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THE LACCOLITHIC SERIES

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ABSTRACT. The paper refers to recent work on albite dolerites in an Ordovician area between Builth and Llandrindod, Central Wales. Near Llandrindod an intrusion formerly mapped as a single dolerite has been proved to consist of 315 separate intrusions each surrounded by Lower Ordovician shales. Most of these are small bodies of mushroom form, and exposures of two of them in quarries show that they were fed along narrow pipe-like channels or stalks at right angles to their bases. The form of the space within which these intrusions are contained is similar to an asymmetrical laccolith. At Welfield near Builth dolerites are intruded as thin interrupted sheets at many different levels in shales; most are of flat mushroom form, but some are wing-like prolongations from short wide masses which are interpreted as feeders. Some very small subcircular intrusions may be feeders like those at Llandrindod. Here also the general form of the intrusive complex is that of a laccolith which shows certain resemblances to a cedar-tree laccolith. In the Western United States intrusions have been described which are transitional between the Welsh examples and Gilbert's ideal laccolith, and the authors regard all these as forms in a laccolithic series, individual examples being distinguished by their internal structure and relative amounts of igneous rock and sediments. Some remarks are made concerning Hunt's recent criticism of Gilbert's ideal laccolith.

INTRODUCTION

THE laccolith was first recognized as an important intrusive body about 70 years ago by Gilbert (1877). The typical laccolith of the Henry Mountains is a dome-shaped mass of igneous rock intruded into horizontally disposed sedimentary rocks, which are arched up by the intrusion, but the base of the intrusion is believed to be flat. An essential feature of this type of intrusion is that the sedimentary cover of the laccolith at any given point is arched by an amount which is equal to the thickness of the igneous rock below that point. Gilbert estimated that the sedimentary rocks which formed the arched cover of the laccoliths may have been from 7,000 to 11,000 feet in thickness and he believed that a considerable thickness of cover was necessary for intrusions to assume a laccolithic form.

A thin stalk at the base represents the igneous rock which congealed in the channel up which the magma travelled through the underlying strata. The rocks below the base of the intrusion retained their horizontal disposition and were unaffected except for the rupture through them of the channel which is now represented by the stalk. It has been said that the stalk was an invention of the artist-geologist, W. H. Holmes. Some years ago, one of us (O.T.J.) during a visit to Holmes at his Washington office took the opportunity of asking him if that was in fact the case. He said he thought something of the kind was required in order to provide a channel for the magma. No such structure has ever been seen in any of the Henry Mountains laccoliths, nor, so far as we know until recently, in any other comparable intrusive forms.

Gilbert recognized that there might be various kinds of laccoliths which departed from his ideal form. He interpreted some igneous masses as compound laccoliths, made of two or more intrusions, situated so close together that the arching of the sediments was due to the combined effect of the intrusions. Another modification commonly occurred where several discontinuous thin sheet intrusions were interleaved with sediments in the lower part of the cover. He also suggested that an intrusive mass, conforming more or less closely to the simple ideal form, might include within it a certain amount of sedimentary rock.

It was not long before other intrusive masses, which conformed more or less to the ideal form yet showing departures from it of various kinds, were recognized elsewhere in the United States of America and other parts of the world with the result that the concept of the laccolith gained world-wide acceptance. Recently there has been an attempt to cast doubt upon Gilbert's simple interpretation of the intrusions of the Henry Mountains and a new interpretation has been proposed by Mr. C. B. Hunt (1942) which differs in essential features from that of Gilbert; some comments are offered later upon this interpretation.

It may be recalled that the Henry Mountains are situated in a relatively stable region of the earth's crust and when the laccoliths were intruded the sediments were on the whole disposed in horizontal layers. Such a region is in strong contrast with the geosynclinal regions of the Cordilleras to the west or of the Appalachians to the east. Certain types of igneous activity appear to be closely associated with stable regions; other types are believed to be related to geosynclinal conditions and yet others to tectonically active regions. This aspect of the subject has been well discussed by Harker (1909) and others.

The work upon which we have been engaged during the past ten years in Central Wales appears to throw new light upon the structure of laccolithic bodies.

THE BUILTH-LLANDRINDOD ORDOVICIAN INLIER

The area which we have investigated is an inlier of Ordovician rocks occupying about 40 square miles and surrounded by unconformably overlying Silurian strata. We have mapped it on the scale of 1:2500 or approximately 25 inches to the mile.

The Ordovician rocks of the inlier and a nearby area consist in large part of dark shales, which can be sub-divided into five graptolite zones, namely, in descending order, *Dicranograptus*, *Nemagraptus gracilis*, *Glyptograptus teretiusculus*, *Didymograptus murchisoni* and *D. bifidus*. The first-named belongs to the Lower Bala, the next two to the Llandeilo and the last two to the Llanvirn, while in the area just outside the inlier Upper Bala grey mudstones also emerge from beneath the Silurian cover.

The base of the Ordovician is not seen in the inlier but by comparison with other areas it is inferred that the Llanvirn is underlain by the Arenig Series, mainly shales, and that series by the Cambrian System consisting probably of shales and sandstones or quartzites, which may be assumed to rest unconformably upon pre-Cambrian rocks. The thickness of rocks actually exposed up to the top of the Lower Bala varies from about 8,000 to 10,000 feet; it is estimated that the total thickness of sedimentary rocks from the base of the Cambrian to the top of the Lower Bala is about 16,000 feet and that they are mainly argillaceous sediments.

In one part of the inlier there is an important development of volcanic rocks, principally of spilitic and keratophyric types; these occur in the zone of *Didymorgraptus murchisoni.* In addition, several hundred intrusions of keratophyres and albite-dolerites occur, each of which is confined to certain restricted horizons in the shales.

The Ordovician rocks up to the end of the Lower Bala period were apparently little affected by earth movements, but after that they were subjected to powerful movements of various types. These latter movements were certainly completed before the Silurian (Upper Llandovery) rocks were laid down and there is reason to believe that they had at least begun and may have been largely completed before the deposition of the Upper Bala rocks. The intrusions, including even those which occur in the Lower Bala (*Dicranograptus* shales), had already been emplaced before these movements began and we believe that the intrusive activity was in some way related to the onset of these movements.

Throughout the early part of the Ordovician the inlier was a relatively stable region and had probably been so from Pre-Cambrian times onwards, but some miles to the west lay the Welsh geosyncline, the history of which has been described by one of us (O.T.J.). We believe that, prior to the intrusive episode which is described below, the stable region, probably extended for many miles to the east.

We have recently described two igneous complexes within the inlier which are characterized by numerous intrusions of albite-dolerite into Llandeilo shales. One of these is at the northern end of the inlier near Llandrindod Wells or Llandrindod as it is commonly called (1948,a); the other is at the southern end at Welfield about 7 miles south of Llandrindod and near Builth Wells, or more shortly, Builth (1946).

LLANDRINDOD COMPLEX

The old one-inch Geological Survey map which was published in 1850 shows a triangular mass of "greenstone" near Llandrindod. We have found that a large proportion of the area so mapped consists in fact of shales into which have been intruded numerous separate masses of dolerite. If an envelope line is drawn so as to enclose the masses which we have mapped, its course is closely similar to the boundary of the "greenstone" as shown on the Geological Survey map. The dolerites are intruded into shales of the *Nemagraptus gracilis* zone and as a result of subsequent earth-movements the rocks have been tilted in a general north-westerly direction at about 40°.

We found that the "greenstone," far from being one continuous mass, consists of no less than 315 separate masses, each separated from the other by shales (fig. 1). Approxi-

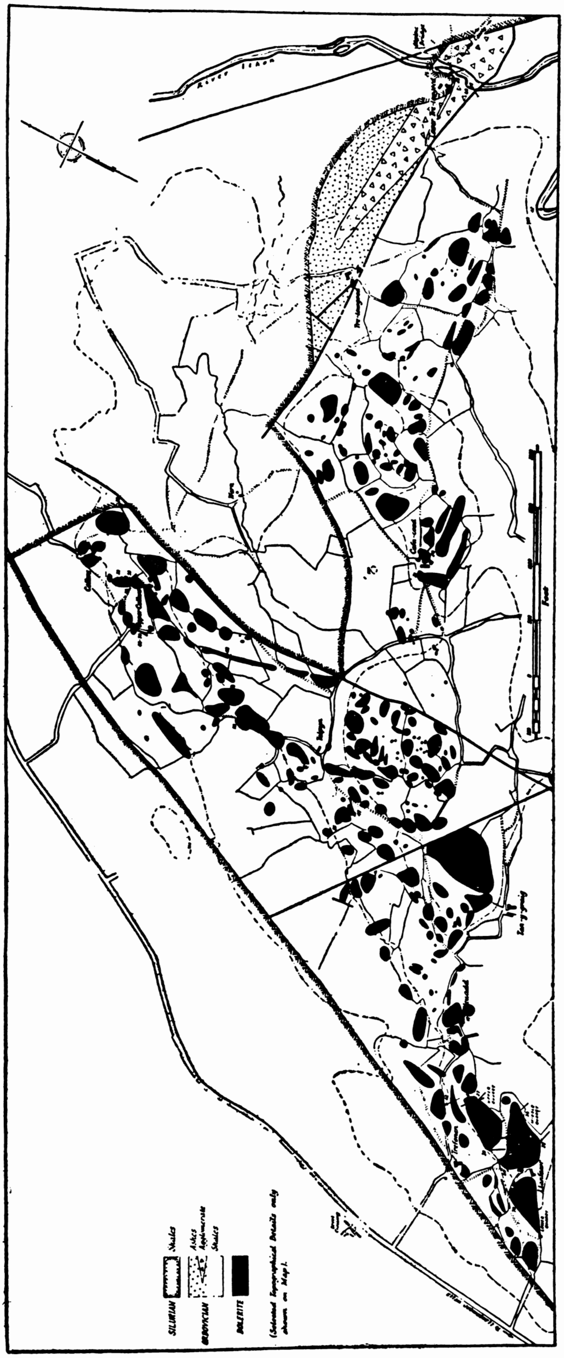

Fig. 1. Map of dolerite complex near Llandrindod (dolerite masses black).

mately two-thirds of this number are oval or ovoid, but occasionally some are of more irregular form. Several of the individual dolerites have been quarried and their relation to the shales by which they are surrounded can be clearly seen. Quarry sections show that the bases of the ovoid masses are conformable to the shales below them and that each was emplaced in the shales in such a way that, while the base was relatively flat, the overlying shales were raised above the base by an amount which was proportional to the thickness of the intrusion. Each of these masses has, therefore, the form of an ideal laccolith but on a very small scale.

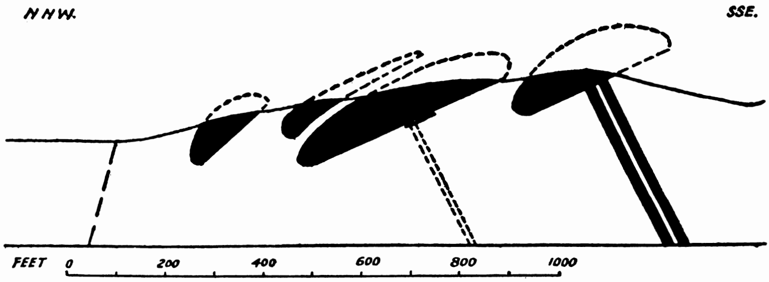

Fig. 2. Section through dolerite masses at Llanfawr quarries, near Llandrindod.

Three large quarries have been worked at the southwestern end of the area near Llanfawr. The dolerite in the middle quarry is 600 feet long and has a maximum width of 300 feet. Quarrying operations have removed the igneous rock from above the shales for a distance of 120 yards and in doing so have uncovered two small masses of dolerite about 55 to 35 feet long by 18 to 16 feet wide, which project through at right angles to the dip of the shales, on which the quarried dolerite formerly rested. Before the shales were tilted, these small dolerite masses were therefore vertical plug-like bodies; we were informed by the quarry foreman that they were joined to the base of the main dolerite and there seems to be no doubt that they were feeders to the masses above them (fig. 2).

When we first visited the upper quarry at Llanfawr there was visible at the northern end of the quarry a narrow bar of dolerite which projected downwards at right angles to the base of the main dolerite and reached the level of the quarry floor. When the lower end of this bar was exposed by excavation, it was found to end downwards in a sill about two feet thick. We were informed that it was first encountered about 30 feet back from the quarry face and its dimensions were therefore about 30 feet by 7 feet or rather more. Although its connection with the main mass was proved, one cannot say that it continued downwards below the thin sill, but it is not improbable that it did so (fig. 2). It is regrettable that this plug has now been largely quarried away but we were fortunately able to secure a photograph of it before it was removed, which is reproduced as a plate in our description of this area (1948, a, pl IV, fig. 2).

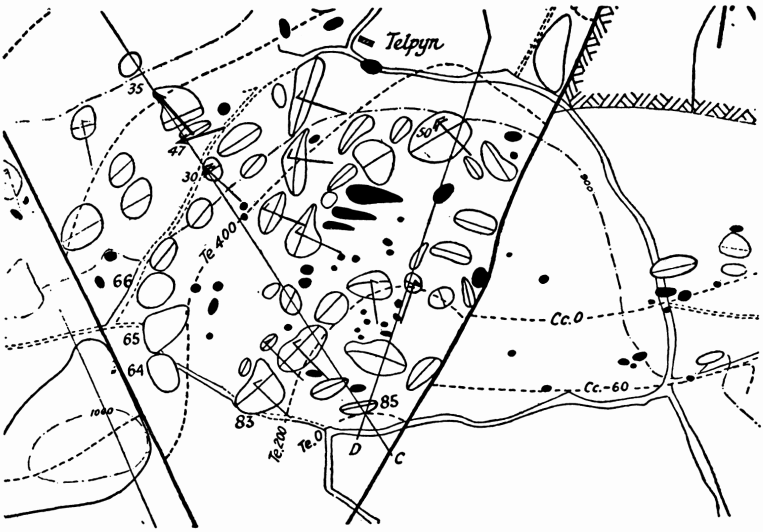

Fig. 3. Map of part of Llandrindod laccolith showing concordant dolerite masses (outline) and feeders (black). Straight lines within dolerite outcrop areas indicate direction of elongation of dolerite outcrops. Single-headed arrow—dip of sedimentary rocks. Double-headed arrow—dip of platy jointing in dolerite. Single-barbed arrow—dip of dolerite mass as inferred from slope of ground. Dashed line—approximate strike lines (in feet; Te.—Telpyn block, Cc.—Cefn-coed block).

Reproduced from part of Plate VI, Quart. Jour. Geol. Soc., 104, 1948, with permission.

We have thus found evidence in these two quarries at Llanfawr of three small oval plugs of dolerite which entered the main dolerite mass from below at right angles to its base. Their size in relation to that of the main mass is comparable with that of the stalk which is diagrammatically represented at the base of Gilbert's ideal laccolith. We have thus established that certain intrusions reproduce closely the form as well as some of the other characteristics of the ideal laccolith, though on a much smaller scale, and that these were fed from below through narrow channels or stalks.

Within the intrusive area at Llandrindod there are numerous small oval outcrops of dolerite which compare in size and shape with the plugs exposed in the Llanfawr quarries; others are almost circular (fig. 3). It is difficult to believe that such small masses could have been concordant intrusions and it is much more probable that most, if not all, of them were feeders to ovoid bodies at a higher level which have been removed by erosion. There are, in addition, some larger masses of oval or elongated form which are discordant in direction with other masses nearby and may also be feeders. They should probably be regarded as short dykes comparable with dolerite masses to be described later in connection with the Welfield complex. The total number of bodies which we infer to be feeders of one type or another is about one-third of the whole or over 100. It is thus probable that there formerly existed in the area at least 100 more concordant masses which have been removed by erosion, but by far the largest number of possible feeders are likely to be concealed beneath the surface.

The concordant ovoid bodies vary in length from about 600 feet to as little as 50 feet; their breadth is usually about two-thirds to three-quarters of their length and in a cross-section the height of the mass is therefore less than half the diameter. These masses tend to be arranged at successive stratigraphical levels through a vertical range of at least 800 feet of shales; this can be seen from the map although it is not immediately obvious. The complex has thus a distinctly layered structure; it is somewhat affected by small folds which cross it nearly at right angles to the general strike of the rocks in this part of the inlier and by two faults which break its continuity.

The former height of the structure is not known. If we consider the space or volume of ground within which the dolerites of the complex have been intruded, it is not unlike an asymmetrical laccolith in form. The base is not everywhere at the same horizon, but examples of laccoliths have also been described in which the base is transgressive.

It is because of the general resemblance between the space within which dolerites occur and the form of a laccolith that we assign this complex to the laccolith series. The essential feature which distinguishes it from the ideal form is that it is a layered structure composed of shales and discontinuous dolerite masses. We estimate that, as exposed in section at the present surface of the ground, the aggregate area of the outcrops of dolerite is only about 25 per cent of the total area defined by an envelope line drawn around the complex. It is, therefore, a very open structure. Moreover, not more than 25 per cent of the height of the domed form of the envelope can be attributed to the lifting of the strata by the intrusions; the other 75 per cent is to be accounted for by the fact that the layers of intrusions are emplaced at successively higher stratigraphical levels in the shales.

It is clear that the distribution of the ovoid masses, as well as the limits of the structure as a whole, were determined by the distribution of feeders. The height to which igneous material ascended in the shales depended possibly upon the size of the feeders and upon other factors, such as the viscosity of the magma and its temperature. At the time of the intrusive activity the shales probably contained a high percentage of water and we believe that most of the characteristic features of the Llandrindod laccolith are due to the fact that the magma was intruded into these wet shales probably beneath a relatively small thickness of cover (Jones and Pugh, 1948,b).

WELFIELD COMPLEX

We had mapped and described the Welfield complex (1946) before we examined the Llandrindod laccolith. The complex forms a prominent ridge north of the River Wye in which dolerites associated with highly baked shales are well exposed. On the west side, Silurian (Upper Llandovery) rocks rest unconformably on Ordovician dolerites and shales which belong to the *Nemagraptus gracilis* zone. These shales are estimated to be about 1,000 feet (or about 1,200 feet if the dolerites are included) higher in the stratigraphical succession than the rocks exposed in Welfield ridge, which are in the upper part of the *Glyptograptus teretiusculus* zone.

In Welfield ridge 44 separate masses of dolerite have been mapped but as the complex is truncated by a tear-fault on the north it seems probable that only about one-half of it is seen (fig. 4); the outcrops of most of the masses are oval. At least five of them, however, are different in form from any masses seen at Llandrindod; they are wing-like prolongations from two roughly oval dolerite outcrops which occur near

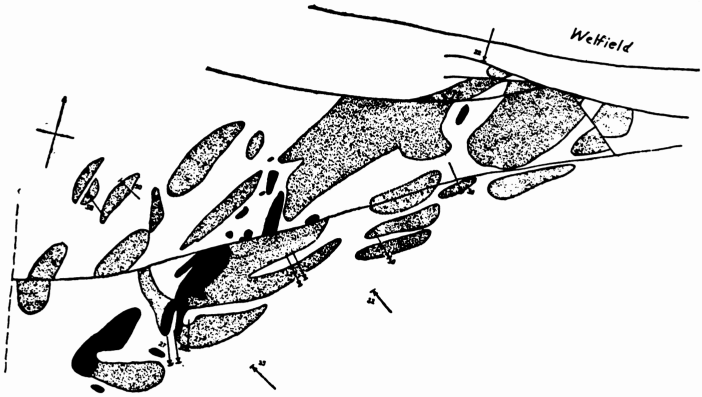

Fig. 4. Map of Welfield laccolith showing feeders and possible feeders in black (other dolerites stippled).

the crest of the structure and are aligned approximately in the direction of its trend. The aggregate area of dolerite outcrops is roughly 50 per cent of the area included between an envelope drawn through the ends of the dolerites and the tear-fault which crosses the complex. From the limited information available the Welfield structure thus has a higher proportion of dolerites within it than the Llandrindod complex. This is in accordance with a rule generally applicable to the dolerites at different horizons within the inlier, which is, that those at lower levels in the stratigraphical succession are more massive and more continuous than those at higher levels.

The Welfield area has been affected by post-Silurian tilting and faulting. If allowance is made for post-Silurian tilting, the Welfield structure had the form of a laccolith with a dip in the western flank of 30° and in the eastern flank of 60°. At the present time the eastern flank dips at about 30° but, a short distance away from the strong feature which defines the eastern margin of the ridge, the Ordovician shales now dip in a westerly direction of 32° to 35°. These westerly dips when corrected for a post-Silurian westerly tilt of 30° become 2° to 5° and in combination with the dip of 60° in the eastern flank of the structure indicate a sharply defined flexure at the edge of the structure. They imply also that the Ordovician rocks at the time of the intrusive episode were almost horizontal. The corresponding differences in the dips on the western margin are probably only about 10° to 20° and the flexure is not so sharply defined. The existence of these flexures is regarded as an important confirmation of our view that the Welfield complex should be assigned to the laccolithic series.

We have no direct knowledge of the inner core of this laccolith. Since the present surface is a random section through the outer skin of the structure, it is probably fair to assume that the arrangement of dolerite and shale there seen is broadly similar to that which occurs below the surface. In other words, the shales at a deeper level probably include many ovoid intrusions with possibly some wing-like bodies given off from the downward prolongation of the dyke-feeders near the crest of the structure or from similar feeders which do not obviously play this role at the surface. In comparison with the Llandrindod complex it is not unlikely that several other masses which we mapped at Welfield may have been feeders also but at that time we had no reason to assume the existence of any type of feeder other than the two dyke-like bodies to which we called attention. These are shown in black in figure 4. We suggested that the unusual degree of baking of the shales may be due to larger bodies concealed beneath the surface.

COMPARISON OF LLANDRINDOD AND WELFIELD COMPLEXES AND OTHER INTRUSIVE FORMS

It is hardly necessary to recall the similarity between the Welfield complex and the Llandrindod complex. They are both layered structures and they differ only in two respects. The Llandrindod structure lacks the wing-like extensions found at Welfield and the latter contains more dolerites in proportion to associated shales.

In comparing the affinities of the Welfield complex with other intrusive forms we found that its nearest analogues were among the various types of laccoliths which have been described and figured from the Western Territories of the United States of America. We were impressed by the fact that

Welfield ridge or as much of it as can be observed revealed all the features that were considered to be characteristic of laccolithic intrusions. Moreover, the relation of the two short dolerite outcrops near the crest of the structure to the five wing-like masses which spring from them inevitably recalled certain parts of a cedar-tree laccolith.

The Welfield complex is a layered intrusion which stands in an intermediate position between the Llandrindod complex on the one hand and a cedar-tree laccolith on the other; and on this ground we assign both complexes to the laccolith series. They are both determined essentially by the incidence of feeders of one type or another.

It is hardly necessary to point out that the cedar-tree laccolith is one of the most striking examples of a layered intrusion that has yet been described. As represented by Holmes (1877), the individual layers all appear to be lateral or wing-like offshoots from a central mass which acts as their parent feeder; in comparison with the length of the wing-like extensions the central feeder is of considerable size.

Whitman Cross (1984, p. 209) has remarked that "as drawn, this intrusion implies a considerable absorption or assimilation of strata, for which no evidence is given and which is entirely improbable." It would be of great interest if this particular feature in the structure of the La Plata Mountains were re-examined and mapped in detail. In the light of our experience it may be found that the bodies which fed the leaves of the intrusion were less massive and more numerous than is indicated in the sketch by Holmes and that the appearance of incorporation of sediments suggested in that illustration may not be confirmed.

It is easy to envisage other intrusions of broadly laccolithic form in which the proportion of sedimentary rock to intrusive rock is considerably less than in any of the examples already mentioned. The el Late laccolith figured and described by Holmes (1877) and discussed by Whitman Cross (1894) appears to be a good instance. It is worth noting that Holmes was examining this and neighbouring areas at the same time as Gilbert was exploring the Henry Mountains. It is not improbable that the broad concept of the laccolith was already in the air at that time although it did not receive its name until 1877. It may be mentioned also that Holmes' sketches and in particular the figures of the el Late structure show that he had correctly envisaged the relation of the arching of the strata to the thickness of the underlying intrusion. This is clearly seen in fig. 5, which reproduces Holmes' sections of el Late; the first of these is well-known but the other two may be less familiar.

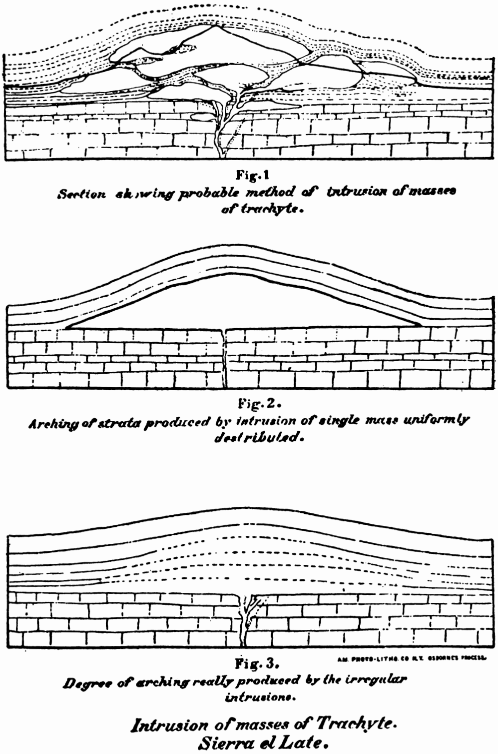

Fig. 5. Sections of Sierra el Late by W. H. Holmes (1877).

In the el Late structure the intrusive bodies are separated by relatively narrow partitions of stratified rocks which, so far as can be judged from illustrations, occupy only about 25 per cent as compared with 75 per cent in the Llandrindod complex. No one has any difficulty in accepting the el Late structure as a variant of the ideal form and in regarding it as a compound laccolith. In the el Late laccolith about 75 per cent of the total amount of arching was directly due to the intrusive rock and only 25 per cent to its layered structure as is illustrated in Holmes's figures but it is clear that the masses in the upper part of the complex were intruded into a higher level of the stratified series than those near the base of the laccolith.

It is unnecessary to discuss the many other types of laccoliths which have been described and are transitional between the el Late laccolith and Gilbert's ideal form in which the whole of the arching of the covering strata is due to the intrusion. If, however, the examples mentioned above are considered together it is possible to recognize every transition between, on the one hand, a much divided structure such as the Llandrindod complex and, on the other hand, Gilbert's ideal form. This is the reason why we assign the rather remarkable intrusive forms displayed at Welfield and Llandrindod to a laccolithic series. Their underlying unity is the form of the space in which the intrusive rock is included and this as in the ideal laccolith is determined broadly by the incidence of feeders. The detailed arrangement of the individual masses which make up the whole structure depends upon many factors. But as Harker (1909, p. 70) says, "In the case of the ideal laccolite intruded in connection with crustal stresses purely of the plateau-building kind, the precise location of the intrusions will depend upon intratelluric conditions beyond our cognisance." So far as the Welsh examples are concerned, we have discussed some of these questions in the publications already mentioned.

COMMENTS ON A NEW INTERPRETATION OF THE HENRY MOUNTAINS LACCOLITHS

Charles B. Hunt (1942) recently claimed that the large symmetrical domes of the Henry Mountains are not due to mushroom laccoliths but have resulted from the injection of stocks. This claim rests not upon actual proof of the internal structure of these mountains but upon certain theoretical considerations. According to Gilbert, these mountain domes resulted from the intrusion of a magma at a certain horizon which lifted up the strata above that level into a dome the height of which depended upon the thickness of the intrusive mass. It was to the igneous rock of this general form that the name laccolith was originally applied; with it were associated sheets of sill-like form, and dykes.

Hunt disguises the issue by re-classifying the igneous rocks into "stocks, laccoliths, bysmaliths, dikes and sills" (p. 197) but the bodies termed laccoliths are defined as "elongate, tongue-shaped masses that were injected radially into the strata adjoining the stocks" (p. 197). These would appear to correspond in general to Gilbert's sheets and are unessential accompaniments of the main body of the laccolith; their presence or absence has no bearing upon the form of that body. By this somewhat arbitrary re-definition of the term laccolith which seems to rest upon no solid basis, Hunt is able to call by the name of stock what everyone has hitherto accepted as *the* laccolith.

In the very small-scale cross-sections (fig. 1, p. 200) which illustrate the paper there is no indication of the horizontal layers which occur at a lower level than the base of Gilbert's laccolith. These horizontally disposed layers are prominently displayed in several of Holmes' sketches but they have no place in Hunt's theory of these domes. He states that "the stocks of each of the five mountain masses must have been emplaced by physical injection because the space occupied by the stocks would be closed if the formations turned up around the stocks were restored to their original horizontal position" (p. 198). This appears to state no more than that the intrusion made room for itself by pushing away the surrounding strata and applies just as well to the ideal laccolith as to the supposed stocks.

The main argument seems to rest, however, upon the statement that the width of the stock, that is, the exposed part of the igneous mass near the centre of the dome in each of the four mountains, Mt. Holmes, Mt. Ellsworth, Mt. Pennell and Mt. Hillers, "is almost a direct function of the amount of uplift" (p. 198). These are compared with the Navajo Mountains on the Colorado Plateau about 50 miles to the south, which is of about the same diameter at the base (6 miles) as each of the above domes. The Navajo dome uplift is estimated to have been about 2,600 feet; it is calculated that the rocks within the basal perimeter which had an area before uplift of 9π or 28.27 square miles must have occupied after uplift an area on the surface of the dome of 28.75 square miles, indicating an areal increase of 0.48 square mile or 1.7 per cent. It is not clear how this figure was obtained. If the uplift was approximately in the form of a spherical cap, the increase of area where the height is one-sixth of the radius of the base, as in this case, should be 2.78 per cent or nearly 0.8 square mile. Hunt's diagram (fig. 1) represents the uplift as conical in form, but if this form is assumed the increase in area with the above ratio is about 1.4 per cent or about 0.4 square mile. Perhaps he has adopted some compromise between these extreme forms between which would lie most dome-like uplifts. It is not, however, with the precise amount of the areal increase that we find difficulty but in the argument on which it is based and on the use which is made of it.

In the Navajo dome, according to the author, the stretching by uplift has not been so great that the strata at the summit of the dome have parted so as to allow of igneous intrusion. The increase in area of half a square mile is thus assumed to give a limit to the amount of stretching that can occur in the cover-rocks without rupture, but the validity of this argument is very doubtful. If, for example, the dome were composed of a rock with a modulus of elasticity of about 5×10^6 lbs. per square inch, such a rock would rupture under a linear strain of about 1/2500 inch per inch. This is not very different from what might be caused by simple thermal expansion. The areal stretching just prior to rupture would be 1/1250, which is only about one twentieth of that attributed to the formation of the Navajo dome. It is obvious, therefore, that the increase in area of the rocks of Navajo dome could not be due to simple stretching but must have been accomplished by rupture, probably by the opening of joints. This process once started can go on to an unlimited extent all over the domed surface but possibly more near the crest than down the flanks and, therefore, can give no basis for the assumption that the rocks can stand so much stretching but no more without opening up.

It is then argued that "greater uplift in areas of the same size in the Henry Mountains has resulted in the parting of the strata and the creation of space to accommodate the stocks" (p. 199). In each diagram of fig. 1 (p. 200), the stippled hypothetical area available for the intrusion of each stock has been reduced by an area equivalent to that represented by the stretching of the strata as determined at Navajo dome. Once the basis of the stretching hypothesis has been proved to be wrong it does not follow that the intrusion of a cylindrical plug-like form is necessary in order that the above relation shall hold. They can be accounted for equally well by assuming Gilbert's ideal laccolithic form, for it is the mere shape and size of the dome that determines these relations and not what is inside it.

There are three features of the Henry Mountains laccolith that tell strongly against this author's interpretation, namely, (1) the existence of horizontal strata below the general level of the inferred base of the laccolith, (2) the distance away from the igneous core to which alteration of the strata has been observed in some cases and (3) the relation of the cover to the igneous core, for example, in Mount Hillers and in Ragged Mountain described by Whitman Cross (1894, p. 181, fig. 29).

We may also add that in our view the injection of a cylindrical plug-like stock must take place by a process of shearing analogous to the driving of a punch into metal; this is accomplished by pushing away and compressing the adjacent material and the effects diminish rapidly as the distance from the shear zone increases. It is therefore most unlikely to give rise to a broad, uniformly curved doming of the strata such as occurs in the Henry Mountains.

According to Hunt, the strata around the Mount Holmes igneous core are metamorphosed and shattered for as much as a mile from the walls of the intrusion. In our experience, this indicates a high probability that the igneous rock is at no great distance below the surface for at least that distance from the exposed margin of the intrusion. In Mount Ellsworth, a narrow tongue-like belt of altered rocks about a mile and a quarter long is represented which likewise suggests the prolongation of the upper surface of the intrusion to at least that distance.

Finally, Hunt appears to agree with some of the arguments presented above, for he remarks that "although the evidence shows that the stocks in the Henry Mountains were forcibly injected, the large domes around the stocks are not necessarily the result of that injection" (pp. 199-200). After considering four hypotheses to account for them and rejecting two which obviously do not apply, he concludes that they may be due either to arching by one huge, deeply buried laccolith of mushroom form or to a vertical push as if by the stocks. He objects to the first of these hypotheses on the ground that it would necessitate the assumption of an almost perfect symmetrical mushroom laccolith (*the* laccolith of Gilbert), whereas the known laccoliths (of Hunt or sheets of Gilbert) are tongue-shaped, elongate bulges. He remarks, moreover, that the assumed mushroom laccolith would have to be 20 times larger than the largest known laccolith (of Hunt, not Gilbert) in the Henry Mountains and about 50 times larger than the average volume of all known laccoliths (again of Hunt) in these mountains. Here we have examples of the confusing effects of the author's attempt at restricting the name laccolith to certain forms arbitrarily selected by himself.

He considers also that the growth of a laccolith to such huge size would probably result in imperfect form. We would comment that in the absence of directional stress a symmetrical form is the most likely to be produced.

A paragraph near the end seems to explain why the above suggestions are made by the author, "Although it is perfectly true that the domes could be the result of arching over laccoliths (? of Gilbert), they could as readily be the result of doming by stocks like those (assumed to occur) in the Henry Mountains. The object of this paper is to stress the need for reconsidering the explanations hitherto applied to large symmetrical domes associated with igneous intrusives." (p. 203.) The words in parentheses in this quotation have been inserted by us.

Our experience in Wales leads us to believe the truth of Gilbert's magnificent conception and we have also been fortunate enough to discover the stalks through which masses of laccolithic form, though on a very small scale, were fed.

Finally, Hunt refers to explorations by boring in the laccolith of the Marysville Buttes described by Howell Williams (1929). Although the original intrusion of the Marysville Buttes is regarded by Howel Williams as a steep-domed laccolith it has been considerably affected by subsequent volcanic and intrusive activity so that its original form has been almost destroyed. It is perhaps significant that a volcanic vent was later opened up just where one would assume the stalk of the original laccolith to have been. Is this accidental or may it give a hint of the existence of a stalk situated centrally below the original laccolith?

Hunt mentions several borings which were carried down for several thousand feet on the flanks of the structure; one of these was within a few hundred feet of the exposed outcrop of the igneous core and was carried to a depth of 7,014 feet. This did not reveal a continuous mass of igneous rock but a number of sills intruded into the domed strata. If a similar boring were put down, say, into the core of the Welfield laccolith, we should expect, in view of our present knowledge of these structures, to find numerous thin intrusive sheets interleaved with sediments and it may be that a similar state of affairs may occur in connection with laccolithic bodies more frequently than has been supposed.

References

Cross, Whitman, 1894. The Laccolithic Mountain Groups of Colorado, Utah and Arizona. 14th Ann. Rep. U.S. Geol. Surv. for 1892-3, 157.

Gilbert, G. K., 1877 and 1880. Report on the Geology of the Henry Mountains. U.S. Geog. & Geol. Surv. of the Rocky Mountain Region. 2nd edition (1880).

Harker, A., 1909. The Natural History of Igneous Rocks. London.

Holmes, W. H., 1877. Geological report on the San Juan district. 9th Ann. Rep. U.S. Geol. & Geog. Surv. of the Territories.

Hunt, C. B., 1942. New interpretations of some laccolithic mountains and its possible bearing on structural traps for oil and gas. Am. Assoc. Petroleum Geologists Bull., **26**, 197.

Jones, O. T., 1938. The evolution of a geosyncline. Pres. Address, Geol. Soc. London Quart. Jour., **94**, 7.

Jones, O. T., and Pugh, W. J., 1946. The complex intrusion of Welfield, near Builth Wells, Radnorshire. Geol. Soc., London Quart. Jour., **102**, 157.

———, 1948, a. A multi-layered dolerite complex of laccolithic form near Llandrindod Wells, Radnorshire. Geol. Soc. London Quart. Jour., **104**, 43.

———, 1948, b. The form and distribution of dolerite masses in the Builth-Llandrindod inlier. Geol. Soc. London Quart. Jour., **104**, 71.

Williams, Howel, 1929. Geology of the Marysville Buttes. Calif. Univ. Dept. Geol. Sci. Pat. **18**, 147.

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