THE MINERALOGICAL MAGAZINE
AND
JOURNAL OF
THE MINERALOGICAL SOCIETY.

No. 91. December, 1920. Vol. XIX.

The fibrous Gypsum of Nottinghamshire.

(*With Plate I.*)

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[Read June 15, 1920.]

I. INTRODUCTION.

THE well-known gypsum deposits of Nottinghamshire occur in the upper Keuper marls. All the workable deposits are to be found in a belt of country running parallel to the Trent, and south of it, stretching from Newark on the north-east to Chellaston in Derbyshire on the south-west.

In the neighbourhood of Newark continuous beds of rock-gypsum are common; between Cropwell Bishop, six miles S.E. of Nottingham, and Gotham the main deposits are in the form of nodules; whilst at Chellaston a peculiar deposit[1] of very fine-grained gypsum is quarried for alabaster. Associated with these deposits, and often occurring as the only form, are veins of fibrous gypsum, or 'satin-spar', reaching their greatest perfection at East Bridgford, half-way between Nottingham and Newark, where this type is mined for the manufacture of ornaments.[2]

[1] B. Smith, The Chellaston Breccia...Quart. Journ. Geol. Soc., 1919, vol. 74, p. 174 (Min. Abstr., vol. 1, p. 105).

[2] For a general account of the deposits see: A. T. Metcalfe, Trans. Inst. Min. Eng., 1896-1897, vol. 12, p. 107; Special Rep. Min. Res. Great Britain, Mem. Geol. Surv., 1915, vol. 3, Gypsum and Anhydrite, p. 20.

A rapid glance over a collection of fibrous mineral-veins reveals many features, which, although common to fibrous veins, are not generally to be observed in ordinary mineral-veins. As further study is made, a strong impression grows that the processes operating to produce fibrous veins are much the same, whatever the mineral involved, and under whatever circumstances the veins may occur. The chief minerals found in veins of this type are chrysotile-asbestos, gypsum, and calcite.

Considerable attention has been given recently to the formation of these veins. In some respects the Nottingham occurrence appears to be peculiar, and it is hoped that a detailed study of these veins may throw some further light on the origin of the type.

II. Description of the Fibrous Veins.

A. Macroscopic Examination.

Type.—All the gypsum veins of the district are of the 'cross-fibre' type, i. e. their fibres extend from wall to wall transversely. Veins of the 'slip-fibre' type with fibres arranged parallel to the walls are unknown. Some veins that apparently have a compact texture are seen on closer examination to be really of fibrous character.

Thickness.—The veins vary considerably in thickness from thin strings a tenth of an inch to veins several inches thick. East Bridgford must be regarded as the type-locality, for there the veins attain both their greatest perfection and their maximum thickness. East Bridgford veins have been found 9 inches thick, although they are usually less than this, and in the rest of the district anything over 3 inches is rare. Cross-fibre asbestiform veins are limited to a few inches, and fibrous calcite, or 'beef', at Charmouth, Dorsetshire, never exceeds 3 inches.[1]

Vein Surface and Walls.—The surface of the vein cleaned of adhering marl has a dull opaque appearance and feels slightly rough to the touch. This is due to the fibres differing slightly in length, although there is no evidence that they project unequally into the marl except on a microscopic scale. Otherwise, the surface is plane and regular. When veins run into one another at a low angle, as they occasionally do, the surface may then be corrugated. This type of surface is, perhaps, more characteristic of thick, vertical veins which usually cut across a number of horizontal and oblique veins. In section, the walls show sharp boundaries, and, unless the specimen is weathered, the marl is readily

[1] I am indebted to the generosity of Dr. W. D. Lang for information concerning 'beef' veins.

separated from the vein. Occasionally, the walls show angular irregularities, and then the opposite walls would doubtless fit together, especially with the help of included lenticles of marl (fig. 1 *a*).

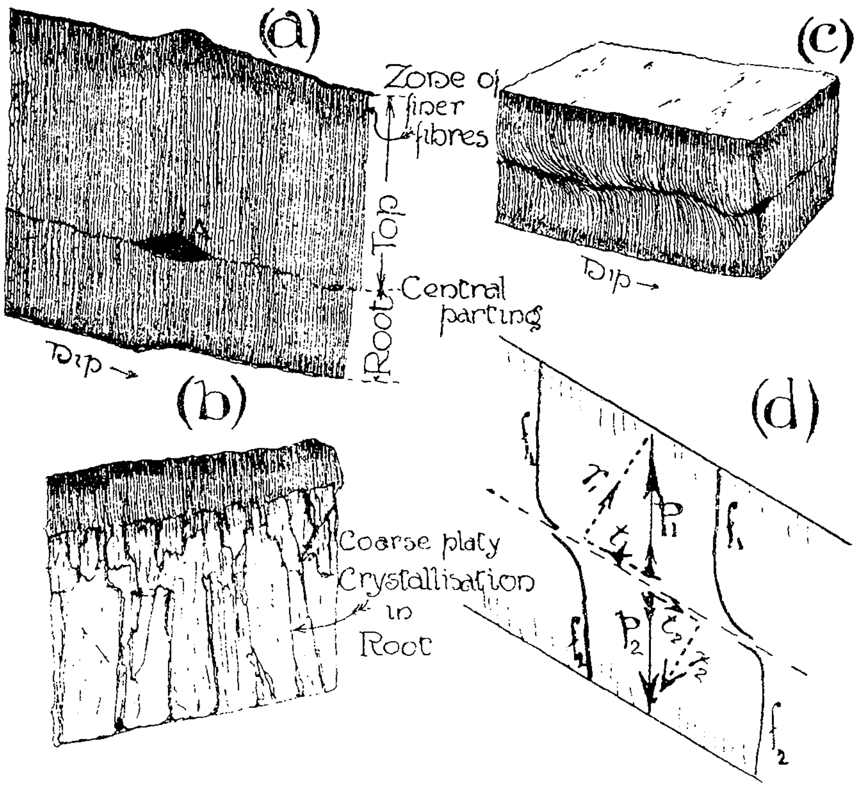

FIG. 1.—(*a*) Fibrous gypsum vein showing typical structure. Cropwell Bishop, Nottinghamshire.

(*b*) Fibrous gypsum vein showing coarse crystallization of 'root'. Radcliffe-on-Trent.

(*c*) Fibrous gypsum vein showing bending of fibres at central parting. Newark.

(*d*) Diagram of forces producing the bending in (*c*).

The surface of the walls separated from the vein shows no signs of slickensiding, or other evidence of movement relative to the vein.

Central Parting.—A line of division runs through the vein, roughly parallel to the walls, as shown in fig. 1 *a*. It is marked, in most cases, by inclusions of red or blue marl, but sometimes it can be traced only as a line of delicate colouring. This plane of division may be called—following Taber and others—the 'central parting'. It is very rarely absent, for I have only two exceptions clearly recorded in my field-notes. The central parting divides the vein into two portions, the upper of which is called by the Bridgford miners the 'top', and the lower the 'root'. It will be convenient to adopt these terms, which are illustrated in fig. 1 *a*.

The ratio of the thickness of 'top' to 'root' varies. The Bridgford veins always have the 'top' thicker than the 'root', and, as a rule, it is from three to four times as thick. In vertically-placed veins the central parting is usually midway between the walls, but in general the ratio may have any value. It frequently varies in the same vein, and then the parting pursues a sinuous course relative to the walls. For the district as a whole it may be stated that the majority of veins show a thickness of 'top' greater than that of the 'root'. A similar statement applies to the 'beef' veins of Charmouth.

The inclusions of marl along the central parting may swell out into lenticles, as at *A*, fig. 1 *a*. These vary from a fraction of an inch to an inch in thickness. In plan they are roughly circular with a mean diameter about four times the thickness. Exceptionally the lenticle may have much larger dimensions. At East Bridgford one was 6 inches thick and 18 inches in diameter. At the junction, the 'top' passes over the lenticle and the 'root' beneath, as sketched in fig. 4 *a*. The central parting shows no division in these cases, thus contrasting with its behaviour when a vein passes a gypsum nodule (see p. 85). In fact, the marl lenticle is an enlarged part of the central line, and the vein in this respect rather differs from a branched vein. It thus happens occasionally that veins, apparently devoid of central partings and exceptions to the general rule, really conform to the normal type, but show an unusual feature in the central parting.

Direction of the Fibres.—A representative collection of hand-specimens reveals the curious fact that the fibres are not generally at right angles to the walls, and may be inclined at a considerable angle. The fibres, however, are parallel to one another except in a few isolated cases, and these are usually thick vertical veins. (See the veins sketched in fig. 1.)

Character of the Fibres.—The fibres are generally fine, and except in Bridgford specimens show a wedging longitudinally. The Bridgford fibres are remarkably straight and uniform, and wider than in the ordinary small veins. Occasionally, coarse platy crystals of selenite, 3 to 4 mm. wide occur; for example at Radcliffe-on-Trent (fig. 1 *b*) and in the Woodlands quarry, Chellaston, although doubtless they might be found in any exposure. The opacity of the sample is a good test of the fineness. The coarse Radcliffe sample is glass-clear; the Bridgford veins are translucent with a satiny lustre, whilst the ordinary veins are quite opaque. The coarse crystallization as a rule affects one portion of the vein only, and this is frequently the 'root'. It may be mentioned that the marl forming the walls is the same in texture whether in contact with coarse crystals or fine fibres.

Portions of the veins in contact with the walls are always more opaque than the rest of the vein. This is due to the fibrous structure in this region being finer (fig. 1 *a*). This finely fibrous character is made evident by artificially staining the vein, when the outer zone, owing to the capillary spaces between the fibres being more numerous, takes a deeper colour than the inner. The opacity, of course, is also due to the closer spacing of capillary pores. The boundary between this outer zone and the inner portion of the vein is rather sharp, showing as an irregular line on the face of the vein. It might at first glance be taken to be of the same character as the central parting, but there is no discernible colouring, and no macroscopic nor microscopic inclusions. The thickness of this zone varies from an inch downwards, and in some thin veins may extend nearly to the central parting. A similar structure can be seen in some specimens of 'beef'.

Bent Fibres.—Not infrequently, the fibres are bent at the central parting. I have seen no specimen where the fibres show any change of direction, either gentle or sharp, at any other portion of the vein. Moreover, the bending is always orientated relative to the inclination of the vein as shown in fig. 1 *c*.

B. Microscopic Examination.

Microscopic examination of thin sections cut from veins confirms the general structure and character revealed by the examination of hand-specimens.

Central Parting.—The delicate colouring, that marks this line in many hand-specimens, is seen to be due to the segregation of numerous minute particles of marl along the central parting (*AB* in fig. 2). These are seen best by reflected light. They are distributed in strings and patches between the ends of the crystals. Similar specks of marl can now and then be discerned sporadically distributed through the body of the vein. They are not included in the crystals, but always entangled between them.

Fibres.—The crystals seem in most cases to be elongated parallel to the vertical axis. They are flattened, sometimes conspicuously, parallel to the crystal-face (010). The fibrous structure seems to be due chiefly to the development of fine elongated crystals, but the (010) cleavage in some cases plays a part. Where exterior fine zones occur, they are probably due to the development of this cleavage, for in one slice this is well developed in an outside crystal, and at its end the cleavage-flakes are splayed outwards like a sheaf.

Strain Phenomena.—Evidences of strain are present in all thin sections, and are described in detail in the paragraphs below. The result of the examination shows that strain becomes more and more intense in all sections examined as the central parting is approached. Along this line the effects of pressure are generally strong, even the best commercial veins from East Bridgford are by no means free from these effects, for the portion adjacent to the central parting is rejected.

Bending.—Fibres are invariably bent at the central parting, and often broken (fig. 1 *c*). This bending may be slight; it may affect only one portion of the vein, but it is never quite absent. It may or may not be visible in the hand-specimen. Moreover, it is a curious fact that where the vein has an inclination sufficiently great to be detected, the direction of the bending shows the same relation to the inclination of the vein, a in the specimen drawn in fig. 1 *c*.

Irregular Extinction.—Shadowy extinctions between crossed nicols are common. Sometimes the shadows move parallel to the long axis, and may be due to the fibrous structure. Typical strain shadows without any particular orientation are also abundant.

Cone-in-cone Structure.—This structure is highly developed in specimens of 'beef' veins. There is nothing in gypsum approaching this in perfection, nevertheless there is a similar structure. In hand-specimens the fibres appear to wedge into one another towards the centre. Under the microscope, this longitudinal wedging is often pronounced, and crenulated margins are developed where the fibre-ends are in contact.

It may be mentioned that the development of glide-planes can also be sometimes observed, but they are, perhaps, not quite so frequently seen as might be expected.

Re-crystallization.—The most noteworthy effect of strain in these veins is re-crystallization. Peg-structure, and, in the bent zone at the centre, something resembling mylonite, are the early stages of it. Granulation between the fibres and at the central parting, where complete re-crystallization may result, is the second stage. Finally, clear prisms of selenite appear, and their long axes are placed at right angles to the direction of the fibres (see fig. 3).

Contact of Vein with Gypsum Nodules.—The general relations of veins to nodules will be described in the following section, but the microscopic description of the contact may be placed here.

In thin section the nodules of gypsum have a structure which may be described as 'porphyritic'. Large crystals, mainly showing prismatic habit and good crystal outlines, are set in a granular mosaic of equidimensional anhedral gypsum. The outside of the nodules appears in all

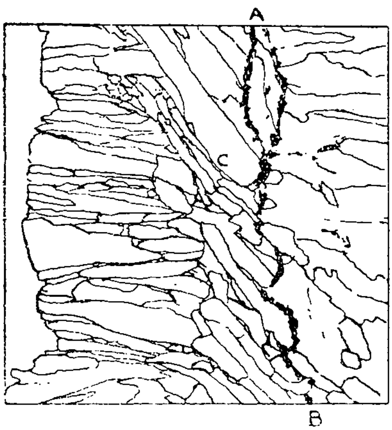

FIG. 2.

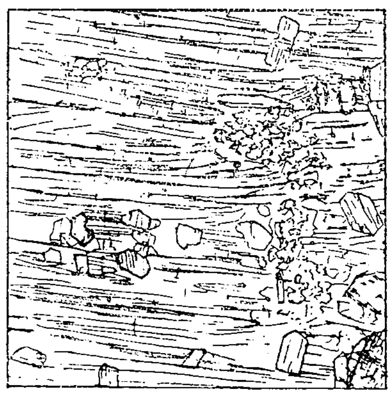

FIG. 3.

FIG. 2.—Fibrous gypsum vein showing plane of division with line of marl and bending of fibres. Cropwell Bishop, Nottinghamshire. × 13.

FIG. 3.—Junction of fibrous vein and nodule showing selenite prisms across the fibres. Cropwell Bishop. × 13.

cases to have a similar structure, but the porphyritic elements are larger and more irregular, whilst the matrix appears finer grained.

Where a fibrous vein is attached directly to the nodule, the contact zone is characterized by all the strain phenomena mentioned above (fig. 3). There has evidently been a considerable amount of re-crystallization. Portions of the fibrous mass are separated from the main vein by intervening patches of clear, granular gypsum. This detachment of fibres along the margin can be clearly observed in all hand-specimens showing the contact (fig. 4 *c*). There has undoubtedly been a transformation of the fibrous gypsum of the vein into the granular variety of the nodule. On the other hand, this cannot have taken place on a very great scale, as measurement of the variation in vein thickness as it passes the nodule clearly shows. There has been just enough re-crystallization to weld the vein securely to the nodule, so that it is only to be separated with difficulty, and never completely. When the vein is attached to a nodule in this way it is spoken of by the miners as 'mother of gypsum', and is detached from the nodule before grinding.

C. The Field Relations of the Veins.

Two types of field occurrence may be distinguished. In the one, gypsum is found only in the form of fibrous veins; but in the other these are associated with other types of gypsum deposit, which seem to exert considerable influence on the distribution of the veins.

Distribution.—The arrangement of the veins at some localities will now be described.

At East Bridgford, where the typical veins occur, there is no other type of gypsum present. The horizon is slightly lower in the Keuper than that of the main deposits between Nottingham and Newark. The deposit is mined by shallow shafts about 25 feet deep. The veins are not continuous over the district, but individual 'beds' are lenticular, and they die out to a 'feather-edge' in all directions. The deposits worked are rudely circular in plan, varying from 20 to 40 feet in diameter. They contain, as a rule, from two to three veins vertically above one another, each lying more or less in a horizontal plane. Where there are several veins in a 'bed', the individual veins are thinner than where there is one only. Impersistent thin beds of sandstone ('skerries') may occur. Sometimes these cover the deposits, but they are quite as frequently absent.

In Cotgrave old brick pit, gypsum veins are again seen without the presence of massive deposits. Here, however, the veins are thinner and less regular than at Bridgford. The largest vein is not more than an inch and a half thick, and many are mere strings a millimetre in thickness. They form a network over portions of the exposed face, and represent pillars of gypseous marl probably lenticular in shape. I made the following measurements of vein thickness at different parts of the same pillar:—

No. 1 set.—Total depth of section measured 2 feet; 16 veins with aggregate thickness 3·4 inches.

No. 2 set.—Total depth of section measured 2 feet; 6 veins with aggregate thickness 3·1 inches.

Thus the total thickness of gypsum per unit of depth is roughly the same: where there are many veins they are thinner individually, and thicker where there are few.

The veins on the quarry face are arranged in a polygonal pattern. The polygons are irregular and have their longest diagonal horizontal and their shortest vertical (Plate I, fig. 1). The appearance thus presented is the same as that of a gigantic septarian. The veins present the same arrangement whether cut in plan or any vertical plane, so that the polygons are sections of blocks of marl completely surrounded by fibrous veins.

At Cropwell Bishop fibrous veins are associated with gypsum nodules. The latter occur in well-defined beds or lines parallel to the bedding of the marls. The largest veins run between the nodules, whilst oblique and vertical veins intersect the marls between these larger veins. The polygonal arrangement noticed at Cotgrave can, perhaps, be seen in this disposition greatly modified, but the polygons have much shorter vertical diagonals and the horizontal members are generally thicker. The thickness of the veins in aggregate now and then almost equals the thickness of the nodules.

The relation of the fibrous veins to the nodules can be studied in the Gotham Company's mine here or in workings nearer Newark. The individual nodules vary in shape from ellipsoids to elongated masses with rounded ends. In the hand-specimen the rock is white; it has a saccharoidal texture, and sparkles with glittering prisms of selenite about a millimetre long. The fibrous veins behave in various ways towards a nodule.

(*a*) The vein may end abruptly at the thin end or 'feather-edge' of a nodule (fig. 4 *b*).

(*b*) In rare cases it may be seen to penetrate the nodule for greater or less distances.

(*c*) It may completely or partially pass the nodule. In this case the vein may either be separated from the nodule by a layer of marl, or it may rest directly on the nodule and be welded to it, as already explained, by re-crystallization of the contact zone. It may only pass a part of the way over the nodule, or may go right across. The pit foreman at Cropwell mentioned that they never found a fibrous vein passing below a nodule. He referred to the large nodules that are worked, for the smaller weighing only a few pounds are often entirely surrounded by fibrous veins. When a vein divides, passing both above and below one of these smaller nodules, the two portions of the vein are complete, each has a 'top' and 'root' separated by a central parting of the usual type (fig. 4 *c*). It is, in fact, typically a branched vein, and this behaviour should be compared with its attitude towards a lenticle of marl (fig. 4 *a*). The upper vein is very generally the thicker. Of the parts of the vein, that in contact with the nodule is invariably thinner whether it be 'root' or 'top'.

FIG. 1.—Group of fibrous gypsum veins with polygonal arrangement. The face is weathered and the fibres are not shown in the photograph, but in all the veins they are orientated vertically. Cotgrave brick pit, Nottinghamshire.

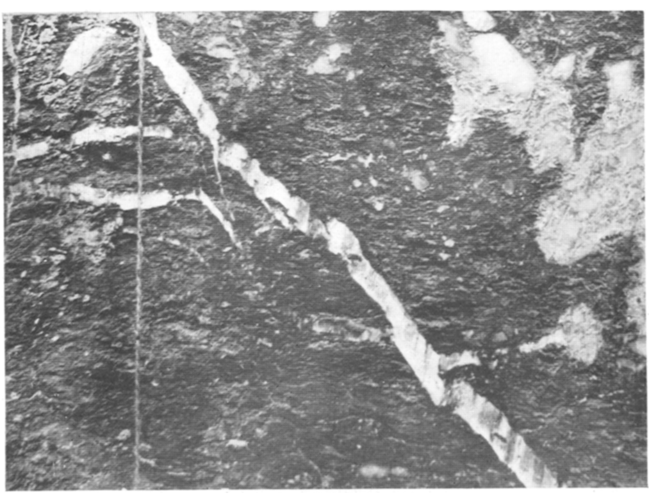

FIG. 2.—Fibrous vein showing the verticality of the fibres. (The vertical is indicated by a string to which a weight is attached.) Forman's quarry, Chellaston, Derbyshire.

W. A. RICHARDSON: VEINS OF FIBROUS GYPSUM.

Thus in one case the vein passing over the nodule was 2 inches thick, its 'top' was $1\frac{1}{2}$ inches, and the 'root' in contact with the nodule $\frac{1}{2}$ inch. The vein below the nodule was $\frac{3}{4}$ inch in total thickness, of which about $\frac{1}{4}$ inch was taken up by the 'top' in contact with the nodule. In the smaller nodule of fig. 4 *c*, the two veins are about equal in size, but the contact halves are much the smaller.

Verticality of the Fibres.—It has already been mentioned that the fibres

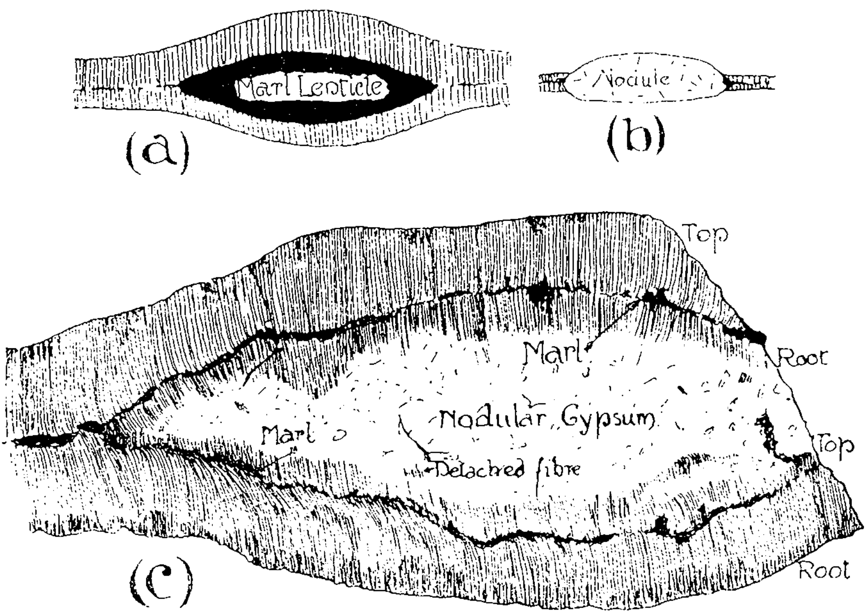

FIG. 4.—(*a*) Diagram of large lenticle of marl included in gypsum vein. East Bridgford, Nottinghamshire.
(*b*) Diagram of gypsum vein terminating at gypsum nodule. Cropwell Bishop, Nottinghamshire.
(*c*) Sketch of gypsum nodule completely surrounded by fibrous gypsum vein. Cropwell Bishop.

are not necessarily at right angles to the vein-walls. When an exposure of the veins is examined it is seen that the fibres are all parallel to one another no matter what may be the inclination or direction of the vein and, further, that they are all *vertical.* This feature is so striking, and so different from what might be expected that it first directed my attention to the subject of the origin of the veins (Plate 1, fig. 2). Sometimes the veins are roughly horizontal, but pursue a gently undulating course;

sometimes they abruptly change their direction; sometimes they divide over a lenticle of marl or compact gypsum, but in each case the fibres remain vertical. The behaviour of the fibres in veins that are quite vertical is instructive. Where these veins are thin, the fibres dip towards the central parting on both sides at a large angle giving the herring-bone structure seen in the vein from Chellaston alabaster quarries sketched in fig. 5 *a*. In general, the vertical veins are rather thick, and here the fibres grow both upwards and downwards from the central parting producing fibrous sheaves. The Keuper marls have only a small dip, but occasionally where there are small local folds the fibres appear to be at right angles to the original bedding-planes. The folds are so gentle, however, that this feature cannot be established with certainty, and the slight departure of some of the fibres from the vertical might well be due to accidental causes. The fibrous calcite of Charmouth always occurs along bedding-planes, and fibres are always at right angles to the walls, but if they depart from the vertical in any marked degree it is always in a noticeable fold.

I have, however, occasionally noted decided exceptions to this rule, scattered over the district. The most interesting cases were in the mines at Cropwell Bishop, where veins highly inclined intersect the marl beneath large nodules. The veins were thin and the fibres practically *horizontal*.

The fibres are stated by some observers, such as B. Smith and J. G. Goodchild, to be at right angles to the walls of the vein; by others, however, among whom may be mentioned A. Irving, attention has been drawn to the general verticality of the fibres throughout the district.[1]

The marl in the neighbourhood of gypsum deposits is a peculiar hard, compact marl, sometimes showing spheroidal weathering. Normally it breaks up into small cubes and finally becomes a stiff clay, indistinguishable from that formed by other types of marl. Whilst this type is not confined to gypsum deposits, it is almost the only kind of marl present; and I venture to think that the predominance of this hard, heavy marl is distinctly a feature of the gypsum beds.

[1] A. Irving, Proc. Geol. Assoc., 1876, vol. 4, p. 76. Geol. of the Country around Lincoln, Mem. Geol. Surv., 1888, p. 8. J. G. Goodchild, Proc. Geol. Assoc., 1888, vol. 10, p. 429. T. O. Bosworth, The Keuper Marls of Charnwood Forest. Leicester, 1912. B. Smith, Quart. Journ. Geol. Soc., 1919, vol. 74, p. 200.

III. The Origin of the Fibrous Veins.

At this stage it will be wise to separate out the features of these deposits that either bear especially upon their origin or call for special explanation. Such are the following:—

1. The general structure of the vein.
2. The fibrous character of the gypsum.
3. The limit in thickness noticeable in these veins.
4. The tendency to the vertical orientation of the fibres.
5. The various strain structures.

These features, except perhaps the vertical parallelism of the fibres, are shared by all other cross-fibre veins, whatever may be the mineral concerned. Hence all are doubtless the result of similar processes.

Different workers have advanced theories to account for some or all of the features presented. These theories may be summarized thus:—

1. The minerals are deposited from solutions circulating in open channels. G. P. Merrill advances this hypothesis in the case of asbestos, and B. Smith applies it to the formation of the fibrous gypsum of Nottinghamshire.

2. The position of the veins is determined by previous lines of fracture or jointing, but primarily due

   (*a*) according to R. P. D. Graham[1], to replacement of the walls;

   (*b*) to deposition from diffusing solutions, the force of crystallization pushing the walls apart. This is the theory of S. Taber.

With regard to these, replacement, as Taber in reply to Graham has pointed out, had no place in producing gypseous veins in marl.

Open Crack Theory.—Since this theory has been applied by B. Smith[2] to the deposits here considered, it will be sufficient to consider his views. It should be mentioned, however, that the subject of fibrous veins is only dealt with incidentally in a long paper on the peculiar deposit at Chellaston. His conclusions may be summarized thus:—

1. The gypsum was deposited in open cracks, growing at the same time from both walls.
2. The central parting is the meeting point of the two sets of fibres.
3. The girder-action of skerry bands protected the cracks and enabled them to keep open.
4. The veins are all of secondary origin and are probably still in process of formation.

The veins do not show any of the characteristics of spaces known to be

[1] R. P. D. Graham, Econ. Geol., 1917, vol. 12, p. 183 (Min. Abstr., vol. 1, p. 105).

[2] B. Smith, Quart. Journ. Geol. Soc., 1919, vol. 74, p. 200.

filled by deposition from circulating solutions. For example, drusy cavities in the centre of the veins are unknown. In some cases horizontal veins cover rudely circular areas of considerable extent. Whilst no doubt an overlying sandstone band, or a continuous bed of rock-gypsum would exert the protecting action mentioned, the veins show no tendency to fail when such are absent. The most serious defect of the open crack theory, however, is its failure to explain the general structure of the vein. Included lenticles along the central parting commonly attain an inch in diameter, and must have remained suspended in mid-air, whilst 'tender fibres . . . built a solid rampart across the gap'. (B. Smith, *loc. cit.*) The central discontinuous films and delicate colouring, due to minute particles of marl that mark the parting, present similar difficulties. It would be necessary to imagine that each fibre carried a particle of marl at its growing point, finally depositing its burden at the common meeting line of the fibres.

The Theory of S. Taber.[1] Taber elaborated a theory of lateral secretion to account chiefly for the origin of cross-fibre veins of asbestiform minerals, but he has extended it to similar veins of other fibrous minerals including gypsum. This undoubtedly explains many of the salient facts better than any other hypothesis yet advanced. The following is a summary of the chief points:—

1. Asbestiform structure is primarily determined by the physical conditions of growth, but is accentuated by excessive development of the prismatic cleavage.
2. The original fineness of fibre is dependent on the pore-spacing of the country-rock. Crystallization from the diffusing solution commences at each pore, fibres elongating therefrom in the direction from which material is accessible.
3. Fibres grow outwards in both directions from a plane determined in general by an incipient fracture. The inclusions along the central parting are fragments torn from the walls at the time of rupture.
4. Growing fibres make room for themselves by pushing apart their walls. Crystals during growth may exert a linear force of the same order as their crushing strength.
5. Growth of fibre follows the movement of the walls in direction. Sudden changes in the direction of the fibres and gradual bending are thus a record of the movements of the walls
6. Serpentine goes into solution under pressure, which may be enormous, due to alteration of the peridotite. The pressure produces exfoliation-cracks, along which fibrous veins of chrysotile are located.

The idea that crystallization proceeded outwards from a plane of rupture under the influence of directional feeding is adequate to explain the

[1] S. Taber, Proc. Nat. Acad. Sci. U.S.A., 1916, vol. 2, pp. 659–664; Trans. Amer. Inst. Min. Eng., 1918, vol. 57, pp. 62–98; Journ. Geol., 1918, vol. 26, pp. 56–73 (Min. Abstr., vol. 1, pp. 104, 105).

general structure of the veins and the production of a central parting with its suite of inclusions.

The serpentinization, with consequent expansion, is stated to be the original cause of the planes of rupture. The distribution of such planes, and of the fibrous veins that now mark them, should correspond to the strain distribution in such an expanding mass. In a previous paper[1] I have shown that these conditions would tend to produce primarily a radial system of cracks widening towards the outside of the mass. In a pretty experiment Taber encloses anhydrous cupric chloride in a sealed porous cup. The salt hydrated by capillary infiltration fractured the cup precisely in the same manner as the exterior of clay balls were fractured by the expansion of the internal core in my experiments. Therefore, if produced by an expanding mass, the veins should be arranged radially widening towards the outside of the rock-body, possibly accompanied by a secondary circumferential system of what Taber calls 'exfoliation' cracks. It seems, however, that there is not even an approximation to such a distribution. On the contrary, according to Dresser and Graham, the veins occur chiefly along ordinary major joint-systems, produced, there can be no reasonable doubt, by the cooling and consequent contraction of the original intrusion.[2]

That a centre of crystallization was started at each pore in the wall seems to be an assumption, that at any rate is not supported by examples from Nottinghamshire. This would mean that the capillary spacing of the walls determined the number and fineness of the crystals in a vein. Some gypsum veins (fig. 1 *b*) have large elongated crystals of selenite, and they are in contact with marl of the same texture as the finer crystals of other samples.

Whilst one may admit that Taber has established the existence of a linear force accompanying crystallization,[3] and that it is of the same order as the crushing strength of the crystals, it is an open question whether this is competent to push apart the rock walls. The crushing strength of fibrous gypsum veins in the laboratory is not high, but without doubt it must be much higher when provided in situ with lateral support. But under the same circumstance the resistance of the rock to providing the necessary room by compression must also be enormously increased. From

[1] W. A. Richardson, Mineralog. Mag., 1919, vol. 18, p. 330.

[2] J. A. Dresser, Canada, Geol. Survey, 1913, Mem. 22; R. P. D. Graham, Econ. Geol., 1917, vol. 12, p. 156.

[3] S. Taber, Amer. Journ. Sci. 1916, Ser. 4, vol. 41, pp. 532–556; Proc. Nat. Acad. Sci. U.S.A., 1917, vol. 3, pp. 297-302 (Min. Abstr., vol. 1, p. 104).

another standpoint it is generally admitted that minerals of flaky and tabular habit that crystallize out under considerable pressures are so orientated that their maximum length is at right angles to the pressure —one might, in fact, expect to find not veins of cross-fibre, but of slip-fibre type under such circumstances. Finally, as Graham remarked, if the rock has been compressed to the extent necessary, some evidence of the compressive strain should be present in the country-rock.

Having then briefly considered hypotheses already advanced, it remains for me to put forward proposals which appear more in harmony with the various features presented by the fibrous gypsum veins of Nottinghamshire, leaving workers more favourably situated to test their competence when applied to similar deposits elsewhere.

The Distribution of the Veins.—I am in agreement with B. Smith in considering that the spaces occupied by fibrous veins were provided by the contraction of the marls. The influence of changes in the sediments can be seen in the distribution of the cracks. Where separation along bedding-planes is rendered easy because of changes in texture, or to similar causes, as at East Bridgford, the principal veins lie along the bedding. The occurrence of gypsum masses along bedding-planes also favours easy separation, and we find thick veins running between the masses and along their margins. Where contraction takes place freely in a uniform medium the characteristic mud-crack structure may be developed, as at Cotgrave (Plate I, fig. 1). The causes of the dehydration of the marls leading to their contraction are obscure. Without doubt the sedimentation water from the Triassic lakes or seas was a highly concentrated saline solution, and possibly played a considerable part in the desiccation of the marls.

The Limit in thickness.—Professor C. G. Cullis drew my attention to the fact that cross-fibre veins are always limited to a few inches in thickness whatever may be the mineral concerned. He further pointed out that there is obviously a natural limit to the contraction of a medium, and consequently to the space available for veins. The size of the veins, therefore, would depend on the contractibility of the medium and the number of veins present. Opportunities for checking this exceedingly reasonable hypothesis are not entirely lacking. Measurements given on p. 84 show that where veins are thin they are more numerous than where they are thick, and that the total thickness of vein in unit depth of marl is constant. Too much emphasis is not to be placed on the closeness of the two sets of figures given, since suitable exposures to establish comparisons of this kind are not numerous, but the general statement that, other things being equal, veins are thinner where they are more numerous is undoubtedly applicable to the deposits as a whole.

The Fibrous Development.—Contraction of a continuous medium sets up tension along certain planes within it, and when a limit, depending on the material and the conditions of desiccation, is reached, rupture ensues. Assuming the Triassic sediments to be charged with concentrated solutions, the relief of pressure produced by rupture would set up physical conditions likely to produce supersaturation of the solutions. If supersaturation were so great that the labile state existed, instantaneous crystallization at innumerable closely-spaced centres would result. The crystals would grow in the general direction of feeding, because expansion in a lateral direction would be prevented by mutual interference of the crystals. If the solution were only slightly supersaturated under the given conditions, there would originate fewer centres more widely spaced, and crystals of greater cross-sectional area would result. The differences in the size of crystals in different veins receives explanation from these considerations. The commencement of crystallization is contemporaneous with the occurrence of rupture, and the growth of the fibres keeps pace with the contraction of the medium so that no open space results, and finally ceases when the limit to the contraction of the medium is reached.

The Direction of Feeding.—The general vertical orientation of the fibres throughout the district, quite independent of the direction of the vein, is best explained on the ground that the feeding solutions diffused vertically. A number of minor features support this view. There is, for example, the general absence of veins in contact with the lower surfaces of large gypsum masses, whilst they are usually if not invariably present on the upper surface. The nodule shelters the region immediately below, and suggests that the diffusion was downwards. Furthermore, the tendency for the 'root' to be greater than the 'top' rather supports the idea that the supply had a downward movement. The sheltering effect of a gypsum mass is perhaps evident also in the occurrence of thin veins placed obliquely beneath a nodule at Cropwell Bishop, for in them the fibres are *horizontal*, pointing to a sideway travel of the solution under the nodule.

Strain Phenomena.—Taber's conception that fibre growth followed the wall in its movements and remained normal to it, is not convincing as an explanation of bent fibres. In these gypsum deposits, at any rate, the behaviour of the fibres constitutes a direct negative to the proposition, for their direction is independent of that of the vein.

The bending of the fibres, moreover, is accompanied by many other structures commonly attributed to strain. These signs of pressure increase in intensity towards the region of the central fibres, and the temptation to explain the phenomena in terms of the hypothesis of vein formation here outlined is strong. For, when contraction of the country has reached its limit, any further attempt on the part of the vein to grow will meet with resistance that must be considerable. Now the bending in all cases apparently bears the relation to the dip shown in fig. 1 *c*, and a very slight inclination quite imperceptible would be sufficient to orientate the bending. The stress conditions set up are shown in the diagram (fig. 1 *d*), where p_1 and p_2 are the pressures set up by fibre-growth.. p_1 and p_2 have components r_1 and r_2 at right angles to the walls, and t_1 and t_2 acting parallel to the walls. These forces are transmitted along the fibres to the central parting, where the tangential forces t_1 and t_2 oppositely directed tend to cause differential movement in the direction represented by their arrows. If any movement does take place at the central parting, the ends of the fibres in contact will ride over one another in the way sketched, and bending such as that found in the specimen in fig, 1 *c* will result. The contortion of the central parting in the same specimen is not a natural sinuous course, but is distinctly due to pressure. Other strain phenomena, shadowy extinction, re-crystallization, and the appearance of glide-planes are further indications of pressure. It should be noted that, in accordance with the general rule, the new crystals are placed with their long axes at right angles to the direction of the fibres and the pressure (see fig. 3). The solubility of gypsum is no doubt favourable to its re-crystallization.

The possibility of this type of bending being caused by a state of simple shear set up by earth-movement would seem to be excluded, since the orientation of the bending in neighbouring but differently inclined veins varies with the inclination. It is hardly possible for the direction of simple shearing forces thus set up to vary with the inclination of the vein.

The effect of a vertical force due to an external load may be considered. The conditions are shown diagrammatically in fig. 5 *b*. Here p_1 is the vertical load due say to the weight of overlying material, and p_2 is the upward directed resistance of the lower strata. The tangential components t_1 and t_2 are now directed oppositely to what they were in the previous case. Consequently the relative motion of the 'top' over the 'root' will be down the dip, and, therefore, the drag of the fibres over one another will cause the upper set to bend up the dip. It would thus seem possible to determine the nature of the forces producing the bending strain, and in these veins it seems to have been generally due to outwardly directed forces generated by the effort of the vein to grow when the limit to rock contraction had been reached.

The frequent occurrence of outer opaque, more finely fibrous zones calls for explanation. There appears to be no physical-chemical reason why the grain of crystallization should change at this stage. The fibres seem segregated into small bundles that distinctly wedge downwards after the manner of cone-in-cone. By applying pressure to a blade of gypsum taken from a good Bridgford sample the two ends become distinctly opaque, apparently by the development of the cleavage under

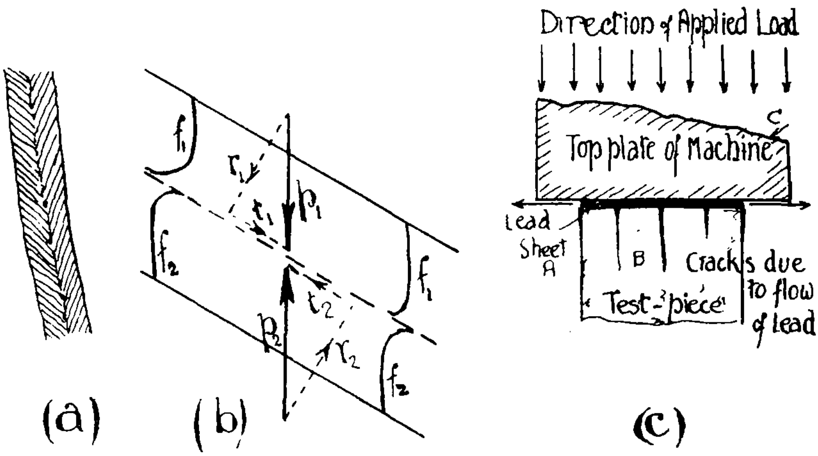

Fig. 5.—(*a*) Sketch of vertical gypsum vein showing the upward and outward growth of fibres from the central parting. Forman's quarry, Chellaston, Derbyshire.
(*b*) Diagram of forces produced at central parting by external vertical loading.
(*c*) Diagram illustrating the formation of vertical cracks in a stone test-piece by flow of the sheet-lead packing.

pressure. The splaying out and separation of the cleavage is actually shown in one of my thin slices. The action involved is of the same type that causes the fraying of a walking-stick at the end when used without a ferrule. The effect of pressure in producing this sort of structure is also illustrated by former practice in testing stone for crushing strength. In order to procure uniform loading a sheet of lead, *A*, fig. 5 *c*, was placed between the stone *B* and the plate *C* of the testing machine. On the application of the load the lead flowed sideways as indicated by the arrows, carrying the surface of the stone with it and producing vertical cracks. So that the adoption of this precaution to ensure uniform loading actually lowered the crushing strength of the material. It would, therefore, appear that the outer opaque zone is due to the separation of the finer units or the development of the cleavage by shearing forces generated at the walls by the same pressure that caused bending of the fibres.

It has been suggested by both T. O. Bosworth and B. Smith that the veins of fibrous gypsum may be still in the course of formation. No evidence of actual vein formation is, however, at hand, and in the course of my investigations I have not seen anything suggesting recent formation. Naturally, since Keuper waters contain a high percentage of calcium sulphate in solution, the possibility cannot be completely denied. On the other hand, the veins show a structure that could not have been produced by filling an empty crack, and they are, moreover, bound together in a definite arrangement that suggests the operation of causes that could only have been operative during dehydration of the original sediments. They are also influenced by other gypsum deposits in a way that convinces me that they were formed at a date not considerably later than the other deposits. Unfortunately, the origin of the compact forms of gypsum cannot be considered as determined. Some workers, for example J. G. Goodchild, regard them as concretionary, but B. Smith has brought forward strong reasons for considering them contemporaneous. It is foreign to my purpose to enter on this question, but, were the concretionary origin determined, the veins would seem to belong to the same period of segregation.

IV. Summary.

The Upper Triassic sediments are assumed to have contained concentrated solutions, which caused, or contributed to, their dehydration and contraction. The contraction of a colloidal mass results in the production of tension planes, and unless compensated by settlement, rupture finally ensues. Relief of pressure by rupture may bring the solutions into the labile state, when innumerable closely-spaced centres of crystallization will be set up. The crystals, fed by vertically diffusing solutions, grow vertically, so long as contraction and feeding continue. When, at length, contraction attains its limit, further growth is resisted, and the stresses set up, transmitted to the central parting, produce bending and other pressure effects in the veins.

My thanks are especially due to Dr. W. D. Lang, Professor G. C. Cullis, Mr. L. Gimson, Mr. Covill of East Bridgford, and to many of the quarry owners of the district.
