XXVIII.—*Desert Conditions in Britain. An Address to the Geological Society of Edinburgh, at their Opening Meeting on the 19th November 1896.*¹ By J. G. GOODCHILD, H.M. Geological Survey, F.G.S., F.Z.S., Curator of the Collections of Scottish Geology and Mineralogy, Edinburgh Museum of Science and Art, *Vice-President*. (Plate XI.)

It has long been recognised by geologists that, amongst the geographical mutations which all parts of the earth's surface have at one time or another undergone; the change from humid to arid climatal conditions has several times had a place. It has now and then happened in past times, even in Britain, that conditions of the normal kind, as regards rainfall, have subsequently given place for a time to true desert conditions, differing in no essential respect from those prevailing in many arid regions at the present day.

By desert conditions, as here understood, is meant that combination of geographical conditions which has led to certain parts of the earth's surface receiving a smaller annual precipitation than suffices for the maintenance of any types of vegetation except those specially adapted by evolution to an environment in which aridity is the dominant feature. As typical examples of the conditions referred to may be cited the Sinaitic Peninsular, parts of Afghanistan, the great Central Asian deserts, as well as the more arid parts of western North and South America. As regards *temperature* these regions widely differ from each other; whence it will be seen that the prevalence of excessive sun-heat is by no means a special characteristic of desert regions.

In one respect all areas of Inland Drainage may be regarded as areas where desert conditions prevail. Under the existing geographical conditions of the earth's surface the areas of inland drainage occupy an area 11,486,350 square miles,² which, as the area of land draining into the ocean is estimated³ at 44,211,050 square miles, makes the proportional area of the one to the other as about as one to four. Dr Murray gives as the total

¹ The same Address was also given as the Inaugural Address to the Philosophical Society of St Andrews, and afterwards before the Geological Society of Glasgow.

² Dr John Murray, *Roy. Scot. Geog. Mag.*, vol. iii. p. 75.

³ *Loc. cit.*

area of the ocean 141,243,300 square miles. The area of inland drainage is to the area of oceanic drainage, therefore, about as one to fourteen. If we assume that the various geographical conditions of the earth's surface in the past periods of its history were, taking one time with another, combined in much the same proportion to each other as they are now, then on this assumption we might expect to find records of marine conditions amongst ancient rocks from twelve to fifteen times as frequently as we should records of conditions of inland drainage. As a matter of observation, this is about the proportion which the rocks formed under conditions of inland drainage bear to those formed in the sea.

Dr Murray defines Desert Conditions as those which prevail where the annual rainfall does not exceed 10 inches. Dr Murray's figures (*op. cit.*, p. 74), give as the area where these climatal conditions prevail 12,214,250 square miles. I should be disposed to modify this definition to a certain extent, and to include under areas of Desert Conditions all those areas where the total quantity of aqueous vapour, normally present in the air, is much below the average. These conditions may prevail where the rainfall exceeds 10 inches; for it may happen that the total quantity of rain precipitated during occasional thunderstorms may amount to considerably more than that, and yet periods of several months, and even years, may elapse without more than an occasional shower, quite insufficient for the needs of vegetation. Arid conditions of this nature are usually due to the fact that the regions where they prevail lie inland in relation to great mountain areas, over which the chief moisture-bearing winds have passed. Such upland areas act as condensers, and wring every available drop of moisture out of the clouds that pass over them, leaving little or none to be transported to the areas on their lee side.

Two results of considerable geological importance result from arid conditions of the kind under notice. Firstly, in a region where the rainfall is either low or very irregular in its occurrence, vegetation of almost every kind fails to retain a permanent footing. As a consequence, sooner or later, large tracts of country, which under normal conditions of climate would be covered with soil, speedily become bare and tend to remain in that condition: animal life, also, tends to be but poorly represented. Secondly, in a region where the percentage of aqueous vapour present in the air is below the normal, both insolation and radiation attain to much higher extremes. It is a well-known fact that the presence of aqueous vapour in the air tends to act as a screen to the sun's rays during the day, thereby very materially tempering their effect upon rock surfaces, and tends

equally to act as a blanket by night, checking the radiation to a very important extent. Where the amount of moisture present in the atmosphere is but small, the sun's rays exert their maximum power, and heat up the rock-surfaces to their fullest extent within a comparatively short time. In like manner the absence of the blanket formed by moist air permits of the rocks cooling down with equal rapidity to a very low point. In arid tropical regions, rocks, stones, and sand, heat up by about 2 P.M. to temperatures so high that the hand can scarcely bear to touch them; while by about 3 A.M. the air in contact with these same rocks may be at or below the freezing point. In arid regions situated within the temperate zones, the effects of insolation and radiation are hardly less marked, and the diurnal range of temperature to which the rocks are subjected is considerably greater there than that which can possibly obtain in more humid regions.

In Walther's "Die Denudation in der Wüste und ihrer Geologischen Bedeutung," the chapter devoted to the diurnal range of temperature in Egypt and the parts adjoining is full of interest in this respect (see p. 359 *et seq.*). Not to enter into details here, it may suffice to point out some of the consequences of geological interest which arise from such an excessive diurnal range. In Britain and other countries where humid conditions prevail, the expansion of rocks caused by sun-heat during the day does not as a rule proceed beyond the mean, and the rise of temperature and the consequent expansion of the rocks takes place gradually. In like manner the fall of temperature and the consequent diminution of volume of the rocks is also moderate, and takes place nearly always at a slow rate. Consequently the effects of insolation and radiation are with us factors in denudation of no more than secondary importance. They are certainly of much inferior importance as factors in denudation to the effect of such chemical causes as the solvent action of rain water charged with the humus acids, and their ultimate term carbonic acid. The difference between arid and humid conditions, especially where limestones and rocks of eruptive origin are concerned, is most marked and important. In the one case the extreme diurnal range of temperature, which may amount to 130° Fahrenheit, splinters and shatters the rocks into angular fragments (some of which may be of several tons in weight), at the same time leaving them almost entirely unaffected by any changes of a chemical nature. In the other case, that of denudation under humid conditions, the waste of the rock is chiefly accomplished by means of chemical changes; the mechanical effects are usually quite subordinate to those which have been termed decomposition. Limestones in arid districts splinter off

from the parent mass in angular blocks, which shew no sign of chemical erosion. Under humid conditions the same rock presents abundant evidence of being fretted and corroded by the acidulated waters, whose action ends only in the entire solution of the rock and its transportal seawards as bicarbonate. Eruptive rocks under humid conditions disintegrate chiefly by the decay of their feldspars, from which the alkalies are removed in solution, combined with CO_2 . Under arid conditions these rocks splinter off in angular fragments, whose constituents, and especially whose feldspars remain quite fresh, and not in the least kaolinised.

Another factor of importance in the present connection relates to the structure of eruptive masses. These, of course, consist of usually three or more crystalline silicates, together with, in some cases, an interstitial ground mass. Supposing, for argument's sake, that these minerals are feldspars of two kinds, quartz, and hornblende, we have a rock whose constituents are different not only in their composition but also in their physical properties. Their specific heats are different, so that under a given temperature they warm (or cool) unequally in a given time. Their rates of expansion for a given rise of temperature are not only different amongst themselves, but are different in different directions for each crystal. Hence, with a rapid change of temperature every twenty-four hours, the unequal expansion and contraction not only loosens the cohesion of the several minerals to their neighbouring minerals adjoining, but, in the case of the hornblende, tends to splinter the individual crystals into fine slender threads, which are easily removed from the wasting rock even by a gentle breeze. The feldspars split along their dominant cleavage planes, and fall away from the rock, retaining, however, their faces as bright and fresh as if they had been newly hammered out of a perfectly sound piece of rock. No such freshness or angularity of feldspar fragments is possible as a result of weathering under humid conditions.

Thus it arises that, in arid regions, eruptive rocks waste in a totally different fashion from what they do in humid areas. Their ferro-magnesian silicates disintegrate under insolation, and are blown away by the wind. Their feldspars break up into fresh and perfectly angular fragments, which, as scree, slide down the mountain sides in the direction of the bottom of the valleys. The quartz, simply detached from its matrix, suffers, at the most, but a mechanical reduction in size. In course of time an occasional thunderstorm bursts over the area, the scree is washed to the bottom of the valley or wady, and are there levelled out by the temporary flood. Then follows a period of

drought, during which the wind takes up the work of deposition, and spreads out more or less horizontal layers of finer material over the torrent *débris* just before brought down. In this way well-stratified alternations of arkose and finer rock material, largely consisting of sand, are being formed in the wadys of desert areas of the present day.

The prevalent tendency of desert denudation is to reduce the inequalities of the surface and not to create valleys. Wadys, therefore, are in all cases the effect of running water, and must have been formed under climatal conditions of a normal or humid character, which formerly prevailed where these now occur.

Excellent examples of the phenomena referred to are to be seen in the Sinaitic Peninsula.¹ In that area the Nubian Sandstone, &c., formerly overspread a nearly level tract formed of gneisses and granitoid rocks. These, subsequently upheaved into great plateaux, were for a long time exposed to the denuding action of rain and rivers, when humid conditions prevailed in that area. Deep and wide valleys were thus excavated. Then came a gradual change, which ended in replacing humid conditions by arid, and in the formation of deserts. The rocks no longer weather in their former fashion, but splinter up under the alternate expansion and contraction due to the high diurnal range of temperature. Angular quartz grains and angular pieces of perfectly fresh felspar are now detached from the mountain sides, while the dark mica and the hornblende blow away as fine black dust. Scree accumulates on the sides of the wadys until one of the occasional torrential rains descends upon them, when they are transported to the bottom of the wady as torrent *débris*, and are spread out by the floods in rudely parallel layers, over which afterwards dunes are drifted, and eventually levelled out. I shall endeavour to show in the concluding part of this address that conditions very similar to these have more than once or twice obtained within the limits of what are now the British Isles.

In a region where the rainfall is low it not uncommonly happens that the wind assumes an importance as an agent of both denudation and deposition far greater than it does in humid climates like our own. Large quantities of the finer material, loosened by insolation, are drifted far and wide by the winds, abrading rock surfaces as they are driven past them in such a fashion as to produce very remarkable surface features.

¹ An extensive series of photographic views of these was projected by the limelight in illustration of this when the present address was delivered.

Some examples of these are figured by Walther in the work above mentioned. (I have long taught in my geology courses that the first rough shaping of the Sphinx itself was due to the long-continued action of this natural sandblast.) Good examples on a small scale, from British localities, are exhibited in the Geological Index Collection in the Gallery of Scottish Geology and Mineralogy in the Edinburgh Museum of Science and Art. Erosion by means of blown sand not only files and rasps away rock surfaces in a fashion different from that produced by any other natural agency, but the sand grains themselves, as well as the material acted upon, are polished, smoothed, pitted, and rounded, in a manner peculiar to this mode of erosion. As the means by which this is accomplished have considerable geological interest, and are not commonly understood, I will devote a few lines to such explanation as may be necessary:—

In the shaping of sand grains in general three principal factors are concerned. These are—(1) Solar energy, which sets the wind and the waves to work; (2) Gravitational Energy, which acts in opposition to the energy directly emanating from the sun; (3) Surface Tension, a form of energy which in the present connection is of especial interest and importance. Solar heat distils aqueous vapour from the broad surface of the ocean, winds drift it landward, where it is chilled and condensed into rain or snow, finally descending under the action of gravitation from the level to which it had been lifted by the sun's energy back again to the level of the sea. Flowing downhill in obedience to the force of gravitation, it transports seawards rock fragments of various kinds, gradually reducing these to successively smaller fragments as it proceeds from higher to lower levels. In order to understand the bearing of this upon the subject of the present address, we must first consider the principles which determine the ratio between the superficial area and the volume (and therefore the weight) of a stone which is undergoing reduction in size under the joint action of gravitation and the forces that work with, or act against, that form of energy.

The *surfaces* of bodies of similar figure, but different in size, vary as the square of their linear dimensions. For example, the surface of a cube 1 inch by the side presents an area of 6 square inches, while that of a sphere of the same diameter is 3.14159 (&c.) square inches. If the linear dimension of the cube be doubled, its surface area is increased in the proportion of $2 \times 2 \times 6$, *i.e.*, 24 square inches; while the same increase in the case of the sphere augments its superficial area in the proportion of $2 \times 2 \times 3.1416$, *i.e.*, 12.566 square inches. If the one-inch cube be reduced to a cube half-an-inch by the side, its

surface area is diminished from 6 square inches to an area of an inch and a half. A sphere with a diameter of 1 inch has a surface area of 3.14159 square inches; while if it be reduced to half that diameter its surface area will diminish to .78539 of a square inch.

But in the case of *volumes* of bodies with similar figure that differ in size, it is well-known that these volumes increase as the cube (or decrease as the cube root) of their respective linear dimensions. A spherical stone 1 inch in diameter has a volume of .5236 of a cubic inch (and a surface area of 3.1416 square inches); but if that stone be worn down from a diameter of 1 inch to that of $\frac{1}{2}$ an inch, its volume is diminished to .06545 of a cubic inch (its surface area, as already mentioned, being .78539 of a square inch.) This is one way of stating the fact that bodies of similar figure, with enlargement of dimensions, increase in volume, and therefore in weight, much faster than they increase in surface; or that, with reduction of dimensions, they decrease in volume, and therefore in weight, faster than they decrease in superficial extent. To put this into simpler language, one may say that, when a grain of sand is being worn down, its surface area does not lessen so fast as its weight does, but becomes proportionately larger; in fact, with each halving of the diameter of a sphere the ratio of its surface area to its weight is doubled. A quotation from Sorby's address may be added here to illustrate one of the applications of this principle (Q.J.G.S., xxxvi., pp. 32-3): "The friction [of a sand grain¹] upon the bottom must be always small . . . and must vary as the weight, and therefore as the cube of the diameter; but the surface from which the material must be worn [or which the grain presents to the fluid] varies as the square of the diameter. Hence, even making no allowance for the extra buoying-up of very minute particles by a current of water, depending upon surface cohesion [now called Surface Tension], the effect of wearing on the form of sand grains must vary directly as their diameter or thereabouts. If so, a grain $\frac{1}{10}$ of an inch in diameter will be worn ten times as much as one $\frac{1}{100}$ of an inch in diameter, and at least a hundred times as much as one $\frac{1}{1000}$ of an inch in diameter. . . . A grain $\frac{1}{10}$ of an inch in diameter would be worn as much in drifting a mile as one $\frac{1}{1000}$ of an inch in being drifted 100 miles."

We may now pass on to consider this form of energy, which is here referred to as Surface Tension. This is as yet somewhat imperfectly understood; but some idea of its general nature may be gathered by studying the phenomena that often accompany the pouring of fluids out of earthenware vessels provided with lips or spouts. Pouring tea out of a glazed earthenware tea-

¹ My own remarks are added in square brackets.

pot shews this in many cases remarkably well. In the hands of those not accustomed to perform this household duty, the tea which is meant to fall in a graceful curve from the spout into the tea-cup, will, instead of doing so, persist in running a variable distance along the underside of the spout, whence it eventually drips off from the vessel at a point far removed from that which was either expected or desired. A study of this homely illustration will enable us to realise the fact that there are evidently in this case two independent sets of forces at work: gravitation (if it be not interfered with) tends to make the tea drop perpendicularly from the end of the spout; while some other force of a different kind is evidently counteracting that of gravitation, and is tending to make the tea adhere to the surface of the glazed earthenware, and so to remain in contact with the teapot as long as possible. This force is that of Surface Tension. The course taken by the fluid is readily seen to be one compounded of motions arising from the joint action of gravitation, surface tension, and the impulse given at the outset by the operator.

Surface Tension, illustrated by this example, operates in nature in a great variety of ways, acting, indeed, between every fluid and any solid with which that fluid may be in contact. The results differ very materially, according to the respective natures of both the fluid and the solid. They differ in the case of the contact of the same fluid with different solids, and in that of the same solid in contact with different fluids. Moreover, in the operation of natural causes, the effect is further complicated by the ratio which the bottom velocity of the transporting medium bears to the superficial area, the weight, and the durability, of the material operated upon, as well as, of course, upon the distance the particles travel, or the time during which the forces act. Much valuable information upon these heads is given in Sorby's Presidential Address to the Geological Society of London (Q.J.G.S., vol. xxxvi, p. 32.) See also Daubree's *Géologie Expérimentale*, and J. A. Phillip's "On the Physical History of Grits and Sandstones" (Q.J.G.S.).

It follows from these considerations that, in the process of wearing down a grain of sand by friction on the bottom, under the impulse imparted by fluids in motion, surface tension becomes more and more effective in proportion as the surface area of the grain increases relatively to the weight. Eventually a stage of reduction is reached at which the adhesion between the moving fluid and the grain is sufficient to counteract the opposing effect of gravitation. When that is the case the grain is buoyed up by the fluid and carried forward as if it were part of the fluid itself. After this, further rounding of that grain in

Fig. 1. ($\times 10$)
Desert Sand, from near Cairo.

Fig. 2. ($\times 10$)
Sea Sand ("Musical Sand") from Lairg Bay, Eigg.

that particular medium is no longer possible. Hence the grains of sand which have been shaped as such in either sea-water or river-water undergo no further rounding after they have been reduced below certain dimensions, which are determined by the factors above mentioned.

[It should be mentioned here that this latter aspect of the subject under notice was most admirably set forth by Professor Heddle of St Andrews in an address on "Sand," delivered before the Edinburgh Field Naturalists in 1896. The writer is indebted to Dr Heddle for many additions to his geological knowledge in this and other directions.]

Like water, air is a fluid, and there is exerted between a given sand-grain and the atmospheric air surrounding it a certain amount of surface tension too. But this is very much lower than it is in the case of water; consequently gravitation in this case acts with more effect. This is another way of stating the fact that a sand grain impelled by the air will tend to be rolled against other sand grains, and bowled along in contact with rock surfaces long after its size has been reduced to that of the smallest which the action of water of any kind can possibly round. Given, therefore, sufficient time, and wind is capable of reducing sand grains of almost all sizes into a more or a less spherical form by prolonged friction against each other and against surfaces of rock. As a matter of fact this is exactly what does happen. The long-continued rolling and drifting to which desert sands have been subjected ends by shaping a large proportion of the sand grains into smaller spheres. The spherical form of the grains and their pitted and polished surface are thus distinctive characteristics of desert sands. (This was well illustrated by photomicrographs of sea-sand and desert-sand exhibited when this Address was delivered, see Plate XI.)

Putting this statement into another form, we may conclude with a tolerable amount of certainty that any sandstone largely composed of well-rounded grains of sand, represents a desert sand, and was formed under arid conditions, on a land surface. We shall presently see that abundant confirmation of the correctness of this inference is afforded by other sets of facts, to which reference will presently be made.

One of the characteristic modes of accumulation of desert sands is in the form of dunes, which are often of considerable size. Their longer axes are said to range, in a great many cases, north and south, as if determined by the earth's rotation. False bedding at exceptionally-high angles is another characteristic of desert sands; and it is said that the dominant direction of these planes inclines from the east westward, as if, again, the earth's rotation had something to do with it. Ripple marks are of very

common occurrence in recent desert sands. It is said that these may be distinguished from ripples formed under subaqueous conditions, by the fact that in the desert sand ripples, the coarsest grains occupy the *crests* of the ripples instead of lying in the troughs. This feature has not yet been investigated in connection with the fossil desert sands, to which special reference will presently be made.

Rock material accumulated under desert conditions at any period of the earth's history may be expected to exhibit some, or all, of the features above described, if we are correct in assuming that geographical conditions prevailing in former times were not essentially different from those met with now. Scree and torrential deposits of angular and quite unweathered rock materials, subsequently compacted into arkoses and breccias, will be found in co-existence with strongly false-bedded sands, whose component grains will show abundant evidence of long-continued rolling under sub-aerial conditions. These deposits, as a whole, will be found to occur in old wadys, or to lie upon exceptionally-irregular surfaces of rock, in which respect desert-formed rocks contrast very strongly with strata laid down under normal marine conditions.

Such deposits as these, which are chiefly sub-aerial in origin, may co-exist, even in desert areas, with deposits formed in comparatively shallow lakes or Schotts. Into such lakes desert sand is transported by the wind in large quantities. Furthermore, rivers of small volume discharge into these shallow lakes water whose matters in solution have already been partially concentrated by evaporation under arid conditions. Amongst the substances carried down in solution by rivers in all parts of the world are some few that merit special consideration in the present connection. The principal of these are—(1) Chloride of Sodium, which, carried up into the air in the form of sea spray during storms, is drifted inland, forms the nuclei of rain-drops, and thence descends to the land. Under ordinary circumstances this Chloride of Sodium completes the cycle by flowing back in rivers to the sea; but under desert conditions the aqueous medium in which it is dissolved is returned to the clouds by evaporation, while the salt is left behind, to accumulate until its precipitating point is reached. (2) Other sea salts, especially Magnesium Chloride. (3) Carbonate of Lime, Magnesia, Iron, etc., dissolved from the rocks of the land by the humic and allied acids and carbonic acid. With these are various sulphates, as of lime, iron, etc., also derived from the land drained by the feeders of the lake. In addition to the substances carried down in solu-

tion are the remains of animals and plants drifted down in suspension. The proportion in which these will occur is, of course, largely determined by the nature of the climatal conditions prevailing within the basin of the rivers draining into the lake. Into the Dead Sea, for example, large quantities of vegetable matter are annually transported by the Jordan. The same is true of fishes and other forms of animal life. It will presently be shown that these organic substances exercise very important influences upon the nature of the chemical deposits taking place under these conditions.

In regard to the history of rock-salt, gypsum, dolomite, and their associates, which have been found under conditions arising from those under notice, I do not propose to dwell in this Address. But in dealing with the evidences of desert conditions in the past, there are three substances which afford important evidence in relation to the history of British rocks. These are Magnesia, Iron, and the Bituminoids. Probably, in the first instance, the two first-named (like lime) have primarily originated from the decay of eruptive rocks. Under normal, humid, or pluvial conditions, these substances find their way to the sea in the form of bicarbonates, which state they reach through the solvent action upon rocks of water charged with CO_2 and the allied humic acids already referred to. But in areas of inland drainage, where the whole of the water carried down by rivers is dissipated by evaporation, these substances in solution are left on the spot, and gradually accumulate (like the salt, gypsum, and dolomite), until their respective points of precipitation are reached, when they are thrown down in the solid form. In the case of such areas of inland drainage some of the carbonate of magnesia either becomes converted on the spot into dolomite, through combination with carbonate of lime, or else it soaks down through the porous strata in which the lake is situated. On meeting with any calcareous matter, even in the solid form, it at once enters into combination with it, and finishes by converting part or the whole of the carbonate of lime into dolomite. This is one very characteristic feature connected with these deposits formed in inland lakes. It is one of considerable importance in the present enquiry, as I have repeatedly pointed out on former occasions to this Society and others.

The history of the ferrous carbonate has been dealt with by Mr Hudleston in his Presidential Address to the Geologists' Association (vol. xi. No. 3, p. 104.) His summary of the chief points of interest leaves almost nothing unsaid with which a geologist is interested. I therefore give part of it here nearly in the author's own words. This part is enclosed within square brackets:—

[Iron, liberated from eruptive rocks, is carried away in solution as *bicarbonate*, which is disseminated through the waters of the lake. The part next the surface seizes upon an additional molecule of oxygen in the proportion of F_2O_3 . This causes it to lose its carbonic acid; but the ferric oxide thus formed immediately combines with water to form the ferric hydrate, and then sinks to the bottom. Portions of such accumulations are from time to time re-dissolved, owing to the abstraction of the extra molecule of oxygen by the carbon of *decaying vegetation*. This extra molecule of oxygen helps to form the CO_2 , or other humus compounds, which dissolve the iron, now reduced to the protoxide. In this way the game of solution and precipitation is kept up indefinitely, and where the balance is in favour of precipitation an accumulation of iron ore will occur. Reduction renders iron soluble and locomotive; oxygenation arrests locomotion and fixes the iron on the spot. Iron is a base, with a strong affinity for the humus acids, and their ultimate term Carbonic Acid. It has also a strong affinity for oxygen, and in the presence of this it forms the nearly indestructible (and, in the *absence of organic matter*), almost insoluble, ferric oxide.

As ferric oxide in the *presence of organic matter*, it provides the oxygen for decay, and its residuary protoxide is itself dissolved by the resulting organic acid, and enters into circulation. . . .

. . . Red rocks have been coloured in the first instance by solutions of ferrous carbonates and sulphates depositing the insoluble peroxide, and, for lack of reducing agents in sufficient amount, the iron of these beds has not been rendered soluble, and therefore remains disseminated instead of being concentrated. . . .]

The author makes no reference to an interesting result which follows from the reactions above described, and which has an important bearing upon the subject of this address. The result referred to is that the deposition of the ferric oxide, like that of the carbonate of magnesia referred to above, is not confined to the strata on the floor of the lake, but is carried down in solution through any pervious strata beneath. We know from geological evidence that this may take place to a depth of fully 600 feet. By this means films of ferric oxide are deposited upon the quartz grains—if little or no carbonaceous matter be present. In this case the quartz grains of the rock below the lake may become coated with ferric oxide to nearly the same extent as happens in the case of the strata in process of formation on the bottom of the lake itself. If, however, carbonaceous matter be present in the strata through which the ferriferous solutions are percolating, then the ferric oxide is wholly or in part

reduced. In this case the strata, instead of being stained a bright red, are tinted various shades of duller colours, among which browns, purples, and puce are prevalent. Shales containing much diffused carbonaceous matter thus reduce the iron almost entirely, and for this reason almost never exhibit any bright red tint. Their black colour, however, is generally replaced in such cases by dull purple, lilac, or puce. The same is true also of sandstones. Those which contain much carbonaceous matter, or are associated with coal seams or with oil shales, rarely exhibit any very marked staining due to this cause. Thick masses of sandstone, however, in which carbonaceous matter is rare or absent, usually stain a very bright red. As examples, may be mentioned the Upper Red Measures of Fife, of the Glasgow coal-fields, the Whitehaven Sandstone of Cumberland, and many others.

[I have before pointed out that the presence of this distinctive colouring is a sure indication of the former presence of Red Rocks over the spot affected. The first reference to this by myself is in the Explanation of Sheet 98 N.E. of the Geological Survey of England and Wales.]

One further result (of considerable commercial interest in the present connection) is the fact that percolating solutions of ferric oxide tend to *replace* any calcareous matter with which they may come into contact. I have stated my belief¹ that nearly all our British deposits of hæmatite are entirely due to this cause.

The next point that claims our attention is the very marked association of petroleum and the bituminoids² with strata formed under conditions of inland drainage. A careful study of the reactions described in Mr Hudleston's paper will make it clear that the precipitation of iron in the form of ferric oxide in inland lakes is one of the results of the absence of any large percentage of organic matter, and especially of matter of vegetable origin. Where much organic matter is present the iron goes back into solution as ferrous carbonate, and is eventually thrown down as ferric hydrate. Where organic matter is rare or absent entirely, and only where that is the case, does the iron go down in the form of ferric oxide. It is precisely under desert conditions that one would naturally expect vegetable matter (and, of course, animal matter too) to be but rarely

¹ Trans. Cumberland and Westmoreland Association, No. viii. (1883), p. 117.

² See Goodchild, "Origins of Oil Shales," in this volume; and "The Origin of the Bituminoid Cement of the Caithness Flagstones," *Proc. Roy. Physical Soc.*, vol. xiii. p. 316.

carried into the schotts, and, even where that is the case, then in but small quantities. We should therefore be prepared to find that where little or no vegetation exists, the strata undergoing deposition would be more or less coloured with the red ferric oxide. Conversely, where we meet with sandstones coloured bright red—especially if these consist largely of rounded grains of sand, and are associated with gypsum, rock salt, and dolomite, and locally contain angular and unweathered fragments of felspar or of limestone—we may correctly infer from these concurrent facts that we are dealing with strata formed under desert conditions. If the underlying sandstones happen to be carbonaceous, and are tinted purples of various hues, and are associated with limestones more or less dolomitised and converted into hæmatite, the inference is considerably strengthened, for the reason given above.

But it must frequently happen that, owing to changing geographical conditions, a region which at one time was under desert conditions may just previously have been, or may soon after become, a region where the conditions may be described as sub-arid, sub-humid, or even humid. Or it may well happen (as in the case of the basin of the Dead Sea, the Salt Lake, and others) that humid conditions prevail and vegetation flourishes in the upper part of the basin, while the lower may be arid in the extreme. Vegetation flourishes in the humid part of the area, and from that part is transported by rivers to the terminal area of the streams, where the water disappears by evaporation. Three chemical changes of importance arise which may perhaps all three be described as changes of a reciprocal nature. (1) Ferric oxide ceases to be precipitated and ferric hydrate goes down in its place. In its turn this brings about a decomposition of the vegetable matter. (2) The sulphate of lime carried into the lake, and there concentrated by evaporation, is decomposed by the vegetable matter, with the concomitant decomposition of precipitates of carbonate of lime. The reciprocal action in this case is that of the action of weak solutions of sulphates, which in the course of time convert the vascular tissues, and even some of the ligneous matter, into one or other of the many hydrocarbon compounds—the bituminoids amongst others. Hence the frequent—or all but universal—association of rock salt, gypsum, dolomite and “abraum salts” with hydrocarbon compounds. It is to this solvent action of solutions of sulphate of lime upon subaqueous masses of ligneous matter that I ascribe the bituminous character of such rocks as the Caithness Flags, the alternations of oil shale and precipitated carbonate of lime which formed the well-known Burdighouse Limestone, the bitumen of the Dead Sea, the petroleum

occurring at so many places within the Aralo-Caspian area, and others. Even the pitch in the Pitch Lake of Trinidad appears to me to be due to the uprise of solutions of sulphate of lime through a subterranean carbonaceous deposit.

One more point, and then we may pass on to consider some British deposits which have been formed under desert conditions. In the case of strata formed in inland lakes many other complex chemical reactions must necessarily arise. Amongst these we may refer to the liberation of silica in solution. It has long been known that weak solutions of silica, bathing clean grains of quartz, will tend to be deposited upon the quartz in a crystalline form, giving rise to what is known as Secondary Quartz. The new quartz is not added on to the old anyhow, or at random, but its molecules are so built up as to be oriented in the same direction as were the molecules of the old quartz represented by the sand grain. Therefore, although many millions of years may have elapsed since the time when the quartz of the sand grain was originally formed, and that quartz may have been knocked about, worn, rolled, built up into sandstone, wasted, used up over and over again—yet when suitable conditions again set in (as they appear very commonly to have done during desert conditions), the new quartz tends to restore the old quartz grain to the crystalline form that nature's forces, perhaps millions of years before, had intended it should take.

This preliminary chapter leaves not much to be said in the remainder of the address. I shall now simply point out that the combination of results arising from desert conditions, of which the foregoing is a summary, may be found not only in deposits which are taking place at the present day, but also in deposits which at various, and often widely-separated, periods in the past, have been laid down in Britain. Briefly, these periods may be stated to be three in number—(1) The New Red Period, which is a convenient general name to include the times when the Trias and the Dyas (Lower New Red, or "Permian") were deposited. (2) The Devonian Period, when the various Old Reds of Scotland, &c., were formed. (3) And, lastly, the Torridonian Period. I need only to notice the more salient features of each, and to remind those who read this Address, that I proceed all along on the assumption that in this, as in other geological matters, we interpret the Past by the Present. If the geological evidence shows that we have in Britain strata of the same kind as those which are now only being formed under Desert Conditions, then Desert Conditions pre-

vailed in Britain at the times when the rocks in question were formed.

Evidence afforded by the New Red Rocks.—While deep water marine conditions obtained on the Continent during the time when the Tyrolian and Panormian (=marine Trias and Dyas) rocks were being formed, inland-continental conditions prevailed in the area now represented by Britain and Western Europe. We have no need to enter into detail in regard to this point; it will suffice to remind the reader that the British strata formed during the period consist largely of bright red sandstones and marls, with which is associated, in the area embracing the north of England and the north of Ireland, a wedge-shaped mass of Magnesian Limestone. With the Marls are also associated both Gypsum and Rock Salt. An inspection of the sandstones shews us that they contain a large percentage of well-rounded grains of quartz, each coated, as a rule, with a thin pellicle of ferric oxide. Plant remains in the red strata are conspicuous by their absence, while the very strongly-marked false-bedding prevalent over large areas at once recalls the diagonal bedding of desert sands.

Breccias, consisting of perfectly-angular and unweathered fragments, occur as old torrential deposits left in connection with the buried wadies, and are therefore found on every platform, from the very lowest to the highest. Throughout the whole of these breccias the angular form and perfectly-unweathered aspect of the rock-fragments, which are also often of large size, is most conspicuous. This is equally the case, whether the breccia consists of a tumultuous assemblage of limestone blocks, as is the case in the Dolomitic "Conglomerate," near Bristol, and, again, in the Brockram of the north of England, or whether the breccia consists of fragments of granite, as it does on the flanks of granite areas in the South of Scotland—for example, near Dumfries.

The uniformity of petrographical characters in these New Red breccias points unmistakably to the occurrence of equally-uniform meteorological conditions over large areas; and shows clearly that these conditions indicate the long continuance of an abnormally-dry atmosphere; a conclusion which no one who studies the facts will venture to call in question.

At the base of the New Red there is some kind of evidence of old wadies; but the inequalities of the old surface are by no means so strongly pronounced as many authors have assumed. In some cases these appear to be due to unequal subsidence.

In Westmoreland (and probably elsewhere in Britain) there is unmistakable evidence of the presence of ice—floating ice in most cases; but in at least one case, that which I have recorded

in the Proc. Geol. Assoc. for 1889, there is evidence of actual glaciation which is shown by the occurrence of stones traversed by true glacial striæ.

Some important results were deeply impressed upon the rocks, which are, or were formerly, covered by the New Red Rocks. These are the abundant infiltration of ferric oxide into the strata beneath, whereby the sandstones were stained various shades of red—the variety of colouration being apparently connected with the presence, or the absence, of carbonaceous matter in the rocks affected. A further result is the partial, or the entire, replacement of calcareous rocks by hæmatite. Nearly all our deposits of hæmatite—extensive or otherwise—are distinctly traceable to this cause. Yet another result is the dolomitisation of the limestones, due to the infiltration of carbonate of magnesia, which has partially replaced the carbonate of lime, and so converted limestone into dolomites. I have more than once stated before this Society my firm conviction (which has been founded upon many years' field-observations), that the presence of this dull-red staining, the occurrence of deposits, great or small, of hæmatite, and of dolomitised limestones, all concur in demonstrating that the regions where these phenomena occur in rocks older than the New Red have formerly been covered by the New Red Rocks, to which these effects are due.

The widespread diffusion of this red staining amongst the Carboniferous rocks in the basins of the Forth and Clyde, the concurrent occurrence of dolomitised limestones, and the sporadic occurrence of veins of hæmatite in these areas, I therefore regard as some of the vestiges of these old desert conditions which ushered in the Neozoic Era in this part as well as over the greater part of the rest of the kingdom.

Desert Conditions during the Devonian Period.—Much of the evidence already referred to under the New Red applies also to each of the Old Red Sandstones. It need not, therefore, be repeated here. There is the same association of arkoses containing unweathered felspar fragments, the same bright red colour on certain horizons, the same strong false bedding, the same evidence of deposition on a very uneven surface, all of which occur in connection with the New Red. In Scotland especially—thanks to the valuable memoir of Sir Archibald Geikie on the Old Red Sandstone of Western Europe¹—we can avail ourselves of a vast mass of information bearing upon the

¹ Trans. Roy. Soc. Edin., vol. xxviii. (1878).

physical geography of the Devonian Period in Scotland. As Sir Archibald has pointed out, the history of these rocks as a whole can be easily comprehended if we can conceive of an unusually-pronounced series of uprisings or Geoanticlinals, as they are now often termed, coexistent with their correlative depressions, or Geosynclinals, at no great distance. Denudation from the zone of upheaval supplied the wasted material which afterwards filled up the depressed area adjoining. This process, I conceive, commencing in the period when the English and Welsh Upper Ludlow Rocks were being formed, converted the whilom marine area of the South of Scotland into an area like that of the Nile Valley and the country to the east of it. Under these conditions the Lanarkian (or lowermost "Old Red") Rocks were formed. Possibly the sea may have gained admittance for a short time and permitted of the formation in Scotland of a limestone of Devonian age. But whether that surmise of mine prove correct or not, it is certain that the continued formation of a series of surface undulations, gradually propagated from the south of Scotland northward, permitted of the formation, one after another, of the various Old Reds, and of the denudation which gave rise to the unconformities that separate them, right up to the very top of the Upper Old Red.

There is evidence that, during the time when the Orcadian Old Red was in course of being deposited, normal pluvial conditions obtained for a time. The deposition of ferric oxide in the old area of inland drainage ceased, chiefly in consequence of the large quantities of vegetable matter which were swept into the old lakes. This latter, in its turn, decomposed the solutions of sulphate of lime, and liberated the calcareous matter, which, in a state of diffusion, or aggregated into nodules, now forms so conspicuous an element in the Orcadian Rocks. Furthermore, the sulphate of lime, in its turn, converted the vegetable matter into the bituminoids, which, in a diffused form, permeates—one might almost say saturates—so much of the Caithness Flagstones. I hold, therefore, that the exceptional durability of the Caithness Flagstones, which, of course, is due to the large percentage of bituminous matter they contain, is due to the fact that conditions of inland drainage, one of the phases of desert conditions, prevailed where these occur during the Devonian Period.

*Desert Conditions during Torridonian Times.*¹—To my mind one of the most striking and significant illustrations of the

¹ During the past three years, when dealing with the geological history of the Torridonian Rocks, I have taught, in my classes, that these Torridonian Rocks were formed under desert conditions, as stated here. I am not aware that this idea has occurred to any other geologist.

principle upon which geologists interpret the records of the Past, by the study of the Present, is to be found in the Torridonian areas of the North-West of Scotland. If we review the conditions obtaining in the Sinaitic Peninsular (as was done with the aid of lantern slides when this lecture was delivered), we find going on there to-day almost the exact counterpart of what must have taken place in Pre-Cambrian times in Sutherland and Ross.

In Sinai, and probably also in Scotland, an area of gneissoid rocks was overlaid by a deposit of derivative origin—the Nubian Sandstone in the one case, and some Pre-Torridonian rocks in the other; the area was then elevated in both cases by earth movements into an upland region, while normal meteorological conditions prevailed. During this time rain and rivers carved deep valleys into the massif, in each case cutting down through the overlying derivative rock into the gneissoid rocks beneath. Then changed meteorological conditions set in. Where, before, rain fell and rivers excavated valleys, rain fell only occasionally, or practically never, and only on those occasions when thunderstorms happened to burst over the regions in question. At other times the arid conditions gave rise to great diurnal ranges of temperature. The rocks in consequence were heated soon after mid-day far above the temperature usual in more humid climates, and by early morning, owing to rapid radiation, had cooled down to the opposite extreme. In a rock composed of constituents of diverse mineral character differential expansion takes place, owing to their different coefficients of expansion. The felspars in the rocks, instead of being slowly kaolinised by the action of rain water charged with carbonic acid, gave way under the strain set up by extreme expansion and contraction, due to the rapid changes of temperature. The ferro-magnesian minerals of the gneissoid rocks, having different coefficients of expansion from that of the other constituents, in like manner splintered into fragments so small that they were easily blown away as dust by the wind. Little by little the rocks crumbled down, and of their wasted portions the larger part slid down the valley side as talus, to be eventually distributed and spread out in the bottoms of the wadies by the action of the occasional torrents arising during storms; the remainder, chiefly in the form of dust, was blown far and wide by the winds. Possibly in the case of the old Torridonian rocks these materials from the old gneissic mountains, and their capping of sedimentary rocks, may now and then have been distributed by the agency of lakes; but the agency of water there, as in Sinai and in arid regions elsewhere, may have been limited to the distribution of

the disintegrated materials by the action of torrents after the heavy rains which occasionally deluge such regions.

In both these cases we have examples of the formation of arkoses, largely made up of the disintegrated materials of the gneiss, with the felspar fragments angular, bright on their cleavage faces, and quite unweathered. The ferro-magnesian constituents in both cases seem to have been shattered to dust, and in that form to have been distributed far and wide by the winds.

In the case of Sinai the disintegration will go on while the present arid conditions prevail, until the wadies are filled with material to the level of the highest point whence their materials can be derived; then their formation must cease and their destruction commence.

In the case of the Torridonian rocks, the old buried mountains, with their wadies levelled up to the brim, were afterwards lowered beneath the waves of the sea, and then planed off to a uniform level, upon which, in later times, when further subsidence had taken place, the Lower Cambrian Rocks were deposited.

The geological importance of the occurrence of desert condition in this, as in other cases, lies in the fact that owing to the felspar fragments being used up in the formation of arkoses before these felspars lost their alkalies, the re-conversion of these arkoses into muscovite schists and muscovite gneisses by dynamic metamorphism affecting them subsequently, was a comparatively simple process. Indeed, owing to these rocks having been formed under desert—instead of pluvial—conditions, the re-conversion of the derivative arkoses into granites or into gneisses will be admitted by most geologists to come well within the range of possibility.

Our British rocks, therefore, present us with records which, when interpreted by the light afforded by modern geographical facts, can only be read as records of desert phases of geographical evolution. As such, they appear to me to possess a high degree of interest, not only on account of the important economic results to which they have given rise, but also because they bring prominently before our eyes the fact that each and all of the various phases of geographical evolution which are taking place upon even the remotest parts of the earth to-day have in the past, at one time or another, found a place in that part of the earth's surface which now forms the British Islands.