Kaolinization and other changes in West of England rocks.

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THE behaviour of a mass of molten but cooling igneous rock under moderate pressure may be compared to that of liquid cupelled silver, which at a certain temperature can no longer retain the oxygen, many times its volume, that it has occluded. Thus, during the submarine eruption off the island of Pantelleria in 1891, blocks of lava that swam for a while on the surface of the sea exploded with violence. Chilling by contact with sea-water had occasioned exactly what Lowthian Bell[1] observed to happen on the sudden cooling of masses of slag by contact with water. There was a discharge within the set outer envelope, at something near a red heat, of previously dissolved water and gases, converting the floating ejectamenta into a species of bombs.

The sight of Vesuvius quiescent, but day after day under its pear-shaped cloud of vapour, helps one to form some conception of what must be the bulk of the emanations of a mass of cooling granite. These undoubtedly are chiefly water, but water the heat of which, not being dissipated in volcanic disturbances, is exercised in the promotion, under pressure of superincumbent strata, of chemical changes both in the partly consolidated outer crust of the granite and in the contact-region.

In the first volume of this Magazine H. C. Sorby remarks of rocks that are molten but are under great pressure—such, in fact, as were the West of England granites—that they probably contain water dissolved either physically as a gas in a liquid or chemically as it is in a hydrate, i.e. the water does not dissolve the rocks, but the rocks the water.[2] As the rocks cool, highly compressed steam remains more or less disseminated in them until the temperature reaches the critical

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[1] L. Bell, Journ. Iron and Steel Inst., 1881, pp. 534 and 540.

[2] H. C. Sorby, Quart. Journ. Geol. Soc., 1858, vol. xiv, p. 489.

point, when the solvent action of greatly expanded liquid water comes into play.

Examination of the outermost exposures of granites in the West of England and of their offsets, or dikes, affords proof of the operation of agencies that scarcely affected the main mass. It would appear that, owing either to changes in the density of the consolidating exterior[1] or, more probably, to convection-currents dependent upon differences rather in vascularity than in temperature,[2] there was a perpetual descent of fragments of solid or streams of more or less fluid rock from the uppermost portions of the magma. These, previous to their descent, discharged their gaseous and vaporous contents into the cooled exterior and the strata in contact therewith. The first results of the action of this discharge (pneumatolysis) upon the outlying portions of the granite were usually increased vesicularity in the quartz and assumption by much of it of the idiomorphic condition, also the formation of tourmaline, commonly brown or yellow, but sometimes blue in parts. Further action is evidenced by the bleaching or destruction of biotite and muscovite, and their replacement by tourmaline or, as in some elvans, by chlorite and rutile, and alteration of felspars, these last being rendered turbid by the production of fluid cavities and some degree of kaolinization, especially in their inclusions of what Dr. J. S. Flett[3] has shown to be oligoclase-albite. Further changes in the felspar result in the production of secondary silica,[4] muscovite, topaz, and probably also andalusite. In the china-clay districts kaolinization is a marked feature. This and further effects of pneumatolysis will be considered later.

The period during which pneumatolytic processes affected the rocks of Cornwall and Devon may have been long protracted, even geologically speaking. It took ten centuries of puy action to effect the softening that led to the sudden shattering of the Kobandi peak of Bandaisan, Japan,[5] and in the West of England both granite and killas can be shown to have undergone more than one series of changes.

To attempt to discuss the source of the water that permeated the West of England rocks at the time of and subsequent to their intrusion would be to go beyond the scope of the present paper. The behaviour

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[1] C. E. Dutton, Amer. Journ. Sci., 1883, vol. xxv, pp. 220-221.

[2] O. Fisher, 'Physics of the Earth's Crust.' 2nd edit., 1889, pp. 47 and 51.

[3] J. S. Flett, Mem. Geol. Surv., Land's End District, 1907, p. 50.

[4] S. Allport, Quart. Journ. Geol. Soc., 1876, vol. xxxii, p. 413.

[5] Michie Smith, Proc. R. Soc. Edinburgh, 1889-90, vol. xvii, p. 65.

of molten slags as solvents of gaseous bodies[1] affords reason for considering that the vapour of water as such or its dissociated elements[2] are directly absorbed by liquid lava. Angelot[3] conceives it to be quite possible for a column of water communicating with the surface of the globe to exert sufficient pressure to keep its base in the liquid condition when actually in contact with molten rock. That meteoric or oceanic water is occluded by the magmas of igneous rocks is, however, regarded as far from proven.[4] Messrs. Chamberlin and Salisbury[5] close their summary of the theories on this subject with the remark that the balance of present evidence seems to favour the view that the steam and other gases of igneous rocks come with them from their source deep in the earth. Hence one might, perhaps, be allowed the deduction that the magmas of the earth's lavas have for long been growing progressively anhydrous. Dr. H. J. Johnston-Lavis,[6] on the other hand, states that there is reason to believe that in their deep-seated sources lavas contain little or no water, and he maintains that when igneous matter is intruded into porous, water-bearing strata a process of dialysis goes on between the colloidal magma and the water in the strata.

Vesicles in quartz containing liquid and commonly a bubble, often abundant in granite, are especially so in its pneumatolysed derivatives, and perhaps most in schorl-rock. Fifty years ago H. C. Sorby[7] noted the occurrence of cubic crystals of salt and of minute prisms, presumably of selenite, in the quartz replacements of large felspar crystals in portions of the granite at Trevalgan, near St. Ives, Cornwall. His deductions from a study of the contents of the vesicles of quartz were questioned by S. Allport[8] on the ground that these contents were variable. This objection, however, loses force when one perceives that the differences in contents were determined by the act of crystallization of the quartz, which distributed from within outwards along lines of fracture (usually with a well-marked conchoidal curve, but frequently

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[1] A blast-furnace slag from Trignac, Allier, France, in the British Museum (Natural History) collection yields hydrogen sulphide as readily as fetid barytes when scratched.

[2] L. Bell, loc. cit., p. 541.

[3] V. F. Angelot, Bull. Soc. Géol. France, 1842, sér. 1, vol. xiii, pp. 188–189.

[4] J. F. Kemp, in 'The Genesis of Ore-Deposits,' published by the Amer. Inst. Mining Eng., 2nd edit., 1902, pp. 687–688.

[5] T. C. Chamberlin and R. D. Salisbury, 'Geology,' 1904, vol. i, p. 607.

[6] H. J. Johnston-Lavis, Quart. Journ. Geol. Soc., 1885, vol. xli, Proc., p. 104.

[7] H. C. Sorby, Quart. Journ. Geol. Soc., 1858, vol. xiv, p. 475.

[8] S. Allport, Quart. Journ. Geol. Soc., 1876, vol. xxxii, p. 408.

obliterated owing to residual plasticity in the silica) the constituents of a cooling gaseous liquid. Some of the little clefts received crystals with liquid and portions of any gas present, and others liquid only. Differences in the size of vesicles in quartz, due partly to irregular scattering of contents during its crystallization, may be ascribed mainly to the varied hydration of magmas. The quartz of a muscovite-tourmaline-granite, with kaolinized felspars, from St. Michael's Mount, is grey with a multitude of minute vesicles, each with its bubble, the mobility of the uncrystallized silica having been insufficient to permit the coalescence of disseminated liquid. In the junction-rock between granite and killas at Trewavas Head, Cornwall, and in the schorl-rock of Baleswidden the vesicles are large. Vesicles, somewhat masked by radiating needles of schorl, are present in the quartz of both luxulyanite and trowlesworthite (fig. 1 A),[1] cavities in a microscopic preparation of the latter showing well-defined salt crystals. Salt crystals (sodium or potassium chloride) are well seen in the quartz-vesicles of the tourmaline-granite of Moor House quarry, Shipley, Devon, of the Leather Tor schorl-rock, the Stenna Gwynn gilbertite-quartz-rock, the china-stone from near Trethosa, Cornwall, and many other West of England derivatives of granite.

An explanation of the development of idiomorphic quartz in the outer zone of granite masses and in their apophyses, the elvans of Cornwall and Devon, is furnished by a consideration of the condition of those rocks previous to their final consolidation. 'We must never forget,' remarks Professor J. W. Judd,[2] 'that in the deep-seated rocks . . . the whole mass, crystals and base alike, must be permeated by liquids and gases; and chemical reactions . . . can readily take place.' This is especially true of the region of pneumatolytic change. In this, among the mineralizing agents continually received from the magma, because less soluble therein than in water, or rejected therefrom during crystallization, there are present, to use the words of Arrhenius,[3] the ions of carbonic and boric acids and hydrogen sulphide, the hydrates of which are highly soluble in water without being dissociated. Silicic acid also is taken up by the water, which not only exercises the remarkable solvent powers it possesses at high temperatures, but facilitates molecular movement by promoting the fluidity of the mass affected.

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[1] Seemingly not detectible in the first microscopic preparation. (See T. G. Bonney, Trans. R. Geol. Soc. Cornwall, 1883, vol. x, pp. 180–186.)

[2] J. W. Judd, Quart. Journ. Geol. Soc., 1889, vol. xlv, p. 181.

[3] S. Arrhenius, in 'The Genesis of Ore-Deposits,' sup. cit., p. 644.

The very general absence of mica from the elvan dikes of the West of England can scarcely be attributed in the majority of instances to the existence of contraction-fissures affording easy passage into them of solvents from below or of surface-water from above and laterally, for the presence in them of idiomorphic quartz is another frequent characteristic. Moreover, the existence of abundant fine muscovite in the groundmass of elvans, as Dr. J. S. Flett remarks,[1] is probably a certain indication of pneumatolytic action, for muscovite is very rarely a primary ingredient of these rocks. This mica, evidently a dekaolinization product, is well seen in the pneumatolysed solid overburden in the Higher Nine Stones clay-pit, St. Austell, a rock exhibiting, with very little primary tourmaline, large, only superficially blanched Carlsbad-twins of orthoclase, and numerous, slightly eroded bipyramids of quartz. Idiomorphic quartz may be met with in those portions of many granitic masses that from their external position may be considered to have undergone some degree of pneumatolytic action, as, for example, the tourmaline-granite of Moor House quarry, on the borders of Dartmoor, that forming the eastern buttress of Gunnislake quarry, and the pinitiferous granite of Kit Hill, Cornwall. We are constrained, therefore, to seek for an explanation of this characteristic in conditions common to both granite and elvan previous to their final consolidation.

In granite subjected to pneumatolysis after crystallization of its constituents the mineral most prone to suffer disintegration and solution would be biotite, and then would follow muscovite and the felspars of the groundmass. Biotite, if not converted into tourmaline, which would require all but about 4·5 or 5 per cent. of its silica, would yield on decomposition some two-fifths of its weight of the latter substance. From muscovite a still greater amount would be obtained. The granules of original quartz in granite more or less liquefied by pneumatolytic action, unless completely dissolved, would serve as nuclei for the growth of idiomorphic crystals, the granules availing themselves of nascent silica derived from mica taken into solution. The removal of the bases of the mica, if effected by flow of the pneumatolysing fluid, would deprive any felspar crystals that had escaped destruction—probably in most cases a goodly proportion—of the alumina and potash they required for fresh growth, and the resultant solid rock would contain an abnormal proportion of quartz to its felspar and no mica. The assumption by the idiomorphic quartz of the bipyramidal prismless

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[1] J. S. Flett, loc. cit.

shape would seem to be conditioned by the nature of the menstruum in which it grew. Whether it is a result of hydrostatic pressure is a question that could be determined only by ascertaining what is the variation with pressure of the molecular surface energy of the various faces of a quartz crystal. The growth of the quartz phenocrysts in dikes is evidently dependent on the temperature of the magma and its degree of liquidity—increased by relief of pressure, on the bulk of the extruded mass and the rate at which it loses heat to adjoining rocks, and on the demands for silica made by growing felspar. It is manifest that the variation in shape of the phenocrysts from bipyramids with slightly blunted edges to rounded blebs must be attributed to erosion subsequent to re-growth. It has been suggested[1] that this rounding may be caused by hydrofluoric acid; the results of chemical experimentation, however,[2] intimate that, in the presence of orthoclase, quartz would be little, if at all, affected by that acid. It seems safe, therefore, to conclude that erosion of the quartz phenocrysts of the West of England and similar elvans was effected by the magma in proportion as it was desilicified by the enlargement or re-formation of felspar crystals.

The common occurrence of tourmaline, usually a dark variety (schorl), at different stages in the metasomatism of granite, indicates the existence of a magma constantly impregnated with some compound of boron. In the Shipley granite, for example, already mentioned, the presence of schorl in fissures in fractured orthoclase demonstrates tourmalinization after considerable progress in consolidation. Sedgwick long ago[3] remarked on the prevalence of schorl in the rocks usually associated with granite in Cornwall. These he groups as rocks composed of the constituents of granite with another mineral, commonly schorl or tinstone; those with no mica, or with chlorite or, more commonly, schorl replacing it; and schorl-rock, i.e. quartz with schorl only. He remarks, too, that the last may have a scoriaceous appearance owing to the removal of original felspar.

In considering the question of the alteration of biotite to tourmaline, it is important to note that tourmaline is a compound unaffected by acids, and decomposable artificially, with liberation of water, only when its chemical individuality is completely destroyed by strongly heated

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[1] J. H. Collins, 'The Hensbarrow Granite District.' 1878, p. 9.

[2] H. Rosenbusch, 'Microscopic Physiography of the Rock-making Minerals,' transl. J. P. Iddings, 4th edit., 1898, p. 108.

[3] A. Sedgwick, Trans. Cambridge Phil. Soc., 1821, vol. i, pp. 105-106.

fused alkaline carbonate.[1] In biotite are present all the constituents, save titanium and boron, that Scharizer[2] has shown to be present in brown tourmaline, which may be found in West of England granites either associated with biotite or without it. The pneumatolysis of an igneous acid rock lacking in biotite or its constituents may result in the formation of such a compost as the topaziferous aplite that occurs in contact with killas at Meldon, Devon,[3] containing, with white mica, tourmaline of a light greenish or, more rarely, of a pink tint. Most commonly, however, in the West of England the rock in which primary tourmaline came to be developed was a typical granite containing an appreciable quantity of biotite.[4] In trowlesworthite manifestly some of the brown tourmaline is secondary, for crystals of it may be seen moulded on plagioclase. Without such evidence it may be hazardous to infer that the dark-coloured tourmaline in a micaless granite probably usurps the place of biotite. In Carn Grey quarry, St. Austell, the selvedge of the granite section shows schorl replacing biotite as the ferro-magnesian mineral. The non-micaceous character of many schorlaceous elvans gives some support to the opinion that their micas have found a new existence in dark tourmaline. In rocks such as luxulyanite, trowlesworthite, and the schorl-rock of Single Rose clay-work, St. Austell, are distributed fair-sized tourmaline crystals of a yellow, orange, or brown colour, sometimes with patches of blue; and these were undoubtedly part of the groundmass of the parent-granite before it underwent kaolinization, and must in many cases be reconstituted biotite. In variability of tint and in presenting longitudinal and transverse cracks these crystals closely resemble the isolated tourmaline crystals to be found in most other borated West of England rocks. Additional features are outlines indicating that they have for the most part suffered irregular erosion before envelopment in acicular schorl of post-kaolinization date (fig. 2). In some instances a crack running through two distinct fragments may be seen to have become discontinuous owing to the intrusion between them of an isthmus of fine-grained quartz-schorl-rock. These fragments by their like optic orientation show that they are parts of one crystal. The same observation was made by Allport with respect to tourmaline in the metamorphic

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[1] R. Scharizer, Zeits. Kryst. Min., 1887, vol. xv, p. 343.

[2] R. Scharizer, loc. cit., pp. 348-349.

[3] J. J. H. Teall, 'British Petrography.' 1888, p. 316.

[4] See T. G. Bonney, 'On the microscopic structure of trowlesworthite.' Trans. R. Geol. Soc. Cornwall, 1883, vol. x, pp. 180-186.

rocks surrounding the Land's End mass of granite.[1] The erosion of some of it possibly explains his conclusion that the quartz of certain of his specimens had impressed its form on the tourmaline, and must therefore have been the earlier to solidify. This, however, is perfectly true of late-formed crystals of brown tourmaline in the Cligga Head granite, some of them being protected on one side by quartz and there intact, and on the other side eroded. The schorl-rock of Leather Tor, Devon, shows fragmentary tourmaline filling in the interstices of a mosaic of quartz. Here the irregular outlines of the tourmaline must be due to both erosion and fracture, for some neighbouring fragments have the same optic orientation. There can be no doubt that the crystallization of the finely acicular schorl of the metasomatized rocks of the Hensbarrow granite district was in part contemporaneous with that of the quartz accompanying it. In a much kaolinized granite on Rosemellyn Farm, in the parish of Roche, Cornwall, quartz instead of schorl has in places crystallized on the eroded felspar crystals projecting into spaces vacated by the groundmass, and its free surfaces have then been capped by acicular schorl (fig. 1B). Luxulyanite, again, exhibits zoning of quartz crystals by dust-like microlites of schorl entangled among extruded liquid particles (fig. 3). In this rock and trowlesworthite the re-growth of the eroded single yellowish or brownish

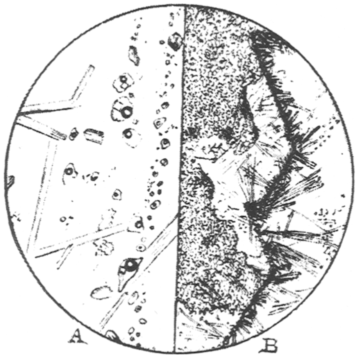

Fig. 1.—A. Quartz with vesicles; in trowlesworthite.
B. Quartz on eroded and altered felspar: Rosemellyn Farm, Cornwall.

Fig. 2.—Eroded tourmaline in quartz-schorl envelope; in luxulyanite.

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[1] S. Allport, Quart. Journ. Geol. Soc., 1876, vol. xxxii, p. 416.

tourmalines seems to have been arrested by the development of the acicular crystals or of a band of blue tourmaline.

It is clear that contact with acids cannot have occasioned the erosion of tourmaline observable in various West of England rocks. As we have seen, tourmaline, like topaz, is unaffected by acids. Its decomposability by melted alkaline carbonates suggests that its erosion may be due to exposure to the action of hot solutions of these salts, their effect being enhanced by the presence of carbonic acid and by pressure. A clue to the source of the alkaline carbonates is afforded by the existence of remnants of china-clay in greisen, schorl-rock, luxulyanite—in short, in West of England tourmalinized rocks generally, and the obvious inference is that the original felspar therein underwent kaolinization. It is evident that the erosion did not take place when a fresh supply of tourmaline, the acicular variety, was being added to the schorlaceous rocks. It is equally obvious that the eroded mineral did not suffer by the pneumatolysis during which it was evolved. If, as appears to be the case, the erosion took place during kaolinization, and the agent therein was a solution of carbonic acid, alkaline carbonates must have come into contact with the tourmaline, whether they were originally present in the solution or not, for their production would be a necessary consequence of the leaching of the alkaline silicates out of felspar and of their decomposition by carbonated water.

A further argument in favour of the theory that the kaolinizing agent was a solution of carbonic acid—possibly very weak, but at a high temperature—is afforded by china-stone. This rock has been defined by Mr. J. H. Collins[1] as intermediate in regard to decomposition between china-clay rock and hard granite. It is a granite that, though tourmaline may be absent from it, has lost, with some 60 per cent. of the potash of its felspar, the whole of its biotite; and what muscovite is present may, like the accompanying gilbertite, be regarded as a secondary, i. e. post-kaolinization product. As observed by Waldemar Lindgren,[2] biotite is unstable under the influence of solutions of carbon dioxide and alkaline carbonates, consequently the kaolinization during which the biotite and doubtless, after it, the original muscovite disappeared may have been the work of those agents. We have in addition the testimony of Prof. J. H. L. Vogt,[3] who rejects the theory of Daubrée,

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[1] J H. Collins, 'The Hensbarrow Granite District.' 1878, p. 31.

[2] W. Lindgren, in 'The Genesis of Ore-Deposits,' op. cit., 1902, 2nd edit., p. 530.

[3] J. H. L. Vogt, ibid., pp. 661–668.

adopted by Mr. J. H. Collins,[1] that kaolinization is due to solutions of fluo-silicates or fluo-borates. Prof. Vogt takes the view that very weak carbonic acid water can remove lime, magnesia, and alkalies, and produce kaolin, whereas water rich in dissolved alkaline and earthy carbonates favours carbonatization and sericitization. He cites the kaolinization of a labradorite-rock at Ekersund-Söggendal, south Norway, by carbonic acid, evidenced by the occasional occurrence of calcite with the kaolin, though most of the metals of the alkalies and alkaline earths have been removed (as soluble carbonates) with the dissolved silica. Noteworthy also are the observations of Mr. R. A. F. Penrose, Jun., in his masterly account of the geology of the Cripple Creek district,[2] to the effect that kaolinization is the result of the rise of heated water from greater or less depths, and that the removal or kaolinization of felspar is a process that might be effected simply by carbon dioxide and water. The conclusions of these two authors with respect to the metasomatic effects of carbon dioxide are quite in accordance with those arrived at by other observers.[3] Prof. C. Le Neve Foster[4] states that emanations of carbonic anhydride are not unknown in Cornwall.

We have, furthermore, evidence as regards the nature of the kaolinizing agent in certain accessory constituents of metasomatic derivatives of granite such as luxulyanite. Though pyrite scattered sporadically and in some abundance among their finer constituents is not characteristic of Cornish granites, luxulyanite and many similar aggregates show by the presence of numerous cubic haematite and limonite pseudomorphs in their groundmass, sometimes associated with residual kaolin, that crystals of that sulphide were freely developed within them. If we assume that these crystals, like those occurring everywhere with the china-clay of the Cripple Creek district,[5] were deposited by a kaolinizing solution, the probability is strong that carbon dioxide rather than any acid or other compound that would affect sulphide of iron occasioned the decomposition of the perished felspars. The evidence of two specimens from fresh-broken and unoxidized ground at Bedford United Mines, Devon, submitted to the Society—the one a much kaolinized fine-grained granite containing a fractured and altered felspar

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[1] J. H. Collins, Min. Mag., 1887, vol. vii, pp. 212–214.

[2] R. A. F. Penrose, 16th Ann. Rep. U. S. Geol. Surv., Pt. 2, 1895, p. 128 *et pass.*

[3] See Sir Charles Lyell, 'Principles of Geology,' 1867, vol. i, p. 413; G. P. Scrope, 'Volcanos,' 2nd edit., 1872, p. 152.

[4] C. Le Neve Foster, Trans. R. Geol. Soc. Cornwall, 1883, vol. x, p. 176.

[5] Penrose, loc. cit.

phenocryst with enclosed pyrite, the other a greisen with bright mispickel and pyrite—seems conclusive on this point. The occurrence in kaolin of secondary pyrite and marcasite, forming granules, nodules, or veins, is noted by H. Rösler.[1] C. W. Schmidt[2] shows that in Iceland solfataric action has followed on the eruption of liparite, so that magnetite has been converted by hydrogen sulphide into pyrite. According to A. de Lapparent,[3] the relatively acid extrusions are characterized by solfataric action and the basic by carboniferous emanations. With respect to the latter opinion, it is important to note a fact referred to by Signor Pietro Zezi,[4] that the first gaseous emanations of volcanoes, e.g. hydrochloric and sulphurous acids, give place as volcanic activity diminishes to hydrogen sulphide and carbonic acid, both abundant in the springs of Sujo and in the Acque Albule, near Tivoli. We may hence be permitted to surmise that the kaolinization of the West of England granites, if wrought by a solution of carbon dioxide containing hydrogen sulphide, is evidence of solfataric action, and was therefore an occurrence somewhat late during the consolidation of those rocks.

The theory that the chief agent besides water that effected the kaolinization of the West of England granites was carbon dioxide disengaged during the metasomatism, by siliceous or acid solutions, of deep-seated calcareous killas or, less probably, dolomite or limestone[5] receives some support from Sorby's discovery that sulphate of calcium and free hydrochloric and sulphuric acids are contained in the fluid of vesicles in the quartz of Cornish granites,[6] and from the presence of calcium sulphate in the lode-water of some Cornish mines.[7] The occurrence of calcite in lodes almost exclusively in the killas of the West of England, presumably owing to the leaching of calcium carbonate out of that rock by waters charged with carbon dioxide, is additional evidence in the same direction. Other relevant facts are the occurrence of pseudomorphs after datolite (a hydrated calcium boro-

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[1] H. Rösler, Neues Jahrb. Min., 1902, Beilage-Band xv, p. 276.

[2] C. W. Schmidt, Zeits. Deutsch. geol. Ges., 1885, vol. xxxvii, p. 739.

[3] A. de Lapparent, Bull. Soc. Géol. France, 1889, sér. 3, vol. xvii, pp. 286-287. Cf. J. W. Judd, Quart. Journ. Geol. Soc., 1890, vol. xlvi, pp. 368-369.

[4] P. Zezi, in 'The South Italian Volcanoes,' ed. by H. J. Johnston-Lavis, Naples, 1891, p. 83.

[5] On Cornish calcareous rocks, see H. T. De la Beche, 'Report on the Geology of Cornwall, &c.,' 1839, pp. 79-89, *et pass.*

[6] H. C. Sorby, Quart. Journ. Geol. Soc., 1858, vol. xiv, pp. 471 and 487.

[7] J. A. Phillips, Phil. Mag., 1871, ser. 4, vol. xlii, pp. 408-413.

silicate) at Haytor, of abundant scheelite (calcium tungstate) in the lodes of the Petertavy district, and of axinite (hydrogen calcium aluminium borosilicate) in altered killas in numerous Cornish localities, and also in the Okehampton district, notably at Belston mine, with lime-garnet.

As to the important part played by carbonic acid in the alteration of Cornish rocks there is abundant testimony in the carbonatization of igneous dikes, noted by De la Beche[1] and by J. A. Phillips.[2] Many of such rocks, like the calc-dolerite of Three Bridges, Lewannick, effervesce freely when treated with acid.

There appears to be good ground for regarding the action of hydrofluoric acid on West of England rocks as deep-seated rather than superficial. The view that this acid or some of its compounds took part in the metasomatism of rocks containing calcium carbonate consorts with the opinion that the liquids discovered in cavities in topaz (a fluoriferous and hydrated aluminium silicate) are certainly in part carbon dioxide. One may remark, however, that the unaltered condition of the granophyric granite of the Mourne Mts., Ireland, in which only the biotite shows noteworthy change, is against the supposition that either that or any other similar topaziferous rock was permeated by hydrofluoric acid. It seems, indeed, quite probable that fluor-spar in solution, and not that acid, was the source of the fluorine of the schorl and apatite and even of the topaz of the tourmalinized and greisenized West of England rocks. Daubrée[3] found that at Plombières hot springs arising in veins of fluor-spar had both deposited that mineral and, by action on bricks, formed near it crystals of apophyllite, which contains fluorine.

It appears indubitable, if the felspars of a tourmaline-granite be comparatively unaltered, that its magma evolved no free hydrofluoric acid at the time that its mica was being resolved into schorl. In the walls of fissures in the unmetamorphosed granite of Colkerrow quarry, Luxulyan, one finds large dark radiating crystals of tourmaline, and the same occur also upon the walls among the following grouped minerals:—quartz, orthoclase, albite, gilbertite (coating both orthoclase and tourmaline), lithia-mica, fluor-spar, apatite, lamellar calcite, and occasionally stilbite. The presence of the last three minerals contraindicates deposition with schorl from a hydrofluoric acid solution. On the other hand, we have in the occurrence together of the calci-

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[1] H. T. De la Beche, loc. cit., p. 88.

[2] J. A. Phillips, Quart. Journ. Geol. Soc., 1878, vol. xxxiv, pp. 477, 482-484.

[3] A. Daubrée, Quart. Journ. Geol. Soc., 1878, vol. xxxiv, pp. 73-74.

ferous mica gilbertite, of calcium fluoride, calcium phosphate and fluoride, calcium carbonate, and a hydrated silicate of calcium and aluminium colour for the contention that the fissures were supplied from some profound source of both fluorine and calcium. The acidic character of the felspars of Cornish granites does not favour the supposition that their decomposition provided the calcium, but it might fairly be urged that a considerable amount of that element could have been derived from the altered plagioclase and augite of the pre-granitic dolerite dikes.

It is perhaps by the occurrence of fluor-spar in the West of England—in china-stone, greisen, and mineral-lodes (those of the Holmbush and Hingston Down mines in particular)—that the best presumptive evidence is afforded of the metasomatism of deep-seated calcareous rocks by hydrofluoric acid or other fluorine compounds. Subsidiary testimony is the very common occurrence of apatite in china-stone, gilbertite-rock, schorl-rock (that of Roche especially), many dolerites, such as the Trevone intrusive near Padstow, in the lodes of various mines, Fowey Consols for example, and in coarse tourmaline-granite at Bovey Tracey.

That the appearance of fluor-spar was not till somewhat late in the metamorphism of the West of England rocks, that is, during a period of dekaolinization, formation of schorl-rock and greisen, and deposition of tinstone and wolframite, but before a final influx of silica, is in accordance with the hypothesis that, roughly stated, the following sequence of events took place :—

Decarbonization of deep-seated calcareous rocks by acid waters, and resultant kaolinization by evolved carbon dioxide and increased porosity of neighbouring granite—partial in china-stone ('petuntzyte', Collins), and complete in typical china-clay rock ('carclazyte', Collins), with some erosion of primary tourmaline. Continued change of the aforesaid decarbonized and partially metasomatized calcareous rocks, containing, possibly, wollastonite, by solutions of boric acid or borates and hydrofluosilicic acid. Formation of fluor-spar and discharge of borated waters containing it by various outlets. Consequent dekaolinization in some areas of china-clay rock, and concomitant formation of a second and abundant growth of usually acicular schorl, mainly anterior to the deposition of silica derived from kaolin and additional sources, and in other areas deposition of fluor-spar, and formation of secondary mica and gilbertite with little tourmalinization. In the peripheral parts of granite bosses, where the movement of mineralizing waters seems to have been exceptionally free, there was gradual development of much secondary mica and of topaz at the expense of kaolin, greisen resulting. Tinstone and wolframite seem to have been present in the dekaolinizing waters more especially at the period of final silicification of the metasomatized rocks.

The abundance of the supply of silica during the final stages of pneumatolysis in the West of England is well illustrated by the extraordinarily vesicular quartz-veins in connexion with some greisens and by the huge bulk of the matrix in proportion to its crystallized inclusions in the schorl-rock of Hornden Down. The evidence of the hornstone pseudomorphs after fluor-spar from Wheal Mary Ann, showing that the water bringing the silica acted as a solvent of the fluor-spar, warrants the suspicion that in trowlesworthite the spaces emptied of groundmass were occupied by fluor-spar before the advent of quartz, and that what, if any, erosion is visible where these two minerals are in contact was occasioned by the siliciferous fluid. Daubrée showed[1] that silica (hyalite) and fluor-spar were deposited at Plombières by one and the same hot spring. The conjecture that in trowlesworthite the fluor-spar crystallized out before the quartz is strengthened by the fact that another Devon rock, a fluor-quartz-felspar veinstone from Brookwood mine, Buckfastleigh, much resembling trowlesworthite in appearance, exhibits phenocrysts of fluor-spar replaced centrally by quartz.

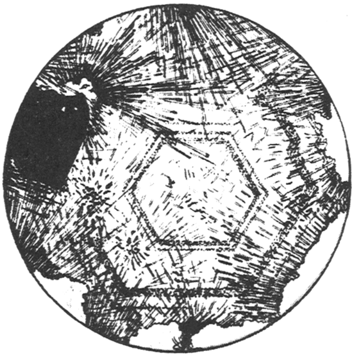

Fig. 3.—Zoned quartz with schorl; in luxulyanite.

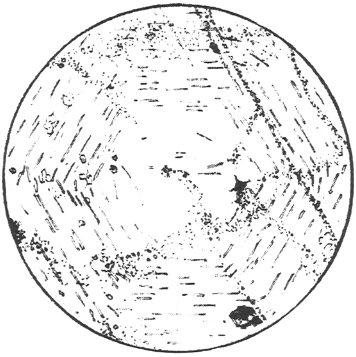

Fig. 4.—Vesicular quartz zoned by tourmaline microliths; in greisen: Gunnislake Clitters mine, Cornwall.

The removal of the groundmass of a granite, but not of its felspar

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[1] A. Daubrée, loc. cit., p. 74.

phenocrysts, may be well seen in specimens adjoining the greisen at Kit Hill, Cornwall (fig. 5). In these, secondary mica is the equivalent of the acicular schorl of luxulyanite and trowlesworthite.

Granted that kaolinization preceded the deposition of secondary schorl in luxulyanite, trowlesworthite, and various other tourmalinized rocks, including some greisens, and that mica was eliminated and more or less felspar was destroyed in this process, it is clearly unsafe to assume as certain that the brown and blue colours of tourmaline occurring therein are due to transmutation from biotite and felspar respectively.[1] When, as in the granite of Cligga Head,[2] as also in that of Gunnislake, and in the greisen of Gunnislake Clitters mine (fig. 4), pale blue tourmaline microliths occur in the quartz (exactly similar in their disposition lengthwise parallel to the edges of crystals) and brown tourmaline crystals in the groundmass, it seems permissible to conclude that the solution yielding the brown tourmaline obtained, when it destroyed the mica, all the available bases that would yield a brown tint. In the Leather Tor schorl-rock there occur with tourmaline crystals that are wholly blue others that are brown within and blue without, suggesting, in accordance with Scharizer's analyses, that the tendency of titanium, calcium, magnesium, and fluorine to go out of solution to form tourmaline is greater than that of aluminium and the alkali metals. The mode of growth seems to be strictly in keeping with that of felspars whose outer and inner zones differ in composition, and to be altogether analogous to that of orbicular diorite, in the magma of which the selection and the rejection of colouring material were carried on by hornblende and felspar respectively in concentric areas.

Against these views the evidence of the coloration of the tourmaline in a great variety of West of England rocks appears to be absolutely conclusive. In one Dartmoor granite are seen tourmaline crystals having a blue centre, but zoned with brown externally, and a brown centre within a blue coating.[3] A partly kaolinized granite from Treverbyn, St. Austell, contains tourmaline that is brown within and blue without and fringed with blue acicular crystals. Luxulyanite, moreover, which has been adduced as proof of the conversion of felspar

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[1] T. G. Bonney, Min. Mag., 1877, vol. i, pp. 216-217.

[2] J. B. Scrivenor, Quart. Journ. Geol. Soc., 1903, vol. lix, p. 151, and Mem. Geol. Surv. Eng. & Wales, Geol. of Newquay, 1906, p. 44.

[3] W. C. Brögger (Zeits. Kryst. Min., 1890, vol. xvi, p. 655) describes a tourmaline occurring in analcime and calcite at Langesundfjord, and showing, from within outwards, a blue nucleus, a deeper blue intermediate zone, and a brown marginal zone.

into blue schorl[1] may be ruled out of court if, as appears certain, kaolin was the origin of that mineral, most of the bases present in the schorl being supplied by the dekaolinizing fluid. Furthermore, examination of a series of microscopic sections of luxulyanite shows that the acicular schorl crystals not perched on the orthoclase phenocrysts or on the yellow eroded primary tourmaline, but arranged in tufts or spherules in the quartz, when viewed in their full length are both blue of various tints and pale brown. In some parts of a section opposed blue and brown tufts pass into one another; in others there is an approach to alternation of the two colours in groups of needles (sections of spherules), and many of the brownish groups are bluish at their origin. The distinctness of these colours might lead one to imagine that in a cooling menstruum two sets of microliths in a given area became pyroelectrically polar, and exercised a different selective action upon various dissolved bases. Fatal, however, to this notion appears the fact that, in places, some of the brown crystals viewed lengthwise and crossing others in the same plane at an obtuse angle give a blue tint where they intersect one another. The colours of the acicular schorl would seem, therefore, in this particular rock, to be considerably dependent on the absorptive and polarizing optic properties of the mineral, modified more or less by the nature and orientation of the medium, crystalline quartz, in which they are embedded. Doubtless the acicular crystals as a whole derived their aluminium from the kaolin of the groundmass as it was taken into solution. This opinion is strengthened by an examination of microscopic sections of the remarkable massive scoriaceous-looking tourmaline of Single Rose claywork, St. Austell, to the history of which it may be well here to devote a few words. In this clay-work, where crystallization of schorl in place of the dissolved quartz and felspar of the groundmass had given a fair amount of solidity to the metasomatized rock before the destruction of the orthoclase phenocrysts, the hollow moulds of these phenocrysts became eventually filled with granular quartz and a little disseminated schorl, as in the case of some of the orthoclase crystals in a rock resembling luxulyanite, near Letcha farm, south-west of St. Agnes.[2] When, however, dekaolinization was rapid, and the supply of boron and basic material was long-continued and abundant, i. e. not less than about three parts by weight to two of combined and free silica in solution, enormous aggregates of quartzless schorl, containing

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[1] T. G. Bonney, Min. Mag., 1877, vol. i, pp. 216-217.

[2] C. Le Neve Foster, Trans. R. Geol. Soc. Cornwall, 1887, vol. x, pp. 8 and 9.

kaolin entangled in its meshes, were formed in cavities caused by the gravitation of masses of dekaolinized and disintegrated china-clay rock. Portions of a single block of this schorl proved to be a full load for a large barrow. The schorl was manifestly formed from a solution of kaolin to which the dekaolinizing agent supplied bases other than alumina. In microscopic section it presents blue, orange, and deep to light-brown crystals of many degrees of tint, showing both a brown nucleus enveloped in a blue subsequent growth and the reverse. It would appear, therefore, that when tourmaline is growing in the presence of a variety of dissolved metallic bases each crystal clears the solution of those bases that are in its immediate proximity.

Decrease of bulk first by kaolinization and then by some degree of dekaolinization, greatest near the contact-zone, sufficiently explains the depressions of the surface of the country ('slads') over china-clay rock in the St. Austell district. Proof of movement of metamorphosed granite during solution of its kaolin and formation of schorl is furnished by specimens of schorlaceous partially kaolinized rock obtained from a well-sinking at Treverbyn. In this, owing to the setting up of new stresses by removal of support through dekaolinization, shifting and breakage of the partially altered orthoclase phenocrysts took place

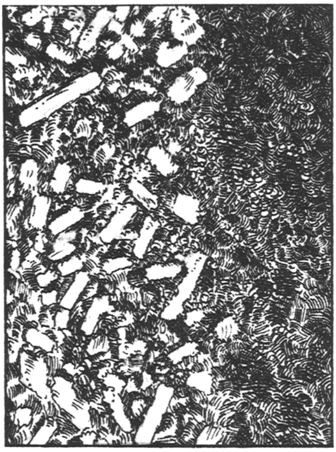

Fig. 5.—Granite with greisenized groundmass adjoining greisen: Kit Hill, Cornwall.

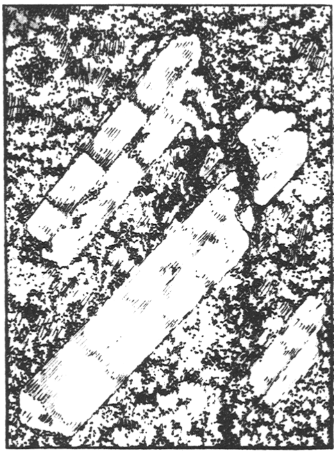

Fig. 6.—Shattered orthoclase in kaolinized schorlaceous granite: Treverbyn, Cornwall.

(fig. 6). To the imperfect substitution of dissolved kaolin by mica and secondary quartz and resultant gravitation under the pressure of superincumbent masses may, in like manner, be attributed schistosity in Zinnwald greisen. The causation of settlement, or creeps, in the course of lodes by action such as dekaolinization may account also for the remarkable contortion, like that caused in boulder-clay by the melting of buried ice, and the brecciation observable in the country-rock of many of the St. Agnes and other West of England mines, Wheal Gurlyn for example.

There seems to be no cogent evidence against the theory, as regards the granites of the West of England, that the alkaline constituents of felspar together with more or less nascent silica, besides, in many instances, the quartz of the groundmass, were carried by the kaolinizing solution completely out of the field of action when not converted into gilbertite, lithia-mica, and other by-products. If so, the kaolin obtained its bases for the construction of schorl from a metasomatizing borated fluid later in date than that by which kaolinization was effected. In this connexion it is interesting to note that Mr. R. A. F. Penrose, Jun.,[1] remarks concerning the veins in the Cripple Creek district that they occupy fissures formed after considerable alteration of the country-rock, and that it is not impossible that the earlier metasomatizing solutions, which acted everywhere throughout the district, differed somewhat in their contents from the later ones, which seem to have acted only locally.

As the statement is still occasionally made that the kaolin of commerce is the result of subaerial action, it may be advisable, in closing this paper, briefly to formulate sundry facts that negative this supposition.

1. The researches of Sorby among others with respect to vesicular quartz, which was formed both before and after kaolinization, show that the West of England granite and its pneumatolysed derivatives cooled and consolidated under enormous pressure of superincumbent rocks—according to his calculations that of 32,400 feet in the St. Austell district.[2] Observations in mines indicate the general absence of surface- or ground-water in rocks below moderate depths (something like 2,000 feet at most, and in some regions 500 feet), 'except in regions of expiring vulcanicity.'[3] Surface-water, even if it descended to great depths, would produce most alteration in superficial rocks. Now the

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[1] R. A. F. Penrose, loc. cit.

[2] H. C. Sorby, Quart. Journ. Geol. Soc., 1858, vol. xiv, p. 494.

[3] J. F. Kemp, loc. cit., pp. 696–702 and 709.

solid granitic overburden covering good china-clay rock is frequently very slightly kaolinized, the felspar phenocrysts presenting a normal appearance within when fractured, as in the Caudle Down and Higher Nine Stones clay-works. The kaolin improves in quality with depth from the surface, and has been worked in the St. Stephen's district at 40 fathoms below it.

2. There is no evidence of abnormal rainfall in kaolin districts. The local and, within a given area, irregular kaolinization of granite suggests its production by some local cause and not by general atmospheric agencies. Satisfactorily to maintain the argument that kaolin was produced by weathering in other British granitic regions, but was removed thence by glacial action, which did not affect Cornwall and Devon, necessitates the discovery of causes why much of the granite of those counties is unkaolinized and why kaolinized rock elsewhere, however deep, has been removed without leaving some remnants, even under crags facing down stream in the line of glacial flow.

3. A local and sufficient cause of kaolinization is known to exist in the ascent of heated solutions through the rocks of various districts, as, e.g. the rhyolites of the Yellowstone National Park.

4. Weathered granite, Rösler points out (loc. cit.), breaks up into imperfectly altered fragments ere final disintegration; also its groundmass felspars suffer from kaolinization before its phenocrysts, the reverse being true of granite kaolinized from below.

5. Kaolinization has been commonly accompanied or followed by the production of many minerals that could not have originated in surface-material—schorl, fluor-spar, tinstone, and topaz, among others.

It remains only to express the author's indebtedness to his friend, Mr. George Wilson, for his careful delineation of the structures shown in the figures accompanying this paper.