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ART. XIX.—*Some Peculiarities of Rock-Weathering and Soil Formation in the Arid and Humid Regions*; by E. W. HILGARD.*

SOME of the differences in the processes and the results of weathering in the arid and humid regions respectively have been long commented upon; but we do not find anywhere a measurably full discussion of the subject. I have discussed the various phases as observed by myself, in various publications; but I desire to give in this place a summary of the points noted, especially as regards soil-formation, and the conclusions to be drawn therefrom.

The potent effects of water upon both the mechanical and chemical processes of rock decomposition being well understood, the relative scantiness of rainfall in the arid regions leads us at once to expect a slower rate of decomposition of rocks and of their component minerals under the arid régime. The old observation of the freshness of the surfaces of half-finished obelisks in the quarries of Syene, and the good conservation of the same in the obelisks of Lower Egypt under slightly more humid conditions, as compared with the fate of Cleopatra's Needle at New York, are familiar to all. It is not, of course, moisture alone, but very essentially the temperature conditions accompanying both its abundance and scarcity, that are concerned in the effects produced.

Aridity being intimately correlated with the existence of deserts, we are at once led to associate sand and dust with arid conditions. The dust storms of the arid regions are as proverbial as are the sands of the desert; and the latter are in the public mind the symbol of sterility. It is only of late that

* Read at the December meeting of the Cordilleran Section of the American Geological Society, at Berkeley, Cal.

the almost invariable high productiveness of the desert sands under irrigation is becoming a somewhat familiar conception, yet accepted with difficulty because in the more familiar humid region, "poor sandy lands" are a well-authenticated fact, and a "strong" or "substantial" soil is one containing a more or less considerable proportion of clay.

The reasonableness of this popular idea is well illustrated in the investigation made years ago by Dr. R. H. Loughridge,* of a very generalized loam soil covering the uplands of Kentucky, of Tennessee, Mississippi, and Louisiana east of the Mississippi river. In this investigation it was shown that by far the greater portion of the recognized plant-food ingredients was contained within the impalpable portion, viz., the "clay" and finest silts, only an insignificant amount being found in the "sandy" portion of the soil. The extreme poverty of the sandy lands of Florida, as shown by analyses subsequently made by him, fully corroborated these points for the humid region of the cotton states at least. And in Europe, the sandy lands of the northern plain are equally sterile without fertilization.

How is it then that the sands and dust of the arid region are so highly productive so soon as irrigated?

A comparative microscopic examination of sands from Florida and that from the arid deserts at once reveals the difference, which is equally accentuated by their chemical analysis. While the Florida or Mississippi soil sand under the microscope shows almost wholly quartz grains with clean, polished surfaces, the typical desert sand shows a great variety of minerals in granular form, coated with half-decomposed, finely pulverulent mineral matter, which also constitutes the "dust" portion of the material. Analyses made of the coarse and fine portions of such soils by Mr. L. M. Tolman† and by E. C. Lea (unpublished), proved that the surface-covering of the coarse sand grains was practically of the same composition as the fine dust itself. The subjoined table shows that in the typical upland clay loam from Mississippi (a soil noted for its high product of cotton) dissolution of soil ingredients substantially ceased when a diameter of only $.036^{\text{mm}}$ of the soil granules was reached; while from that limit, in the coarser portions of the California soils, obtained by the same process of hydraulic eleutriation, and up to half a millimeter diameter, there was not only no diminution but an actual increase of acid-soluble matters.

It thus appears that while in the humid Mississippi soil, solubility of plant food practically ceased above a grain-diameter

* This Journal, Jan. 1874.

† Rep. Calif. Exper. Station for 1898-1901, p. 33.

of $\cdot 036^{\text{mm}}$, in the arid California soils as large an amount was found in the sand-grain sizes between $\cdot 12$ and $\cdot 50^{\text{mm}}$ as in the $\cdot 016$ to $\cdot 025^{\text{mm}}$ silt of Mississippi.

How does this radical difference between the sands of the arid and humid regions come about? The pulverulent nature of the soils formed under arid conditions supplies the answer. The binding material, the "clay," that forms so important a character of the prevalently clayey and loamy soils of the humid region, is in the properly arid soils present in minute proportions only; except of course where clays from preexisting clay formations have taken part in soil formation, or where,

Sediments.	Per cent in Soil.	Potash.	Lime.	Magnesia.	Phos- phoric Acid.	Soluble Silica.	Alumina.	Total soluble.
<i>Colloidal clay, ? diameter.</i>								
Mississippi	21.64	.32	.03	.29	.04	7.17	3.97	11.82
California (Chino) ...	7.60	.16	.14	.17	.04	1.70	1.35	3.56
California (Jackson) ..	16.43	.13	.12	.08	.05	2.83	2.13	5.34
<i>Very fine silt, $\cdot 016^{\text{mm}}$ diam.</i>								
Mississippi	35.10	.41	.15	.36	.07	2.87	1.36	5.22
California (Chino) ...	18.53	.24	.53	.29	.06	4.96	1.76	7.84
California (Jackson) ..	34.90	.10	.04	.08	.02	2.50	2.44	5.18
<i>Fine silt, $\cdot 016$–$\cdot 025^{\text{mm}}$ diam.</i>								
Mississippi	13.67	.12	.09	.10	.02	.32	.17	.82
California (Chino) ...	5.49	.05	.11	.02	.01	.80	.51	1.50
California (Jackson) ..	9.96	.08	.04	.10	.01	1.01	1.01	2.25
<i>Silt, $\cdot 025$–$\cdot 036^{\text{mm}}$ diam.</i>								
Mississippi	---	---	---	---	.36	---	---	.36
California (Chino) ...	3.92	---	---	---	---	---	---	lost
California (Jackson) -	7.68	.06	.02	.05	.01	.82	.74	1.70
<i>Silt, $\cdot 036$–$\cdot 047^{\text{mm}}$ diam.</i>								
California (Chino)	6.40	.05	.18	.07	.01	.80	.55	1.66
California (Jackson) ..	8.21	.04	.01	.003	.001	.43	.64	1.22
<i>Coarse silt, $\cdot 047$–$\cdot 072^{\text{mm}}$ diam.</i>								
California (Chino) ...	7.92	.06	.20	.03	.02	.89	.59	1.79
California (Jackson) ..	5.91	.03	.01	.01	.003	.42	.30	.77
<i>Fine sand, $\cdot 072$–$\cdot 120^{\text{mm}}$ diam.</i>								
California (Chino) ...	11.87	.06	.26	.10	.03	.98	---	1.43+
California (Jackson) ..	4.03	.01	.01	.005	.003	.28	.09	.408
<i>Coarser sand, $\cdot 120$–$\cdot 050^{\text{mm}}$ diam.</i>								
California (Chino) ...	36.11	.11	.69	.12	.04	2.43	1.59	4.98,
California (Jackson) ..	10.10	---	---	---	---	---	---	not detd.

as in swamps or marshes, humid conditions exist in the arid region as well.

Since kaolinization, which must precede the formation of colloidal, plastic clay material, is essentially a process of hydration, the presumption is that it will progress more slowly in regions of deficient rainfall. That this is actually the case can hardly be questioned by any one who has studied comparatively the results of rock decay in both the arid and humid regions; the contrary assertion, lately made, cannot, so far as I know, be supported by any facts properly observed and interpreted. The contrasts between the condition of the granites and granodiorites on the upper portions and the lower slopes of the Sierra Nevada and of the Sierra Madre of southern California, and still more between the latter and the southern Alleghenies, are so strongly accentuated as hardly to require discussion. The enormous deposits of almost fresh granitic sand at the base of the southern arid ranges, so coarse that the trees and seeds must be planted far below the surface in order to maintain life, while in the Alleghenies a clay subsoil formed in place lies within a foot of the surface on which the planting is done, are a practical demonstration of the greater intensity of clay-formation in the humid regions.

These differences in characters of the regolith of the two regions may be schematically illustrated in a diagram. This would show that in the humid region the humous "soil" as a rule extends only from six to nine inches from the surface, these being the depths prescribed by the Eastern Experiment stations for the taking of samples of "surface soil"; beneath which follows almost invariably a more clayey subsoil, which as a rule is unadapted to the growth of crops, so that not more than half an inch of it is allowed to be plowed up to the surface at once, on pain of spoiling the seed-bed for the succeeding season at least. No such restriction applies to the typical arid soils, in which the "surface" or humous soil is rarely less than three feet in thickness, and frequently extends to a much greater depth even with a considerable humus-content. This state of things is illustrated by the columns of California soils, in two of which the humus has been determined as reaching to the depth of twelve feet, as shown in the table here presented; and doubtless to at least one foot beyond.

The root of a hop plant here before you illustrates one of the practically most important results of this great depth and pulverulent texture of soils in the arid region. This root at ten feet is still over a millimeter in diameter, and of course went at least two feet deeper than the specimen shows. Now

since a root cannot perform its functions in the absence of the oxygen of the air, it is clear that the air readily penetrates to the depth shown; and in many cases observed, even to as much as twenty feet and more. And since both air, moisture and humus are found at these depths, this implies not only that the farmer in the arid region can fearlessly plow to any practicable depth, but also that the mass of his available soil is from three to five times as great as that of an equal area of land in the humid East. In other words, he has several farms one above another, instead of a single one with one or two feet of available soil and subsoil.

If this be so, then it might be allowable in the arid region to use the regolith materials thrown up from cellars directly as cultivable soils. Daily experience shows this to be the case. Except where heavy clay soils prevail, or where wet maceration has at some time consolidated the subsoil mass, the materials from eight or ten feet depth dug out of cellars or the foundations of houses can oftentimes be directly used as surface soils in garden and fields; and the farmer in grading his land for irrigation ordinarily excavates it as deeply as may be necessary without fear of the "raw subsoil," as would be needful in the humid East. The prompt natural afforesting of the placer and even hydraulic mines in California teaches the same lesson.

Searching for the physical and chemical causes of this state of things, we see at once that it is mainly referrible to the pervious, pulverulent nature of the regolith, which is itself the result of the absence or great deficiency of plastic clay. It is immaterial whether or not this is concurrent with a slow rate of kaolinization, as the microscope seems to indicate. It is quite certain that the *plastic* clay substance, the "colloidal clay," is formed only in small amounts; and this is quite consonant with what we know of the transformation of kaolin into plastic clay. Mere pulverization will not accomplish this; under wet trituration* it is certainly at least a physical hydration process, which does not occur in the case of other fine powders. It is true that the latter may be molded into shape when wetted; but that shape is not retained after drying if any pressure is applied, while clay proper dries into a hard, resistant mass, such as in arid climates like that of Mesopotamia has not even required burning to retain the Assyrian inscriptions for thousands of years. These ancient nations understood the peculiar character of plastic clay better than those who to-day contend that its plasticity is simply due to the fineness of its particles; for we nowhere find that chalk or

* See Johnson and Blake, this Journal, May, 1867.

other easily obtainable fine powders have been similarly used. Nor will the finest "slickens" of our quartz mills, which remains suspended indefinitely in distilled water, serve for modeling, any more than for pottery or porcelain. The utmost possible comminution of graphite or talc, so closely similar to kaolinite in softness and crystalline texture, will fail to impart to them anything resembling the adhesive plasticity of colloidal clay.

In the humid region the abundant and long-continued rains cause the plastic clay in the surface soil to diffuse in the soil water and to be carried into the subsoil, where much of it stops at a shallow depth and thus produces the clayey subsoils of humid regions. In the arid region, notwithstanding the extreme fineness of many soils which causes them to rise as dust at the slightest breath of wind, no such action occurs and thus opportunity is afforded for the deep penetration of roots, which allows much of the ordinary vegetation brought from the humid region to do without rain or irrigation during a six months drought.

The fact that in most parts of the arid regions, the scanty rains occur during the coldest portion of the year, probably accounts in a large measure for the retardation of rock decay; which, others things being equal, is probably in all cases accelerated by heat. On the other hand, the abrupt and constantly recurring changes of temperature account for a large part of the physical disintegration which produces the great masses of pulverized rock or sand which we find in "desert" regions. The intense radiation of heat into space through the far undersaturated air of the arid climates, which occurs so soon as the sun disappears and often results in the violent disruption of cobbles from unequal contraction, naturally affects profoundly the macrocrystalline rocks especially; crumbling their surface and enabling the torrents to carry off almost fresh "sand" composed of all the mineral rock-constituents into the arid valleys; where under the influence of vegetation and increased moisture their chemical decomposition can progress more rapidly.

Not, however, rapidly as in the humid region, where the humus acids aid materially in mineral decomposition. For not only is the humus-content of arid soils usually very much less than in the humid, but so soon as formed such acids are neutralized by the carbonate of lime always present in far greater proportion than in the humid soils, save when the latter are directly derived from calcareous formations. This leads us to the consideration of chemical peculiarities of arid and humid soils respectively.

*Average Composition of Soils in the Humid and Arid Regions of the United States.**

No. analyzed.	Humid. 696	Arid. 573
Insoluble residue	84·17	69·16
Soluble silica	4·04	6·71
Sum of insoluble residue and soluble silica	87·68	75·87
Potash	·21	·67
Soda	·14	·35
Lime	·19	1·43
Magnesia	·29	1·27
Br. ox. of manganese	·13	·11
Peroxide of iron	3·88	5·48
Alumina	3·66	7·21
Phosphoric acid	·12	·16
Sulphuric acid	·05	·06
Water and organic matter	4·40	5·15
Hygroscopic moisture	--	5·46
Humus	1·22	1·12
Nitrogen in humus	5·00	15·23
Nitrogen in soil	0·17	0·14

The table before you shows these peculiarities, which I have somewhat elaborately discussed elsewhere. A glance shows the main points of difference to lie just where they would be expected as resulting from a diminished rainfall, causing a corresponding diminution of the leaching-out process, which in the humid climates is the necessary consequence not only of a large rainfall, but especially of its occurrence during the warm season, when the concurrent effects of warmth and the consequent evolution of carbonic acid, both from the roots of vegetation, and from the oxidation or fermentation of dead vegetable matter, can be exerted. Hence we see that the lime which in the humid region is constantly and abundantly leached out into the drainage and streams, is in the arid retained to an extent amounting to from ten to thirteen times the average content found in humid soils not directly derived from calcareous formations. A similar condition is found as regards magnesia, through to a less degree. Potash averages the triple amount. It may seem strange that a similar relation is not shown here as regards soda; the reason is that for fairness of comparison, alkali soils are not included in the list. It is well known that in the case of zeolitic silicates, such as are known to exist in soils, potash is retained more tenaciously than soda. The latter is therefore washed down to the lower ground, and there gives

*Soils directly derived from calcareous formations have, equally in both regions, been excluded from this comparison.

rise to "alkali soils," which characterize the arid region to a greater or less extent all over the world. Their chief soluble salts are usually the *chloride*, *sulphate* and *carbonate* of sodium, varying in relative proportion from place to place at short distances. These differences are largely due to cross-reactions between the salts of the alkalies and alkaline earths under the influence of carbonic acid formed within the soil by the usual processes, resulting, e. g., in the formation of sodic carbonate and calcic sulphate from sodic sulphate and calcic carbonate. Magnesian sulphate is similarly formed. But on exposure of the soil to free diffusion of air, the process may go backward so far as to re-form the original compounds.

The peculiar effects of sodic carbonate upon clay, causing it to diffuse from the flocculent condition into single-grain structure, frequently results in the formation of "alkali hardpan" at the depth to which the annual rainfall usually reaches. This characteristic of "black alkali lands" is illustrated in the diagram before you, showing that at the depth of three feet there is a maximum of accumulation of carbonate, cementing the soil into a hard, tough mass which is quite inaccessible to ordinary means of disintegration, and yields reluctantly even to dynamite; but is quickly and completely resolved into a pile of crumbs when subjected to the chemical action of gypsum and water. This affords a ready means of reclaiming "black alkali" lands, so far as the present price of land plaster will permit; since the sodic sulphate thus formed is at least four times less injurious to vegetation than the carbonate.

Unfortunately there is no practically available chemical reaction by which the highly injurious common salt could be changed into sulphate. The same is true of the calcic and magnesian chlorids, which are occasionally, though fortunately not very frequently, found in the soluble salts of alkali lands.

The difficult solubility of calcic phosphate explains why the leaching process which causes such large differences in the other important plant-food ingredients, is not apparent in the average phosphoric acid-content of the two regions.

It goes without saying that so far as plant-food ingredients are concerned, alkali lands are from their very origin very rich in them, and when reclaimed by leaching or otherwise are profusely and lastingly productive. Aside from a high "reserve," they always contain *water-soluble* potash, and very commonly nitrates and phosphates also.

What action these salts exercise in the weathering process is not well established except as regards the sodic carbonate, which undoubtedly is active both in dissolving free silica and in decomposing silicates.* That common salt in presence of

*On the Geologic Efficacy of Alkali Carbonates. This Journal, August, 1897.

the humus acids of the soil might exert "aufschliessende" action also, seems at least probable from its effect in "rusting" metals, and from that of lactic acid in the animal stomach. The sulphate is probably very inert in this respect.

An interesting and important difference exists in the nitrogen-content of the arid and humid soils, respectively. The average humus-content of the properly arid soils is materially less than that of the humid, as might be expected from the much smaller amount of vegetable debris that finds its way into the soil. As a matter of fact, the leaves of all the spring vegetation of the arid region remain outside of the soil and are oxidized away during the hot summers, leaving little more than their ash behind. It follows that the humus of the arid soils is almost wholly derived from the decay of roots alone; and the deep penetration of the latter, already referred to, explains the occurrence of humus down to the great depths shown in the small table below, which gives the humus percentages found in a bench soil in which hop roots penetrated over twelve feet.

Humus in Russian River bench soil, from one to twelve feet depth.

Depth, feet	1	2	3	4	5	6	7	8	9	10	11	12
Humus %	1·21	1·16	1·14	1·17	·74	·60	·47	·78	·54	·52	·53	·44

But the total humus percentage in arid soils is usually so small that in the humid region it would be considered wholly inadequate. So it would be, from two causes: first, that it is there among the first things needful for the maintenance of proper tilth in the clayey lands, while in the pulverulent soils of the arid region this is much less necessary; second, because we find the nitrogen-content of arid humus to be on the average three or more times higher than is the case in the humid. Hence the adequacy of the minute amounts of humus found in many of the most esteemed arid soils (.25 per cent and even less); to which may be added the at least probable greater intensity of nitrification when no great excess of carbon and hydrogen compounds is present to compete with the activity of the nitrifying organisms; an activity which, moreover, can evidently progress at much greater depths in the pulverulent, pervious arid soils.

The physical and chemical details of this subject are quite complex, so that a full discussion is necessarily lengthy. But the summary here given is probably enough to show its wide theoretical as well as practical interest, and the need of caution in applying the maxims of the humid region in arid climates.