appointment of commissioners authorized to take action in cases of improper exploitation of properties, or unreasonable or prohibitive conditions imposed by landowners for royalties and wayleaves; (2) the provision and administration of a fund for the purpose of undertaking experimental work.

Since Sir Lionel Phillips wrote his report an Imperial Mineral Resources Bureau has been set up. It has been designed as an Imperial link between the respective Mines and Mineral Departments of the self-governing Dominions, India, and the United Kingdom, and its constitution would not appear to permit of its being attached to a Mines Department of the United Kingdom. The Bureau is, we understand, already at work on its internal organization. It is an Imperial body to be incorporated by Royal Charter under the Presidency of the Lord President of the Council, with a governing body containing representatives appointed by the self-governing Dominions, India, and the United Kingdom, as well as certain technical men appointed by the Minister of Reconstruction to represent the mineral, mining, and metal industries generally. In the collection of statistical information it will work through the Mines Departments of all parts of the Empire, including the United Kingdom, and as an Imperially constituted body its relations to a Home Mines Department should be of similar nature to those of the self-governing Dominions.

From what has been said, however, it must be clear that it would be a great advantage for the dispatch of important business relating to the mining industry of this country to bring under one official head the functions performed by so many different governing bodies. Whether an independent Ministry should be formed or to what existing Department of State a Mines Department should be attached are questions of comparatively minor importance. But if a Ministry to deal with Commerce and Industry were to be formed this would obviously be the proper home for a Department of Mines and Minerals, just as in France the *Conseil général des Mines* is a department of the *Ministre des travaux publics*.

IV.—The Interior of the Earth.

By R. D. Oldham, F.R.S., F.G.S.

Being the Introduction to a Geophysical Discussion organized by a Committee of the British Association for the Advancement of Science, and held in the rooms of the Royal Astronomical Society on November 19, 1918.

When I received the invitation to open this discussion my first feeling was of diffidence, for, the interior of the earth being necessarily inaccessible to direct observation, the solution of the problems connected with it has principally been left to mathematical research, and this must remain the final court of appeal. In these circumstances it seemed verging on presumptuousness to address an audience consisting so largely of mathematicians in inauguration of a discussion on the interior of the earth. Second thoughts showed

that there was much to be said against this view, for, though mathematics is the court of appeal, it can only decide on the facts placed before it by the sciences of observation, and so the discussion seems profitably prefaced by a statement of the leading facts which have been collected, and those conclusions which are so directly derived from them as to have almost the validity of observation.

The first, and still one of the most important, of these observations is that the temperature rises regularly to the greatest depth yet penetrated into the earth, the rate of increase being on the average about 1° C. for every 25 m. of depth; we also know that at depths from which volcanic eruptions take place the temperature reaches at least 1000° C. So long as the nebular hypothesis held undisputed sway, it was natural to suppose that the increase of temperature was continuous to the centre of the earth, and, as long ago as 1793,[1] we find Benjamin Franklin indicating the necessary corollary from this, that below a certain depth the material, of which the earth is composed, must necessarily be in a molten, and, at a still greater depth, be converted into a gaseous, condition, an hypothesis very similar to that associated in recent times with the name of Arrhenius.

The fundamental assumption on which this deduction is based has been sapped by the discovery that the radium content of the outer layers of the earth is amply sufficient to account for the whole of the temperature gradient observed in its superficial portion, and, other considerations being ignored, the hypothesis which has been seriously proposed, that the innermost parts of the earth may be intensely cold, approaching the absolute zero temperature of space, is a possible one. We have also the demonstration that the earth as a whole is something like twice as rigid as an equal-sized globe of solid granite, which precludes the assumption that the interior can be in a fluid or gaseous condition in any ordinary sense of the word, but here we must allow for the effect of pressure. When it is remembered that at a depth of but 4 km., or about 2½ miles, the pressure is already greater than the crushing strength of the strongest known rock, and that at the centre it is about three thousand times as great as this, it becomes evident that the properties of matter may be very greatly modified and that the terms used to describe the three states, as we know them under surface conditions, may need to be used in a very esoteric sense when transferred to the interior of the earth. For the present all that need be said is that material, which can be shown to be from twice to six times as rigid as strong granite, can only be described as fluid or gas in a very Pickwickian sense of the word, and it is possibly a mere accident that the threefold division of the interior, outlined by Benjamin Franklin, comes so near that which I propose to show is the deduction to be drawn from the present state of knowledge.

Taking the outer layers of the earth first, we find that the rocks which are exposed at the surface consist in part of material which has been disintegrated by the processes of surface denudation, transported, deposited, and resolidified, and partly of rock which has not

[1] Trans. Amer. Phil. Soc., iii, pp. 1–5, 1793.

yet undergone these processes, but is thoroughly cooled and solid in every sense of the word. To the greatest depth yet reached the rocks are of this type, and it evidently continues for some distance below the depths which can be reached by direct observation or by immediate deduction. This outermost portion of the earth, in which the physical condition is similar to that of the surface rocks, is commonly known in geology as the crust, a name which originated in the days when the earth was supposed to consist of a molten interior and an outer solid crust, and has survived that supposition for want of a better, and after all the word does not necessitate a fluid interior; a loaf of bread, for instance, has a crust, though the interior should be solid. At the present day the term means no more than the outer layers in which composition and constitution have not undergone any great change, as opposed to the more deeply seated material, which differs on one or both of these characteristics. The thickness of this outer crust has been estimated by various methods, the increase of temperature, the pressure under which certain minerals must have been formed, the strength of the crust as indicated by the anomalies of gravity, and some others, all of which agree in putting the lower limit at about 50 km., or some 30 miles, well under one-hundredth of the radius of the earth.

In the outer regions of the crust geological investigation has shown that movements of displacement have taken place on a large scale. Over widths of some hundreds of kilometres rocks have been compressed to the extent of one-third to one-half or less of their original extension, as is shown by the folds into which originally horizontal strata have been thrown. In other cases clean-cut, gently sloping, or horizontal fractures have been recognized, and, along these fractures, displacements have taken place to the extent, well established, of over 60 km. and in some cases possibly of over double this, or from $\frac{1}{2}°$ to 1° of the circumference of the earth. In other places there is evidence of extension, much less capable of measurement than the compression, which, though probably smaller on the whole than the compression, may be comparable in amount. Displacements in a vertical direction have also been well determined, along defined surfaces of fracture the displacement of opposite sides of faults has been established up to about 5 km., and possibly to half as much again, and, as regards places less than a couple of degrees apart, such as the crests of the Himalayas or Andes compared with the plains at their foot, or the mountains of Japan with the bottom of the Tuscarora deep, the vertical displacements may be as much as 15 km.

The cause of these great earth movements is still an unsolved problem of geophysics. At one time they were generally attributed to compression of the earth's crust through contraction due to gradual cooling, and the notion is by no means extinct, but the curiously local distribution of the compression is against this interpretation, no less than the fact that the amount is largely in excess of any contraction permissible on this hypothesis, and besides we have the equally well-established facts that regions of very considerable extent show signs of tension and expansion of their dimensions.

Especially in the case of the great thrust-faults is explanation difficult; the appearances are such as suggest a simple fracture and displacement by compression due to approach to each other of the limits of the region affected, but it can easily be shown that the thrusts involved in this explanation are many times greater than those which could be transmitted by the material of which the blocks are composed. The final explanation must wait until it can be treated by one who is at the same time fully cognisant of the geological results and of the physical principles involved, probably also till a further advance is made in our knowledge of the physical properties of the material under conditions such as exist, even at the comparatively small depths involved.

Leaving this question aside, it is clear that extensive displacements have taken place in the outermost layers of the crust, and these are presumably taken up, possibly in a somewhat different form, by the lower layers, but in any case necessitate that, below the rigid and solid crust, must come material which possesses some of the properties attributed to a fluid, though not necessarily more than the power of changing its form when exposed to stresses of sufficient magnitude and of long enough duration. This has been recognized for some time, and we were content to accept the general conclusion without giving it a name, but this does not satisfy American thought, and Professor J. Barrell has not only introduced the name asthenosphere for the region of material comparatively weak as against permanent stress, but has given a numerical estimate of this weakness or strength. According to him the material at the weakest part of the asthenosphere reached by his investigation, placed at 400 km. from the surface, is about $\frac{1}{25}$ of that of massive surface rocks, and of the order of a capacity of sustaining stress differences of about 1,000 lb. per sq. in. with extreme permissible limits of 100 and 5,000 lb. per sq. in. At this depth the conclusions drawn from his method of deduction become distinctly doubtful, but, at the lesser depth of 50 km., the strength is only about six times that quoted and at 100 km. about four times this amount.[1]

The nature of the transition from the solid crust, or lithosphere, to the underlying asthenosphere is of interest, and on it two lines of reasoning can be brought to bear. First, we have Professor Barrell's calculations, according to which the permanent strength between the depths of 20 and 30 km. amounts to about four to five times that of granite, and at a depth of 50 km. to only one-quarter, showing a very rapid diminution of strength at depths below 30 km. and a tolerably abrupt transition from the crust to the underlying material. The other line of reasoning depends on the phenomenon of reflection of earthquake waves. It is now pretty well established that long distance records, when clear enough, show the arrival not only of waves which have travelled from the origin by a direct path, but of others which have been reflected at or near the surface. In the mathematical treatment of these waves it is necessary to assume

[1] *Journal of Geology*, xxiii, p. 44, 1915.

a spherical body with a definite outer surface, from which reflection takes place, and it was not unnatural to regard this as the outer surface of the earth, but there are some very real difficulties in the way of this interpretation. Just thirty years ago Dr. C. G. Knott showed[1] that, in the heterogeneous material of which the outer layers of the earth are composed, simple condensational and distortional waves could not be transmitted, as each would undergo a breaking up into two forms at every passage from rock of one kind to that of another; ten years later Professor M. P. Rudzki further showed[2] that only a very small proportion of known rocks possessed those characters of elasticity which would enable them to transmit unaltered the two simple forms of elastic waves, and the records of seismographs show that the movement of the wave particle at the surface is of a very complicated nature, having no relation to the simple movements required by the theory of reflection. For these reasons it seems probable that the reflection, of which we find evidence in long distance records, does not take place at, but a short distance below, the surface, and it is natural to place it at the limit where the more heterogeneous rocks of the outer layer pass into the more homogeneous material of the central core—in other words, at the lower limits of the crust or at about 30 km. below the outer surface. Professor Barrell's figures suggest that the limit is probably sufficiently defined to give rise to reflection, and the fact that the reflected waves are not always equally conspicuous is in consonance with the natural assumption that the lower limit of the crust may be more sharply defined in some places than in others, an assumption which is strengthened by fact that these reflected waves are especially conspicuous where the point of reflection lies under the great nexus of mountains forming the Pamir Plateau and the "Roof of the World". It is not unnatural to suppose that this region, unique as regards surface features, should be equally singular in the character of the under surface of the crust, and so give rise to the more than usual prominence of the reflected waves, where incidence takes place under this region.

For the rest of the interior of the earth we are principally dependent on the results obtained by the modern development of seismology. When it was recognized that the long distance records of great earthquakes represented the arrival of mass waves which had travelled through the earth it must have occurred to more than one worker that they would give information regarding the constitution of the material traversed by the wave paths, but I know of no published work previous to a paper by myself, read before the Geological Society in February, 1906, on the "Constitution of the Interior of the Earth as revealed by Earthquakes",[3] to which, doubtless, I owe the honour of having been invited to address you to-day, and in treating the subject the most convenient course

[1] Trans. Seismol. Soc. Japan, xii, pp. 115 ff., 1888.
[2] Beiträge z. Geophysik., iii, pp. 519–40, 1898.
[3] Quart. Journ. Geol. Soc., lxii, p. 456, 1906.

will be to outline the position as there presented, and the modifications which have been introduced by subsequent work. In 1905 there were twelve earthquakes of which direct and accurate knowledge was available of the place and time of origin, and two of which the place was known, but the time had to be inferred from distant records. Tabulating the records of these earthquakes, it was found that the intervals taken by the first and second phases to reach the place of record increased regularly up to a distance of about 120° from the origin. The rate of transit increased more rapidly at first, less rapidly later, and showed that the deeper the wave path penetrated the greater became the rate of transmission, which meant that the wave paths were curved with a convexity towards the centre of the earth. Up to 120° there was no breach in the regularity of the time curve, and the ratio between the rate of propagation of the condensational and distortional waves remained much the same; beyond 120° distance an irregularity appeared, the first phase, or commencement, was appreciably delayed, and the second phase completely disappeared, only at about 140° did something reappear which was recorded as second phase, but must either be distinct from the second phase at lesser distances, or be delayed by about ten minutes in its arrival. From these facts it was concluded that the earth, down to the depth reached by wave paths emerging at 120°, or to a little more than half the radius measured from the surface, was composed of material capable of transmitting the two primary forms of wave motion, and that down to this depth there was no indication of any change of condition, the increase in elasticity, indicated by the increasing rate of propagation, being no more than might be attributed to the increased pressure and compression of the material. Beyond this depth there is a rapid transition to a material which can only transmit the condensational waves at a somewhat reduced rate, and is either incapable of transmitting the distortional waves, or transmits them with a reduction to about half the velocity attained in the lower parts of the outer shell; at that time it was impossible to decide between the two alternatives which were both presented, with some leaning towards the former.

In dealing with subsequent developments it will be convenient to take the two parts of the time curve, and of the resulting parts of the earth's interior separately. Beginning with the outer shell the first work to be noticed is the often quoted paper by Professor Wiechert, which appeared in 1907,[1] where the subject is treated in a more elaborately mathematical form, and appended to it is a detailed discussion of the records by K. Zöppritz, the most important part of which, from the present point of view, is the discussion of the depth reached by the wave paths. For those emerging up to a distance of about 45° the depth reached by the two wave paths is about the same, and increases rapidly at first, then less rapidly; from 45° to about 70°, where the depth reached is about 1,400 to 1,500 km., there is very little increase, but a considerable difference

[1] "Ueber Erdbebenwellen": Göttingen Nachrichten, 1907.

in the depth reached by the two forms of waves; beyond that distance the depth reached increases again, and gradually becomes more equal for the two forms of wave motion till the limit of about 120° is reached. In detail these results have been modified by later work and more exact and numerous determinations of the time intervals, which Professor H. H. Turner has, within the last three years, found to require considerable corrections; it is also a fact that the mathematical methods were not altogether sound, and quite recently the problem has been tackled anew by Dr. C. G. Knott.[1] He informs me that he has succeeded in solving the integrals in an unequivocal manner, no longer needing the use of any assumptions, as had previously been used by himself and by Professor Wiechert. From this he has computed and plotted the wave paths for various distances, which show that those emerging at from 45° to about 75° are crowded together in their deepest-lying parts, in a zone lying just outside about one-quarter of the radius from the surface, or at a depth of 1,300 to 1,500 km. The flattening of the wave paths in this region shows that the increase in rate of propagation suffers a check, and in the case of waves emerging at 73° the lower part of the path is actually concave towards the centre, indicating a temporary decrease in the rate of travel.[2]

The coincidence of these results make it apparent that a change of some kind takes place in the neighbourhood of 1,400 km., or rather less than a quarter of the radius, from the surface, but it is equally clear that it is not a change of state, for both here and at greater depths the two forms of simple mass waves continue to be propagated at about the same relative rates as is demanded by theory. The change indicated is rather of chemical composition than of physical constitution, and in discussing this it is necessary to hark back.

There is a considerable body of evidence, principally astronomical, though partly also geological, which goes to show that the central portion of the earth is composed of metal, principally iron, surrounded by a sheath of stony material. In part this deduction is reached from spectroscopic analysis of the sun and stars, in part from the composition of meteorites, which, whether regarded as the fragments of older worlds, or as the material from which worlds are built up, may be regarded as fair samples of the composition of our earth, and in part from certain geological observations which indicate that deep down in the earth masses of metallic iron are associated with the

[1] Not yet published in full; for an abstract see *Nature*, November 21, 1918, p. 239.

[2] In this connexion it is noteworthy that just a year ago Dr. G. W. Walker announced his conclusion that many of the earthquakes which give rise to long distance records originate at about this depth (Brit. Assoc. Rep., 1917). The conclusion cannot be regarded as fully established, and there are some difficulties in the way of its acceptance, but it is an important and interesting suggestion, which must receive serious consideration, with the reservation that the origin is not of the earthquake proper but of the bathyseism, of which the surface quake, which is felt and does damage, is a secondary result (see Quart. Journ. Geol. Soc., lxv, p. 14, 1909).

stony matter of the outer layers. This hypothesis was mathematically investigated by Professor S. Wiechert in 1897,[1] who found that, within permissible variations, the earth might be regarded as composed of a central core of density about 8 and an outer sheath of density about 3, the dimension of the core being from about three-quarters to less than four-fifths of the radius of the earth, according to the actual densities adopted, and that such an earth would satisfy the known conditions of mean density, as well as of precession and nutation. On the latter I can offer no opinion or criticism; the former is easy of verification, the densities are about right for the stony casing and the mainly iron core, allowing for the effects of pressure and compression, so that the hypothesis may be accepted as at least a possible one, and it is noteworthy that the limit of the two parts of the earth lie just where the earthquake records indicate a change in composition, unaccompanied by change in state, of the material of which the earth is composed.

There remains the central part of the earth, penetrated by wave paths emerging beyond 120° from the epicentre. In 1906 it was still doubtful whether the so-called second phase at these distances represented the much delayed distortional waves, travelling by a direct path, or was of a different character. In Professor Wiechert's paper, already referred to, the slowing down of the rate of transmission, at depths below a little more than half the radius, was recognized, but the second phase was accepted without question as representing the same phenomenon as at distances of 100° and less, and this has remained the interpetation accepted by the Göttingen school, up to the latest publication which has reached us. In this country the trend of thought has been different; the first noteworthy landmark was the demonstration by Dr. G. W. Walker that what was recorded as the second phase at these great distances synchronized with the time at which waves reflected at, or near, the surface of the earth would reach the place of record,[2] and this seems still the most probable interpretation. Lately Professor H. H. Turner has attacked the same problem and, in the latest reports of the British Association and the Shide Bulletins, has shown, by statistical methods, that the so-called second phase at distances beyond the limit of 120° must be a different phenomenon from the second phase at lesser distances. Meanwhile, by an entirely different path, I had myself arrived at a similar conclusion; the examination of records of instruments of the type generally used in Italy, which give the second phase in an exceptionally clearly marked and conspicuous manner, showed that the so-called second phase at very long distances was of a different type altogether, and a few years ago I was able to examine some of the records of the Galitzin instrument at Eskdalemuir, which gave just the same result. The typical second phase, when well developed, shows a distinct commencement, a well-marked maximum and a less rapid dying out; it is, in fact, patently the record of a single group of waves of one character and

[1] *Göttingen Nachrichten*, 1897, pp. 221–43.

[2] *Modern Seismology*, 1913.

form. At long distances, on the contrary, the commencement is more gradual; there is no well-marked maximum, but two or more succeeding each other, and the record bears the impress of being due to the successive arrival of more than one group of waves, just the appearance, in fact, which would be anticipated from Dr. Walker's interpretation. Taking all this into consideration it is not possible to accept the supposed second phase at distances beyond 120° as being identical in character with the feature which is so well marked at lesser distances, and in these very long distance records nothing can be recognized which may be identified as the arrival of condensational waves travelling by a direct path from the origin; if present they are much reduced in intensity and delayed in arrival. Hence we may conclude that the wave paths which penetrate deeper than the outer limits of a central nucleus, extending to something less than half the radius of the earth from the centre, encounter a material which is devoid of rigidity even against stresses of only a few seconds' duration.

A similar conclusion seems to have been reached by Mr. Harold Jeffreys, if I understand him aright, as the result of a mathematical investigation of the viscosity of the earth,[1] based on tidal deformation and the periodic variation of latitude, so that we have two entirely independent lines of research leading to the same conclusion.

To sum up, we have found that the interior of the earth is divided into three distinct regions, characterized by differences in the physical condition of the material. They are:—

1. An outer crust, of matter which is solid in every sense usually attaching to the word. Its thickness is comparatively insignificant, being little more than half a hundredth of the radius. At its lower limit this passes rapidly into

2. A shell of about half to three-fifths of the radius in depth, consisting of matter to which neither the term solid nor fluid can be applied without introducing a connotation which is contradictory to some of its properties, for while highly rigid as against stresses of short duration, or even of duration measured by years, it is capable of indefinite yielding to stresses of small amount if of secular duration. At its lower limit this passes somewhat rapidly, but more gradually than at the outer limit, into

3. A central nucleus consisting of matter having little or no rigidity, even against stresses of very short duration. Here the material may be described as fluid, whether liquid or gas, without introducing any contradictory connotation.

In composition, as distinct from constitution, the earth appears to consist of two parts; a central portion mainly metallic and principally iron, extending to somewhere between three-quarters and four-fifths of the radius, and an outer envelope composed of stony material.

Geologically, we have a twofold division, into the outer crust composed of material more or less similar, in composition and constitution, to the surface rocks with which we are acquainted, and an inner core which differs in one or both of these characters. Etymologically the word "geology" should apply equally to the study of both these regions, but, for convenience and from the limitation of the individual human mind, it is usually confined to the problems presented by the rocks composing the crust, while those of the deeper regions lie outside its scope.

Such, briefly, are the conclusions which may be drawn from the sciences of terrestrial observation. The statement, I know, is incomplete and imperfect; some at least of the conclusions will doubtless be traversed and regarded as incompatible with the results obtained from other lines of research, but in their main features of the threefold division of physical condition and the twofold division of chemical composition they seem to me so well founded that the burden of proof lies with those who would traverse, rather than with those who are prepared to accept, them.

[1] Monthly Notices of R.A.S., May, 1917, p. 454.

V.—Notes on Ammonites.

By L. F. Spath, B.Sc., F.G.S.

I.

THE following notes were compiled, for the most part, some years ago, but their publication in the present form suggested itself to the writer on the perusal (during a short "leave" from active service) of a number of recent papers on Ammonites, principally Professor Swinnerton and A. E. Trueman's study of the "Morphology and Development of the Ammonite Septum".[1] The main part of that inquiry is devoted to the development of the septum, illustrated by successive "septal sections", and it is claimed that where sutural development cannot be worked out, "septal sections" will to some extent serve as a substitute. The writer has no intention of discussing the usefulness of "septal sections"; but some of the suggestions put forward, and conclusions arrived at, by the authors, as well as certain opinions, which they adopt from other workers on Ammonites, invite critical examination. Since, in the present paper, other recent work on the morphology and physiology of the Ammonite septum and suture-line, not yet embodied in textbooks, is also included, and since the writer ventures to put forward opinions that differ in many essentials from the views of both textbooks and other authors, it is hoped that the paper may prove of general interest.

The Forward Bulge of the Septum.

Swinnerton and Trueman give interesting contoured plans of the second and of the adult septum of *Dactylioceras commune*, Sowerby sp., and graphs illustrating the average profile of these two septa, and restate that "on the whole the second septum tends to be concave rather than convex forwards" (p. 37), and that "it appears that the [adult] septum as a whole is convex forwards" (p. 32). Professor

[1] Quart. Journ. Geol. Soc., vol. lxxiii, pt. i, pp. 26–58, pls. ii–iv, 1917.