The collections sent from Eubœa and the neighbouring mainland are of great interest.

The specimens in the freshwater limestone of Oripò are undoubtedly *Lymneus longiscatus* and a Paludina, both characteristic of the Smyrna freshwater tertiaries, and indicating an eocene epoch.

But those from Koumi have a much more recent aspect. In the strata there we find a Planorbis, which is most probably the existing *P. orientalis*; a Paludina, nearest an existing Greek species; also a Cyclas, very near one which I found in Asia Minor. With these are numerous and beautifully preserved remains of plants, leaves of a Beech, two species of Oak, a Laurus, a Salix?, a Celtis?, an Oleander, and leaves and fruit of Pine.

The fish, now in the collection of Sir Philip Egerton, have been examined by Prof. Agassiz, and pronounced undescribed.

I infer that the Koumi tertiaries belong to a more recent epoch than those of Oripò and Smyrna.

DESCRIPTION OF THE PLATES TO LIEUT. SPRATT'S PAPERS ON
SAMOS AND EUBœA.

PLATE II.

Geographical map of a portion of the Greek Archipelago, to show the relative position of Samos, Eubœa and Smyrna.

PLATE III.

Geological map of a portion of the island of Samos.

PLATE IV.

Geological map of a portion of the islands of Eubœa and Bœotia.

DECEMBER 2, 1846.

The Right Hon. Sir E. Ryan, W. Bainbridge, Esq., G. E. Dennes, Esq., and J. B. Birch, Esq., were elected Fellows of the Society.

The following communication was read:—

On Slaty Cleavage. By DANIEL SHARPE, Esq., F.G.S.

Introduction.

DURING the last few years the subject of slaty cleavage has gradually attracted the attention of geologists, and much valuable information regarding it has been accumulated. Professor Sedgwick's clear description of the leading phænomena connected with cleavage*, led geologists into the right path, and since the publication of his views in 1835 we rarely meet with those unintelligible descriptions, so common in the earlier writers, in which the cleavage and the stratification are confounded together in hopeless confusion. Subsequent observers have added materially to our knowledge, and various remarks illustrating the subject will be found scattered

* On the Structure of large Mineral Masses, &c. Trans. of Geol. Soc. 2nd Series, vol. iii. p. 469, &c., read March, 1835.

through the writings of Professor Sedgwick, Sir R. I. Murchison, Professor Phillips, Sir H. T. De la Beche and Mr. Austen, in addition to which Mr. Darwin has just given us a large collection of observations upon cleavage made in various parts of South America, with some important generalizations to which the extended field of his researches gives great weight. The most valuable of his remarks appear to be those which connect together the cleavage of slates and the foliation of gneiss, mica slate, &c.

Still we had no knowledge of the general laws which governed the formation of the cleavage and regulated its direction, and without previously discovering these it was idle to speculate upon the causes which had produced it. I have now endeavoured to supply part of this deficiency and to establish some general laws relating to the subject, which have been deduced from new observations and from combining insulated facts recorded by others. The appearance of symmetry which has resulted from putting these together, gives me great confidence in the soundness of the results, and should those which relate to the connection between the elevation and the cleavage of rocks be confirmed by other observers, they promise when followed out to throw great light on the theory of elevation.

Connection between the distortion of the Organic Remains found in Slaty Rocks and the cleavage of the beds.

In determining the species of the fossils of the older formations, great difficulties arise from the distortion of form which they have frequently undergone; which sometimes makes it impossible to ascertain the species or even the genus to which they belong. This distortion varies very much in specimens from the same locality, and still more so in those from different districts.

While examining the fossil shells from the Ludlow rocks of Westmoreland, most of which are slightly distorted, it struck me that if we could find out that the changes of form in the shells followed any certain law we might make allowance for them, and thus discover the original form of the shell. Following up this idea, I found that whenever the impressions of several shells occurred on one slab of stone, they were all distorted in the same direction; the change having no reference to the original figure of the shells, but to their position on the stone: it appeared as if every specimen had been contracted in the same direction. This remark enabled me to throw together many shells which I was before disposed to consider distinct species.

Examining other specimens to see how far this observation could be extended, I found that it held generally true, and also that there was a connection between the direction of the cleavage planes and what may be called the axis of distortion. Instances were met with showing the greatest variety in the amount and nature of the changes of form in fossil shells, from a slight alteration in the outline to the most extravagant and complicated distortion in which the proportions of the parts were completely changed; but whenever the rock showed

a trace of cleavage, there was evidently some connection between the direction in which the specimens had been altered and the direction of the cleavage. But that connection appeared so complicated that I saw no prospect of understanding it without visiting some localities where the phenomena might be examined on the spot on a large scale. Besides certain agreements in the direction of the cleavage and the distortion, it appeared to be nearly a general rule that the shells are most distorted in those beds which are most slaty; which confirmed the idea that the two phenomena were intimately connected.

The only remarks I could find on the subject are contained in a short paper by Professor Phillips, read to the British Association in 1843, 'On certain Movements in the Parts of Stratified Rocks,' from which the following is an extract:—"The layers of shells in slaty rocks were generally distinctly marked by ferruginous lines, caused by their decomposition, and the form of their outlines was often remarkably changed. The *Leptænæ* in North Devon assumed the form of *Nuculæ*, and the *Spirifers* were crumpled up, or else extremely attenuated. The *Trilobites* of the Llandeilo flags were found in three distinct forms, arising from the distortion taking place in a longitudinal, transverse, or oblique direction; this seemed to be the result of a *creeping* movement of the particles of the rock along the planes of cleavage, the effect of which was to roll them forward, in a direction always uniform, over the same tract of country: the movement does not seem to have affected the hard shells, but only those which were thin, as also the *Algæ* and *Trilobites*: the latter are covered with little folds, parallel to the wave of motion. In these distorted fossils the amount of movement might be estimated; as, in the space occupied by a *Trilobite*, it amounts to a quarter or even half an inch*," &c. It is evident from this extract, that Mr. Phillips had already discovered a connection between the distortion of the fossils and the cleavage of the rocks containing them; but I am not aware that he has followed up the subject.

I had no hesitation in selecting Tintagel and South Petherwin as the most favourable spots to visit for the accomplishment of the object in view; the former locality especially so, as it affords large specimens of *Spirifers* most extravagantly distorted†. The size of the specimens facilitates comparison and measurement, and it is obviously desirable to have to do with shells originally equilateral; for though distortion may be visible in such shells as *Aviculæ*, *Pterinea* and *Posidonæ*, their forms are essentially so irregular that we can form no calculation of its amount. Our colleague Mr. S. R. Pattison, who collected the Tintagel specimens figured in the *Geological Transactions*, was kind enough to accompany me to Tintagel, and to assist me in my researches both there and in his own neighbourhood of Launceston.

Tintagel stands upon the upper part of the beds of the Devonian system: to the south of the village some large slate quarries have been worked on the face of the cliff, but they are now abandoned.

* Report of the Meeting of the British Association at Cork, 1843, pp. 60, 61.

† *Geol. Trans.* 2nd Series, vol. v. plate 55.

The fossils are most abundant in Mr. Bishop's quarry. The beds generally dip about 5° to the W.S.W., but they are occasionally a little bent, so that the dip varies in different parts of the quarry. The prevailing dip of the cleavage is to the W.N.W. at 10° ; in some parts the bedding and the cleavage have been slightly displaced in the same direction, but this is not usual, and the angle between them is not constant, varying from the smallest angle up to about 10° ; in some spots the bedding and cleavage coincide in direction. These differences in the angle at which the cleavage intersects the bedding appear to have had an influence on the amount of distortion of the organic remains, as these are usually most altered in form where the angle of incidence of the two planes is the least. The most abundant fossil at Tintagel is that which Mr. Sowerby has named *Spirifer giganteus**; but there are also some Terebratulæ, stems of Encrinites, &c.: all the shells are more or less distorted, but the impressions of the encrinite joints are rarely altered.

The South Petherwin limestone quarries are worked upon the line of an anticlinal axis running nearly E. and W.; but the beds dip at different angles on the opposite sides of the quarries, and there are also several minor faults. The planes of cleavage are also bent over in a flat arch, of which the axis running E. and W. coincides in direction with the axis of the beds, but the cleavage planes are less inclined than the beds. From these irregularities the angle of incidence of the planes of bedding and cleavage varies in different parts, between 20° and 90° . The upper beds consist of rotten, grey, argillaceous slate, separated by thin beds of soft ochreous earth, crowded with organic remains too frail to bear removal, but whose forms may be seen on the spot. There are many fossils in the slates, especially near their junction with the ochreous beds. Below these are alternations of beds of limestone and slate, containing fewer fossils. The beds of different mineral character have been differently affected by cleavage, which is most seen in the upper slates, and only affects the limestones slightly, but is hardly to be traced in the thin beds of ferruginous or ochreous earth. The distortion of the organic remains in each bed is in proportion to its cleavage; in the slates they are extravagantly distorted, in the limestones slightly so; while in the soft ochreous beds, in which there is little cleavage, the fossils have preserved their form nearly unaltered. Although at present the loss of the calcareous matter of the shell has left these thin beds softer and more rotten than the others, it is possible that when they were full of shells they were better able to resist pressure than the other beds, which are now the hardest. The encrinite joints are usually free from distortion, although nothing remains but the hollow impressions left by them: apparently when the distortion took place these joints were still solid bodies, capable of resisting the force to which the other fossils yielded. This exception does not hold good everywhere: in the slaty beds to the north of Barnstaple, the impressions of the stems of encrinites are often as much compressed as the other fossils. The species found at South Pether-

* Geol. Trans. 2nd Series, vol. v. pl. 55, figs. 1 to 4.

win are very numerous; a list of them has been given by Professor Phillips in the 'Palæozoic Fossils of Cornwall,' &c., p. 142: the most common is the *Spirifer disjunctus*.

For convenience of comparison I shall draw most of my illustrations from the *Spirifer giganteus* and *S. disjunctus* of Sowerby, which I believe to be one species*. At South Petherwin the specimens of *S. disjunctus* found in the limestones are much smaller than those in the slates, from which we learn that lime was not favourable to the growth of the species, and we need not be surprised that it reached a larger size at Tintagel, where no lime is present; but the difference in the size of the South Petherwin and Tintagel specimens appears greater than it really is, owing to the greater distortion of all the Tintagel shells. Moreover, a careful comparison of the series of beds in the two localities convinced me that the Tintagel shells come from the same bed as those of South Petherwin. To establish a term of comparison with the distorted specimens shortly to be described, we require the original form of this species, which will be found in fig. 1, copied and slightly restored from Mr. Sowerby's figure of *Spirifer disjunctus* just referred to. Fig. 2 gives a supposed outline of the section of the same shell, restored from several specimens. These figures give the following proportions: A B the length of the shell, measured from the hinge-line to the bottom of the mesial fold, is half the length of the hinge-line C D; the thickness of the shell E F is two-fifths of the length of the hinge-line C D.

Fig. 1.

Fig. 2.

The same letters will have the same signification in all the illustrations. The proportions here given are not always true, but they are the best approximations we can get, and as such are used in the calculations which follow.

Besides other causes, partly unknown, the amount of distortion appears to depend upon the angle at which the cleavage cuts the bedding; the distortion being greatest where the angle between them is the least. It has also had a very different effect upon flat and

* See Sowerby, Trans. of Geol. Soc. 2nd Series, vol. v. description of figs. 12 and 13, pl. 54. De Koninck, Description des Fossiles de Belgique, p. 254. De Verneuil, Russie, vol. ii. p. 158.

gibbous shells, as in the latter the parts of the shell lie in different directions towards the plane of cleavage.

There are some preliminary points to be mentioned. Among the palæozoic fossils we never meet with the real shell, and seldom with anything representing its substance; we have only impressions and casts, sometimes with a hollow space showing where the shell has been; but frequently this space has been filled up by pressure, and we find on splitting the rock one impression which represents both the inside and the outside of the valve; and among the most distorted fossils there is rarely any appearance of fracture. It must therefore be considered that we are reasoning upon such impressions as are made on wax, of which the form may be altered without breaking it by drawing out or compressing the mass.

In all the arguments drawn from the present forms of the distorted shells, it will be assumed that the original form of the shell is known and its original size unknown; and constant use will be made of the alteration of the markings on the shell in estimating the nature and direction of the distortion; among these markings the ribs of the *Spirifers* are most useful, from the well-known symmetry of their arrangement. If we had to deal with the changes in the forms in smooth bodies, of which we know only the original form but not the original size, we should find it impossible to analyse the movements which had produced the change; for an impression of a flat circular form might be changed into an oval by the shortening of one of its diameters, by the lengthening of the other diameter, or by a combination of both causes; either of the three explanations would be equally possible: but if the circular impression had been crossed by symmetrical curves, of which the direction and relative distances were known, the alteration in these lines would betray the nature of the change. The same will hold true of a solid.

Let us now proceed to the description of the distorted shells, beginning with those found in beds intersected by the cleavage at a high angle. The change is the simplest where the shells are flat, and therefore lie entirely in the plane of the bedding; in these cases the shells all appear contracted in a direction perpendicular to the strike of the cleavage across the bed, and this apparently without any lengthening of the shell in the contrary direction, although it is difficult to be sure of this latter point. This change is shown in fig. 3, where several nearly flat brachyopodous shells are lying in various directions on a slab of slaty rock from Aber-y-Wynant, near Dolgelly: the apex of each is marked A, the direction of the cleavage across the bed is shown by the lines Z Z. Every shell appears shortened in a direction contrary to that of the lines Z Z, as if the whole mass had been pressed together in one direction. The shells probably belong to one of the concentrically marked *Atrypæ*, but the longer forms might be mistaken for *Lingulæ*. The surface of each is covered with small wrinkles, parallel to the strike of the cleavage Z Z; in this instance the cleavage cuts the bedding at an angle of about 40°: not having the original form of the shell as a guide, we cannot calculate the amount of distortion accurately, but

judging from their present forms, they appear shortened at least twenty-five per cent. in a direction perpendicular to the strike of the cleavage across the bed.

Fig. 3.

Similar instances are common where flat shells are found in slaty beds: the large *Posidonæ* in the black shale above the limestones at the base of the culm-series of Devonshire are frequently distorted in the same manner; at the limestone quarry of Bickington, one mile and a half south of Barnstaple, thousands may be seen in the shale thrown off the top of the quarry, every one of which is contracted in a direction perpendicular to the line of strike of the cleavage across the bed, and which are all covered with folds parallel to that line. The cleavage intersects the bedding at an angle of about 50° . The case of the Trilobites in the Llandeilo flags, mentioned by Professor Phillips in the passage already quoted, is analogous to these. In all these cases the shells appear to have suffered from lateral pressure, which has altered their forms and produced the parallel folds on their surface.

Fig. 4.

The same lateral pressure has produced a different effect on gibbous shells, which are usually flattened in a direction perpendicular to the cleavage and drawn out or squeezed out considerably in the direction of the dip of the cleavage planes. The result is seen in the *Spirifer disjunctus*, represented in figs. 4 and 5, from one of the slaty beds at South Petherwin, met by the cleavage at an angle of about 60° . Figure 4 shows the shell as it lies on the bed, its length reduced about one-half, from A to B, by compression perpendicular to the cleavage planes, the strike of which across the bed is shown as usual

by the lines *Z Z*. In the side view of the same shell, fig. 5, we see that it has been greatly expanded in the direction corresponding to the dip of the cleavage planes.

Fig. 5.

From these and similar cases, we learn that the shells have been compressed by a force acting in a direction perpendicular to the planes of cleavage, and that the compression of the mass between the cleavage planes has been counterbalanced by its expansion in a direction corresponding to the dip of the cleavage.

Where the cleavage intersects the bedding at an angle of 10° or 15° , the present forms of the shells are very various and remarkable, yet the changes may be traced to the operation of the same causes under different circumstances, of which the oblique direction in which the pressure has acted on the shells appears to have had the most important share in modifying their form. The distortion in these cases is much greater than in those already described, and it is of a more complicated character. In a large majority of cases, in which the shell is of an arched form, the changes consist in a great lengthening of one side of the shell, and a comparative shortening of the other side, which is frequently crumpled up and squeezed under the middle of the shell: this will be best understood from the drawings.

Fig. 6 represents a specimen of *Spirifer disjunctus* from South Petherwin, lying in an oblique direction towards the cleavage planes: the lines *Z Z* show the strike of the cleavage across the bed, and *Y Y* the direction of the dip of the cleavage. The specimen is a good deal flattened, and looks as if it had been pressed towards the upper line *Z Z* by a force moving in the direction of *Y Y*, and pressing downwards and forwards at the same time; the friction or the resistance of the mass in which it was imbedded regarding the advancement of

Fig. 6.

Fig. 7.

the front part of the shell, its thickest part is pressed over and partially conceals its upper portion: the unnatural curves assumed by the ribs help to show the direction in which it has given way. Besides this forward pressure, there is evidence, as in the former cases, that the whole has been compressed together in the direction perpendicular to the planes of cleavage and lengthened in the direction of the dip of the cleavage, by which the proportion of the two sides of the shell, and also of each fold and rib, has been altered. Another specimen of a cast of the same species, which has suffered still more alteration, is copied in fig. 7: the larger part of the shell has been squeezed under and concealed, while the remainder is so much expanded that the impressions of the hinge-plates are nearly double their usual length, the expansion being as usual in the direction of the dip of the cleavage.

To understand the effect that must be produced upon an arched body by a contraction of the mass in which it is imbedded in one direction and its expansion in another, we must recollect that the parts of the body lying in different planes will be differently affected by the two forces; for instance, in fig. 8, let C A D be the section

Fig. 8.

Fig. 9.

of an arched shell lying in a mass of rock intersected by the cleavage planes whose section is seen in Y Y; if the mass is expanded in the direction of Y Y (the dip of the cleavage) and contracted in the contrary direction X X, drawing with it in each case the impression of the shell, the line C A D of fig. 8 will be changed by one of its

sides being drawn out and the other contracted till it takes the form *c a d* of fig. 9. In most cases these two operations appear to have acted uniformly together; the contraction of the one side being in proportion to the expansion of the other.

The origin of the oblique pressure on these fossils is easily found: the expansion of the masses of rock in the direction of the dip of the cleavage must cause an oblique pressure on the surface of every bed which is cut obliquely by the cleavage; the fossil shells lying between an expanding mass and a resisting weight of matter have given way before the pressure in the manner described. But as the expansion of the rock in the one direction may have been caused by its compression in the contrary direction, it follows that all the effects yet described may have originated in the compression of the mass of the rock in a direction perpendicular to the cleavage planes.

The next cases chosen for illustration are those where the angle of incidence of the planes of bedding and cleavage is below 5° . These need not detain us long as they are exactly the same as the last in principle, and only differ in the distortion being more exaggerated. The specimens are from Tintagel, and belong to *Spirifer giganteus* of Sowerby. The shells are placed in the same position relatively to the cleavage as before: that of fig. 10 is analogous to that of fig. 6; the wing *D A B* lengthened and so much flattened that the ribs are nearly lost; the other wing *C A B* contracted and with the ribs well-marked. The shell fig. 11 is more distorted; and as the two valves are united, the change of form can be determined accurately: fig. 12 shows a longitudinal section of this shell. The left wings *D A B* are nearly equally elongated in both valves in the direction of the dip of the cleavage *Y Y*, their extent, as seen in the section, being *D E* and *D F*; the two right wings are so much contracted that in the section they only reach from *C* to *E* and *F*. Many other specimens show a similar result in different degrees; but the most extraordinary that I have seen is the *S. giganteus*, as represented in fig. 13, from a bed at Tintagel intersected by the cleavage at an angle of about 1° . In this cast the elongated half of the hinge-line *D A* is three times the length of the other half *C A*: the hinge area and foramen are of an unnatural size, while a great part of the body of the shell is lost. There is here the most distinct proof that a flexible cast of the shell has been pressed forward towards the upper line *Z Z*.

Fig. 10.

Fig. 10. The diagram shows a cross-section of a fossil shell, likely *Spirifer giganteus*, illustrating the effect of oblique pressure. The shell is shown in two parts: a left wing labeled 'C' and a right wing labeled 'D'. The left wing 'C' is more elongated and has more pronounced ribs, while the right wing 'D' is more contracted and has fewer ribs. The hinge line is labeled 'A' at the bottom. The shell is shown in a position where it is being pressed forward towards the upper line 'Z Z'.

Thus these most distorted cases require the same explanation as the others, and can be accounted for by supposing them to have been subjected to a pressure acting obliquely on the shell and pressing it, as it were, downwards and forwards at the same time. This pressure, acting in a constant direction upon shells scattered about in different positions, has produced the variety of extravagant forms which are to be found at South Petherwin, Tintagel, and every other locality where fossils are found in rocks much cut up by cleavage. The oblique pressure may always be resolved into the same two direct forces, one forwards along the plane of cleavage, towards the intersection of the cleavage and the bedding, the other downwards in a direction perpendicular to the cleavage. These are the directions of the compression and expansion previously demonstrated. Mr. Phillips has apparently alluded to this oblique pressure in the passage already quoted. But the facts already stated and others to be brought forward, show that his explanation is not sufficient to include the variously complicated cases of distortion.

When the bedding and cleavage exactly coincide at Tintagel, the shells

Fig. 11.

Fig. 12.

Fig. 13.

are flattened and drawn out considerably in one direction, without the crumpling up or folding under of any part of the shell; as in fig. 14 representing a specimen of *Spirifer giganteus* restored where the hinge had been broken off. The pressure of the rock in

Fig. 14.

the direction perpendicular to the cleavage has caused the flattening of the shell, and there has been an expansion of nearly 50 per cent. in another direction along the plane of cleavage. Not having seen this or any similar specimen *in situ*, I could not learn the direction of the line of elongation, but there can be little doubt that it is parallel to the dip of the cleavage planes; for in every other case the elongating force has acted in a direction parallel to their dip, notwithstanding variations in the position of the bedding.

Having examined all the principal cases of distortion in detail, we may take a broader view of the subject and consider them with reference to the position of the shells in the bedding. The beds of slate vary much in thickness and are frequently separated by thin layers of shells, some of which are impressed on each of their surfaces. When we compare the fossils on the opposite sides of a bed of slate, we find them distorted along lines of which the direction is parallel; but if there has been any oblique pressure, it has acted in opposite directions on the two sides of the bed. This will be better understood from fig. 15, which represents the section of part of a thin bed of slate at South Petherwin, of which the lines *A B*, *a b*, are the upper and lower surfaces, each of which bears in relief flattened and distorted casts of bivalve shells *C D*, of which one side is seen, the other being buried in the slate; the cleavage *Y Y* is very oblique. Before the slab was removed it rested of course upon a bed of rock below, and was covered by another above which offered resistance to

any pressure arising within this bed. On the upper side of the slab a specimen of *Spirifer disjunctus*, C E D, has been flattened by an oblique pressure moving from B towards A. On the lower side are two

Fig. 15.

specimens of *Orthis resupinatus*, C F D, pressed in a contrary direction, or from *a* towards *b*. But in both cases the pressure is such as would be produced by an expansion of the mass in the direction of the dip of the cleavage Y Y. Such an expansion would produce a pressure on each surface equivalent to a force moving from the centre of the bed, in the direction of the lines Y Y. It is here obvious that there can be no difference in the distortion of the specimens which come from the upper or the under side of a bed; and it is impossible to distinguish them. The same proof of the expansion of the mass along the planes of cleavage may be found in beds of every thickness. A bed of slate from Tintagel not the third of an inch thick exhibits exactly the same phenomena.

The comparison of the two sides of the thin beds of shells which separate the slate beds gives the same result: the shells are pressed in what appear opposite directions, but which are in each case the directions of a force pressing from the centre of the mass towards each surface along the oblique planes of cleavage. Fig. 16 shows

Fig. 16.

the section of two slabs of slate enclosing a thin bed full of shells of the *Spirifer giganteus* from Tintagel: one side of each shell is seen in relief on the surface of the slabs, the other being hid: part of the central bed has dropped away leaving a hollow space. A B, *a b*, represent the surface of the beds and Y Y the cleavage planes. The two surfaces are covered with shells C D, of which those on the upper surface are all pressed from B towards A, and on the lower

surface in the opposite direction from *a* towards *b*, the pressure having been towards each surface along the cleavage planes *Y Y*.

Similar instances will be found in every bed of fossiliferous slate; and they prove that the mass forming each bed of slate has been expanded in the direction of the dip of the cleavage. A motion of the whole mass upwards in the direction of the cleavage would produce a compression of the fossils in one direction only: but a pressure acting equally but in contrary directions on the opposite sides of the same bed, or in other words, a force pressing from the centre of a bed towards each of its surfaces, proves that an expansion of the mass of each bed has taken place, which, as already stated, may have been caused by pressure in another direction.

From this examination of distorted fossils under various circumstances, we may conclude that their present forms may be accounted for, by supposing that the rocks in which they are imbedded have undergone compression in a direction perpendicular to the planes of cleavage, and a corresponding expansion in the direction of the dip of the cleavage. It is true that my proofs have been drawn from a limited district; but similar evidence is found in all the fossiliferous slaty rocks with which I am acquainted, including beds of different ages in Cornwall, Devonshire, Cumberland and North Wales. And if we find certain changes connected with their slaty character to have taken place in all fossiliferous slate rocks, it may be inferred that the same have taken place in all slate rocks; though, in the absence of organic remains, we have not that evidence of the changes which the distortion of the fossils has afforded. Therefore it may be asserted as probable, that all rocks affected by that peculiar fissile character which we usually call slaty cleavage have undergone—

1st. A compression of their mass in a direction everywhere perpendicular to the planes of cleavage.

2nd. An expansion of their mass along the planes of cleavage in the direction of a line at right angles to the line of incidence of the planes of bedding and cleavage; or in other words, in the direction of the dip of the cleavage.

No proof has been found that the rock has suffered any change in the direction of the strike of the cleavage planes. We must therefore presume that the masses of rock have not been altered in that direction.

Symmetry in the arrangement of the planes of cleavage over large areas, and connection between the direction of the cleavage and the position of the beds.

Every one who has attended to the geology of any slate district is familiar with the frequent agreement in the strike of the cleavage and bedding of the slates; this is so remarkable that it has everywhere attracted attention. But unfortunately few geologists have troubled themselves with the dip of the planes of cleavage; even if its direction is loosely mentioned, the exact angles are rarely given.

However, most important results may be drawn from attention to this subject.

To begin with the strike of the cleavage planes : Professor Sedgwick stated in 1835, as a rule subject to few exceptions, "where the cleavage is well-developed in a thick mass of slate rock, the strike of the cleavage is nearly coincident with the strike of the beds*." I adopted nearly the same view many years later, after examining several extensive slate districts†. But a somewhat different statement was made by Professor Phillips, that "the cleavage planes of the slate rocks of North Wales are always parallel to the main direction of the great anticlinal axes‡." This view was taken by Mr. Jukes, who appears to have paid much attention to the subject§. Mr. Darwin has lately added his testimony to the same effect : in summing up his observations upon cleavage in various parts of South America, he says, "the cleavage laminæ range over wide areas with remarkable uniformity, being parallel in strike to the main axes of elevation, and generally to the outlines of the coast||."

The difference between these two views may appear slight, and in districts where, as is frequent, the strike of the beds agrees with "the main direction of the great anticlinal axes," there is no discordance between them ; but the two statements really lead to widely different theoretical conclusions. In a case like this, which turns on generalizations drawn from observation, the greatest weight must be given to the geologist whose opportunities of observation have been the widest : in this all must yield to Mr. Darwin ; I have therefore no hesitation in giving up my former opinion, and concluding that the direction of the strike of the cleavage is parallel to the main direction of the axes of elevation, and has no necessary connection with the strike of the beds.

The distance for which the cleavage strikes uniformly in nearly the same direction is very remarkable, and has been often noticed : over more than two-thirds of Wales the direction is between N.N.E. and E.N.E., except where it has been modified by what must be considered as local causes of disturbance. Extensive as this area may appear, it is trifling compared with the regions in South America over which Mr. Darwin found a uniformity in the strike of the cleavage planes, and of what he regards as analogous to them, the planes of foliation of the gneiss and mica schists.

Mr. Darwin is the only geologist who appears to have sought for order in the arrangement of the dip of the cleavage planes¶ : he

* Transactions of the Geological Society, 2nd Series, vol. ii. p. 473.

† Quarterly Journal of the Geological Society, vol. ii. p. 309.

‡ Report of British Association, 1843, p. 61.

§ Excursions in Newfoundland, vol. ii. p. 324.

|| Geological Observations on South America, p. 163. The reader should study the whole chapter, from p. 141.

¶ When the above passage was written, I had not seen the notice in the Edinburgh New Philosophical Journal, vol. xxxiii. p. 144, of a memoir on the "Cleavage of Slate Strata," presented by Professor H. D. Rogers at the sixth annual meeting of American geologists and naturalists, April 1845, in which Professor Rogers describes the direction of the cleavage planes through the Appalachian

says in the sentence following that already quoted, "The dip is as various both in angle and direction (that is, sometimes being inclined to one side and sometimes to the directly opposite side) as the strike is uniform*." And again at p. 164, speaking of gneiss, mica slate, &c.: "As in the case of cleavage, the angle of the dip in foliated rocks is generally high, but variable, and alternates from one side of the line of strike to the other, being sometimes vertical." Again, describing the mount at Monte Video, he states, "It consists of hornblendic slate, which has an east and west nearly vertical cleavage:" "the laminæ on the north and south sides near the summit dip inwards, as if this upper part had expanded or bulged outwards." Again in more general terms at p. 164: "On the flanks of the mountains, both in Tierra del Fuego and in other countries, I have observed that the cleavage planes frequently dip at a high angle inwards, and this was long ago observed by Von Buch to be the case in Norway: this fact is perhaps analogous to the folded, fan-like, or radiating structure in the metamorphic schists of the Alps†, in which the folia in the central crest are vertical, and on the two flanks inclined inwards." Again at p. 135: "I suspect that the varying and opposite dips may be possibly accounted for by the cleavage laminæ, though to the eye appearing straight, being parts of large abrupt curves, with their summits cut off and worn down."

These are all the statements met with tending to elucidate the subject. Following up this information by my own observations, I find that not only is the strike of the planes of cleavage uniform for great distances, but on the same line of strike the direction of their dip is the same, and its angle of inclination nearly uniform; so that each plane appears to hold its course at a certain inclination with great regularity. Lines many miles long will be found along which the cleavage planes are vertical, and on each side of such a line of vertical cleavage the planes usually dip towards that line, first at a very high angle, then at an angle which gradually diminishes in inclination as the distance from the vertical line increases; thus producing the fan-like arrangement noticed by Mr. Darwin. This regularly descending series of planes being found on each side of parallel lines of vertical cleavage, the two series either meet in the centre in a sort of anticlinal axis, or coalesce into an arch; thus forming the figure represented by the section, fig. 18. The irregularities which disturb this arrangement are so trifling in comparison to the general uniformity, that they may be disregarded in all theoretical reasoning.

Thus the arrangement of the planes between two lines of vertical cleavage appears to form a complete whole, and the area bounded by two lines of vertical cleavage may be considered as belonging to

chain, and endeavours to account for it. The Appalachian chain appears analogous, as regards position and cleavage, to the chain of Snowdon, which will presently be described (p. 90). The explanation fails, being built upon a partial view of the position of the cleavage planes.

* Professor Sedgwick says, in the memoir already quoted, "the planes of cleavage are inclined at various angles to the planes of stratification."

† Studer, in *Edinburgh New Philosophical Journal*, vol. xxxiii. p. 144.

one system of cleavage, and may be called an area of elevation of the cleavage. These general views will be confirmed by the examination of particular districts, where we must first ascertain the lines along which the cleavage planes are vertical.

Area of elevation of Carnarvonshire and Merionethshire.

A line of vertical cleavage runs along the slate beds which lie on the western flank of the Snowdon chain, from the valley of the Llynfi to the coast near Aber on the N.E. of Bangor, a distance of more than twenty miles: this line runs N.E. It cannot be followed farther to the south, as the direction of the beds changes suddenly near Clynog. On the W. of the vertical line there is a long band of greenstone, and then a broad bed of gravel which completely conceal the stratification and cleavage. On the E. side of the vertical line, over an area of about seventeen miles wide, the cleavage dips with few exceptions to the N.W., at various angles which will be stated shortly; farther eastward for a similar distance of seventeen miles, the cleavage planes dip at various angles to some point between S.E. and E: the nearest line at which a vertical cleavage is met with, runs through the great slate quarries between Dinas Mowddu and Mallwyd striking N.N.E. Thus thirty-five miles from the line of vertical cleavage at the W. flank of Snowdon, runs another vertical line nearly parallel to it. Not having followed up this second vertical line, I can only lay down its course by drawing it between those points where the cleavage dips at very high angles towards a common axis: from such help I infer that the cleavage will be found vertical a little to the W. of the pass of Bwlch-y-groes, and thence to the N.N.E. at about two miles E. of the Bala Lake as far as the Dee. From some observations made by Mr. J. E. Davis, I conclude that the line runs from Mallwyd to the coast in a direction from N.E. to S.W., passing about five miles N. of Machynlleth through a mountainous district of some elevation, and reaching the coast a little to the N. of Aber Dovey. We might here give up our line as lost beneath the sea, but Sir R. I. Murchison has recorded that on the N. side of Whitesand Bay near St. David's, vertical cleavage planes, coinciding exactly with the bedding, strike E.N.E. subject to some undulations. The direction of the cleavage planes at this spot and its bearing from the points before stated, show this to be the continuation of the same line of vertical cleavage. The distance from the Dee near Bala to Whitesand Bay is 110 miles.

We have thus established two nearly parallel lines of vertical cleavage in North Wales, the western perfectly straight, the other slightly bent, which enclose an area thirty-five miles wide, within which the cleavage planes usually strike nearly N.E.; except in all that large district between the coast and the porphyritic chains of Cader Idris, the Arenigs, Arran Mowddu, &c., where the cleavage usually strikes N., but is subject to great irregularities both of dip and strike; these porphyritic eruptions appearing to have disturbed the uniformity of arrangement of the cleavage: still we are able

to trace a general plan of two series of planes dipping from a central axis towards the boundaries of the area.

On the western side of the area the dips of the cleavage follow certain laws with a great regularity. I measured the dip of the cleavage at every convenient opportunity along two sections. On the Holyhead road proceeding eastward from the W. flank of Snowdon where the cleavage is vertical, there is a gradual decrease in the inclination at which the cleavage dips to the N.W.: at the Penrhyn quarry its angle of dip is 85° , and in crossing the Snowdon chain it diminishes 25° , being 60° at Capel Cerrig; for about six miles it continues at about 60° , and close to the Bryn-Ddinas dike, at the forty-seventh mile-stone, it is 50° ; beyond this spot the strike of the beds and of the cleavage changes to E., and we enter suddenly another area of elevation.

The section through the pass of Llanberris, and thence eastward to Bala, gives a complete line across the whole area: in crossing Snowdon the angle of inclination of the cleavage decreases gradually about 25° , being vertical at the Glyn slate-quarries and dipping at 65° to the N.W. at Llyn Gwinant; the regularity is broken by a reversal of the dip near the village of Llanberris for about half a mile, beyond which the series recovers its order. On the E. of Snowdon the angle continues falling with the greatest regularity as we proceed eastward, as may be seen in all the slate-quarries near Ffestiniog, till it reaches 35° about two miles E. of that village: we have then a mile or two of disturbed country at the great anticlinal axis of the strata near Rhaiadr Cwm, between seventeen and eighteen miles from each of the two lines of vertical cleavage which bound the area: at this spot the direction of the cleavage planes is confused. E. of the axis at Rhaiadr Cwm the dip of the cleavage planes suddenly changes to E.S.E. with an inclination of 50° , and it continues to dip either in that direction or to the E. or E.N.E. with a gradual increase of inclination, till we reach the line of vertical cleavage beyond Bala; but there is less regularity here than on the Snowdon side of the area.

E. of the vertical line of Bala and Mallwyd the dip again changes to N.W., and on that side of the line it has a westerly dip all the way from the Dee to St. David's, the greatest variation being between W. and N.W.

Omitting therefore minor irregularities and local disturbances, these statements show a symmetrical arrangement of the cleavage planes over an area thirty-five miles wide, with a dip in opposite directions away from a central axis, their inclination increasing with the distance from the axis, till it reaches the perpendicular at an equal distance on each side. And on the only side which we have the opportunity of examining, we find on passing the vertical boundary the commencement of another similar arrangement.

Mr. Darwin suggested in a passage already quoted, "that the cleavage laminae, though to the eye appearing straight, may be parts of large curves*." The arrangement just described bears out that

* Geological Observations on South America, p. 155.

suggestion, as the lines appear to correspond to portions of curves having a common axis. But as each of the planes runs in the same position for a great distance, if the curves were completed they would represent a series of semicylinders turned over a common axis*.

The arrangement of the planes of cleavage on so symmetrical a plan is in itself deserving of attention; but when their direction is compared with the position of the beds over the same area, we find coincidences too remarkable to be due to accident, and which lead to considerations of great importance connected with the elevation and disturbance of portions of the crust of the globe. The remarks which follow will be made intelligible by reference to my map of part of North Wales†, and to the sections figs. 17 and 18, in which the

Figs. 17 and 18.

minor irregularities are omitted and only the main features preserved, to prevent the attention from being distracted by minutiae all subordinate to the larger phenomena. Fig. 17 represents the position of the beds along a section of the country from the W. side of Snowdon to the slate bed E. of Bala, fig. 18 the dip of the cleavage planes along the same line of section.

At Rhaiadr Cwm, which is on the axis of the elevation of all the planes of cleavage of the area, there is an anticlinal axis of the stratification along which the oldest rocks of this part of North Wales are brought to the surface in a low flat arch‡, which forms but a slight feature in the country; this now proves of great significance, as it must be considered the true axis of elevation of the whole area, both of the cleavage planes and the stratification. We cannot trace this axis for more than a few miles either to the N.E. or the S.W., as in both directions it is entangled in great masses of erupted igneous rocks. In Professor Sedgwick's map of North Wales§, the line laid down as the "great Merioneth anticlinal" is parallel to the axis at Rhaiadr Cwm, but is drawn five miles to the S.E. of it.

On both sides of this central axis, there is a relation between the inclination of the cleavage planes and the elevation of the strata: where the dip of the cleavage is at the lowest angle, the elevation of the beds is most moderate and they are but slightly disturbed; where the cleavage dips at a higher angle, the beds are more elevated and disturbed and their dip occasionally reversed; and near the boundaries

* Although in theory we ought to regard the cleavage as arranged in curves, I have continued to use the term cleavage *planes* to which we are accustomed, from dislike to introducing a new term, and because to our senses they appear planes, and not *curves*.

† Quarterly Journal of Geological Society, vol. ii. pl. 12.

‡ *Ibid.* vol. ii. pp. 291 and 293.

§ *Ibid.* vol. i. pl. 1.

of the area where the cleavage is vertical or nearly so, the beds have been broken up and thrown into great confusion*. Along this section the cleavage planes usually dip 20° or 30° more than the bedding; but this is not general elsewhere, for in the middle of Devonshire and Cornwall they are less inclined than the bedding.

A remarkable point of contrast in the two sections 17 and 18 is, that in this wide area we have only one axis of the cleavage, but there are several anticlinal and synclinal axes of the stratification; these (with the exception of the central one at Rhaiadr Cwm) have had no effect on the cleavage, which follows its own direction indifferently through beds dipping in opposite directions. Still there is so much relation between the direction of the cleavage planes and the position of the beds, that we might infer from this section alone that the cause which produced the cleavage of the rocks had helped to determine the elevation of the beds.

The area of elevation of Carnarvonshire and Merionethshire is bounded on the N.E. by an irregular line reaching from the mouth of the Conway to the junction of the Dee and the Calettwr about three miles E. of Bala, with a general bearing of N.N.W. to S.S.E., which is nearly at right angles to the direction of the axis of elevation. Commencing at the mouth of the Conway, it follows a great fault which for about fifteen miles is nearly on the line of that river; it then runs along or close to the Bryn-y-Ddinas dike: the rest of its course has still to be traced a little S. of the Holyhead road through a district not yet examined. To the N.E. and E. of the district described, the cleavage planes mostly strike E. and W. in conformity with the prevailing strike of the beds, which must be referred to another area of elevation. The south-western boundary of our area is lost in the sea, except from Clynog to Tremaddoc, where a line of beds striking E. and W. forms its limit.

Direction of the cleavage planes in Anglesea.

It will be desirable to ascertain the direction of the cleavage planes through the districts lying on both sides of the area already described. For Anglesea I can only refer to the remarks scattered through Professor Henslow's description of that island in the first volume of the Transactions of the Cambridge Philosophical Society, from which I gather that the strike of the cleavage is almost always to the N.E., and that the most usual direction of its dip is to the N.W. at high angles. But between Dulas and Llanerchymedd the laminae are vertical, thence to the Menai they are mentioned at some places as dipping to the N.W. In the chloritic slate at the S.W. point of Carnarvonshire the cleavage dips at 50° to the S.E. These slates, lying beyond the Snowdon line of vertical cleavage, must be referred to the area of elevation of Anglesea. Thus there are indications of another arch of the cleavage commencing on the E. side of the Menai and including Anglesea.

* This relation between the inclination of the cleavage and the position of the beds appears to be very general, and has been observed in many other districts.

tion and the cleavage cuts the beds diagonally. Sir H. T. De la Beche has described the culmiferous beds as "ridged, furrowed and twisted in lines, which, when not much affected by the granitic bosses, have a general direction from a few degrees N. of W. to a few degrees S. of E.*;" and the same author speaking in general terms of such phænomena says, "the lateral pressure in these older movements is very considerable, so that if the multitude of contortions, domes, cavities and flexures into which the beds have been forced were flattened out, the area covered would be far more extensive than that now occupied by the same beds in their squeezed and crumpled state†." This passage is peculiarly applicable to the centre of Devonshire.

But to return to the cleavage: I traced the continuance of low undulations of the cleavage, such as are described above, across a band of more than five miles wide in the neighbourhood of Launceston from Yeolm Bridge to South Petherwin, without seeing its full extent; on the coast it reaches at least fifteen miles from Boscastle to Padstow, and it may extend still farther. With so many similar arches of the cleavage, it is impossible to fix upon any one line as the general axis to the cleavage of the whole district, which must be ascertained by drawing an arbitrary line half-way between the two boundary lines of vertical cleavage.

I can find no record of the dip of the cleavage between the central portion of the district and its boundary at Bickington, nor for some distance to the S. of South Petherwin. But farther southward some few facts may be picked up which may be thus arranged in the order of distance from the centre: near Endsleigh the cleavage dips southward‡; on the Dart below Totness it dips at 45° to the S.§; near Brixham, to the S.E. at a high angle||; at Dartmouth the cleavage dip is southerly ¶; at Bigbury Bay its dip is S., but nearly vertical ¶¶.

These scanty materials make it probable that the cleavage planes are arranged across these counties somewhat as in the section across Carnarvonshire and Merionethshire, fig. 18, the principal differences consisting in the greater diameter of the area, and in the flat undulations of the cleavage over the centre of the district. There are here also distinct proofs of the commencement of a fresh system of cleavage elevation on each side of the area described.

The comparison of the position of the cleavage planes with that of the beds along the same line is interesting. Throughout the central area where the cleavage is nearly horizontal, the beds undulate in a succession of waves already described without offering any marked features. These undulations are sharper towards Bideford, where we may expect to find the cleavage highly inclined**. At the Bicking-

* Report on Cornwall, &c., p. 124.

† Memoirs of the Geological Survey of Great Britain, vol. i. p. 222.

‡ De la Beche, Report on Cornwall, &c., p. 108.

§ Sedgwick and Murchison, p. 655.

|| De la Beche, Report on Cornwall, &c., p. 45.

¶ *Ibid.* p. 77.

** See wood-cut at p. 123 of Sir H. T. De la Beche's Report.

cleavage is southerly ; to the S. of the Stokenham line it is northerly *. A line of vertical cleavage which must be considered identical with that of Start Point appears to run to the N. of the Lizard Point ; at least we are told that on the N. of the serpentine of that point, the laminæ of the hornblende slate dip to the N. and N.W., which being the reverse direction to the rest of the district, shows that we have here passed the vertical line. The bearing of these two places is about W. by S. to E. by N., which is nearly the line of strike of the cleavage for the district.

In the N. of Devonshire the cleavage is vertical in the middle of the quarry of black limestone containing *Goniatites* at Bickington, a mile and a half S. of Barnstaple. The cleavage here strikes nearly E. and W. ; at the N. end of the quarry it dips 70° to the S., and at the S. end 80° towards the N. Between six and seven miles N. of this spot, the cleavage is vertical at Swinham Down with a strike to the E.N.E., and between these two lines the planes usually dip to the N.N.W., but with occasional reversal of dip and irregularity. Between Swinham Down and the Bristol Channel the cleavage always dips S., S.S.W. or S.S.E., the angle diminishing as we recede from the vertical line, so that at Hillsborough near Ilfracombe it has fallen to 60° and at Linton to 35° . The Bickington line of vertical cleavage appears the boundary of the Devonshire area of elevation, and the Swinham line that of another parallel area, of which the northern limit must be sought on the opposite coast of Pembrokeshire and Glamorganshire ; the band between Swinham Down and Bickington being neutral ground lying between the two areas.

We thus establish two lines of vertical cleavage, 60 miles apart, the one at Stoke Fleming, the other at Bickington, to serve as boundaries to the area to be examined. In the centre of this area there is a broad band of country over which the cleavage planes undulate in low flat waves, so that considered as a whole they are nearly horizontal. The axes of these flat curves bear between E. and E.N.E., and the cleavage dips alternately to about N.N.W. or S.S.E. at angles which rarely reach 10° . The curves of the cleavage frequently correspond with an anticlinal arch of the bedding, both having the same axis ; but the inclination of the beds is always greater than that of the cleavage. The section fig. 19 would represent any one of these

Fig. 19.

The continuous lines represent the bedding, and the dotted lines the cleavage.

waves as they are seen near Launceston, or on the coast near Tintagel. In other cases the two axes have a slightly different direc-

* Report on Cornwall, &c., p. 77.

tion and the cleavage cuts the beds diagonally. Sir H. T. De la Beche has described the culmiferous beds as "ridged, furrowed and twisted in lines, which, when not much affected by the granitic bosses, have a general direction from a few degrees N. of W. to a few degrees S. of E.*;" and the same author speaking in general terms of such phenomena says, "the lateral pressure in these older movements is very considerable, so that if the multitude of contortions, domes, cavities and flexures into which the beds have been forced were flattened out, the area covered would be far more extensive than that now occupied by the same beds in their squeezed and crumpled state†." This passage is peculiarly applicable to the centre of Devonshire.

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* Report on Cornwall, &c., p. 124.

† Memoirs of the Geological Survey of Great Britain, vol. i. p. 222.

‡ De la Beche, Report on Cornwall, &c., p. 108.

§ Sedgwick and Murchison, p. 655.

|| De la Beche, Report on Cornwall, &c., p. 45.

¶ *Ibid.* p. 77.

** See wood-cut at p. 123 of Sir H. T. De la Beche's Report.

ton limestone quarry, where the vertical line of cleavage passes, the beds are most violently contorted. Beyond this line is low ground at Barnstaple, in the band between the two lines of vertical cleavage. From Pilton to Ilfracombe, with cleavage highly inclined, the strata are elevated in high hills, and at Linton, where the inclination of the cleavage is only 35° , the beds seldom dip more than 5° . So again on the S. coast of Devonshire, disturbed and elevated strata occur in company with a highly inclined cleavage. These observations are less complete than those relating to Carnarvonshire, but the theoretical conclusions to be derived from them are the same.

The regularity of the direction of the cleavage is not at all broken in the neighbourhood of the granite of these counties, from which it is to be inferred that the granitic eruptions had taken place and become solid before the cleavage was produced: indeed some remarks of Sir H. T. De la Beche's lead me to suppose that the cleavage is continued through the granite*.

Application of the laws of compression and expansion of slaty rocks to an area over which the position of the cleavage planes has been ascertained.

It has been shown in the first part of this paper, that there was reason to believe *that all slaty rocks had undergone a compression of their mass in a direction perpendicular to the planes of cleavage*. Now that we have discovered the system upon which the cleavage planes are arranged, we may judge of the direction of the pressure which compressed the slates, and endeavour by that means to find out its cause. I have endeavoured to prove, that though each plane of cleavage runs on for great distances in a uniform direction, the planes are so arranged side by side as to make it probable that they are not true planes, but rather portions of great curves having a common axis and bounded by vertical lines.

Assuming these positions to be correct, it follows that the pressure must have radiated either from a point on the common axis, or from a curved surface of which the outline must be similar to the curve into which the cleavage can be resolved. The first case is too improbable to be worth discussing; the second will be made more intelligible by a diagram representing a section of the supposed area. The

Fig. 20.

black lines represent the dips of the cleavage at the various parts of the surface, and the dotted lines point out the direction of the pres-

* Report on Cornwall, &c., p. 163.

sure, perpendicular to the cleavage at each place. The curve below shows the outline of a mass below the surface whose expansion or elevation would produce the pressure which we know to have acted on the mass above.

This is the form which a fluid mass would assume if forced upwards through a fissure below the crust of the earth coinciding in direction with the axis of the area of elevation. As beds of a slaty character are usually found in close connection with igneous rocks, we may refer the elevation to the upheaval of a mass of fluid igneous matter. The area over which the effect of the upheaval has extended, is obviously bounded by the lines of vertical cleavage.

It has also been shown, that *the compression of the slaty mass was compensated by its expansion in the direction of the dip of the cleavage, but that no change was observed in the direction of the strike of the cleavage.* The explanation of these laws is easy, now that the direction of the cleavage and its position relatively to the elevation of the area are ascertained. The elevation of a mass of rock into a curve by increasing the breadth of the surface of the area, would give room for the expansion of the mass in the direction of the curve, in the proportion of the length of the arc thus formed to its chord; and the curve by the terms of the proposition represents the dip of the cleavage. But as long as the elevation continued uniform over a straight axis, nothing would occur to weaken the resistance to the expansion of the mass in the direction of the axis, which is, as already shown, the direction of the strike of the cleavage. If the elevation should prove sufficient to break up the surface, the fissures would be parallel to the boundaries of the area; and when the mass was once broken in longitudinal fissures, its power of resistance to an expansive force would be farther diminished in the direction of the dip, but would still remain the same along the strike.

These considerations relate to the case of a longitudinal area of elevation, or as Mr. Hopkins has appropriately named it, a case of cylindrical elevation*, because these are the only cases in which I have had an opportunity of studying slaty rocks. It would be very interesting to find a case where slate had been formed round a conical elevation, and to check the accuracy of the laws deduced from the cases considered, by observing the modifications required to adapt them to new circumstances.

Depression of an area at some period posterior to its elevation and to the cleavage.

There are several circumstances which tend to show that the centre of an elevated district may have somewhat sunk down again, after the completion of the original elevation and of the cleavage. Such a sinking is probable, in the first instance, from the relaxation of the central pressure when the igneous matter was allowed to escape through the fissures formed at the sides, and again at a later period

* Abstract of a Memoir on Physical Geology, p. 12.

when the heated mass cooled and a contraction took place in consequence.

The undulating surface of the cleavage over the central parts of Devonshire in low waves which either coincide with more boldly arched waves of the bedding, the two having a common axis parallel to the boundaries of the area, or which cut obliquely through the curves of the bedding, is a phenomenon which requires for its explanation the depression of the centre of the area after the formation of the cleavage. The elevation of the bedding in folds parallel to the axis might be regarded as part of the original movement; but not so the undulations of the cleavage; and the peculiarity, that the waves of the bedding and cleavage sometimes coincide in direction and sometimes differ, refers them to two operations, of which the cleavage being the less disturbed seems only to have undergone the later one. This undulation of the cleavage has only been noticed over the centre of the flat arch of elevation of Devonshire: in districts where the beds and the cleavage planes are tilted at considerable angles, a lowering of the arch might have taken place which it would be difficult to detect.

The foreign crystalline matter which is frequently found between the planes of cleavage, shows that at some period after the cleavage was completed the rock had a tendency to gape along them. Mr. Darwin has collected many instances of the kind from his own observations and those of Professor Sedgwick*, of which the most remarkable is the occurrence of trap dikes in Tierra del Fuego between the laminæ of the slates†.

In the cliffs at the foot of Hillsborough and in other places near Ilfracombe, many instances may be seen of the insertion of sheets of quartz between the laminæ of slate, as shown in the section fig. 21.

Fig. 21.

The horizontal lines represent the beds, the oblique dotted lines the cleavage, and the thick black lines the sheets of quartz.

The quartz, which is often an inch thick, lies partly between the beds

* Darwin, Geological Observations on South America, pp. 152, 160 and 163
Sedgwick, Transactions of the Geological Society, 2nd Series, vol. iii. p. 471.

† Had I been aware of this observation, I should have sought for similar phenomena among the greenstone dikes of Carnarvonshire, which strike with the cleavage and bedding of the district, but of which the dip has not been satisfactorily ascertained.

and then turns down the cleavage forming irregular sheets between the slates, which frequently do not cross the whole thickness of the bed of slate. This has apparently followed upon the irregular gaping of some of the cleavage planes.

Both in this case and in the instances mentioned by Mr. Darwin, the cleavage dipped at a high angle. The opening of the rock along the cleavage would have been impossible as long as the original pressure continued, and, to account for it, it requires a cause exactly opposite to that which produced the pressure, such as the sinking of the elevated area.

Position of the beds over a given area of elevation.

I must now consider some theoretical questions connected with the elevation of portions of the crust of the earth, in the hope of finding how to ascertain, from the position of the beds, what is to be considered as one area of elevation, or in other words, of learning the extent of surface over which the present position of the rocks is to be regarded as produced by a single cause. This is not irrelevant to my principal object; for if it can be ascertained, we shall be able to compare conclusions drawn from the position of the cleavage planes with those derived from the stratification, and thus test their accuracy. In this I shall have to pass over some of the ground on which Mr. Hopkins has laboured so efficiently; but as the points at which I am aiming are not exactly those to which his papers are devoted, I shall derive assistance from the general tenor of his arguments, and when unable to refer to particular passages for authority, I shall still be benefiting indirectly by his guidance*.

The districts I have referred to, and of which I wish to explain the phenomena, belong to the case which Mr. Hopkins has appropriately termed *cylindrical elevation*, namely that where the area is of indefinite length and bounded laterally by parallel lines. Mr. Hopkins has so fully explained all that relates to cross fractures and cross lines of elevation, that I shall not touch upon that branch of the subject, but confine myself to the primary lines of elevation, which are those parallel to the boundaries of the area.

We meet with two series of longitudinal cases of elevation, producing very different results on the beds they affect. The simplest is that where a mass of igneous matter has broken through the surface, as in the Malvern Hills. Here the greatest disturbance is close to the line of eruption: the beds nearest to it are highly inclined, and as we recede from the axis we find them less and less raised, till the effect can no longer be traced: the dip in these cases is from the axis of elevation, unless the violent raising of the beds has caused them to give way, and then we may find minor synclinal and anticlinal axes parallel to the main line. In these cases we see the

* Hopkins, *Researches in Physical Geology*, Transactions of the Cambridge Philosophical Society, vol. vi.; *Abstract of a Memoir on Physical Geology*; On the Wealden district and Bas Boulonnais, Transactions of Geological Society, 2nd Series, vol. vii. p. 1. I have principally consulted the last two, which are addressed to geologists who are not mathematicians, and have had them always before me in writing the following pages.

disturbing agent, and the connection between it and the effect it has produced are obvious.

A more difficult case is that of an elevated area which has not been broken through in the middle by any great igneous eruption; where we can only infer what was the nature of the disturbing cause from observing the effects it has produced. This is the case of the Wealden elevation which Mr. Hopkins has illustrated. This is also the case of the elevations of Carnarvonshire and Merionethshire, and of Devonshire and Cornwall; for though in all these counties abundant eruptions of igneous matter have taken place, some probably connected with the elevation we have to consider, these are secondary phenomena resulting from a wider-spreading cause; and in Devonshire and Cornwall the great granitic eruptions do not form part of the case under consideration, for they were evidently hardened and solidified on the surface before the elevation took place which was connected with the cleavage and gave it that symmetrical arrangement we now find.

The hypothetical case put by Mr. Hopkins, of a fluid mass below the surface forced upwards along a rent bounded laterally by two parallel walls, and covered over by the beds forming the crust of the earth, is in itself probable, and will be found sufficient to explain most of the phenomena observed. The effects produced on the mass above will depend on the width of the rent relatively to the fluidity of the moving mass, supposing always, for simplicity of argument, that the fluid matter finds no means of escape between the beds, but continues always to press upwards. If the rent is narrow compared to the matter forced into it, the surface must give way in a long crack through which the fluid will escape, as in the Malvern Hills. If the rent is broader the fluid must force up the beds above it in a curve, for the surfaces of the fluid mass must rise more in the middle than at the sides.

Fig. 22.

Figure 22 represents a section of the supposed case; the lines A B are the vertical walls of the fissure bounding a fluid mass which can only escape upwards by displacing the mass above, of which the part first opposed to it is shown in its original position by the line C. The beds above will be successively raised into each of the curves *a c a*: since the pressure is greatest in the middle of a fluid column, and the resistance of the mass above is greatest at the sides

where the beds join on to undisturbed masses lying beyond the line A B.

If this operation is continued until the beds give way, their fracture must be expected where they are most bent, that is, on each side somewhere about the points *d d*: and as the pressure is upwards, two anticlinal ridges will be formed over those points near the boundaries of the area and parallel to it. Their importance will be much increased if a continuance of the pressure forces part of the fluid upward through the rent thus formed. On each side of this elevated ridge we should expect at least one synclinal axis resulting mechanically from the raising upwards of a portion of the surface. And between the anticlinal ridges and the boundaries of the area, the beds would be much crushed together and broken, but not elevated. Thus in each great area of elevation the principal features of disturbance should be the raising up of the beds in an arch or anticlinal axis along the central line, an important anticlinal axis near each of the boundary lines, with great confusion between that axis and the boundary, and a synclinal axis on each side between the centre and the anticlinal axes: besides these, there may be many other minor disturbances parallel to and depending upon those principal ones. The outline of the area thus described is shown in fig. 23.

Fig. 23.

- C. The central arch or anticlinal axis.
- D D. The great lateral anticlinal axes.
- S S. The principal synclinal axes.
- B B. Disturbed districts near the boundaries of the area.

If the preceding reasoning is correct, we should find this combination of features common; the proportions varying in every case, and the whole modified by local causes; and every district presenting all these characters must be considered a complete area of elevation. Of Mr. Hopkins's sections across the Wealden elevation*, Nos. 18, 20, 22 and 23 correspond more or less closely to the ideal section given above. The elevation of Carnarvonshire agrees exactly with this section, and in fact it suggested the view here taken: see fig. 17. Its principal features are the central axis of Rhaiadr Cwm, the synclinal axis between the centre and Snowdon, and the great anticlinal axis of the Snowdon chain, on the outside of which the beds are low but in great confusion. The Snowdon antilinal has been raised to a disproportionate height by the igneous matter forced up through it. On the Merionethshire side of the area the features are less regular, but some of them may still be seen.

It follows from the preceding reasoning that the elevating movement of which the axis passes Rhaiadr Cwm, and which gave their

* Hopkins on the Wealden District, Transactions of the Geological Society, 2nd Series, vol. vii. pp. 46 and 47.

present position to the beds of Carnarvonshire and Merionethshire traversed by the section fig. 17, ceased to exert its influence at the boundaries which limit the area of elevation of the cleavage; the lines of vertical cleavage serving to mark the boundaries both to the cleavage elevation and to the elevation of the beds. Thus the arrangement of the cleavage planes and the present disturbed position of the beds, appear the consequences of one elevation; which was probably caused by fluid igneous matter forcing its way upwards along a longitudinal rent below the crust of the earth. It is also probable that the greenstones which rise along the centre and flanks of the Snowdon chain are portions of that fluid mass.

In accordance with the preceding reasoning, we find the lines of vertical cleavage passing at the outside of the flank of the principal mountains included within an area of elevation. Thus the line first described runs just to the W. of the extreme flank of Snowdon; the second line described passes between Plynlimmon and Cader Idris. In the case of the Devonshire area this is less marked, still both the vertical lines pass through ground lower than that on each side of it. I have also some evidence to show that a line of vertical cleavage runs close along the southern edge of the Lake Mountains, passing near Coniston and Ambleside.

Near Barnstaple there are two lines of vertical cleavage, the one already described at Bickington, the other six or seven miles more to the N. passing through Swinham Down; and between them there is some irregularity in the dip of the cleavage. So again on the S. of Devonshire near the Start Point there seem to be two vertical lines running parallel between one and two miles apart. It is probable that this will generally be the case. Each line must be considered as the boundary of its own area of elevation, and the narrow band between as neutral ground, in which the dip will probably always be found irregular.

I have not the means of judging whether Devonshire presents the features of elevation here described; as there are several parts of that county where the dip of the beds has never been described, so that no section across it yet published is really complete. But it may be inferred from Sir H. T. De la Beche's account of the joints prevailing in the granite of Devonshire and Cornwall that these counties have been elevated since the solidification of the granite, by the upheaval of a mass below the surface whose axis extended from W.S.W. to E.N.E. The prevailing divisional joints of the district are found in two directions (with many exceptions which are stated); these directions are about from N.N.W. to S.S.E. and at right angles thereto, or from W.S.W. to E.N.E.* The latter of these lines is parallel to what appears to be the axis of the elevation of the cleavage planes. Mr. Hopkins has taught us to expect fissures both parallel to the axis of elevation of an area and at right angles to it, so we may conclude that the axis of elevation of these counties runs nearly from W.S.W. to E.N.E., coincident with the axis of the elevation of the cleavage

* Report on Cornwall, &c., p. 274.

planes; and that the joints bearing from N.N.W. to S.S.E. are secondary fissures at right angles thereto. The variations observed at different places both in the direction of the joints and in the strike of the cleavage, make it probable that the axis of elevation will be found not a straight line, but slightly bent.

Conclusion.

Throughout all the preceding pages I have abstained from expressing any opinion of the cause producing the cleavage; and now that I have gone through the subject, I must still leave the immediate agent in the operation undiscovered; although I hope that its discovery may be facilitated by the progress made in ascertaining the circumstances under which it took place.

Pressure appears to have been concerned in the operation; for the cleavage is uniformly at right angles to the direction in which pressure is seen to have taken place; and also the amount of cleavage appears to bear some proportion to the compression suffered by the rock. On the other hand, there are reasons for thinking that pressure could not be the sole agent in the operation, for the cleavage did not take place on the first upheaval of the district, when the crust not having yet given way the pressure might be supposed the greatest, but only after the beds had assumed their present position and the various anticlinal and synclinal axes had been formed.

Heat may have had some share in producing the cleavage: if the elevation was caused by a heated mass below, the conduction of heat must have followed the same direction as the pressure; and each sheet of slate must from its position have received the heat sooner than the sheet above it while the temperature was increasing, and parted with it later while the mass was cooling.

Galvanism has been supposed to have caused the cleavage of slate rocks, and the experiments of Mr. R. W. Fox*, since repeated and extended by Mr. R. Hunt†, have been brought forward in proof of its agency, and the fact that lamination has actually been produced in clay by galvanic action tells much in its favour; but before it can be admitted to have produced the cleavage, it ought to be shown that the circumstances of the case were such as would have produced galvanic action, and that it would have acted in the direction required.

Lastly, Mr. Darwin has suggested an explanation built upon a combination of mechanical and crystalline forces, viz. "that the planes of cleavage and foliation are intimately connected with the planes of different tension to which the area was long subjected, after the main fissures or axes of upheavement had been formed, but before the final cessation of all molecular movement‡." And that "this difference in the tension might affect the crystalline and concretionary processes§."

These seem to be the agencies among which we have to seek,

* Report of Cornwall Polytechnic Society, 1837.

† Memoirs of the Geological Survey of Great Britain, vol. i. p. 433.

‡ Geological Observations on South America, p. 168.

§ Ibid. p. 167.

either separately or in combination, for the immediate cause of slaty cleavage. I leave others to decide between them, contenting myself with having supplied some of the materials upon which the decision may be built.

Much remains to be done before the subject can be exhausted, and the direction of the cleavage planes must be examined over many districts before the explanations here proposed can be received as general laws. All that important branch of the subject which is connected with crystallization has been left untouched, and since Mr. Darwin has shown a connection between the cleavage of slate and the foliation and apparent stratification of gneiss and other rocks of similar character*, this alone will require long study in different districts. These inquiries and others to which they may lead, may guide us to conclusions very different from those which we might be disposed to adopt in the present state of our knowledge.

* Geological Observations on South America, chapter 6.