

On the MICROSCOPICAL STRUCTURE of CRYSTALS, indicating the ORIGIN of MINERALS and ROCKS. By H. C. SORBY, Esq., F.R.S., F.G.S., Corresponding Member of the Lyceum of Natural History of New York, and of the Academy of Natural Sciences of Philadelphia, &c.

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[PLATES XVI.—XIX.]

CONTENTS.

History of the Subject.

I. Structure of Artificial Crystals.

- § 1. Crystals formed from Solution in Water.
 - a. Mode of Preparation and Examination; general and special characters.
 - b. Number, size, form, and arrangement of Cavities.
 - c. Expansion of Fluids by Heat.
 - d. Effects of Pressure.
 - e. The Elastic Force of the Vapour of Water.
- § 2. Crystals formed by Sublimation.
- § 3. Crystals formed by Fusion.
- § 4. General Conclusions.

- § 2. Water contained in Crystals.
- § 3. Minerals contained in Secondary Rocks.
 - a. Rock-salt, Calcite, &c.
 - b. Quartz-veins.
- § 4. Metamorphic Rocks.
- § 5. Minerals and Rocks formed by cooling from a state of igneous fusion.
- § 6. Minerals and Rocks formed by the combined operation of Water and Igneous Fusion.
 - a. Minerals in the blocks ejected from Vesuvius.
 - b. Granitic Rocks.
 - c. Temperature and Pressure under which Granitic Rocks have been formed.

Description of the Plates.

II. Structure of Natural Crystals.

- § 1. Methods employed in examining Minerals and Rocks.

In this paper I shall attempt to prove that artificial and natural crystalline substances possess sufficiently characteristic structures to point out whether they were deposited from solution in water or crystallized from a mass in the state of igneous fusion; and also that in some cases an approximation may be made to the rate at, and the temperature and pressure under which they were formed.

History of the Subject.—The existence of cavities in quartz, topaz, and fluor-spar, containing fluid, has long been known. Mr. Sivright found them also in calcite, barytes, and selenite. Sir David Brewster discovered them in emerald, beryl, cymophane, peridot, felspar, and rock-salt, as well as in a number of crystals formed artificially. In his admirable paper in the 'Transactions of the Royal Society of Edinburgh' (1824, vol. x. pt. 1. p. 1), he remarks that, being persuaded that water thus mechanically enclosed will be found in every crystal deposited from solution, he was next desirous of finding it in crystals formed by heat or sublimation; but, in no case having been able to discover the slightest trace of its existence, he considered, in the absence of all other information on the subject, the result highly favourable to the supposition of the aqueous origin of all minerals in which cavities containing water had been discovered. No distinc-

tion, however, was made by the author between minerals occurring in veins, and those forming the constituents of rock-masses; so that in this paper, and others published subsequently (Trans. of Geol. Soc. vol. iii. p. 455, and of Roy. Soc. of Edinburgh, vol. x. pt. 2. p. 407, Ed. New Phil. Journ. April 1845, p. 386, Phil. Mag. vol. xxxi. Aug. 1847, p. 101, and vol. xxxiii. Jan. 1849, p. 489), though of the highest interest optically and physically, can scarcely be considered applications of the subject to pure geology.

In the 'Philosophical Transactions of the Royal Society' (1822, p. 367), Sir H. Davy described the experiments which he made to determine the nature of the fluid contained in the larger cavities of rock-crystal. He found that it was nearly pure water, and that the bubble along with it was either azote or a vacuum. In some cavities he found a kind of mineral oil or naphtha.

In his 'Note sur les émanations volcaniques et métallifères' (Bulletin de la Société Géologique de France, 2e série, t. iv. p. 1249), M. Elie de Beaumont alludes to the presence of cavities, with fluid, in quartz, as an argument in support of his views respecting the origin of granite. Similar remarks are also made by Bischoff (Chemical and Physical Geology, Cavendish Society's Translation, vol. ii. pp. 16 and 477) and by Scheerer (Discussion sur la nature plutonique du granite, Bull. Soc. Géol. de France, 2e sér. t. iv. p. 468); but they all treat the subject as if these cavities were comparatively rare. Such as are large enough to be distinctly visible to the naked eye are, indeed, rare; but when a high magnifying power is employed, it is easy to see that the proportion of many millions to a cubic inch is very common in some minerals.

Such, so far as I am aware, was the state of this subject when my attention was directed to it by examining the excellent collection of "fluid-cavities" in the possession of Mr. Alexander Bryson of Edinburgh, who told me he had found some in the granite of Aberdeen. I immediately perceived that the subject could not fail to lead to valuable results when applied to geological inquiries, and soon proved that my supposition was well founded. In my paper on the microscopical structure of mica-schist, read before the British Association at Cheltenham, I argued that "the vast number of fluid-cavities containing water indicates that the metamorphic changes have been due to an aqueous process and an elevated temperature, and not to heat alone and a simple partial fusion." (Report for 1856, Trans. Sect. p. 78.)

I. STRUCTURE OF ARTIFICIAL CRYSTALS.

§ 1. Crystals formed from solution in water.

a. Mode of preparation and examination; general and special characters.

Great and small are relative terms; and therefore it will be well to adopt a scale, so that the actual size of the cavities described by such terms may be known. Since a very common size is about $\frac{1}{1000}$ th of an inch in diameter, I shall adopt the following scale, and call

- Cavities above $\frac{1}{100}$ th of an inch in diameter, very large.
 „ from $\frac{1}{100}$ th to $\frac{1}{1000}$ th, moderately large.
 „ from $\frac{1}{1000}$ th to $\frac{1}{10000}$ th, moderately small.
 „ less than $\frac{1}{10000}$ th, very small.

In some respects it is best to mount crystals formed in the wet way, in as shallow glass cells as will hold them, in a concentrated cold solution of the salt itself; for then, never being dried, none of the cavities can lose their fluid, which is not the case if they are mounted in varnish or Canada balsam. Independent of that, some facts are seen to greater advantage when crystals are mounted in clear varnish in cells which may be made out of cardboard with a wadding-punch; and I therefore usually adopt both methods. The magnifying powers generally required are from 50 to 400 linear; and when the crystals possess strong double refraction, a polarizer or analyser should be used, so adjusted that only one image of the cavities is visible; or else they appear indistinct.

I have in nearly all cases lithographed the accompanying figures (Pls. XVI.—XIX.) as seen with one adjustment of the focus, but have slightly shaded the enclosed crystals, although they are sometimes quite colourless, in order to distinguish them from irregularities on the surface of the cavities. The figures with a dotted outline represent portions of crystals, whereas all the rest are entire crystals or detached cavities, as if the surrounding paper were the clear substance of the larger crystals in which they occur.

Few substances could be more suitable, as characteristic types, than the chlorides of sodium and potassium, sulphate and bichromate of potash, alum, and sulphate of zinc.

When a solution of chloride of potassium is allowed to evaporate spontaneously, the character and form of the crystals vary most remarkably, according as the weather is cold or warm, moist or dry. In cool damp weather, when evaporation goes on slowly, sometimes all the crystals are similar to fig. 1, having a square patch towards the centre, which is white by reflected, but black by transmitted light, whilst the rest of the crystal is clear and transparent. When much more highly magnified, it is seen that the opacity of the central portion is due to vast numbers of minute cavities, the amount of which varies in bands parallel to the sides of the crystal, and also in such a manner as to give rise to the peculiar cross seen in the figure. These cavities are full of the liquid from which the crystals were deposited; and this having a smaller power of refraction than the substance of the crystal, the contents reflect and strongly refract the light, and, like the bubbles of air in the water of a cataract, give a white appearance as seen by reflexion, or darkness and opacity when viewed by transmitted light.

The manner in which these cavities are formed is well illustrated by fig. 2, where the unshaded portion represents part of the extreme edge of a crystal of common salt, and the shaded the concentrated solution from which it crystallized, entering into a deep notch formed by the irregular growth of the crystal. If, on the further growth

of the crystal, more salt were to be deposited at the upper part of the notch than at the bottom, as shown by the dotted line, a portion of the liquid would be enclosed in the crystal, and form a fluid-cavity like that seen on the right-hand side; whereas, if the crystal grew so as to enclose the projecting portion of fluid by a plane parallel to the face of the crystal, a fluid-cavity like that on the left side would be produced. These two cavities, as well as figs. 3, 4, and 5, illustrate the usual character of those in common salt or chloride of potassium. When deep, they have a broad dark outline, like fig. 4; but when flat and very shallow, they are bounded by a narrow black line, as in fig. 5. Often they are much longer in one direction than in any other, so as to be tubes, like fig. 3; and this is especially the case in the long prismatic crystals of chloride of potassium sometimes formed on the cooling of a warm solution.

The manner in which the cavities are produced necessarily causes them to be *full of fluid* at the time of their formation. If this takes place at the ordinary temperature, and they are kept in fluid, they remain quite full, and none of the cavities contain bubbles. When, however, they are formed at a higher temperature, the fluid of course contracts on cooling, and, just as happens on the cooling of a glass-tube filled with hot water, a vacuity like a bubble makes its appearance, as shown in fig. 7. In order to obtain crystals slowly deposited at the heat of boiling water, I employ a flat-bottomed flask, over the mouth of which I tie a piece of blotting-paper, and keep it in a bath of boiling water, with the long neck projecting through a hole in a metal plate covering the bath.

For these experiments no substance is more convenient than common salt, because it is so very little more soluble in hot than in cold water. Having, then, a concentrated solution in the flask, it evaporates through the blotting-paper, and crystals are slowly deposited at the heat of boiling water. When a number of about $\frac{1}{30}$ th of an inch in diameter are formed, the hot solution is quickly poured off, and a small quantity of a concentrated cold solution added, so as to prevent the deposition of salt when the remaining solution becomes cold; and then, separating the larger and very small by means of sieves, the crystals of about $\frac{1}{30}$ th to $\frac{1}{50}$ th of an inch in diameter are mounted in glass cells in a concentrated solution of the salt. On examining them with the microscope, it is seen that the greater part of the cavities contain small bubbles, produced by the contraction of the fluid. Adopting the same method with chloride of potassium, in some cases most excellent thin flat crystals are formed, containing many very interesting cavities. A portion of one of these crystals is drawn in fig. 6, which serves to show the great number and peculiar form of the cavities, and how they occur in bands parallel to the edges of the crystal. Unlike when formed at the ordinary temperature, many of the cavities are of very complicated forms, as shown in figs. 8 and 10.

In order to ascertain the relative size of the fluid and bubbles in the cavities, it is best to measure with the micrometer such long re-

gular tubes as figs. 9 and 50. It may also be determined with sufficient accuracy from cavities like figs. 101 and 113, which are equally deep throughout, and have a flattened vacuity, so that the proportion between their *areas* is that between their *volumes*. If, however, neither of these kinds can be found, the best approximation that can be made is to be derived from such cavities as are nearly equiaxed, so that the relative magnitude of the cavity and vacuity equals the cube of the ratio of their diameters.

In the very excellent tubular cavity (fig. 9) in chloride of potassium formed at a heat not much below that of boiling water, the vacuity is about $\cdot 025$ of the fluid; but, if the cohesion of the sides produced no effect, it should have been about $\cdot 030$. Hence I think we must conclude that the cohesion of the liquid to the sides of so small a cavity slightly diminishes the size of the vacuity, either by stretching the fluid or the substance of the crystal. That very minute cavities do produce such an effect, is proved by the fact that they often contain no bubbles, as though the cohesive force entirely counteracted the contraction of the fluid, and operated like the reverse of a very great pressure; and M. Berthelot has also shown (*Annales de Chimie*, 3^e sér. t. xxx. p. 232) that this occurs to a certain extent, even in glass-tubes.

When fluid-cavities are large, the bubbles move about, if the crystal be turned, like those in spirit-levels; but when small, this test is not easily applied. We can readily see, with a high magnifying power, that the constant tremor of the ground causes the bubble in a level to be in constant motion; but no such movement can be seen in the larger fluid-cavities. In the very small, however, the bubbles move in a most striking manner, as if they were minute animalcules swimming about and exploring every part of the cavities. The true physical cause of this movement still remains to be determined; for hitherto I have not been able to form any theory that was not apparently upset by facts subsequently discovered. Whatever be the cause, the fact of the movement is of very great value in these inquiries, since, when a bubble moves about, the substance in the cavity must of course be a liquid.

The peculiarities of fluid-cavities formed when crystals are deposited from a solution containing some other salt, can be studied to great advantage by crystallizing common salt from a solution of bichromate of potash. If the solution be saturated with the bichromate at the ordinary temperature, it is of a deep yellow colour, and the fluid-cavities in the crystals of common salt deposited from it are seen to be filled with this yellow liquid; and the crystals are thus rendered yellow, and remain so when mounted in a colourless solution of common salt. If, however, the crystals be formed at the temperature of boiling water in a solution containing more of the bichromate than can remain dissolved at the ordinary temperature, small crystals of the deep red colour of that salt are deposited inside the fluid-cavities, as shown by figs. 11 and 12. When the solution is saturated at 100° C. with both common salt and the bichromate, so that, on slow evaporation at that temperature, crystals of both salts are deposited,

the common salt encloses some small crystals of the bichromate, like fig. 14. Occasionally these so interfere with the crystallization, that they give rise to small attached fluid-cavities, as seen on the right-hand side of fig. 15; or there may be more than one crystal and a larger fluid-cavity, like fig. 16. These fluid-cavities differ from those just described, in containing no small crystals of the bichromate, that which could not be retained in solution having been deposited on the larger preexisting crystals. Moreover, as shown by fig. 16, these enclosed crystals project beyond the general boundary-line of the fluid-cavities, whereas in the other case they are merely deposited on the surface of the cavities. Great numbers of that kind do also occur; and often so many crystals are deposited, that the cavity appears to be quite full of them, as shown by fig. 17. It is, however, well worthy of remark, that many of the smaller cavities remain for months full of a deep yellow liquid, which I have supposed to be represented by the shading in fig. 13, containing far more of the bichromate in solution than can be retained when in large quantities, as if these minute cavities exercised the same influence in preventing the deposition of crystals, that, according to Dr. Percy's and my own observations (Dec. 1857), minute tubes exercise in preventing the freezing of water until the temperature is much lower than that at which it freezes at once in larger tubes.

When, instead of bichromate of potash, chloride of potassium is employed, small cubic or rectangular crystals are deposited in the fluid-cavities of the common salt, as shown in figs. 18 and 19; and in every case that I have seen, their edges are all parallel to the rectangular planes of the cavities. If a concentrated solution of hydrochlorate of ammonia be used, the fluid-cavities in the common salt contain crystals of the salt of ammonia of a very rounded character, as shown by fig. 20, so as to appear like enclosed globules of a dense liquid.

These experiments (March 1858) therefore show that, when crystals are formed at an elevated temperature, evidence of it is afforded by the contraction of the fluid enclosed in the cavities giving rise to a vacuity, and the reduction of its solvent power causing the deposition of crystals. Since, of course, the amount of the contraction of the fluid depends upon the height of the temperature from which it has cooled, the relative size of the vacuity must indicate how much the temperature at which the crystals were formed was above that at which they are examined, in the same manner as the sinking of the mercury in a self-registering-maximum thermometer shows the difference in the temperature.

Figs. 21 & 22 in nitrate of potash, 23 in binoxalate of ammonia, 24 and 25 in sulphate of zinc, represent fluid-cavities of rather striking forms,—the shading in figs. 24 and 25 being like the appearance produced by planes inclined to the line of vision. In many substances the fluid-cavities are commonly in the form of tubes, which are often of irregular width, and, as it were, pass into rows of smaller, shorter cavities, as shown by fig. 26, representing a portion of alum. Some of the cavities in this salt are as shown in fig. 27;

but the more common forms are like figs. 28, 30, and 31. When deposited at a heat of 50° C. (122° F.), the cohesion of the sides is sufficient to entirely counteract the small amount of contraction, and prevents the formation of vacuities. Besides fluid-cavities, a few most interesting larger cavities full of air were formed, which appear as if they had been bubbles, given off from the solution, that were enclosed in the growing crystal. Small quantities of this air are also in some cases caught up in the fluid-cavities; so that a few contain bubbles of considerable size in proportion to that of the cavity. The difference between the cavities full of fluid and those full of air is most striking. The refractive power of the fluid being nearly the same as that of the crystal, the cavities containing it are almost invisible by reflected light, and give only a narrow outline by transmitted, whilst, the refractive power of the air being so much less, the cavities containing it shine brilliantly by reflected light, and by transmitted light have a very broad and dark outline, as shown by fig. 29.

Hitherto all my descriptions refer to crystals that were mounted in liquid and never dried. When, however, exposed for some time to dry air, it is as if some of the cavities were not so completely closed as to prevent the slow passage of liquid from them; and therefore bubbles make their appearance, gradually increasing in size, and becoming quite large, as shown by figs. 30 and 31, which are cavities in alum, originally quite full of fluid at the ordinary temperature. In the case of some crystals, especially those like alum, containing chemically combined water, perhaps the fluid may actually pass off through their solid substance; but this is apparently confined to cavities near the surface. In many crystals, however, and especially in the more solid parts, where the fluid has been completely shut up, it appears to remain nearly or quite permanently—at all events for many years—even when they have been kept quite dry. These facts must be carefully borne in mind when attempting to deduce the temperature at which crystals were formed; and care must be taken not to confound cavities that have lost some fluid by drying, with those in a normal state enclosing bubbles that have been produced by the contraction of the liquid on cooling. They may often be distinguished without much difficulty, because when fluid is lost there is a great inequality in the relative size of the bubbles in different cavities, whereas in the other case it is nearly uniform.

If the planes of a fluid-cavity are inclined at certain angles to the line of vision, they may totally reflect the transmitted light, and the cavity appear like a fragment of some black and opaque substance enclosed in the crystal. This is often the case in sulphate of potash; and an example from that salt is represented by fig. 33.

When a solution of common salt is evaporated at 100° C. in an open-mouthed flask, a crust is formed on the sides, above the level of the solution. In this case, during the growth, the crystalline crust is alternately exposed to the solution and the air; and when a portion is mounted in fluid and examined with the microscope, it is seen to have a peculiar and very interesting structure. Some of the cavities

are precisely like those formed below the level of the solution, whilst others are as if it had been partially evaporated in the cavities before they were finally enclosed in solid crystal; and therefore they contain much solid matter, as shown by fig. 37. Minute crystals of sulphate of lime are also enclosed in the solid crystal; and some have been deposited inside the fluid-cavities before they were finally shut up, as shown in fig. 36. Other cavities have caught up air as well as fluid, so that they contain very large bubbles, as shown in fig. 34; whilst in others, like fig. 35, there is no fluid;—these various kinds gradually passing into one another. In a similar manner when the solution of salt contains less bichromate of potash than can be held in solution at the ordinary temperature, there occur, in the crystalline crust, cavities like those in crystals formed below the level of the liquid when a dilute solution is employed, as well as like those when a saturated hot solution is used, on account of its becoming variously concentrated by drying on the surface of the crust.

b. Number, size, form, and arrangement of cavities.

There is generally a most intimate relation between the number of cavities in a crystal and the rate at which it was formed. This is well illustrated by the chlorides of sodium and potassium; for when very slowly deposited, they are transparent, and contain but few, whereas, when deposited more quickly, they are so full of cavities as to be very white and opaque. In some cases the deposition proceeds rapidly at first, and white opaque nuclei are formed; and afterwards it proceeds more slowly, and the exterior of the crystals is clear and transparent, as shown by fig. 1,—the change from opaque to transparent being either sudden or gradual, according to circumstances. This also usually happens when substances are crystallized by the cooling of a strong hot solution; for then deposition proceeds rapidly at first, but slowly towards the close of the process. Sulphate of potash, however, contains nearly as many cavities when formed slowly as when deposited quickly. There is also a considerable difference in the number of cavities in different salts, though formed under similar conditions. Thus, if solutions of alum and chloride of potassium be evaporated moderately quickly side by side at the ordinary temperature, the chloride of potassium contains so many cavities as to be perfectly white and opaque, whereas the alum contains very few, and is perfectly transparent. The same is the case when a mixed solution of common salt and alum is evaporated.

In general the size of the cavities varies inversely as their number; for when the crystals are slowly formed, they are larger, though less numerous, as shown to great advantage by the different parts of fig. 1. If the rate of growth be the same, crystals formed at a high temperature contain fewer and larger cavities than those formed at a lower.

When the sides of the cavities are definite and straight, they are planes of the crystal; and therefore there is a connexion between the

form of the crystal and that of the cavities. For example, in the cubic crystals of the chlorides of sodium and potassium they are rectangular, as seen in figs. 4, 17, & 19; and in the octahedral crystals of alum they are often equilateral triangles, like figs. 28 & 30; but, from forms thus essentially related to the planes of the crystals, they pass into all kinds of irregular shapes only slightly related, as shown in a remarkable manner by the cavities in chloride of potassium formed at 100° C. (figs. 8 & 10).

The arrangement of the cavities is also sometimes related to the form of the crystal, as shown in fig. 1; and bands parallel to the bounding edges are very common, being in fact lines of growth, probably indicating variations in the rate of deposition. In some cases they occur as bands of single cavities, twisting and curving about without any very definite connexion, as shown by fig. 32; or they are scattered promiscuously through the entire crystal.

c. Expansion of fluids by heat.

By the experiments described above, I have shown that, at the temperature at which they are formed, the fluid-cavities in crystals are full of the fluid, and that, if they be examined at a lower temperature, they contain vacancies, owing to the contraction of the fluid on cooling. Hence I think it is only reasonable to conclude that, provided the temperature were not known, it might be ascertained approximately by determining what increase of heat would be required to expand the fluid so as to fill the cavities. In some cases this can be learned by direct experiment; but generally it cannot, and we must have recourse to calculation. From the nature of the case the temperature is that required to cause the liquid to expand so much that the increase in volume is equal to the size of the vacuity. Taking, then, the volume of liquid for unity, and representing the relative sizes of the vacuity by V , it is easy to perceive that, if the law of the expansion of the liquid were known, and the value of V had been ascertained by observation, the temperature could be calculated.

In order to be able to do this, I have (June 1858) made an extensive series of experiments to ascertain the law of the expansion of water and saline solutions up to a temperature of 200° C. (392° F.). This I did by hermetically enclosing the liquid in strong glass tubes about 2 inches long and $\frac{1}{8}$ th of an inch internal diameter, and heating them in a bath of paraffine, with such arrangements that the increase in volume could be measured, by means of a micrometer microscope, to within the $\frac{1}{1000}$ th of an inch. This, however, is not the place for anything but the general conclusions. By appropriate experiments and calculations, I find that the increase in volume may be represented very accurately by an expression of the form $V = Bt + Ct^2$, where t is the temperature in degrees Centigrade, and B and C constants, the value of which depends upon the nature of the aqueous solution. Perhaps, indeed, in reality there may be terms involving higher powers of t than t^2 ; but if so, they are so nearly

compensated for by the unequal expansion of the mercury of the thermometer itself, by the expansion of the glass tube, or the compression of the liquid by the rapidly increasing tension of the vapour, that their value up to 200° C. is so small that they do not produce any clearly marked effect in the results. The action of water on glass at temperatures above 200° C. is so powerful that I was unable to determine the volume at a greater heat; but from 25° to 200° there is such a very close agreement between calculation and experiment that I think the formula would give sufficiently accurate approximations to the truth up to at least 300°. The law does not hold good near the freezing-point; but that is of no consequence in the present inquiry. The following are the actual values for water and various saline solutions, the volume at 0° C. being taken for unity:—

1. Water	$V = \cdot 0001344t + \cdot 000003245t^2$
2. " with 10 p. c. of chloride of potassium ..	$V = \cdot 0001868t + \cdot 000002524t^2$
3. " " 25 p. c. of chloride of potassium....	$V = \cdot 0003006t + \cdot 000001410t^2$
4. " " 12½ p. c. of chloride of potassium + 12½ p. c. of chloride of sodium..	} $V = \cdot 0003280t + \cdot 000001422t^2$
5. " " 25 p. c. of chloride of sodium.....	
6. " " 25 p. c. of sulphate of soda.....	$V = \cdot 0003077t + \cdot 000001644t^2$
7. " " 25 p. c. of mixed salts, being the mean of 3, 4, 5, & 6.....	} $V = \cdot 0003221t + \cdot 000001461t^2$

On examining this table, it will be seen that the addition of salts to the water increases the value of the coefficient of t , but decreases that of t^2 ; thus causing the expansion to be more uniform, by making it greater at low, and at the same time considerably less at high, temperatures. As far as I have been able to ascertain, the most trustworthy experiments indicate that the product of these coefficients is nearly constant, and that the increase in the value of the coefficient of t varies in simple proportion to the quantity of salt in the solution, the amount of water being taken as constant. Probably these laws are not strictly correct, but still sufficiently so to enable us to determine the effect of variation in the strength of the solution as accurately as is requisite for the purpose of the present paper.

d. Effects of pressure.

These conclusions of course apply to those cases where the pressure to which the liquid is exposed is only equal to the elastic force of the vapour; but since, in nature's laboratory, crystals have no doubt often been formed under very great pressure, it will be necessary to take into account the compression of the fluid. The amount of this has been determined with great accuracy by a number of observers (Gmelin's Handbook of Chemistry, Cavendish Society's Translation, vol. ii. p. 62); but I would particularly refer to the paper of M. Grassi (Annales de Chimie, t. xxxi. p. 437). He there shows that the amount of compression of pure water, for a pressure equal to one atmosphere, is $\cdot 0000502$, but decreases as the temperature increases. It is less for saline solutions, but increases as the tempera-

ture increases; being, for a concentrated solution of common salt, $\cdot0000379$. In the case of both pure water and saline solutions, the diminution of the volume is in simple and direct proportion to the pressure. Since, then, the amount of the compression of pure water decreases as the heat increases, but that of saline solutions increases, I think it extremely probable that, at very high temperatures, both would converge toward a similar amount; and, since it would be extremely difficult, or even perhaps impossible, to ascertain the fact by experiment at a very high temperature, we may adopt provisionally the mean of the two, as being probably not very far from the truth, especially in the case of moderately strong saline solutions. From this, however, must be deducted the amount of the compression of the crystal itself; and if it be the same as that of glass, we should have an apparent compression of $\cdot0000358$ for the pressure of each atmosphere, or $\cdot00000271$ for that of each foot of rock of sp. gr. 2.5, which I adopt as a unit because it seems more congenial with the subject before us. In accordance with this and other principles already described, the fluid about to be caught up in a fluid-cavity being expanded by the heat to $1 + V$, would have its volume reduced $(1 + V) \cdot 00000271$ for the pressure of each foot of rock. Therefore, when crystals are formed at a high temperature, under a pressure equal to p feet of rock, the real volume of the highly heated but compressed liquid, caught up so as to fill a cavity, would be $1 + V - (1 + V) \cdot 00000271 p$; and when cold and the pressure removed, as it must be when a vacuity has been formed, the size of the vacuity would be the difference between this and the volume of the fluid taken as unity, viz. $V - (1 + V) \cdot 00000271 p$.

e. The elastic force of the vapour of water.

This has been determined in a very satisfactory manner by Dulong and Arago (Quart. Journal of Science, Jan. to June 1830, p. 191); and they give an empirical formula, which they say is particularly applicable to high temperatures. Adopting this, and modifying it so that t represents single degrees above 0°C ., and e the elastic force expressed in feet of rock, we have $e = 13 \cdot 2 \{ 1 + \cdot 007153 (t - 100) \}^{\frac{1}{2}}$.

From the various facts described above, I deduce the following equations.

Adopting as units, for the temperature, degrees Centrigade; for the pressure, feet of rock of sp. gr. 2.5, so that 13.2 feet equal one atmosphere; and for the volume of the vacuities, that of the fluid in the cavities at 0° ,—

- If t = the temperature,
 p = the pressure beyond that equal to the elastic force of the vapour at t ,
 V = the relative size of the vacuity at 0°C ., corresponding to t , when $p = 0$,
 v = the relative size of the vacuity as *actually observed* liable to the influence of the pressure p ,
 e = the elastic force of the vapour of water at t .

B and C = two constants, whose values depend on the nature and strength of the saline solution in the cavity,

Then we have

$$V = Bt + Ct^2 \dots \dots \dots \text{equation (1)}$$

$$= \frac{v + \cdot 00000271p}{1 - \cdot 00000271p} \dots \dots \dots (2)$$

$$t = \frac{\sqrt{4CV + B^2} - B}{2C} \dots \dots \dots (3)$$

$$= \frac{\sqrt{4C \frac{v + \cdot 00000271p}{1 - \cdot 00000271p} + B^2} - B}{2C} \dots \dots \dots (4)$$

$$v = (Bt + Ct^2)(1 - \cdot 00000271p) - \cdot 00000271p \dots (5)$$

$$p = 369,000 \frac{V - v}{1 + V} \dots \dots \dots (6)$$

$$e = 13 \cdot 2 \{1 + \cdot 007153(t - 100)\}^5 \dots \dots \dots (7)$$

If $p = 0$, $v = V$.

These equations can be considered strictly accurate only for moderate values of t and p ; but for greater there must certainly be a limit past which they would cease to give accurate results. At present, however, it is impossible to say what that limit is; and therefore I think we cannot do better than adopt them provisionally.

It will be seen from (5) that the actual relative size of the vacuities depends on both the temperature and the pressure at which the cavities were formed. Therefore we have single equations involving two unknown quantities; so that, unless the value of one be known, that of the other cannot be determined. If the pressure were known, the temperature could be calculated from (4), and thus the fluid-cavities be made use of as self-registering thermometers, whilst, if the temperature or the value of V were known, the pressure could be calculated from (6), and thus the fluid-cavities be employed as spring-balances. They are, in fact, in this respect analogous to air-thermometers, which may be used as thermometers or barometers, according as the real pressure or temperature is known. If the actual pressure be known only approximately, but must have been the same for any two or more crystals having v different, the difference in the temperature could be calculated from (4); or, if the temperature were the same, and an approximation to the value of V known, the difference in the pressure could be ascertained from (6). I do not think there is any reason to believe that the actual size of the fluid-cavities can invalidate these general principles. Is not the proportion between the diameter and circumference of a circle the same, whether it is visible to the naked eye or cannot be seen without a high magnifying power? Similarly, since there appears to be no connexion between the actual quantity of fluid and the proportionate increase in the volume by heat or decrease by pressure, we

may, I think, as fully rely on the *ratios* deduced from the minute tubes enclosed in solid crystal, as from the larger tubes employed in our experiments. Sometimes, indeed, it is difficult to determine that ratio accurately; but very often a close approximation can be made by means of the microscope-micrometer, as already described.

§ 2. Crystals formed by sublimation.

In this case, if no fluid be present, of course no fluid-cavities can be formed; but irregularities in the growth of the crystals cause them to catch up gas or vapour, so as to form what may be conveniently distinguished by the names *gas-* or *vapour-cavities*. Such cavities are well seen in hydrochlorate of ammonia, as shown by fig. 38, or in corrosive sublimate, fig. 39. They are, in fact, like bubbles of more or less regular form, enclosed in the solid crystal, and differ from full fluid-cavities in having a broader and darker margin. If formed at a high temperature and under great pressure, since the enclosed highly compressed vapour might be condensed on cooling, the cavities might be covered with small crystals, or contain some liquid, according to the nature of the enclosed vapour.

§ 3. Crystals formed by fusion.

The formation of crystals from a state of igneous fusion is in every respect analogous to what takes place when crystals are formed in water. It is simply the deposition of crystals from solution in a liquid that becomes solid at a high temperature, or the crystallization of that liquid itself, in the same manner as when crystals are deposited from solution in water, or the water itself freezes. Nevertheless the temperature at which water and melted rocks become solid are so very different, that the two processes may be conveniently classed under different heads. It is quite inaccurate to suppose that the presence of water is essential in the formation of crystals; for, as every chemist well knows, many can be formed without a trace of water being present.

A glass is a liquid which, on cooling, becomes more and more viscous, and at length solidifies without undergoing any sudden and definite change in physical structure. If, however, the liquid, after cooling to a certain temperature, crystallize, it undergoes a sudden and entire physical change, and the structure becomes stony. In most cases the crystals thus formed possess double refraction, and therefore depolarize polarized light; whereas the uncrystalline glass has no more influence on it than such a liquid as stiff Canada balsam.

The best illustration I have met with of the characteristic structure of crystals formed artificially by the cooling of a heterogeneous mass in the state of igneous fusion, are the thin flat crystals of basic silicate of protoxide of iron, so common in the slags of copper- and nickel-ores. Their surfaces are covered with deep striæ; and when crystals sufficiently thin to be partially transparent are mounted in Canada balsam and examined with a microscope, it is seen that many such striæ have been covered up, so as to form tubular cavities

enclosing the material of the slag surrounding the crystals, as shown by fig. 40. In one part is a long, straight, open depression on the face of the crystal; and in another is a tubular cavity of varying width, enclosed in the solid crystal; whilst in other parts are smaller and shorter cavities, related to the larger in precisely the same manner as those occurring in alum, shown in fig. 26. When more highly magnified, some are seen to be as shown by figs. 41 and 42, which, in containing bubbles, closely resemble fluid-cavities. They were indeed *fluid-cavities* when first formed; but it was a fluid that did not remain *liquid* at the ordinary temperature, being in fact a *glass*. It of course appears more natural to call a space inside a crystal, containing only a gas or liquid, a *cavity*; but if it thus contain a solid glassy substance, since some convenient name is requisite, it appears to me that we cannot do better than adopt a term analogous to that so generally adopted for fluid-filled cavities, and call these glass-filled cavities *glass-cavities*.

The most characteristic difference between fluid-cavities and glass-cavities is the movement of the bubbles in the fluid-cavities; for of course bubbles cannot move in solid glass. However, since many of the bubbles in fluid-cavities do not move, we are sometimes compelled to have recourse to other tests. Strongly heating the crystal expels the fluid from fluid-cavities, but produces no effect on glass-cavities unless the heat be sufficient to melt the enclosed glass. They may also often be distinguished, without spoiling the object, by the difference in the relation between the dark exterior and transparent centre of the bubbles. The dark exterior is of course due to the refraction and total reflection of the light in passing through the bubble, which vary as the refractive power of the substance. Therefore, since that of the glass is considerably greater than that of the aqueous solutions in the fluid-cavities, the dark zone is considerably wider; and if the bubbles be spheres, the bright central spot, seen with a particular adjustment of the focus of the microscope, is relatively nearly twice as large in fluid-cavities as in glass-cavities.

Sometimes the glass-cavities in the basic silicate of iron contain crystals of a dark colour, that have been deposited from the glass on cooling, as shown by figs. 44 and 45, and are thus analogous to the fluid-cavities in crystals deposited from a strong hot solution of another salt. Others, like fig. 43, are analogous to those in which contemporaneously formed crystals were caught up along with the fluid, and project beyond the general outline of the cavity. In other cases they are entirely filled with the dark substance that became crystalline on cooling, as shown by fig. 46; and these, being stone-filled cavities, may be distinguished by the name of *stone-cavities*, in order to carry out the same general nomenclature. These are analogous to what cavities containing water would be if the ordinary temperature of the atmosphere was so low that the fluid froze, and the whole cavity was filled with minute crystals of ice and of any salt previously in solution in the water.

A few good glass-cavities occur in the crystals of Humboldtite,

so common in many slags of iron-furnaces, as shown by fig. 48; and in some crystals of pyroxene in the slag of the blast-furnaces at Masborough, good examples of stone-cavities are found, one of which is represented in fig. 47.

The connexion between the form of the crystals and that of the cavities is precisely the same in the case of glass- and stone-cavities as of fluid-cavities. Thus, in fig. 45, four, and in figs. 41 and 46 two straight sides are directly connected with planes of the crystals, whilst in figs. 42, 44, 47, and 48 they are curved and scarcely in any way related. There is thus a most perfect analogy between glass- and stone-cavities and fluid-cavities, in every respect except the nature of the included substances. These, however, differ from one another as much as the fusing-points of the liquids from which the crystals were deposited, and as the two processes of igneous fusion and aqueous solution; and are so essentially connected with those processes as to point out most clearly how the crystals were formed.

When a perfectly pure homogeneous substance crystallizes on cooling from a state of fusion, of course no cavities like those just described can be formed; but some substances in passing from the liquid to the solid state give off gas that was soluble in them when liquid, but cannot be dissolved by them when solid. This fact is well illustrated by the freezing of water, the bubbles enclosed in ice being gas-cavities produced in this manner by the cooling and solidification of a substance fusing at a low temperature. When heated to the melting-point, the ice thaws round about these cavities, as described by Dr. Tyndall (Proceedings of the Royal Society, vol. ix. p. 76); and they then contain both water and a bubble, like the fluid-cavities in crystals deposited from solution in water at an elevated temperature. It is, however, merely a deceptive *analogy*, without any true *affinity*. The real relationship is to what would in all probability occur if crystals formed by the cooling of a substance that becomes solid at a high temperature were heated to the point of fusion, when probably it would fuse first round about the few gas-cavities which such crystals often contain.

The most important result that could be produced by the operation of great pressure, in the formation of crystals by igneous fusion, is what might occur if it were so great as entirely to counteract the elastic force of the vapour of water, and permit it to be present in a liquid state along with the melted stony matter. It would be extremely difficult to prove by actual experiment what is the structure of crystals formed under such conditions; but I think the general principles derived from the experiments already described enable us to form a very satisfactory conclusion on the subject. Some crystals might be deposited from solution in the highly heated water, and catch up small portions of the fused stone, whilst others might be formed by the crystallization of the melted stone, and catch up small portions of the liquid water. In both cases the characteristic structure would be the presence in the same crystal of the peculiarities of crystals formed from a state of igneous fusion, combined with the peculiarities of those deposited from solution in water; and it might

be difficult, or even impossible, to decide which process was essential, or whether their combination was requisite for the production of any particular kind of crystal. When, therefore, formed under great pressure by the combined influence of liquid water and melted stone, we may, I think, conclude that the crystals would contain glass- or stone-cavities, and perhaps gas- and vapour-cavities, as well as fluid-cavities, the relative size of the vacuities depending on the temperature and pressure,—whilst both the fluid- and vapour-cavities might contain small crystals, deposited on cooling.

§ 4. *General Conclusions.*

The various facts described above will, I think, warrant the following general conclusions:—

1. Crystals possessing only cavities containing water more or less saturated with various salts were formed by being deposited from solution in water.
2. The relative size of the vacuities in normal fluid-cavities depends on the temperature and pressure at which the crystals were formed, and may in some cases be employed to determine the actual or relative temperature and pressure.
3. Crystals containing only glass- or stone-cavities were formed by being deposited from a substance in the state of igneous fusion.
4. Crystals containing only gas- or vapour-cavities were formed by sublimation or by the solidification of a fused homogeneous substance, unless they are fluid-cavities that have lost all their fluid.
5. Other circumstances being the same, crystals containing few cavities were formed more slowly than those containing more.
6. Crystals possessing fluid-cavities containing a variable amount of crystals, and gradually passing into gas-cavities, were formed under the alternate presence of the liquid and a gas.
7. Crystals in which are found both cavities containing water and cavities containing glass or stone were formed, under great pressure, by the combined action of igneous fusion and water.
8. Crystals having the characters of 6 and 7 combined were formed, under great pressure, by the united action of igneous fusion and water alternating with vapour or a gas, so as to include all the conditions of igneous fusion, aqueous solution, and gaseous sublimation.

Such then are the general principles I purpose to apply in investigating the origin of minerals and rocks. It will be perceived at once that, in one way or other, they may be brought to bear on almost every branch of physical and chemical geology. In this communication I shall illustrate the subject by applying them to some of the leading branches of inquiry, without attempting to treat each in a complete manner.

II. STRUCTURE OF NATURAL CRYSTALS.

§ 1. *Methods employed in examining minerals and rocks.*

In examining the microscopical structure of rocks and minerals, I have in many cases prepared sections sufficiently thin to admit of

the use of transmitted light with very high magnifying powers, for which purpose they should be from about $\frac{1}{100}$ th to $\frac{1}{1000}$ th of an inch thick. I here particularly draw attention to the necessity of not using any *polishing powder*, because it enters into, and fills up, cavities and flaws, and would easily give rise to factitious appearances that might mislead most fatally. This must be carefully borne in mind when the manner in which a section has been prepared is not known; for otherwise it might be worse than useless. The surfaces of the rock or mineral should be dressed extremely fine, with water, on a perfectly flat piece of very hard and smooth Water-of-Ayr stone, when they usually become quite sufficiently polished. One side of the section is of course fixed on glass with Canada balsam before it is rubbed down very thin; and when finished, thin glass should be mounted over the upper surface with the same substance. This not only preserves the object from injury, but has the most important effect of rendering it far more clear and transparent. In many cases, however, it is unnecessary to prepare such sections. Portions of the mineral can be broken off sufficiently thin, and when mounted under glass in Canada balsam can be most readily examined with high magnifying powers. This method has not only the advantage of saving much time, but, there being no necessity for a strong heat, the risk of expelling the fluid from the fluid-cavities is obviated. For some purposes, however, thin sections are quite indispensable; and in mounting them care should be taken not to employ a higher temperature than is absolutely necessary.

For the examination of mounted fragments, I have found Messrs. Smith and Beck's $\frac{1}{4}$ th-inch object-glass of very great value on account of not approaching the object too closely; and by using along with this their second eye-piece with a micrometer, the size of anything can be measured at once. This is the power I have chiefly employed, and is about 400 linear; the divisions of the micrometer are $\frac{1}{8000}$ th of an inch; and thus cavities much less than that are quite distinct, their contents are easily seen, and their dimensions and that of the vacuity can be measured to within $\frac{1}{8000}$ th of an inch.

§ 2. *Water contained in crystals.*

The difference between the water *mechanically enclosed* in the fluid-cavities of a crystal, and that *chemically combined* with the substance of which it is composed, is of course most complete. That, chemically combined is one of the essential constituents of the mineral, cannot be seen with any kind of magnifying power, and is probably not in the state of liquid water; whereas that in the fluid-cavities is altogether unessential to the existence of the substance, and is in the form of a visible liquid, merely enclosed mechanically.

When a mineral contains fluid-cavities, of course it does not necessarily follow that the fluid is *water*; and it is often difficult to ascertain what it is when *in* the cavities. If, however, the mineral contains no chemically combined water, it is easy to prove what it is when *out* of the cavities. On applying a strong heat, the expansion of the

fluid, or the elastic force of the vapour, bursts the cavity and often causes the crystal to fly to pieces with great violence. When subsequently examined with the microscope, it is seen that the fluid has been expelled; and in order to ascertain whether or not the fluid thus given off is water, I adopt the following method. I have a glass tube 8 inches long and with a $\frac{1}{4}$ -inch bore, closed at one end; and, having placed in it fragments of the mineral dried at 100° C., I fill the tube with air dried by passing over chloride of calcium. The open end is then closed with a well-dried cork, and the other passed through two holes in the opposite sides of a small box containing a mixture of pounded ice or snow and salt, so as to project about a couple of inches. A sufficiently strong heat is then applied to the closed end, containing the fragments, to expel the fluid from the cavities. If they contained water, it is condensed as small crystals of ice on the cold part of the tube; and when the whole has cooled, it is withdrawn from the box and placed in a strong solution of common salt, at a temperature several degrees below the freezing-point of water, and the form of the enclosed crystals examined with a magnifying glass. By carefully noticing the rise of a thermometer as the solution of salt becomes warmer, the temperature at which they cease to be solid and pass into a liquid is easily ascertained; and if it be found that the crystalline form and melting-point of the liquid thus given off from the fluid-cavities are the same as those of water, I think we may safely conclude that the liquid seen in the cavities is *water* or some *aqueous* solution.

§ 3. Minerals contained in Secondary Rocks.

a. Rock-Salt, Calcite, &c.

In proceeding now to apply the above general conclusions to the investigation of the circumstances under which natural crystals were formed, it will be best to commence with rock-salt, since its peculiar structure can be imitated artificially with perfect accuracy. It often contains excellent fluid-cavities, which, besides a fluid, sometimes enclose a variable, and often a considerable, quantity of mud. On the whole, the specimens I have examined do not contain much of this substance; and in the solid parts of the crystals the cavities are full of liquid. Hence the salt must have been deposited very slowly from solution in more or less muddy water, at a heat not very considerably, if at all, higher than the ordinary temperature of the atmosphere, unless it was formed under a very great pressure. Much the same conclusions apply to the selenite in gypseous marls; but most of the cavities have lost fluid by drying,—which need not surprise us, since it contains combined water and has a very laminar structure.

When pure calcite containing no fluid-cavities is heated, it does not decrepitate, and gives off no water; but when it contains fluid-cavities, the crystals fly to pieces and give off water, and I therefore conclude that the fluid in the cavities is water. I have found many excellent fluid-cavities in the calcite of modern tufaceous deposits, in

that of the veins in limestone, and in many trappean rocks ; also in fluor spar, in the sulphates of baryta and strontia, and in several other minerals found in ordinary veins, as if they had been deposited from solution in water. In most of the cases I have examined, the vacuities in the normal fluid-cavities are very small ; and, unless they were formed under great pressure, the temperature must have varied from that of the atmosphere up to about that of boiling water. Much, however, remains to be determined ; and the variations in temperature have too local a connexion to be considered in this paper.

b. Quartz-veins.

Since the facts to be learned from the study of the fluid-cavities in quartz are extremely interesting, I must describe them in some detail. As is well known, they are occasionally of considerable size, so as to be perfectly visible to the naked eye, and contain bubbles that move about like those in spirit-levels. The fluid contained in them was proved by Sir H. Davy (Philosophical Transactions, 1822, p. 367) to be nearly pure water ; and my own experiments confirm that conclusion. I froze the fluid in a cavity about $\frac{1}{4}$ th of an inch in diameter in a transparent crystal, and found that it thawed exactly at the thawing-point of ice. When clear quartz containing no fluid-cavities is heated in a tube, no water is given off ; but that with fluid-cavities gives off a fluid condensing, at a low temperature, into crystals whose form and thawing-point are the same as those of ice. Besides this water, there is often another substance given off, which condenses as a solid nearer to the hot end of the tube than where the water is deposited. I have ascertained that this is chloride of potassium or sodium. The water also often has a strong acid-reaction, due to hydrochloric acid, either derived from the decomposition of the above-named salts by the heated quartz, or, as is certainly the case in some instances, existing in a free state in the fluid-cavities.

In order to ascertain the nature of the salts dissolved in the fluid in the cavities, I reduce the carefully-washed crystals to powder, so as to break open the cavities, and then dissolve out the soluble salts with distilled water. When rendered quite clear by filtering and standing for some days, on evaporating this solution to dryness, the nature of the salts can be ascertained by the microscope and appropriate chemical tests. In this manner I have found (July, 1858) that the fluid in the cavities often contains a very considerable quantity of the chlorides of potassium and sodium, the sulphates of potash, soda, and lime, and sometimes free acids. This explains why I was not able to freeze the fluid in some rock-crystal from Ceylon, containing very excellent fluid-cavities of about $\frac{1}{100}$ th of an inch in diameter, at a temperature of about -20° C. (-4° F.); for though, according to my own observations, pure water in tubes less than $\frac{1}{300}$ th of an inch in diameter does not freeze till the temperature is reduced to about -15° C. (3° F.), it freezes at once at that temperature in those of the diameter of these fluid-cavities. It also serves to explain the amount of expansion by heat. I had ascertained from most ex-

cellent data, that the vacuities were uniformly very nearly $\cdot 141$ of the enclosed liquid at 0°C .; and therefore, calculating from the results of my experiments, if the fluid had been pure water, it would have expanded so as to fill the cavities at 189°C . However, on heating a portion of the quartz in a bath of paraffine, so arranged that it could be examined with the microscope, I found that at 217°C . very minute bubbles were still visible in the fluid-cavities; but at 220° they had most certainly disappeared. We may therefore conclude that the fluid expands so as to fill the cavities at a temperature of from 218° to 219° . On reducing some of the crystal to powder, I obtained so much of alkaline chlorides and sulphates that I do not think they could amount to less than 15 per cent. of the fluid in the cavities. They could not amount to above 30 per cent.; or else crystals would have been deposited in the cavities. If in equation (3) we substitute the values of B and C, previously determined for a solution containing 25 per cent. of mixed alkaline chlorides and sulphates, we obtain

$$t = \sqrt{684462V + 12144} - 110 \dots \dots \text{equation (8)}$$

and substituting in this the value, $V = \cdot 141$, we find $t = 219^{\circ}\cdot 4$. Calculating from the laws of the variation due to a difference in the amount of salt in solution, if less or more than 25 per cent., the value of t would be reduced; so that, if 20 or 30 per cent., it would be 218° . If therefore, as is probable, the fluid in the cavities is a strong solution, the temperature determined by calculation almost exactly agrees with that previously ascertained by actual experiment. It is seldom that the size of the cavities is sufficiently large to enable me to verify my calculations in this manner; for the experiment cannot be made when very high magnifying powers are requisite; but the agreement in this case is so remarkable as to cause me to have very considerable confidence in those that cannot thus be verified.

Equation (8) of course gives the temperature requisite to expand the fluid so as to fill the cavity, and does not indicate the temperature at which the crystal was formed, unless the pressure was only equal to the elastic force of the vapour. This true temperature is expressed by substituting the value of V given by equation (2), in (8), when we obtain

$$t = \sqrt{684462 \frac{v + \cdot 00000271p}{1 - \cdot 00000271p} + 12144} - 110 \dots \dots \text{equation (9)}$$

which, of course, becomes (8) when $p = 0$.

Some quartz contains cavities enclosing two immiscible fluids, like those occurring in Brazilian topaz, described by Sir David Brewster (Transactions of the Royal Society of Edinburgh, vol. x. pp. 1 and 407). Since, however, their peculiarities have been so well explained by him, and they occur so rarely in quartz as to be quite an exception to the general rule, I need not do more than refer to fig. 52 as an illustration of their general character. They appear as if they contained two bubbles, one inside the other, owing to the fluid which has a less refractive power containing a bubble, and collecting itself

into a globular form. Since the bubble moves about in the central fluid, and this also moves in the exterior fluid, both must be liquids; and I very strongly suspect that further research will prove that one is water and the other a condensed gas.

In determining the relative size of the vacuities in fluid-cavities, of course, care must be taken not to make use of such as have caught up bubbles of gas along with the fluid, which is more likely to happen with large cavities than with small. There is also a greater risk of the large coming across flaws in the crystal, so as to lose fluid. The very minute should, however, be avoided, as being too much affected by the cohesion of the liquid to the sides. It is therefore best to select those of moderate size, which have vacuities of very uniform relative magnitude, in parts where vapour- or gas-cavities do not occur and the crystal is very solid. Sometimes we may distinctly see that the quartz has been cracked, and the cracks afterwards filled up with quartz. This, like the formation of the large veins described below, appears in some cases to have taken place at a lower temperature, and explains why bands of cavities occasionally occur with vacuities relatively less than those in the fluid-cavities of the general mass. As already mentioned, whenever it is possible, such tubular cavities should be chosen as that represented by fig. 50.

In the trachyte of Ponza there occur veins of quartz, as described by Scrope (Transactions of the Geol. Soc. 2nd ser. vol. ii. p. 208). These contain many fluid-cavities with water holding in solution the chlorides of potassium and sodium, the sulphates of potash, soda, and lime, and free hydrochloric acid. In this case we may, I think, conclude that the pressure was not very great, so that $v=V$, and the relative size of the vacuities would indicate the temperature at which the crystals were deposited from the aqueous solution. The mean of many good observations is $v=.143$, which, when substituted in equation (8), gives $t=$ about 220° C. (428° F.). At this temperature the elastic force of the vapour of water is, from (7), equal to 292 feet of rock.

The quartz of the veins in Cornwall has precisely the same structure as the above in every respect; the fluid-cavities contain the same salts in solution; and at a great distance from the granite, making no allowance for pressure, the relative size of the vacuities indicates the same temperature, but if the pressure was great, a still higher. On approaching the granite, the temperature and pressure appear to have been much greater; for the relative size of the vacuities in the fluid-cavities in the quartz of the veins is nearly the same as in those in that of the granite itself. Thus, the mean of the means for the quartz of the granite at St. Michael's Mount and Mousehole is $v=.148$, and for the quartz of the associated quartz-veins, also containing mica, tin-ore, wolfram, and other minerals, $v=.133$. In cases like this, I think we may consider the pressure equal for both, so that the *difference* of the temperature may be calculated by means of equation (9). If the pressure was no greater than the elastic force of the vapour, these facts indicate that the quartz of the veins crystallized at a temperature not more than

16° C. lower than that at which the quartz of the granite itself crystallized; but, as I shall show below, it is far more probable that the pressure was very great, and the temperature a dull red heat visible in the dark, and, if so, substituting in (9) the value, $p=43,100$, deduced from equation (10), given further on, I calculate by equation (9) that the difference in the temperature must have been about 13°. These results clearly show that a great variation in the actual temperature and pressure produces only a small variation in the calculated *difference* in temperature. Perhaps some may think such calculations an impossible refinement; but the facts appear sufficiently distinct to warrant them. In a similar manner I find that the quartz first deposited in a vein in granite at Camborne indicates a temperature quite equal to that at which the granite crystallized; but in the quartz deposited towards the close of the process the relative size of the vacuities is so much less that the temperature must have fallen fully 30° or 40° C., which is quite probable.

The number of the fluid-cavities in the quartz of veins is often very great, as if it had been deposited rapidly. They are frequently on an average less than $\frac{1}{1000}$ th of an inch apart, which corresponds to upwards of a thousand millions in a cubic inch; and they are the chief cause of the very usual whiteness of the mineral. As an illustration of their forms, I refer to figs. 49, 50, and 51. Fig. 49 is of very irregular shape, whilst fig. 50 is a tube extremely well fitted for determining the relative size of the vacuity with great accuracy. Clear and transparent crystals contain few or none, as if deposited far more slowly; and very often crystals, which at their base are white and opaque on account of the number of cavities, are clear and transparent at their extremities from containing very few, as though, like what so very commonly happens in making artificial crystals, deposition proceeded rapidly at first, but much more slowly towards the close of the process. The form and arrangement of the fluid-cavities are also in every respect analogous to those in crystals prepared artificially; and every peculiarity in the structure of the quartz of veins, and their relation to the granite, can be most completely explained by supposing that it was deposited from water holding various salts and acids in solution, at a temperature varying from about 200° C. to a dull red heat visible in the dark. In those cases where we must suppose a very high temperature and a great pressure in order to explain the relation between the fluid-cavities in the quartz of the veins and in that of the granite itself, such other minerals as mica, felspar, and tin-ore were often deposited, especially towards the commencement of the process, as if water at a very high temperature were the effective cause of their production. Tin-ore contains many excellent fluid-cavities, though they are usually very small*.

Of course these conclusions do not apply to all quartz, for, as I have shown, some must have been deposited from nearly pure water;

* These deductions are strongly confirmed by the fact, that several of the above-named minerals have been formed artificially by the action of water at temperatures similar to those just described.—Senarmont, Ann. de Chimie, 3^e sér. t. xxxii. p. 129; Daubrée, Ann. des Mines, 5^e sér. t. xii. p. 289.—Oct. 1858.

and that associated with chalcedony in veins or in cavities contains very few fluid-cavities with relatively small vacuities, indicating a slow deposition from water at a much lower temperature.

§ 4. *Metamorphic Rocks.*

In some portions of the granite containing large crystals of felspar at Trevalgan, near St. Ives, Cornwall, the felspar has been more or less completely removed, and its place filled with quartz, mica, or schorl, either alone or variously mixed. These most interesting and important pseudomorphs appear to have been almost entirely overlooked; though I have found them in so many other localities in Cornwall that they cannot be very rare. The removal of the felspar from the centre of the surrounding, fine-grained granite, and the introduction of the quartz, mica, and schorl, cannot I think be explained except by the action of water. In this quartz are many very interesting fluid-cavities, and in some parts nearly all contain small cubic crystals, as shown by fig. 53. In other cases, besides such cubes, there occur prismatic crystals, like in fig. 55, or more rarely rhombic, as fig. 54. Occasionally the angles of the cubic crystals are corroded and rounded, as shown by fig. 55; and some cavities, as fig. 56, are so full of crystals that their form cannot be determined. The quartz also contains gas- or vapour-cavities, and every connecting link between them and the other cavities. In all respects therefore the structure of this quartz is analogous to those crystals that are formed artificially above the surface of a hot liquid, and exposed alternately to water and air. When reduced to powder, water dissolves out much chloride of sodium, and a good deal of sulphate of lime, and hence the cubic crystals in the fluid-cavities are no doubt chloride of sodium, and perhaps some of the prisms may be selenite. Even if the effects of pressure are supposed to have been not material, the relative size of the vacuities indicates a heat of 220° C.; but, since the relative size of those in the fluid-cavities in the granite is nearly the same, in accordance with the principles described below, the pressure was probably very great, and the temperature nearly or quite equal to a dull red heat, visible in the dark.

It therefore appears, that to the action of water at a very high temperature, holding various salts in solution, must be ascribed the removal of the felspar, and the production of the mica, quartz, and schorl. In a paper read at the British Association (Report, 1857, p. 92), I showed that the material of the quartz and mica might be derived from felspar, decomposed by the removal of part of the alkaline bases; and we thus have a key to those cases of metamorphosis where deposits of decomposed felspar-clays have been converted into crystallized mica and quartz, so as to constitute mica-schist. In the bands of quartz in mica-schist and gneiss, which are as it were irregular concretions passing along the foliation, and in the carbonate of lime and iron sometimes associated with the quartz, occur vast numbers of fluid-cavities containing water. The quartz mixed up with the mica, forming the chief constituent of the schist, also abounds with fluid-cavities; and I have even found them in some of the

garnets. These facts led me to argue, in my paper on mica-schist already referred to (Report of British Association, 1856, p. 78), that the alteration of deposits of decomposed felspar into crystallized mica and quartz was not the effect of dry heat and a partial fusion, but was due to highly heated water disseminated through the rock. If so, it is no wonder that ordinary shales have never been converted into mica-schist artificially, by the mere heat of furnaces, since the conditions are not those met with in nature—water is absent.

The mean relative size of the vacuities in the fluid-cavities in the quartz of the slightly metamorphosed schists in Cornwall, at a considerable distance from the granite, is $\cdot 125$, which corresponds to a heat of at least 200° C. (392° F.); and therefore a considerable thickness of rock must have been raised to a high temperature. If the pressure was great, the temperature must have been still higher; and on approaching the granite, the relative size of the vacuities indicates nearly as high a temperature as that at which the granite itself was consolidated, which agrees with the gradual passage from gneiss to granite, and might be used as a strong argument by those who contend that some granites are only thoroughly metamorphosed stratified rocks. The vacuities in the fluid-cavities in the mica-schist of the southern border of the Highlands of Scotland are relatively so small ($v = \cdot 05$) that, if they were formed under no great pressure, they indicate a temperature of only 105° C. (221° F.). It, however, appears to me far more probable that the heat was really as high as in the case of analogous rocks in Cornwall, but the pressure greater. If so, from equation (6) we deduce that the Highland rocks were metamorphosed under a pressure equal to about 23,700 feet of rock more than those in Cornwall, or probably when at a much greater depth from the surface; a result which is confirmed in a most remarkable manner by a comparison of the fluid-cavities in the elvans and granites. These conclusions only apply to when the quartz crystallized: it does not follow that the rock was never heated to a still higher temperature.

§ 5. *Minerals and rocks formed by cooling from a state of igneous fusion.*

The most instructive glass-cavities that I have met with in natural minerals are those in the crystals of clear, transparent felspar contained in some of the pitchstone of Arran. Pitchstone, like obsidian and some artificial slags, consists of a glassy base, having no action on polarized light, in which are scattered small crystals that decompose it and show colours. The basis of the pitchstone surrounding the crystals of felspar is transparent, and nearly colourless, but contains vast numbers of minute, green, prismatic crystals, probably some variety of pyroxene, often arranged in radiate groups, which impart a deep green colour to the rock. These may be seen to great advantage in thin splinters, but the glass-cavities in the felspar can be studied to far greater advantage in thin sections of the rock. The surfaces of the crystals of felspar are in some cases irregular,

and portions of the surrounding pitchstone project right into them. Such projecting portions of the glassy basis have often become enclosed in the solid crystal, in precisely the same manner as the fluid-cavities in crystals formed from solution in water, as shown by fig. 2. Fig. 57 is a very good example of one of the larger of these glass-cavities. The centre is full of glass, precisely like the general basis of the pitchstone, except that the groups of green crystals are not so large and well developed, whilst somewhat larger prisms than those in the centre are attached to the sides, as if deposited during the cooling of the glassy solvent. The accompanying bubble is no doubt the effect of the contraction of the glass before it became solid. Fig. 58 is an example of a smaller cavity, having all the green crystals attached to the sides. It also contains several bubbles, which is a fact very characteristic of glass-cavities, since it never occurs in fluid-cavities, except under very peculiar circumstances, seldom met with. A common kind of cavity is shown by fig. 62; but the very smallest of all contain no green crystals, like fig. 60, corresponding therefore to those very small fluid-cavities in which crystals have not been deposited from a supersaturated solution. Fig. 61 is a case where the bubble has been much distorted, and crystals project from the sides quite into it, proving that the crystals were deposited before the glass became solid. Besides these glass cavities, the felspar has caught up small, colourless, contemporaneously-formed, prismatic crystals, to which in some cases glass-cavities are attached. A very excellent example of these is shown by fig. 59; and it is a striking fact, that very nearly all the green, prismatic crystals have been deposited on the included large crystal. The felspar also contains bands of vapour-cavities, and it is near to them that cavities with several bubbles occur; but, at a distance from them, the glass-cavities almost always, if not invariably, contain a bubble from $\frac{1}{4}$ th to $\frac{1}{2}$ th the diameter of the cavity. In some cases, however, there are cavities like fig. 63, which do not contain the prismatic crystals or a bubble, being more like stone-cavities.

In the pitchstone are also some dark crystals, not visible except in sections, which look extremely like augite. The glass-cavities in these do not contain the green crystals; and if the two minerals are the same substance, this fact agrees with what takes place in crystals formed from solution in water, the material being merely deposited on the sides, and not as independent crystals. They, however, contain bubbles, relatively of a smaller size than those in the felspar; whilst the glass-cavities in another mineral, the exact nature of which I have not been able to determine, contain many green crystals, but no bubble, as shown by fig. 64, probably owing to these minerals contracting more than felspar in cooling from a high temperature.

The analogy between these glass-cavities and fluid-cavities is therefore in many respects very striking; and, as will be seen, their peculiar characters can be most perfectly explained, if we suppose that the glassy base, when in a state of fusion, acted like a solvent liquid and dissolved various mineral substances, which were deposited on cooling in precisely the same manner as crystals are deposited on

the cooling of a saturated, aqueous solution. There is therefore, in my opinion, no more necessary connexion between the temperature at which the crystals were deposited from this glassy solvent and their own fusing-point, when heated alone, than between the temperature at which crystals are deposited from solution in water and their own fusing-point, even if they be fusible. In both cases, the only necessary connexion is, that the crystals could not be deposited in a *solid* form, except at a lower temperature than that at which they become *liquid*; but it might be any heat less than that high enough to cause the glossy solvent to be sufficiently fluid. These facts are of very great importance in the study of igneous rocks, and serve to explain several peculiarities in their structure. Such glass-cavities, however, differ essentially from fluid-cavities, in containing bubbles that never move, and do not change their place or disappear when the fragment containing them is heated, unless the heat is strong enough to melt the enclosed glass, which is more fusible than the felspar.

The best examples of glass-cavities that I have met with in the erupted lavas of Vesuvius occur in the augite. One very excellent case is shown by fig. 65. They contain, at least, two kinds of crystals, which sometimes project beyond the general outline of the cavities, as shown in the figure, as if they were formed at the same time as the augite, and were caught up in it along with the fused material of the glass-cavity, which on cooling deposited other crystals, and by contracting gave rise to a small bubble. In some cases long prismatic crystals have been caught up in the augite, as shown by fig. 66, having two glass-cavities attached to them, one with a bubble and the other without, which is not unfrequently the case in detached cavities, as if, like in some fluid-cavities, the cohesion of the sides had overcome the contraction of the melted glass.

The leucite in the lava of Vesuvius often contains many cavities, the material in which has to a great extent become crystalline, and therefore they are very commonly stone-cavities. An example of one, partially stone and partially glass, is shown by fig. 68, which is somewhat analogous to those in the felspar of the pitchstone, represented by fig. 63. Another form is shown by fig. 70, and a very curious, almost circular, flat cavity is seen in fig. 69, containing three different kinds of crystals; whilst fig. 67 represents a crystal enclosed in the solid leucite, with a small stone-cavity attached to it. In no case have I seen decided bubbles in the cavities in leucite; but their absence from cavities containing many crystals is easily explained, because many substances expand in crystallizing to such an extent as would compensate for the previous contraction from a high temperature. In the felspar of the trachyte of Ponza the cavities are all filled with stony matter, as shown by fig. 71. A very long tubular cavity is represented by fig. 72.

The general arrangement of these various glass- and stone-cavities is precisely analogous to that of those in crystals formed artificially; and, independent of the fact that, in all their essential characters, they are identical with the cavities in the crystals in artificial furnace

slags, their very nature proves the igneous origin of the minerals containing them. This is especially the case with glass-cavities; for nothing but igneous fusion could so liquefy the enclosed glass that perfectly spherical bubbles could be produced.

Besides stone- and glass-cavities, the minerals of erupted lavas contain gas- or vapour-cavities, as if they had caught up small quantities of gases and vapours that were in contact with them; but I have never found any fluid-cavities, and hence the purely igneous origin of the characteristic minerals of erupted lavas appears to be completely proved. The zeolites, however, occurring in the cavities of lava that has been exposed to the action of water since it was erupted, contain no glass- or stone-cavities, but a few fluid-cavities, as if deposited very slowly from solution in water. The best examples I have met with are in the Arragonite in the lava of Vesuvius, which have the vacuities equal to about $\frac{1}{10}$ th of the fluid, corresponding to a temperature of 160° C. (320° F.).

Precisely the same conclusions apply to far more ancient trappean rocks. The augite in some of the basaltic rocks of Scotland has the same characteristic structure as that in the modern lavas of Vesuvius. A very good example of a glass-cavity is shown by fig. 73, containing a bubble and many small crystals deposited on the sides of the cavity. In the case shown by fig. 74, many most distinct crystals have been formed on the sides, but it contains no bubble, whilst sometimes, as fig. 75, there is a bubble but no crystals. In the felspar of a porphyritic greenstone from Arthur's Seat near Edinburgh, there occur many stone-cavities; but, like the felspar itself, they have undergone a great amount of alteration by the subsequent action of water. Fig. 76 is much like some of the cavities in leucite, whilst that shown by fig. 77 evidently contained a bubble like a glass-cavity, but it has been filled with the chloritic mineral that has been introduced by water into nearly all parts of the rock. In fact the microscope clearly shows that the amount of alteration effected by the action of water on these ancient volcanic rocks is very much more than is generally supposed; and rocks, which to the naked eye appear to contain only two or three minerals, are seen to be made up of ten or twelve. Some of these are the igneous minerals containing glass- or stone-cavities, and others are zeolitic minerals containing fluid-cavities, which indicate that they have been deposited from more or less heated water. The characteristic structure of the minerals of which ancient trappean rocks are composed is, therefore, so analogous to, or even identical with, that of the constituents of modern lavas, that the purely igneous origin of these ancient lavas appears to me to be completely established; but, at the same time, their present aspect is often to a very great extent due to the subsequent action of water. In fact they have frequently been as much metamorphosed by water as some stratified rocks have been by heat. The production of zeolites, by the action of the thermal springs at Plombières on the ancient masonry, strongly confirms these deductions. (Daubrée, *Annales des Mines*, 5^e série, t. xii. p. 289, and xiii. p. 227.)

§ 6. *Minerals and Rocks formed by the combined operation of water and igneous fusion.*

a. Minerals in the blocks ejected from Vesuvius.

As is well known, in the blocks ejected from Vesuvius during eruption, a large series of minerals occurs, which do not exist in the erupted lava. Many of these are found in the limestone blocks in the Conglomerate of Somma, and, as pointed out by Delesse (Bulletin de la Société Géologique de France, 1852, t. ix. p. 136), in their number and character they differ so much from erupted lava, that it is little probable that the rock was ever in a state of simple igneous fusion. This conclusion is completely borne out by the microscopical structure of the minerals, for they contain many fluid-cavities, as well as glass- and stone-cavities, indicating that they were formed by the combined action of water and igneous fusion.

In the calcite associated with light green mica, I have found many very excellent fluid-cavities, as shown by fig. 78. When heated they give off *water*, and on reducing the spar to powder, water extracts the chlorides of potassium, sodium, and magnesium, and the sulphates of potash, soda, and lime. Hence I think there can be no doubt that the cubic crystals seen in the cavities are chloride of potassium or sodium, and the fluid a concentrated aqueous solution of those salts. I have not been able to ascertain the relative size of the vacuities with great accuracy, but it is nearly $\frac{1}{4}$ th of the volume of the fluid. Similar cavities occur in the nepheline of ejected blocks, and they all contain one or more cubic crystals of chloride of potassium or sodium, as shown by figs. 79, 80, and 83, no doubt deposited from the fluid on cooling, like those seen in the cavities formed artificially (figs. 18 and 19). Occasionally there are crystals of some other substance, as in fig. 79. I have very carefully determined the relative size of the vacuities, and find that it is about $\cdot 28$ of the fluid; and it is so uniform as to forbid us from supposing that the vacuities are owing to a loss of fluid. In calculating the temperature in this and the other cases given below, I shall assume that the pressure was not much greater than sufficient to counteract the elastic force of the vapour, so that we may consider $v=V$, and make use of equation (8). Judging from the change in the amount of expansion produced by an increase in the amount of salt in the experiments already described, the temperature indicated by relatively large vacuities would be nearly the same when there was more salt than can be retained in solution at the ordinary temperature, as when there was only 25 per cent.; the small difference being singularly enough almost exactly compensated for by the increase in the bulk of the salt on crystallizing. This is a fortunate circumstance in this inquiry; since, when, as in the case of the fluid-cavities in many modern volcanic minerals, the vacuities and included crystals are relatively large, it is unnecessary to take anything into account but the relative size of the vacuities, and substitute their values in equation (8). In this manner I deduce that this nepheline and

calcite must have been formed at a temperature of about 340°C . (644°F .). Of course, if the pressure was greater than supposed, the temperature must have been still higher. Since then (Gmelin's Handbook of Chemistry, Cavendish Society's Translation, vol. i. p. 167) solid bodies begin to be dull red in the dark at 335°C ., and bright red at 400° , this temperature would be that of a very dull red heat only just visible in the dark, at which, from equation (7), the elastic force of the vapour would be equal to a pressure of 1954 feet of rock.

On heating the fragment containing the cavity shown by fig. 80 to a very dull red heat visible in the dark, it became as fig. 81. The small crystals had disappeared, and the vacuity and crystal had changed their places; thus proving that the cavity contained a liquid, and that the crystals were soluble in it. On heating to a very decided red heat, the cavity became as fig. 82; the fluid had disappeared, and the nepheline had partially fused and collapsed over the altered crystal. When another fragment containing the cavity, fig. 83, was heated to a dull red heat, the cavity lost its fluid, and the crystal melted into a globule, as shown in fig. 84. All these results agree perfectly with the supposition, that the fluid is an aqueous solution, and the crystals chloride of potassium or sodium; and it will be seen that the expansion of the liquid is not sufficient to burst the cavities until the heat is that of redness, which agrees perfectly well with calculation, if we consider that the enclosed crystal was not all dissolved on account of being exposed to a high temperature for only a short time. All, or nearly all, the fluid-cavities contain the crystals, which are on an average equal to about $\frac{1}{3}$ rd of the bulk of the liquid, or about four times as much as is deposited from a solution of chloride of potassium saturated at the heat of boiling water, and many times more than from a solution of chloride of sodium. This entirely confirms the conclusion derived from the size of the vacuity, since, to dissolve so large an additional quantity, a very high temperature would certainly be requisite. Some cavities, as shown by fig. 85, are as though many minute crystals had been deposited over their whole surface, except where prevented by the attached cube.

Most excellent gas-cavities also occur in the same nepheline, as shown by figs. 86 and 87, being like bubbles of gas enclosed during the growth of the crystal, in the same manner as in some of the artificial crystals already described. Others, like fig. 88, are as if some highly compressed, heated vapour had been enclosed, and on cooling had condensed into small crystals. Such cavities can be distinguished from stone-cavities by the fact of being partially transparent in the centre. The same fragment of nepheline also contains excellent glass-cavities, figs. 89 and 90, in all respects analogous to those in crystals formed when melted stony matter is present. As will be seen, the outline is very obscure, and quite different from that of the fluid-cavities, and is rendered apparent chiefly by the small crystals. The difference is also strongly marked by the presence of several bubbles, as shown by fig. 90. This glass-cavity was

in the same fragment as the fluid-cavity, fig. 80, and when heated to a very dull red heat, it remained nearly as drawn. When, however, heated a little higher, the minute crystals disappeared, and the bubbles changed their places; whilst at the same temperature the fluid-cavity still retained its fluid. At the temperature at which the fluid was expelled, it became as fig. 91, where all the crystals had disappeared, and the bubbles not only had changed their places, but two had coalesced. It is therefore clearly proved by experiment (April 1858) that, at a heat not sufficient to expand the fluid in the cavities so much as to burst them, the substance in the glass-cavities is melted, so as to dissolve the small crystals it had previously deposited on cooling more slowly, and permit a change in the position of the bubbles, all which results agree most perfectly with the supposition that the crystals were formed at a red heat visible in the dark, when melted stony matter, gases, vapours, and liquid water saturated with soluble alkaline salts, were all present and alternately in contact with the growing crystals, so that the conditions of fusion, sublimation, and solution were all united.

In the idocrase forming along with calcite the general mass of a block ejected from Vesuvius, many fluid-cavities occur, which often contain so many crystals that it is difficult to determine their form. A very good example is given in fig. 92, with crystals like those in the fluid-cavities in nepheline. Fig. 93 shows clearly that the relative size of the vacuities is very great. On an average, they are equal to one-third of the fluid, and therefore indicate a temperature of 380°C . (716°F .), or a decided red heat; at which temperature the elastic force of the vapour of water is, from equation (7), equal to the pressure of 3222 feet of rock. Similar cavities occur in hornblende, indicating a heat of 360°C . There are also very good fluid-cavities in the crystals of felspar found in the ejected masses of ice-spar. These contain many crystals of two or three kinds (as shown by fig. 94). On reducing the felspar to powder, I found the usual chlorides and sulphates, but besides these a very considerable quantity of the carbonates of potash and soda, and, therefore, probably the presence of these carbonates is the reason why the crystals in the cavities differ so much from those previously described, though in other specimens they are quite similar, all being cubes. As shown by fig. 95, the vacuities are very large, and of about the same relative size as those in idocrase, indicating a temperature of 380°C . Other cavities, like fig. 96, have caught up vapour or gas along with the fluid, in the same manner as sometimes occurs in artificial crystals; whilst others are quite full of the gas or vapour, which in some cases has been condensed into crystals on cooling, so as to cover the surface, as shown by fig. 97, seen out of focus in the centre. The same crystal also contains most decided and excellent glass-cavities, like fig. 98, and others, as fig. 99, that have become to a great extent crystalline, and contain no bubbles; both of which are very analogous to cavities in the felspar of the pitchstone of Arran.

We are thus led to conclude that the peculiar minerals characteristic of the blocks ejected from Vesuvius were formed at a dull red

heat, under a pressure equal to several thousand feet of rock, when water containing a large quantity of alkaline salts in solution was present, along with melted rock and various gases and vapours. Whether or no the presence of this water was instrumental, or even essentially requisite, in producing some of the minerals, still remains to be proved; but I think no one could compare the drusy cavities in the ejected blocks with the crystalline cavities in the slags of furnaces, without perceiving that the occurrence of various minerals, placed one over the other in regular order, is a most striking difference, which could be accounted for most completely by the action of water. It would also probably serve to explain why, according to Daubeny (*Treatise on Volcanos*, 2nd edition, p. 236), the minerals most characteristic of the ejected blocks are never found in the erupted lavas, the crystalline minerals of which were apparently formed when no *liquid* water was present. I therefore think we must conclude provisionally, that at a great depth from the surface, at the foci of volcanic activity, liquid water is present along with the melted rock, and that it produces results that would not otherwise occur.

It may perhaps be thought that the spheroidal condition assumed by water in contact with highly heated substances, would explain why it might be present at a less depth, and under less pressures, than those I have described; but it appears to me that water could not remain in the spheroidal state, unless the vapour could escape, and that the temperature it remains at is essentially connected with the boiling-point at the pressure to which it is exposed, and therefore the permanent presence of water at such a high temperature necessitates a great pressure, even if it was in the spheroidal state. But I think no one who has made experiments on the subject, would think it possible for water in that state to enter into tubes less than ¹⁰⁰100th of an inch in diameter. This, however, has constantly occurred in the minerals of the ejected blocks, and hence it appears to me almost demonstrated that it was not in the spheroidal state, separated by a layer of vapour, but in actual contact with the crystals at a high temperature, and under great pressure.

The presence of genuine gas- and vapour-cavities side by side with the fluid-cavities, and the existence of so large an amount of salts in solution in the fluid, prove that the water was caught up in a *liquid* state, and not as *vapour* so highly compressed as to condense into an equal bulk of water (see Cagniard de La Tour's paper, *Annales de Chemie*, 1822, t. xxi. p. 127); for in that case, since in the nepheline there is no gradual passage from fluid-cavities to vapour-cavities, we should have to conclude that the two gaseous bodies were not mutually diffusible, and that a very large amount of various alkaline salts was present as *vapour* along with the vapour of water; both of which suppositions are I think quite inadmissible.

Perhaps some may suppose that possibly the water penetrated into the cavities long after the minerals were formed. This, however, would necessitate percolation through the solid substance of the crystals, a fact differing as much from percolation through a rock, or amongst the minute crystals of which such substances as agate

are composed, or even through the pores existing in imperfectly solidified metals, as the passage of water through solid glass would differ from its passage amongst closely-packed fragments of glass. Not only does this appear to me most improbable, but actually opposed by facts. In the first place, the proportion between the amount of fluid and the size of the cavities in the nepheline is so uniform that I cannot believe it to be the result of accident, as we should have to suppose if they were not all filled full at the same temperature. If, to overcome this difficulty, it be supposed that the fluid penetrated into the cavities when in a highly heated state, it would require it to have been at the same temperature as that at which I have supposed it entered in the same legitimate way that it enters into the fluid-cavities in artificial crystals. But, even then, the facts are against the supposition; for, besides fluid-cavities, there occur gas-cavities like figs. 86 and 87; and though there is no absolute line of division between their form and that of the fluid-cavities, their general characteristic shape is very different, because, as in artificial crystals, in one case the crystal is moulded to the bubble of gas, whereas in the other the irregular growth of the crystal determines the form of the cavity. Moreover, besides these gas-cavities, there are the bubbles in the glass-cavities, which never contain a fluid. If then we suppose that the fluid percolated through the solid crystal into the fluid-cavities, we are led to conclude that it selected these cavities like artificial fluid-cavities, but avoided those resembling artificial gas-cavities, and the vacuities in the glass-cavities, a conclusion which is so extremely unreasonable that we must reject the proposition that leads to it.

b. Granitic Rocks.

In some of the trachyte of Ponza of solid character, as if it had been formed under considerable pressure, there occur a few small crystals of quartz, forming one of the genuine constituents of the igneous rock, in every respect like those in many elvans and some granites that contain but little quartz. They can scarcely be distinguished in the rock in its natural state, but are readily seen in a thin section. When I examined this (April 1858), I found that the quartz contains very excellent fluid-cavities, as shown by figs. 100, 101, and 102. There is no doubt that they contain a liquid, for the bubbles move about in it. They are usually very flat, like fig. 101, and, when inclined in particular positions, the transmitted light is totally reflected from the bubble, which therefore appears like a black opaque substance, as shown by fig. 102. By careful measurements, I find that the relative size of the vacuities is very nearly $\cdot 30$. Assuming then, that, like in the fluid-cavities in the minerals of ejected blocks, and in the quartz of the veins in the self-same trachyte, as well as in those in the quartz of elvans and granite, the enclosed fluid is a strong aqueous solution of alkaline chlorides and sulphates, I deduce, from equation (8), that the temperature at which the crystals of quartz in the trachyte were formed was at

least 356° C., which closely corresponds with the mean deduced from the fluid-cavities in the blocks ejected from Vesuvius. At this temperature the elastic force of the vapour of water is equal to about 2400 feet of rock, and therefore the quartz must have crystallized under that pressure, at least. Considering the nature of the rock, the pressure cannot, I think, have been very much more than that, though it must have been somewhat more, and then of course the calculated temperature would be higher; but it would require a pressure equal to upwards of 19,000 feet of rock to alter it to 400° C. If it was equal to about 4000 feet, the calculated temperature would be 360° C. (680° F.). This is a very dull red heat visible in the dark, and the elastic force of the vapour of water would be equal to 2500 feet of rock. It does not necessarily follow that the rock was finally consolidated under such a pressure, or at such a depth, since the strength of quartz is such, that, if the crystals had been formed at a considerable depth, they might be carried to a much less without the elastic force of the fluid bursting the cavities. To completely fuse such a rock, a white heat is necessary; but I find that, when in a glassy state, thin fragments become soft enough to bend at a very moderate red heat, so that the temperature at which it became *quite solid* probably could not differ very materially from the dull red heat deduced from the fluid-cavities, the two independent facts strongly confirming each other.

Along with these fluid-cavities occur most excellent stone-cavities, as shown by fig. 103, in every respect analogous to those in the crystals in slags, and especially like some in leucite; and it may easily be seen that they are small portions of the surrounding felspathic material of the trachyte, that have been enclosed in the growing crystals of quartz. That they were caught up when their substance was in a fused, or at all events in a soft state, is proved by the fact, that their form is related to, and they are moulded upon, the crystalline planes of the quartz; whereas, if they had been solid fragments, the quartz would have been moulded to their own form. It therefore appears to me to be completely proved, that these crystals of quartz were generated under similar physical conditions to those concerned in the development of the minerals of the ejected blocks, by the combined influence of a dull red heat, liquid water, and partially melted rock.

The structure of the quartz of many elvans and some granites is in every respect analogous to that in the trachyte just described. The only sensible difference is that the fluid-cavities are seldom so flat, and gas- or vapour-cavities more numerous. The proof of the igneous origin of elvans is complete, for the stone-cavities are very well developed. Examples of these are shown by figs. 104, 105, 106, and 107, from the elvans near Penrhyn and Gwennap. As will be seen, fig. 104 is extremely like those in the trachyte, differing only in being of rather coarser grain, and in containing a long prism of schorl. Very often long hair-like crystals of that mineral occur in the quartz itself, sometimes attached to stone-cavities, as shown by fig. 106; like the crystals with attached stone-cavities in leucite,

fig. 67. Fig. 105 represents a cavity of more irregular shape, and fig. 107 is from an elvan of much coarser grain, and has a gas- or vapour-cavity attached to it. These gas- or vapour-cavities often occur in distinct bands, like those in augite and other volcanic minerals; but sometimes they are mixed up with fluid-cavities, which in that case have bubbles of variable relative size, caused by the irregular combination of fluid and vapour in the same cavity; whilst in other parts fluid-cavities occur alone, with vacuities of very uniform relative size. As in the case of artificial crystals, the form of the fluid-cavities is often related to the crystalline planes of the quartz, as shown by fig. 108. Fig. 109 is a fluid-cavity containing prismatic crystals, which in some cases must certainly have been caught up during the growth of the quartz, and not deposited from the solution on cooling, for they often pass through the cavities, as shown by fig. 110, and appear to be schorl.

The passage from elvans to granite is quite gradual, and this is also the case with the peculiarities in the microscopical structure of their constituent minerals. The quartz of granite often abounds with most excellent fluid-cavities, and as an illustration of this fact, I have in fig. 111 represented a portion of the quartz of the granite of St. Austel, which occurs as distinct crystals, precisely like that in the trachyte described above, and not as a residue of crystallization. In many granites the fluid-cavities are so numerous in the quartz, that on an average they are not above $\frac{1}{1000}$ th of an inch apart. This agrees with the proportion of a thousand millions in a cubic inch; and in some cases there must be more than ten times as many. They also really constitute a most important part of the whole bulk of the quartz, for sometimes they make up at least 5 per cent. of the volume; and I have found that the loss of water on heating the quartz of the granite of Cornwall to redness is on an average about 0.4 per cent. of its weight, which is equivalent to about 1 p. c. of its bulk. These fluid-cavities are not confined to veins of granite, or to that part near the junction with the stratified rocks, but are quite as numerous in the most solid rock, far away from the junctions; as though the fluid was not an *accidental* ingredient, due to the percolation of water to a fused mass naturally containing none, but as if it was a *genuine* constituent of the rock when melted. Their number varies very much in different granites, but hitherto I have found them in all specimens I have examined; and, though there are exceptions to the rule, yet on the whole they are more numerous in granites than in elvans, and in coarse-grained, than in fine-grained granites*.

The felspar of the Cornish granites is usually so opaque, on account of partial decomposition, that it is difficult to see the fluid-cavities.

* This is especially the case near Aberdeen; for in the quartz of the coarse-grained veins, having crystals of mica, felspar, and schorl several inches long, the fluid-cavities are so numerous, large, and distinct, that even with only a moderately high magnifying power they may be seen to greater advantage than in any other granite I have hitherto examined; whereas in the rather fine-grained stone used in building, they are few, small, and obscure.—Oct. 1858.

Fig. 112 is one in this mineral, but they are undoubtedly very rare. Few also occur in this mica, but they are certainly sometimes met with, as shown by fig. 113, which is very flat and shallow. The presence of so many in the quartz, and of so few in the felspar and mica, is analogous to what occurs when a mixed solution of common salt and alum is evaporated, as already described; and, when solutions of alum and chloride of potassium are evaporated side by side, the crystals of chloride of potassium are even more loaded with fluid-cavities than the quartz in granite, whilst some of the crystals of alum contain none.

By many experiments, I have proved most conclusively that the fluid in the cavities in the quartz of granites and elvans is *water*, holding in solution the chlorides of potassium and sodium, the sulphates of potash, soda, and lime, sometimes one, and sometimes the other salt predominating. Since the solution has often a most decided acid reaction before, or even after, having been evaporated to dryness, there must be an excess of the acids present. This occurrence of *free* hydrochloric and sulphuric acid is, I think, a very interesting fact, when we bear in mind how very characteristic they are of modern volcanic activity. Sometimes the amount of salts dissolved in the heated water was greater than could be retained in solution at the ordinary temperature, and cubic crystals of the chlorides have been deposited, as shown by fig. 114. Near the granite, this is also sometimes the case with the fluid-cavities in the quartz of metamorphic schists and quartz-veins, which cavities contain the same saline solution as those in the quartz of the granite itself, as if in all these cases the quartz had been deposited from the same liquid, which, at a greater distance from the granite, became more dilute, on account of being mixed with pure water. Besides the cubic crystals, the fluid-cavities in the quartz of granite occasionally also contain prismatic crystals, as seen in fig. 115, and therefore agree very closely with those in the blocks ejected from Vesuvius. There is often a considerable variation in the amount of crystals contained in the fluid-cavities in the same portion of quartz, as if the strength of the solution had varied during the consolidation of the rock; and there is also sometimes a passage from fluid- to vapour-cavities, as if there had been an alternation of liquid and vapour or gases; both of which circumstances would be likely to occur.

The stone-cavities are not well developed, except in granites whose structure approximates somewhat to that of elvans. The most distinct I have yet found are in the quartz of the granite of St. Austel, containing the fluid-cavities, fig. 111. They are entirely similar to those in the quartz of the trachyte of Ponza or of elvans, as will be seen on comparing fig. 117 with figs. 103 and 104. As I have already remarked, when some substances pass into the crystalline state they occupy more space than when melted, and therefore, if entirely enclosed in a solid substance, they might expand so much as to crack it, like we all know often happens when water freezes. This appears to have occurred in the cavity fig. 119, there being three cracks radiating from it, as drawn. This increase in the bulk of the

included stone, explains why there are no vacuities in the stone-cavities of granites and elvans. In the quartz of very coarse-grained granites the stone-cavities are generally obscure and of irregular shape, as shown by fig. 118. Those in the felspar are often so much obscured by the partial decomposition of that mineral, that it is difficult to distinguish them from small decomposed patches; but in some very clear from the granite of Lamorna they are sufficiently distinct, and, as shown by fig. 120, are very analogous to those in the felspar of the trachyte of Ponza, figs. 71 and 72.

Besides fluid- and stone-cavities, the quartz of granite often contains vapour-cavities, like those in minerals from modern volcanos. Some are almost perfect spheres, and exactly like enclosed bubbles of gas; but others are of more irregular shape, and gradually interfere with and pass into fluid-cavities, in the same manner as occurs in some of the minerals of ejected blocks, and in crystals formed artificially by alternate exposure to liquid and the air. Some of these empty cavities may be fluid-cavities that have lost their fluid, but I have found them in specimens obtained on the sea-coast below low-water mark, which were afterwards kept under water and never dried, and therefore some must certainly be genuine gas- or vapour-cavities.

On the whole, then, the microscopical structure of the constituent minerals of granite is in every respect analogous to that of those formed at great depths and ejected from modern volcanos, or that of the quartz in the trachyte of Ponza, as though granite had been formed under similar physical conditions, combining at once both igneous fusion, aqueous solution, and gaseous sublimation. The proof of the operation of water is quite as strong as of that of heat; and, in fact, I must admit, that in the case of coarse-grained, highly quartzose granites there is so very little evidence of igneous fusion, and such overwhelming proof of the action of water, that it is impossible to draw a line between them and those veins where, in all probability, mica, felspar, and quartz have been deposited from solution in water, without there being any definite genuine igneous fusion like that in the case of furnace slags or erupted lavas. There is, therefore, in the microscopical structure a most complete and gradual passage from granite to simple quartz-veins; and my own observations in the field cause me to entirely agree with M. Elie de Beaumont (Note sur les émanations volcaniques et métallifères, Bulletin de la Société Géologique de France, 2 série, t. iv. p. 1249) in concluding that there is also the same gradual passage on a large scale.

My remarks respecting the possibility of the water having passed into the fluid-cavities in nepheline after they were formed, will, to a considerable extent, apply to the fluid-cavities in the quartz of elvans and granites. If they had contained *nearly pure* water, and were quite full, and easily lost it on drying, such a supposition would have been sufficiently probable. It is, however, not mere water, but various *saline solutions*, with *free acids*, precisely like the fluid in the cavities of some modern volcanic minerals. Moreover, that a very great pressure will not cause water to pass through solid crystal, ex-

cept by cracking it, is proved by the fact, that when the quartz from Ceylon, in which the fluid expands so as to fill the cavities at about 218° C., was heated to at least 350° , some of the fluid-cavities still retained their fluid, though, judging from the force calculated to be necessary to counteract the expansion of the fluid, they must have resisted a pressure equal to about 40,000 feet of rock. Also in my experiments in treating fragments of nepheline to a red heat, a thickness of only $\frac{1}{100}$ th of an inch must in some cases have resisted a pressure of several thousand feet. Since water has not penetrated into the vapour-cavities, or into the vacuities in the glass-cavities, in ancient trappean rocks, it should appear that a considerable pressure for a very long time will not cause it to pass through the solid substance of crystals. In my opinion this could only happen by the formation of *actual cracks*, which, as sometimes happens with cracked glass, were healed up by the adhesion of the sides, after the fluid had entered. This, however, would differ as much from the escape of the fluid when the crystal is strongly heated, as the breaking of an arch by a symmetrical pressure from above would differ from a fracture produced by a pressure from the inside; and, therefore, if fluid-cavities can resist so great a pressure from within, it appears to me that none at all probable could burst them from without. That the fluid remains permanently in many of the cavities in quartz, is, I think, proved by the fact that, when specimens are obtained below low-water mark on the sea-coast, and afterwards kept in water, the cavities are in no respect different from those in very thin fragments which have been kept dry for years. On the whole, in the absence of any proof of the contrary, I think these reasons are sufficient to warrant the conclusion that the aqueous solutions enclosed in the fluid-cavities in the quartz of granitic rocks, were caught up during the formation of the crystals, and have remained ever since, hermetically sealed up in their solid substance, without any increase or diminution of the fluid; and that therefore we may determine from their present condition the circumstances under which the rock was originally formed.

In my opinion, the water associated with thoroughly melted igneous rocks at great depths does not dissolve the rock, but the rock dissolves the water, either chemically as a hydrate, or physically as a gas. In the case of those obsidians and pitchstones which, when heated to redness, give off water having a strong acid reaction, it may probably be in the form of a hydrate, retaining its water when heated under pressure. It is also sufficiently probable that, as suggested by M. Angelot (*Bulletin de la Société Géologique de France*, 1 sér. t. xiii. p. 178), fused rock, under great pressure, may dissolve a considerable amount of the vapour of water, in the same manner as liquids dissolve gases. In either case, if the fused rock passed by gradual cooling into anhydrous crystalline compounds, the water would necessarily be set free; and, if the pressure was so great that it could not escape as vapour, an intimate mixture of partially melted rock and liquid water would be the result. It is difficult to form any very definite opinion as to the actual amount of this water, and

to decide whether or no it exercised an important influence over the crystalline processes that took place during the consolidation of such rocks as granite. The comparatively large quantity of alkaline chlorides and sulphates, dissolved in those portions caught up in the growing crystals, indicates that the amount cannot have been *unlimited*; but, bearing in mind the facts I alluded to when describing the fluid-cavities in the blocks ejected from modern volcanos, and knowing, as we do, that the action of highly heated water is so very energetic, I cannot think that its influence was unimportant. On the contrary, seeing that the fluid-cavities in the quartz of quartzveins contain the selfsame salts and acids as those in the granite, as though it had been deposited from portions of the liquid which had passed from the granite up fissures, I think the amount, though limited, must nevertheless have been *considerable*, and that its presence will serve to account for the connexion between granite and quartzveins, and the very intimate relation of both to the metamorphic rocks, and explain many peculiarities in the arrangement of the minerals in the cavities in granite or in the solid rock, even if it was not the effective cause of their elimination and crystallization. These analytical deductions have been confirmed in a most striking manner by the admirable experiments of M. Daubrée (*Observations sur le métamorphisme, &c.*, *Annales des Mines*, 5^e sér. t. xii. p. 289), who, in having produced felspar and quartz artificially, by the action of water at a similar temperature to that I have deduced from the fluid-cavities, has removed some of the principal objections that might have been urged against my conclusions. I therefore must confess myself to be a very strong adherent to the views of Scrope (*Treatise on Volcanos*; and on the nature of the liquidity of lava, *Quarterly Journal of the Geological Society*, vol. xii. p. 338), Elie de Beaumont (*Note sur les émanations volcaniques, ut supra*), and Scheerer (*Discussion sur la nature plutonique du granite, &c.*, *Bulletin de la Société Géologique de France*, 2 sér. vol. iv. p. 468, and vol. vi. p. 644), though, as will be perceived, I by no means agree with them in every particular.

c. Temperature and pressure under which granitic rocks have been formed.

In studying the fluid-cavities in elvans and granite, it is particularly necessary to bear in mind the influence of pressure. As already shown, the temperature requisite to expand the fluid so as to fill the cavities is that at which the crystal was formed only when the pressure was not greater than the elastic force of the vapour, and when in equation (9) $p=0$; but if the pressure was very great, that temperature would necessarily be far short of the actual heat. Therefore, as already described, the true heat can only be determined when the approximate value of the pressure is known; and the pressure cannot be deduced unless we can in some way or other approximate to the temperature. The trachyte of Ponza was probably formed under so small a pressure that it scarcely need be taken into account; but, in the case of granites, such a supposition would lead to the con-

clusion that sometimes they did not solidify from a state of fusion until the temperature was as low as that of boiling water. In the present state of the inquiry (July 1858), it therefore appears to me that the best course is to suppose that the quartz of the various igneous rocks crystallized at about the same temperature, and that the greatest value of v yet observed, viz. in the trachyte of Ponza, was when p was not so great as to prevent the value $\cdot 3$ being a sufficiently accurate approximation to V to be substituted in equation (6), so as to enable us to calculate the value of p from the observed value of v by the equation

$$p = 369,000 \frac{3-v}{1+\cdot 3} \dots \dots \dots \text{equation (10).}$$

Considering the very strong analogy between the structure of this trachyte and that of elvans and granites, this supposition appears to me quite admissible as an approximation until a more correct is known. Of course the results deduced from the equation are the amounts of *pressure* in feet of rock, and not the actual *depth*. In some cases the pressure was probably much greater than that of the superincumbent rocks, for otherwise they could not have been fractured and elevated; whereas in other cases it may have been much less, if the internal pressures had been in any way relieved. Fortunately, a considerable variation in the strength of the saline solutions in the fluid-cavities would be to a great extent compensated for, because, though a more dilute solution would expand more by heat, it would be more compressed by pressure. Moreover, according to the principles described by Mr. James Thompson (Transactions of the Royal Society of Edinburgh, vol. xvi. p. 575), which have been strikingly verified by the experiments of Professor Wm. Thompson on the thawing of ice (Philosophical Magazine, 3rd ser. vol. xxxvii. p. 123), by those of Bunsen on spermaceti and paraffine (Poggendorff's Annalen der Physik und Chemie, 1850, vol. lxxxi. p. 562), and by those of Hopkins and Fairbairn on spermaceti, paraffine, sulphur, and stearine (Report of the British Association for 1854, p. 57),—if a substance expands in solidifying, it would become solid at a lower temperature when under a greater pressure; whereas if it contracts, it would solidify at a higher temperature. Therefore if, as I have already shown, the stone-cavities in the quartz of granite indicate that the general fused mass from which the quartz crystallized expanded in the act of solidification, it would probably become solid at a lower temperature when under greater pressure. We may, however, be nearly certain, that at very great pressures the compression of water would be relatively less than at moderate; for, if not, a finite pressure would compress it into nothing; and therefore, since the force required to produce this relatively less compression of the liquid, which was not so much expanded by the lower temperature, might be nearly the same as would produce the greater compression of the more heated and expanded liquid assumed in the above equation, it is obvious that these two sources of error have a tendency to counteract one another, and therefore perhaps the equation would give a toler-

rably accurate approximation to the truth when the pressure was very great, as well as when only small. Even if the real amount of the compression of the highly heated liquid differed from that supposed to be the most probable, the difference would affect all the results in similar proportion, and therefore, though not *actually* correct, they would be sufficiently accurate *as compared with each other*. The chief point about which there may be some doubt is whether, when the rock contains much quartz, it became crystalline at a higher temperature than when it contains less. I have, indeed, found cases where there was evidence of the first-formed quartz having crystallized at a higher temperature than the last, but the facts were scarcely sufficiently decided to be fully relied on, and in the present state of the inquiry this cannot be accurately taken into account; nor, indeed, if mean results are employed, do any other facts seem to require that it should. That even highly quartzose elvans and granites did not become finally solid at a temperature much higher than a dull-red heat, is, I think, clearly proved by the great number of hair-like crystals of schorl enclosed in the quartz; for schorl readily melts at a bright-red heat, and therefore must have crystallized at a lower temperature than that. The properties of the pyrognomic minerals described by Scheerer (*Discussion sur la nature plutonique du granite, &c., ut supra*) indicate a temperature not higher than a brown-red heat. It therefore appears to me in the highest degree probable that granites and elvans became finally solid at about the dull-red heat calculated from the fluid-cavities in the quartz of the trachyte of Ponza. Still, however, taking everything into consideration, the following deductions must only be looked upon as the best approximations that can be made at present, for so many data are only imperfectly known.

From the nature of the case, equation (10) gives the *excess* of pressure over and above that under which the quartz of the trachyte of Ponza crystallized, whatever, within moderate limits, the *real* temperature and pressure might be. If then we consider these to have been 360° C., and 4000 feet of rock, that amount would have to be added to the calculated value of p , in order to obtain the *total* pressure.

The greatest value of v that I have yet found for any elvan is for one at Gwennap, in which it is very nearly $\cdot 25$. This, from equation (8), indicates a minimum temperature of about 320° C. (608° F.), or very little lower than a dull-red heat visible in the dark. Substituting this value of v in equation (10) we obtain $p=14,100$ feet, to which, as explained above, must be added 4000 feet to arrive at the total pressure, which was therefore about 18,100 feet. The least value of v for any elvan in Cornwall is $\cdot 125$, for that at Swanpool, near Falmouth, which corresponds to a pressure of 53,900 feet. The mean of my observations in the elvans of Cornwall gives a pressure of 40,300 feet; but, for the analogous quartzose porphyry-dykes in the Highlands of Scotland, 69,000 feet.

I have never yet found any granite in which v is greater than $\cdot 2$, which is the relative size of the vacuities in that of St. Austel. This

indicates a minimum temperature of 256°C . (493°F .), and a pressure equal to about 32,400 feet of rock, or considerably less than some of the elvans. In the Cornish granite I have never found v less than $\cdot 09$, in that from the Ding Dong mine near Penzance, which corresponds to a pressure of 63,600 feet; and the mean of all my observations gives 50,000 feet, or 9700 feet more than the mean for the elvans. This, I think, is a very satisfactory result, since the association of those rocks clearly proves that granite must have been consolidated at a considerably greater depth than elvans.

The conclusions derived from my examination of the various granites in the neighbourhood of Aberdeen are very striking. In the main mass, at a considerable distance from the stratified rocks, v = about $\cdot 04$; and the great difference between vacuities of that size and those in the fluid-cavities in the quartz of the trachyte of Ponza will be seen on comparing fig. 116 with fig. 100, both magnified to the same extent. If the pressure were not taken into account, this would indicate a temperature lower than that of boiling water; but if the temperature was the same as that at which the quartz of the trachyte of Ponza crystallized, the pressure must have been equal to about 78,000 feet of rock. If the temperature was higher, the pressure must have been still greater. In the exterior part close to the stratified rocks v = $\cdot 071$, which indicates a pressure of 69,000 feet. This is the same as for the porphyries, but 9000 feet less than for the centre of the granite, which appears to me a very reasonable result, since it is extremely probable that the pressure on the outside would be considerably less than in the interior. In some more recent veins of very coarse-grained granite intersecting the other, v = $\cdot 166$, which corresponds to a pressure of only 42,000 feet, as though the conditions under which it was consolidated differed materially from the other case, either on account of the elevation of the rocks, or some other physical change. The general mean of all my measurements in the main masses of granite in the south border of the Highlands from Aberdeen to Ben Cruachan indicates a pressure of about 76,000 feet, or 7000 feet more than the quartzose porphyry-dykes. The number of cavities is also much less than in those granites formed under a less pressure, as if the crystallization had taken place more slowly, on account of a more gradual cooling, which would probably be the case, if the thickness of the superincumbent rocks was greater.

Comparing these conclusions and that derived from a comparison of the metamorphic rocks, we have as under:—

The granites of the Highlands indicate a pressure of 26,000 feet of rock more than those of Cornwall.

The elvans of the Highlands indicate a pressure of 28,700 feet of rock more than those of Cornwall.

The metamorphic rocks indicate a pressure of 23,700 feet of rock more than those of Cornwall.

This remarkable agreement cannot be the result of mere accident, but I think clearly points out that the consolidation of the granites and elvans, and the metamorphosis of the stratified rocks, took place in the Highlands at a very much greater depth than in Cornwall,—

a conclusion which appears to me to agree extremely well with the general association of facts on a large scale.

Of course all the pressures deduced as above involve any error there may be in the amount of compression supposed to be the most probable for highly heated water, and would be materially altered by variations in the temperature; but, considering all the circumstances of the case, it appears to me as likely that they are too little as too great, and, therefore, at present we cannot do better than adopt them provisionally.

In order that the various results may be compared more conveniently, I subjoin the following Table. The first column gives the temperature in degrees Centigrade requisite to expand the fluid so as to fill the cavities, if the pressure was not greater than the elastic force of the vapour, which, of course, is the lowest temperature at which the rock can have been consolidated, since the excess of pressure could not be less than nothing. In the other column is given the pressure in feet of rock requisite to compress the fluid so much that it would just fill the cavities at 360°, being, therefore, the actual pressure, if in each case the rock was consolidated at that temperature.

	Tempera- ture.	Pressure.
Trachyte of Ponza.....	356	4,000
Elvan at Gwennap	320	18,100
Granite at St. Austel	256	32,400
Mean of the Cornish elvans	250	40,300
More recent veins of granite at Aberdeen	245	42,000
Mean of Cornish granites	216	50,000
Elvan at Swanpool, near Falmouth.....	203	53,900
Granite from the Ding Dong Mine, near Penzance	162	63,600
Mean of the Highland porphyry-dykes.....	135	69,000
Exterior of the main mass of the granite at Aberdeen	135	69,000
Mean of the Highland granites	99	76,000
Centres of the main mass of the granite at Aberdeen...	89	78,000

It will thus easily be seen that, if pressure is not taken into account, there is a gradual decrease in temperature on passing from trachyte to granite; whilst if, as is far more probable, the temperature was nearly the same, the pressure increases in passing from trachyte through elvans to granite; and I think all geologists will agree with me in thinking that this is a very satisfactory result.

It therefore appears that the fluid-cavities indicate that all the elvans and granites I have hitherto examined were consolidated under pressures varying from about 18,000 to 78,000 feet of rock. These are certainly very great pressures; but, bearing in mind that they probably represent the forces concerned in the elevation of mountains, I think they are sufficiently reasonable. They also correspond very well with the pressure under which, in many cases, the lava at the foci of modern volcanic activity must become solid, as is well illustrated by the Peak of Teneriffe. It is upwards of 12,000 feet high, and the bottom of the ocean from which the volcanic district of the Canary Islands rises is 12,000 feet deep, and at no great distance westward it is 16,800 feet (Lieut. Maury's Physical Geo-

graphy of the Sea, 1st edition, plate xi.). If, as is sufficiently probable, the lava at a great depth extends some distance westward of the exhibition of volcanic activity at the surface, there must be a considerable thickness of rock between it and the bottom of the ocean, or else it could not, as it does, resist the pressure of a column of lava at least 20,000 feet high, when an eruption takes place from the Peak. If a few thousand feet is sufficient for that purpose, when the internal forces are relieved by an eruption of lava near the summit of the Peak, there would be a pressure of an actual column of at least 30,000 feet of melted rock on the lava at the base. Probably, however, part of the lava is at a greater depth than a few thousand feet below the general bed of the ocean, and the pressure may be more when not relieved by an eruption, and therefore it appears to me reasonable to suppose it might in some cases be solidified under double that pressure. At all events the best conclusions we can deduce from this modern volcano agree so well with the amounts calculated from the fluid-cavities in granitic rocks, that I cannot but conclude that the pressure under which granites and elvans were consolidated was of the same *order of magnitude* as the pressure under which the lava of modern volcanos must be solidified at the foci of their activity, as though these rocks were the unerupted lavas of ancient volcanos, variously protruded amongst the superincumbent strata.

As is well known, the temperature of rocks increases with the depth; and it becomes an interesting question to determine whether the rate of increase might give the temperature deduced from the fluid-cavities in the quartz of the trachyte of Ponza, at a depth which would correspond with the amount of pressure deduced from a comparison with those in the quartz of granite. According to M. Cordier (*Edinburgh New Philosophical Journal*, 1828, vol. iv. p. 273), the rate of increase is not uniform in all countries, being in some as rapid as 1° F. for each 24 feet, and in others not more than 1° for each 104 feet, as if owing to an irregular distribution of the subterranean heat. If the increase was the same for great depths, there would be a temperature of 630° F. at a depth varying from 15,100 to 65,500 feet. According to Mr. R. W. Fox (*British Association Report for 1857*, p. 96), the rate of increase in various mines in Cornwall is by no means uniform, but varies from 1° for each 32 feet to 1° for 71 feet, being on an average 1° for 49 feet, which would give a temperature of 680° at a depth of 30,900 feet. However, he states expressly that the increase is more rapid in shallow than in deep mines; and, according to information kindly furnished to me by Mr. Robert Hunt, the rate is 1° for every 50 feet in penetrating through the first 100 fathoms; for the next 100 fathoms 1° for 70 feet; whilst, when the depth exceeds 200 fathoms, it is only 1° for each 85 feet of depth. If this be the true rate of increase far below the surface, there would be a temperature of 680° F. at a depth of about 53,500 feet. These results will be best compared with the pressures under which granites were most probably formed, by means of the following Table:—

<i>Depth in Feet.</i>		<i>Pressure in feet of Rock.</i>	
Cordier's results	15,100 to 65,500	Various granites	32,400 to 78,000
Fox's mean	30,900	Cornish granites	32,400 ,, 63,600
Hunt's results	53,500	Mean of ditto.....	50,000

It will thus be seen that, if the rate of increase to a very great depth is the same as near the surface, the calculated temperature would occur at a less depth than corresponds with the calculated pressure, although the general order of magnitude of the two quantities is very similar; whilst, if the rate of increase to a very great depth is the same as below 200 fathoms, it would occur in Cornwall at a depth which corresponds remarkably well with the calculated mean pressure for the granites in that district. Very variable elements enter into the calculations; there are many possible sources of error; the number of feet of rock expressing the pressure might differ very considerably from the actual depth, and the distribution of heat in the earth's crust, when the granite was consolidated, might not be the same as now. Still, however, we must admit that the rate of increase in the heat of the rocks indicates that the temperature at which the quartz of granite probably crystallized would in all probability occur at a depth agreeing very well with the pressure to which it appears to have been exposed. Since, then, as I have already shown, the metamorphic rocks near the granite crystallized at about the same temperature as the granite itself, I think, even if we do not give our entire assent, we must acknowledge that the above fact is a strong argument in favour of the supposition that the temperature concerned in the normal metamorphosis of gneissoid rocks was due to their having been at a sufficiently great depth beneath superincumbent strata.

It will, therefore, be seen that the application of the principles I have described leads to many very striking and remarkable results, which agree so extremely well amongst themselves and with other general circumstances, that I cannot for one moment believe them to be the effect of accident. On the contrary, they clearly point to definite laws; and though, in the infancy of such a wide subject, involving many very difficult physical questions, considerable errors cannot be avoided, yet the character of the results indicates that the general principles are correct.

With respect, then, to minerals and rocks formed at a high temperature, my chief conclusions are as follows. At one end of the chain are erupted lavas, indicating as perfect and complete fusion as the slags of furnaces, and at the other end are simple quartz veins, having a structure precisely analogous to that of crystals deposited from water. Between these there is every connecting link, and the central link is granite. When the water intimately associated with the melted rock at great depths was given off as vapour whilst the rock remained fused, the structure is analogous to that of furnace slags. If, however, the pressure was so great that the water could not escape as vapour, it passed as a highly heated liquid holding different materials in solution up the fissures in the superincumbent rocks, and deposited various crystalline substances to form mineral

veins. It also penetrated into the stratified rocks, heated, sometimes for a great thickness, to a high temperature, and assisted in changing their physical and chemical characters, whilst that remaining amongst the partially-melted igneous rock served to modify the crystalline processes which took place during its consolidation. These results are all derived from the study of the microscopical structure of the crystals; but my own observations in the field lead me to conclude that they agree equally well with the general structure of the mountains themselves, and serve to account for facts that could not have been satisfactorily explained without the aid of the microscope. And here I cannot but make a few remarks in conclusion on the value of that instrument, and of the most accurate physics in the study of physical geology. Although with a first-rate microscope, having an achromatic condenser, the structure of such crystals and sections of rocks and minerals as I have prepared for myself with very great care can be seen by good day-light as distinctly as if visible to the naked eye, still some geologists, only accustomed to examine large masses in the field, may perhaps be disposed to question the value of the facts I have described, and to think the objects so minute as to be quite beneath their notice, and that all attempts at accurate calculations from such small data are quite inadmissible. What other science, however, has prospered by adopting such a creed? What physiologist would think of ignoring all the invaluable discoveries that have been made in his science with the microscope, merely because the objects are minute? What would become of astronomy if everything was stripped from it that could not be deduced by rough calculation from observations made without telescopes? With such striking examples before us, shall we physical geologists maintain that only rough and imperfect methods of research are applicable to our own science? Against such an opinion I certainly must protest; and I argue that there is no necessary connexion between the size of an object and the value of a fact, and that, though the objects I have described are minute, the conclusions to be derived from the facts are great.

DESCRIPTION OF PLATES XVI. to XIX.

The number of times that the objects are magnified in linear dimensions is expressed by the sign \times . The figures with a dotted outline are portions of crystals, and the rest are entire separate cavities and crystals.

PLATE XVI.

CAVITIES IN CRYSTALS FORMED ARTIFICIALLY.

§ 1. *From solution in Water.*

- Fig. 1. A single crystal of chloride of potassium deposited on slow evaporation in winter. $\times 60$.
- Fig. 2. A portion of the edge of a crystal of chloride of sodium, $\times 200$, showing how the fluid-cavities are formed.
- Fig. 3. A fluid-cavity in chloride of potassium formed at the ordinary temperature. $\times 800$.
- Figs. 4, 5. Fluid-cavities in chloride of sodium formed at the ordinary temperature. 4, $\times 800$; 5, $\times 1000$.

- Fig. 6. A portion of a crystal of chloride of potassium formed at 100° C. $\times 150$.
 Fig. 7. A fluid-cavity in chloride of sodium formed at 100° C. $\times 400$.
 Figs. 8, 9, 10. Fluid-cavities in chloride of potassium formed at 100° C. 8, $\times 300$; 9, $\times 400$; 10, $\times 200$.
 Figs. 11, 12, 13. Fluid-cavities in chloride of sodium formed at 100° C., in a strong solution of bichromate of potash. 11, 13, $\times 1000$; 12, $\times 600$.
 Figs. 14, 15, 16. Crystals of bichromate of potash and attached fluid-cavities, in chloride of sodium formed at 100° C., in a concentrated solution of the bichromate. 14, 15, $\times 100$; 16, $\times 70$.
 Fig. 17. A fluid-cavity in chloride of sodium formed at 100° C., in a concentrated solution of bichromate of potash. $\times 800$.
 Figs. 18, 19. Fluid-cavities in chloride of sodium formed at 100° C., in a strong solution of chloride of potassium. 18, $\times 800$; 19, $\times 1200$.
 Fig. 20. A fluid-cavity in chloride of sodium formed at 100° C., in a strong solution of hydrochloride of ammonia. $\times 800$.
 Figs. 21, 22. Fluid-cavities in nitrate of potash formed at the ordinary temperature. 21, $\times 400$; 22, $\times 200$.
 Fig. 23. A fluid-cavity in binoxalate of ammonia formed at the ordinary temperature. $\times 150$.
 Figs. 24, 25. Fluid-cavities in sulphate of zinc formed at the ordinary temperature. $\times 130$.

PLATE XVII.

- Fig. 26. A portion of a crystal of alum formed at 50° C. $\times 100$.
 Figs. 27, 28. Fluid-cavities in alum formed at 50° C. 27, $\times 100$; 28, $\times 400$.
 Fig. 29. A gas-cavity in a portion of a crystal of alum formed at 50° C. $\times 50$.
 Figs. 30, 31. Fluid-cavities in alum that have lost water by drying. 30, $\times 800$; 31, $\times 400$.
 Fig. 32. A portion of a crystal of bichromate of potash, with bands of fluid-cavities. $\times 200$.
 Fig. 33. A fluid-cavity in bisulphate of potash, which totally reflects the transmitted light. $\times 200$.
 Figs. 34, 36, 37. Fluid-cavities in chloride of sodium formed above the level of the liquid at 100° C. 34, $\times 800$; 36, 37, $\times 1000$.
 Fig. 35. A gas-cavity in chloride of sodium formed above the level of the liquid at 100° C. $\times 600$.

§ 2. Formed by Sublimation.

- Fig. 38. A gas-cavity in hydrochlorate of ammonia. $\times 600$.
 Fig. 39. A gas-cavity in corrosive sublimate. $\times 400$.

§ 3. Formed from a state of Igneous Fusion.

- Fig. 40. A portion of a crystal of basic silicate of protoxide of iron, from a copper slag. $\times 200$.
 Figs. 41, 42, 43. Glass-cavities in a portion of a crystal of basic silicate of protoxide of iron, from a copper slag. 41, $\times 1600$; 42, $\times 400$; 43, $\times 600$.
 Figs. 44, 45. Part glass-, part stone-cavities in a portion of a crystal of basic silicate of protoxide of iron, from a copper slag. 44, $\times 1200$; 45, $\times 1600$.
 Fig. 46. A stone-cavity in a portion of a crystal of basic silicate of protoxide of iron, from a copper slag. $\times 1600$.
 Fig. 47. A stone-cavity in pyroxene, from a blast-furnace slag. $\times 800$.
 Fig. 48. A glass-cavity in Humboldtite, from a blast-furnace slag. $\times 400$.

FLUID-CAVITIES IN NATURAL MINERALS.

- Figs. 49, 50, 51. In quartz of a vein at Mousehole, near Penzance. $\times 800$.
 Fig. 52. A fluid-cavity containing two fluids, in the quartz of a porphyry at Cove, near Aberdeen. $\times 2000$.

Figs. 53, 54, 55, 56. Fluid-cavities containing various crystals, in quartz replacing felspar, at Trelvalgan, near St. Ives, Cornwall. 53, $\times 1600$; 54, 55, 56, $\times 800$.

PLATE XVIII.

GLASS- AND STONE-CAVITIES IN THE MINERALS OF ERUPTED LAVAS, &c.

- Figs. 57, 58, 59, 60, 61, 62. Glass-cavities in the felspar of a porphyritic pitchstone in Arran. 57, $\times 300$; 58, $\times 330$; 59, $\times 360$; 60, $\times 1600$; 61, $\times 600$; 62, $\times 400$.
- Fig. 63. A cavity of a different character in the felspar of a porphyritic pitchstone in Arran. $\times 600$.
- Fig. 64. A glass-cavity in a prismatic crystal in a porphyritic pitchstone in Arran. $\times 300$.
- Figs. 65, 66. Glass-cavities attached to crystals in the augite of the lava of Vesuvius. 65, $\times 500$; 66, $\times 400$.
- Fig. 67. A stone-cavity attached to a crystal in the leucite of the lava of Vesuvius. $\times 300$.
- Figs. 68, 69, 70. Stone- and glass-cavities in the leucite of the lava of Vesuvius. 68, $\times 600$; 69, 70, $\times 800$.
- Figs. 71, 72. Stone-cavities in the felspar of the trachyte of Ponza. $\times 800$.
- Figs. 73, 74. Glass-cavities in the augite of a trappean rock at Balloch, Dumbarton. 73, $\times 450$; 74, $\times 600$.
- Fig. 75. A glass-cavity in the augite of a trappean rock near Glasgow. $\times 600$.
- Figs. 76, 77. Altered glass- or stone-cavities in the felspar of a porphyritic greenstone at Arthur's Seat, near Edinburgh. 76, $\times 400$; 77, $\times 200$.

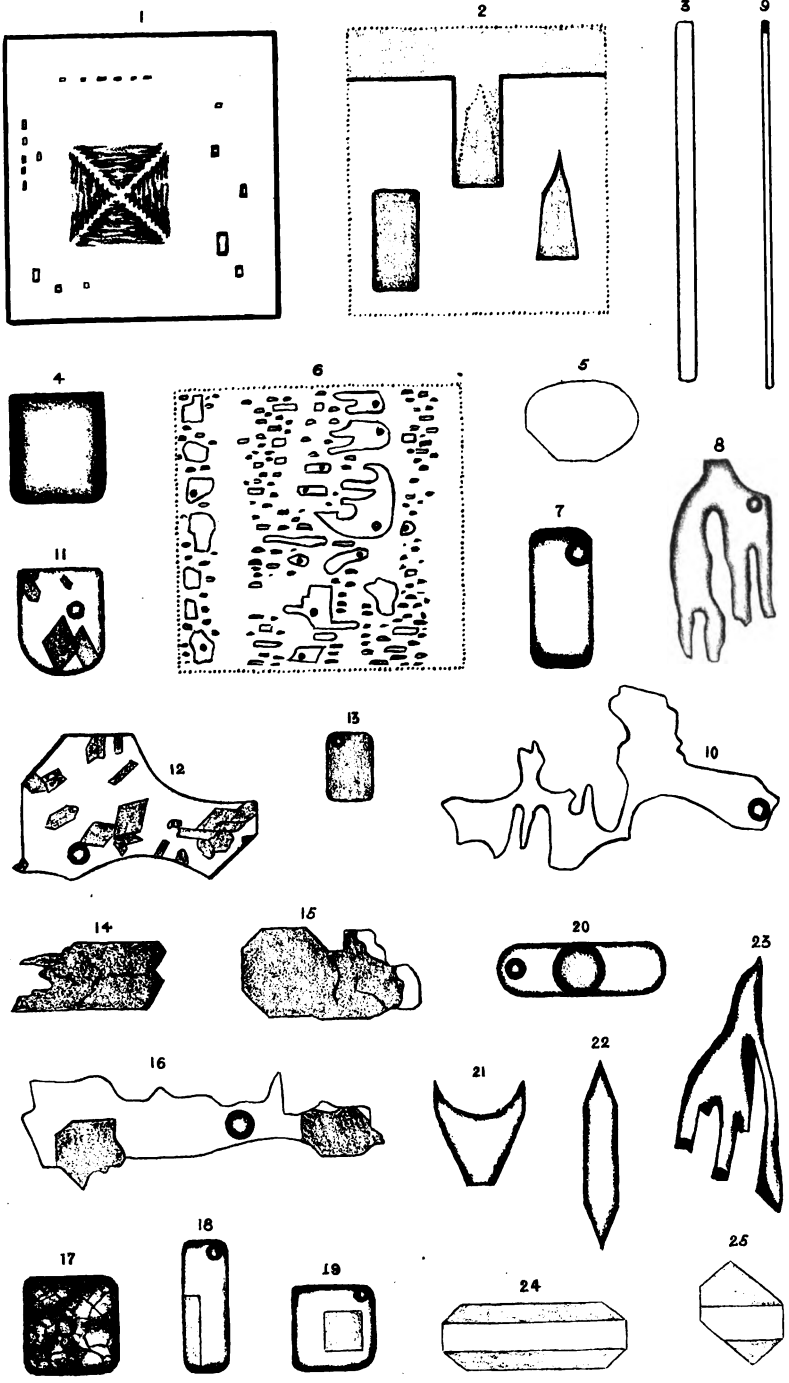
FLUID-, GAS-, VAPOUR-, STONE- AND GLASS-CAVITIES IN MINERALS FORMED BY THE COMBINED ACTION OF WATER AND IGNEOUS FUSION.

- Fig. 78. A fluid-cavity in the calcite of a block ejected from Vesuvius. $\times 300$.
- Figs. 79, 80, 83, 85. Fluid-cavities in the nepheline of a block ejected from Vesuvius. $\times 1000$.
- Figs. 81, 82, 84. Fluid-cavities in the nepheline of a block ejected from Vesuvius, after having been heated to a more or less bright red heat.
- Figs. 86, 87. Gas-cavities in the nepheline of a block ejected from Vesuvius, in a natural state. 86, $\times 1000$; 87, $\times 400$.
- Fig. 88. A vapour-cavity in the nepheline of a block ejected from Vesuvius. $\times 800$.

PLATE XIX.

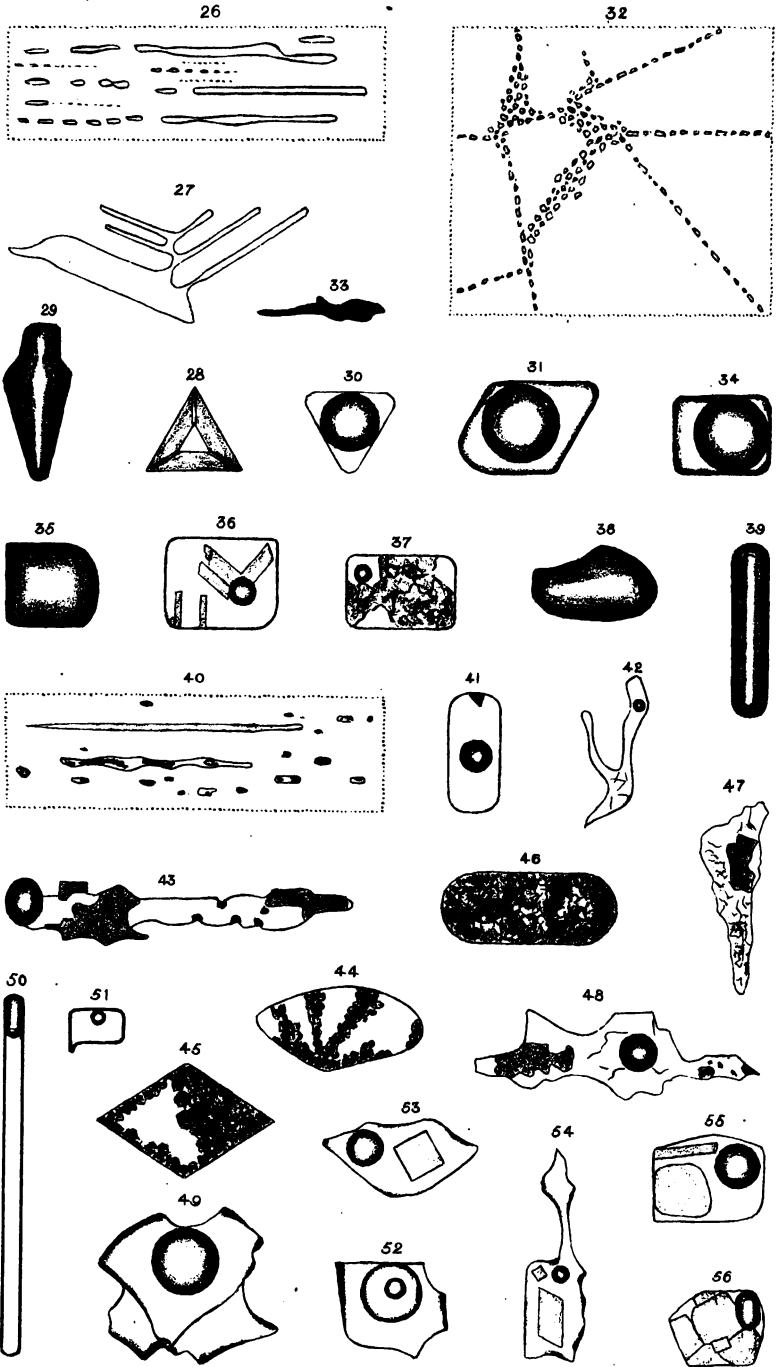
- Figs. 89, 90. Glass-cavities in the nepheline of a block ejected from Vesuvius. 89, $\times 400$; 90, $\times 1200$.
- Fig. 91. The cavity, fig. 90, after having been heated to bright redness.
- Figs. 92, 93. Fluid-cavities in the idocrase of a block ejected from Vesuvius. $\times 1200$.
- Figs. 94, 95. Fluid-cavities in the felspar of a block ejected from Vesuvius. 94, $\times 800$; 95, $\times 1600$.
- Fig. 96. A fluid-cavity in the felspar of a block ejected from Vesuvius, with much enclosed vapour. $\times 500$.
- Fig. 97. A vapour-cavity in the felspar of a block ejected from Vesuvius, out of focus in the centre. $\times 500$.
- Fig. 98. A glass-cavity in the felspar of a block ejected from Vesuvius, out of focus in the centre. $\times 400$.
- Fig. 99. A stone-cavity in the felspar of a block ejected from Vesuvius, out of focus in the centre. $\times 500$.
- Figs. 100, 101. Fluid-cavities in the quartz of a trachyte from Ponza. 100, $\times 2000$; 101, $\times 800$.
- Fig. 102. A fluid-cavity in the quartz of a trachyte from Ponza, $\times 1600$, so placed that the bubble totally reflects the transmitted light.
- Fig. 103. A stone-cavity in the quartz of a trachyte from Ponza. $\times 400$.

- Figs. 104, 105. Stone-cavities in the quartz of an elvan near Penrhyn, Cornwall. 104, $\times 250$; 105, $\times 800$.
- Fig. 106. A stone-cavity attached to a crystal of schorl in the quartz of an elvan near Penrhyn, Cornwall. $\times 400$.
- Fig. 107. A stone-cavity attached to a vapour- or gas-cavity in the quartz of an elvan near Gwennap, Cornwall. $\times 800$.
- Fig. 108. A fluid-cavity in the quartz of an elvan near Gwennap. $\times 2000$.
- Figs. 109, 110. Fluid-cavities in the quartz of an elvan near Gwennap, enclosing or attached to crystals of schorl. $\times 1200$.
- Fig. 111. A portion of the quartz of the granite at St. Austel, Cornwall, $\times 200$, with many fluid-cavities, and one vapour- or gas-cavity.
- Fig. 112. A fluid-cavity in the felspar of the granite at Penrhyn, Cornwall. $\times 1600$.
- Fig. 113. A fluid-cavity in the mica of a granite-vein at Polmear Cove, Cornwall. $\times 1600$.
- Figs. 114, 115. Fluid-cavities in the quartz of the granite from the Ding Dong Mine, near Penzance. 114, $\times 2000$; 115, $\times 800$.
- Fig. 116. A fluid-cavity in the quartz of the main mass of granite at Aberdeen. $\times 2000$.
- Fig. 117. A stone-cavity in the quartz of the granite at St. Austel. $\times 1000$.
- Fig. 118. A stone-cavity in the quartz of a rather coarse-grained granite near Cape Cornwall. $\times 800$.
- Fig. 119. A stone-cavity in the quartz of the granite at St. Austel, with radiating cracks. $\times 600$.
- Fig. 120. A stone-cavity in the felspar of the granite at Lamorna, near Penzance. $\times 800$
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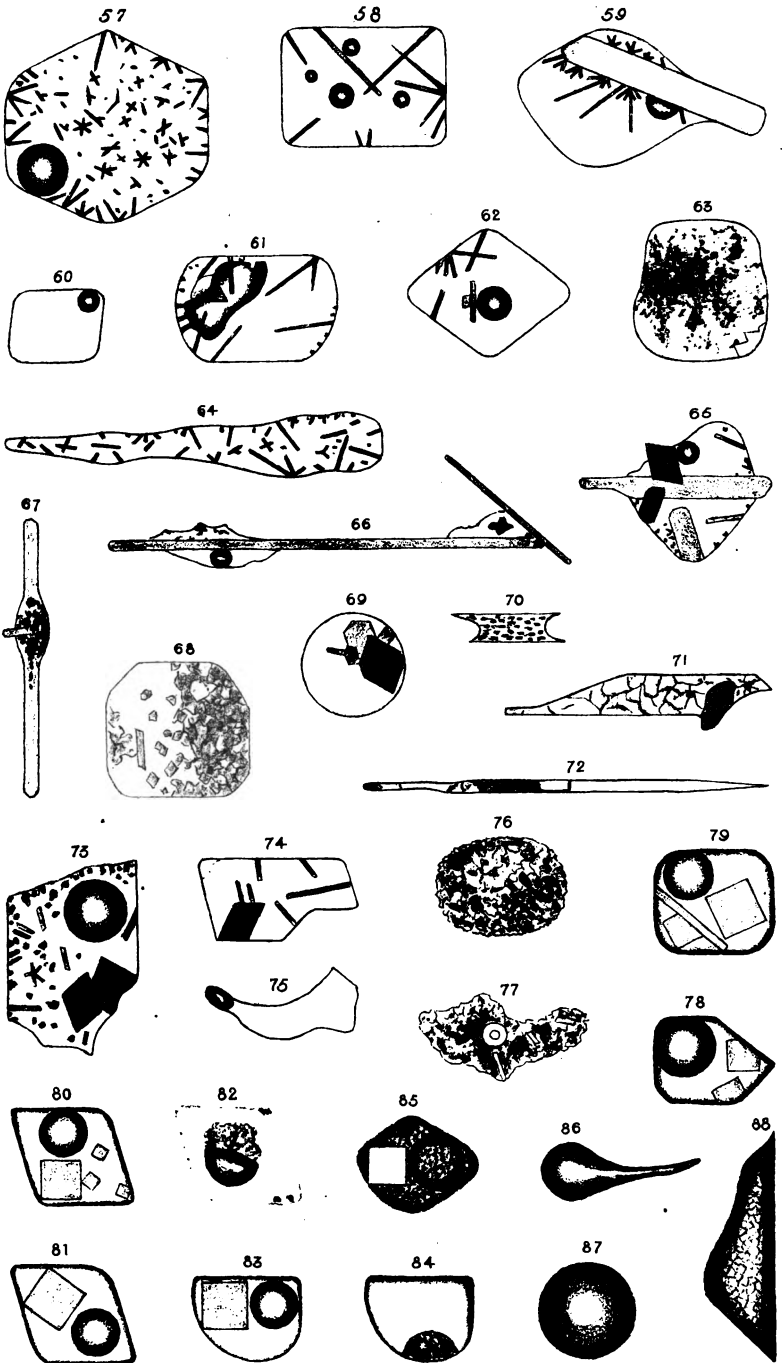
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STRUCTURE OF CRYSTALS.



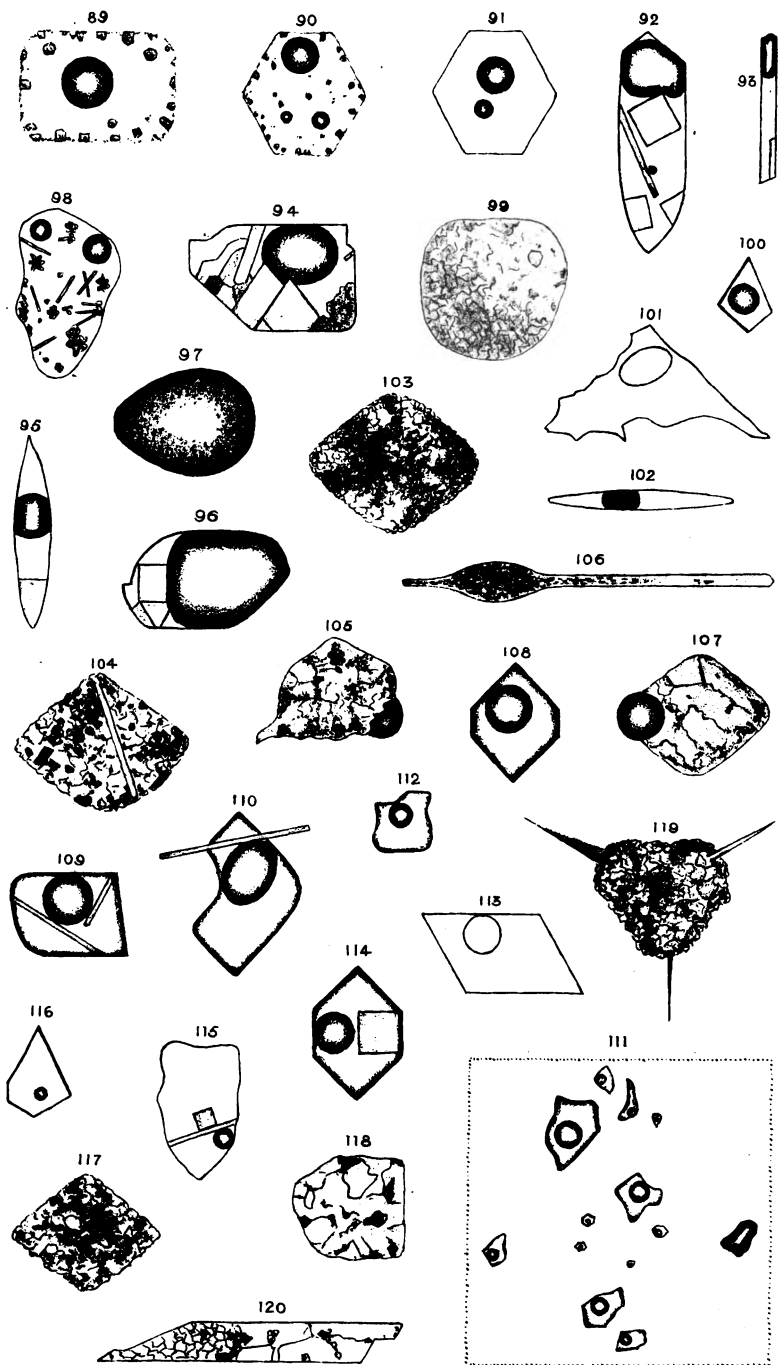
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