other agencies than ice may produce a similar displacement of decayed material. Belt, in 1874, in his *Naturalist in Nicaragua* (page 94), describes a movement of the mantle of decayed crystalline rock on hill-sides in that country, as due to land-slides in wet weather. The layer of ground and "reworked" decayed material resting on the gneiss found by Hartt in Brazil (*Scientific Results of a Journey*, etc., pp. 28, 573) and referred by him to glaciation, may perhaps be a similar phenomenon. More recently, Kerr, in 1879, has described the results of a slow downward motion of the decomposed surface on mountain-sides in North Carolina, as due to the alternate freezing and thawing of the contained water. To this displaced and modified layer, which resembles that produced by glacial action, he gives the name of *frost-drift*. (*Proc. Amer. Inst. M. Engineers*, viii, 462.)

Thus the rounded surfaces and the closed rock-basins so often observed in glaciated regions of crystalline rocks are seen to be but the natural results of the process of rock-decay, which preceded and prepared the way for denudation.

§ 50. Similar views as to glacial erosion have since been advocated by Nathorst, and more lately by Reusch, who, in a memoir on the geology of Corsica, presented to the Geological Society of France, in November, 1882,⁶⁰ has described the disintegration of the granitic region of Corsica to a depth of several meters, giving to the surface smooth slopes instead of the bold escarpments seen in like rocks in Scandinavia. He notes in these disintegrated rocks in Corsica enclosed balls or ellipsoidal masses, fresh in appearance, but like in composition and in structure to the enclosing rock, which, when detached, have been taken for erratic blocks. With this region, he contrasts the similar rocks near Christiania, in Norway, with hard, rounded surfaces, marked by glacial scratches, where it is difficult to find any trace of superficial decay. He does not believe that the ice of the Glacial period removed any considerable portion of the hard rock, to form fiords, valleys, etc., but supposes "a profound disintegration of the Scandinavian rocks before the Glacial period," and conceives the present relief to "represent the surface of the unaltered syenite after the removal by the glaciers of all the decomposed part."

The salient rock-masses of the Norwegian coast are, like the fiords, arranged in a north and south direction, and this, according to Reusch, corresponds with that of fissures, more or less nearly vertical, which traverse the rock, and, as he well remarks, prepared the way for its disintegration in depth, the extent of which would depend upon differences in the nature of the rock. Many of the lake-basins of this region were, according to him, formed through the removal by glaciers of the decayed material from depressions, while others are due to the action of moraines, serving as dykes.

§ 52. It is difficult to state more clearly the consequences which follow from the conception that the decomposition of rocks is "a necessary preliminary to glacial action and erosion, which removed previously softened materials." Reusch, however, seems, from some misconception, to regard this pre-glacial disintegration of the rocks as distinct from kaolinization, of which the crumbling of the granites in Corsica, as in other regions, doubtless represents an incipient stage, such as we meet with in depth, in regions where the superficial and more completely decayed portions have been removed (§ 46).

⁶⁰ Bull. Soc. Géol. de France, xi, 62-67.

CONCLUSIONS.

§ 53. The points insisted upon in this paper may be thus briefly resumed:—

1st. The evidence afforded by recent geological studies in America, and elsewhere, of the universality and antiquity of the sub-aërial decay both of silicated crystalline rocks and of calcareous rocks, and of its great extent in pre-Cambrian times.

2d. The fact that the materials resulting from this decay are preserved *in situ* in regions where they have been protected from denudation by overlying strata alike of Cambrian and of more recent periods; or, in the absence of these coverings, by the position of the decayed materials with reference to denuding agents, as in driftless regions, or in places sheltered from erosion, as in the Appalachian and St. Lawrence valleys.

3d. That this process of decay, though continuous through later geological ages, has, under ordinary conditions, been insignificant in amount since the glacial period, for the reason that the time which has since elapsed is small when compared with previous periods, and also probably on account of changed atmospheric conditions in the later time.

4th. That this process of decay has furnished the materials not only for the clays, sands and iron-oxides from the beginning of Paleozoic time to the present, but also for the corresponding rocks of Eozoic time, which have been formed from the older feldspathic rocks by the partial loss of protoxide-bases. The bases thus separated from crystalline silicated rocks have been the source, directly and indirectly, of all limestones and carbonated rocks, and have, moreover, caused profound secular changes in the constitution of the ocean's waters. The decay of sulphuretted ores in the Eozoic rocks has given rise to oxidized iron-ores, and also to deposits of rich copper ores in various geological horizons.

5th. That the rounded masses of crystalline rock left in the process of decay constitute not only the boulders of the drift, but, judging from analogy, the similar masses in conglomerates of various ages, going back to Eozoic time; and that not only the forms of these detached masses, but the outlines of eroded regions of crystalline rocks, were determined by the preceding process of sub-aërial decay of these rocks.