THE ORIGIN OF LACCOLITHS
WITH SPECIAL REFERENCE TO THE
THEORY OF WILLIAM H. HOBBS

by

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Contents.

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The laccolite has been known to geologists as a rather unusual variety of igneous intrusion since the year 1877. At that time appeared G.K. Gilbert's famous report, "The Geology of the Henry Mts.", describing intrusions of igneous rock in Utah which seemed to be the result of magma being injected through fissures into flat lying sediments, insinuating itself in these on some bedding plane, and doming up the strata into a quaquaversal arch. For these intrusions, Gilbert supplied the term, "laccolite", meaning "cistern-stone". Although not the first to notice their peculiar character, Gilbert was the first to give laccolites scientific publicity.

There have since been numerous studies and papers on the subject, and most of these are essentially in agreement with Gilbert on the manner of their formation. However, Professor William H. Hobbs in 1921, after a comprehensive study of the literature, introduced a new theory for laccolites. This theory is so opposed to the original ones, and so novel, that it deserves much attention. McCarthy and Gould, in their respective papers both refer to this theory, but neither makes any extensive inquiry into the question it developed. Therefore, the writer feels justified in reporting on a study of the laccolite literature, and on the evidence which he has found ~~he finds, which supports the Gilbert theory throughout.~~

The procedure will be to review as briefly as possible the significant details of the various contributions to the subject, to draw from these the essential points of the opposing theories, and to discuss the several criteria which constitute an analysis of the problem. Some attention will also be given to a few additional features of laccolites, which have no or little bearing on the principal question of formation. A bibliography is included.

REVIEW OF THE LITERATURE.

All of the important works on laccolites are included here, and many also that are unimportant. Undoubtedly some have been neglected. No attempt is made to outline, but only to select from the literature the critical points which bear on the problem of laccolite formation.

Peale (1877) was the first to point out this peculiar type of eruptive mountain (named later by Gilbert). After describing these formations very briefly from several mountain groups, namely; the Elk, La Sal, Abajo, SanMiguel, LaPlata, ElLate, and Carriso mountains, Peale stated that they were caused by injections of igneous rock which had been derived from fusion of metamorphic rocks in the depths. He noticed varying degrees of contact metamorphism surrounding the intrusions, variable selection of bedding, sometimes spreading out beneath, sometimes breaking across the sediments, and a decided tendency to intrude into sediments rather than into metamorphic rocks.

When Gilbert (1877) published his classical treatise on laccolites in the Henry Mountains he described 23 different laccolites and doming of strata to indicate the existence of at least 13 more. All visible ones occurred in shales, but 5 were supposedly intruded in sandstones. There is no regularity of their distribution in plan, except in a cluster which roughly forms an oval with ratio of diameters about 1:4. The elongation of this cluster roughly parallels the Water Pocket Flexure some 10 miles to the west. Contact metamorphism was present in all cases, on the floor and side walls of the laccolite, and mostly on the roof. It was always greatest at the actual contacts; sandstones were speckled by iron segregation here, and shales were baked to hornstones. In the surrounding sheets, contact metamorphism was very slight, but great alterations in the sediments were observed in the zones of reticulated dikes above the larger laccolites. In some cases it extended for over 100 feet from the contact, and sediments were unrecognizable. Fragments of sediments were found included in the igneous rock. One dike was found isolated from all other intrusions, which, for various reasons, Gilbert considered a feeder to a former laccolite, since removed by erosion. No other feeders were seen. Gilbert found the laccolite base usually flat, sometimes convex upwards, the top generally a neat convex dome; the ratio of height to width reaches 1:3 but averages only 1:7; the plan was generally circular but in cases oval as much as 3:2 in diameter; the sizes varied from ½ - 4 miles across. No distortions of strata were measured, but there was computed a probable lengthening of 300 feet in 3 miles of cover strata for the Lesser Holmes arch, making about two percent. Practically horizontal strata surround the Henry Mountains in all directions.

Gilbert believed that at any given depth a laccolite must obtain a definite minimum size which he termed a "limital area", before it can grow by raising the cover. "Limital area" increases with depth, and the largest laccolites were the deepest, in the Henry Mountains. Differential densities were called to play to account partly for the energy of vulcanism, but orogeny was not.

Hills, (1890), described 8 laccolites in the Spanish Peak region. One of these, very perfect in its laccolitic form, had a long dike of the same igneous rock extending away for a mile in the shales. There is a possibility that this was a lateral feeder.

Cross (1895) reviewed the work of Gilbert, Peale, and Holmes, on the Henry, West Elk, San Miguel, La Plata, Carriso, El Late, Abajo, and La Sal Mountains, the Mosquito Range, and the Ten Mile District. With regard to the igneous rocks, he demonstrated that they are similar in alumina and alkalies, and remarkably so in the constancy of the alkali total. Contact metamorphism is prominent in the West Elk and San Miguel Mountains, and so are included fragments of sediments in the El Late and Abajo Mountains. He suggests that orogenic movement, accompanying intrusions of laccolites in the Ten Mile District and the Mosquito Range, caused compression of the strata and relief of load so that the magma could find easy parting planes for the intrusion of multiple sills. At Mount Marcellina in the West Elk Mountians, the laccolite has domed up the strata on one side, but faulted them upward on the other. This fault may have graded into an even fold higher up. Following Dana, Cross states that density of magma (considered important by Gilbert) is negligible for the selection of horizons, once a great volcanic force is recognized. Much of the work deals with petrography.

Weed and Pirsson (1896-b) described a roughly circular uplift in the Little Rocky Mountains. The geology shows an arching of Cambrian sediments over a core of crystalline schists, and an intrusion of granite porphyry between the two. Although much eroded away, the surrounding circle of dipping Cambrian strata show the dome-like uplift. Contact metamorphism was limited to within a few yards of the contacts. The cause of the uplift is uncertain, and the intrusion is scarcely to be considered a true laccolite.

The same authors simultaneously brought out a report (1896-a) on the Castle Mining District of Montana, describing two laccolite-like intrusions of large dimensions (5-7 miles in diameter). The surrounding strata had been domed up in some places, in others, broken across. Contact metamorphism was apparently a minor feature. It was considered obvious that sediments were not absorbed by the magma. The laccolitic nature of the intrusion is only briefly dwelt on.

Gilbert (1896) describes more laccolites, this time in southwestern Colorado. Two are readily apparent, and again a swarm of smaller ones appear to exist from the doming of strata. Contact metamorphism was found for several feet from the laccolite contacts, and for some inches from the numerous associated dikes. Inclusions of sandstone and shale similar to the sedimentary walls are described; of especial interest are included fragments of granite which Gilbert believes must have been derived from granite far beneath.

Weed and Pirsson (1897) in the geological description of the Judith Mountains, count 6 principal and 16 subordinate laccolites, most of which are exposed by erosion, and associated stocks and sills. These show a haphazard clustered arrangement in plan, are of generally circular or slightly oval base, and domed in all gradations from flat sills to convex laccolites. Sills or sheets in the sediments, circling the exposed laccolites, are common. Horizons selected for intrusion were nearly always shaly. Contact metamorphism exists in all cases and in varying amounts, generally less than around volcanic plugs or batholiths, but as far as 300 feet from the contact in places, and sometimes making slates and quartzites. There is not the least evidence of orogeny, and the sediments are uniformly horizontal in the plain surrounding the laccolitic mountains. As factors influencing the formation of laccolites, the viscosity of the lava, load of sediments, cohesion and tenacity of strata, and rapidity of intrusion, are recognized. It is suggested that on the one hand stocks might result from a highly viscous magma or rapid intrusion, on the other, sills from slow intrusion or very fluid magma; laccolites would result from intermediate conditions.

Iddings (1898) defined a "bysmalith" as a stock-like intrusion. It differed from a stock in being essentially a single igneous eruption, and from a laccolite, in breaking across the strata, though leaving them arched up somewhat around the edge. The Holmes bysmalith is the type form.

Blake (1898) described from Cutch, 32 cases of domes of sediments, in 10 of which igneous rock was found. Some of these were so aligned as to indicate a modified anticline; the author, however, expresses a conviction that they are a result of intrusion, not orogeny. Likeness of the doleritic cores lead him to believe that they were all derived from the same magma.

Weed and Pirsson (1899) in the "Geology of the Little Belt Mountains" describe 15 laccolites, 1 stock, and several sills. These were all superimposed upon a broad dome-like uplift with secondary folds. The laccolites were generally assymetric, due probably to being formed on the flank of an anticline. They vary from 2 to 5 miles in diameter and up to 3000 feet in thickness. There was a general linear disposition of them along the edge of the uplifted area. Shales were the favored planes of intrusion, especially those of the Cambrian where alternating harder beds served often as the roof.

Contact metamorphism extended only a few yards into the sediments and was greatest usually on the cover. Distinct mineralogical differences gave good negative evidence of any absorption of sediments by the magma. The strata were broken across in places instead of uplifted; a good gradation was exhibited between laccolites and stocks. Although sheets were frequent in the roof strata, only one dike was found there. The absence of more than one overhead dike was attributed to the plasticity of the shales and disinclination to fracture. The occurrence of the intrusions, only where the thick belt terrane is absent, is understood to be due to the lighter load there. Great chemical similarity between the different intrusions refers them all probably to the same magma, whose eruption is correlated supposedly with the anticlinal uplift. Orogeny and intrusion are supposed to have worked together.

Iddings and Weed (1899) reported in the Gallatin Mountains, a dome-shaped laccolite about 1200 feet thick. Contact metamorphism was scarcely noticeable, or only for a few inches on the limestone floor, and on included fragments of limestone and shale was imperceptible beyond the contact.

Irving (1899) describes several laccolites in the Black Hills. Floor and roof are of shales, doming is perfect, contact metamorphism very small. Over the Ragged Top laccolite the roof has been faulted into several blocks which enhance the uplift.

Jaggar (1900) gives an extensive account of the laccolites of the Black Hills. Gradation of all sorts was found between laccolites and sills of many sizes. The Cambrian-Algonkian contact was a favorite horizon of intrusion. Contact metamorphism is scarcely mentioned. Feeders were exposed for the Deadman, Whitewood, and Tilford laccolites, and for many sills. Various deformations of the strata were observed. In one case, shales thinned out above the laccolite but seemed to grow thicker around the margin; the limestone cover of the Terry Nolo complex was thinner immediately over the core; over the Dome Laccolite, the roof stratum was much fractured and cut by dikes. As in the Henry Mountains, larger laccolites seemed restricted to the lower zones. Jagger drew several conclusions as follows: the intrusion of smaller laccolites at higher horizons, in opposition to Gilbert's idea, is considered due to greater viscosity, less pressure, and less coherent strata here; size of laccolites had nothing to do with superior load; intrusions were minor features of a great uplift; lifting of the load may be accomplished by orogenic forces while intrusion is permitted by fractures; thick soft shales favor the formation of laccolites, alterations of shale and hard beds the production of sills; the inclination of the conduit may affect the laccolite's shape; doming may be absorbed by soft strata above so as to gradually fade out at higher horizons; laccolites are often large beneath a competent bed; thinness of roof cover is believed to be a cause of doming at that weak point, not a result of intrusion.

Pirsson (1905) treated the igneous geology of the Highwood Mountains which he had previously described in collaboration with Weed (Weed and Pirsson - 1895). Here four laccolites with sills and stocks are of unusual interest. The major Shonkin Sag laccolite is about a mile in diameter, 100 feet thick, and flat or disc-like throughout. Sandstones form both the floor and the cover and are metamorphosed below to a dark dense rock for a foot from the contact. A thin even sheet extends in both directions from this laccolite, and in one direction for several miles. Sediments beneath the Palisade Butte laccolite are much indurated. In contrast with the little contact metamorphism here, at the Middle Peak stock it extends for 1000 feet into the sediments. Close similarity in composition is shown for the several intrusions. It should be pointed out that orogeny is not capable of lifting up the strata for a flat disc-shaped intrusion like the Shonkin Sag. Interesting magmatic differentiation in this laccolite is discussed.

Coleman (1907) suggests a laccolitic nature for the Sudbury sheet, 32 miles long by 16 broad. The upper beds are less fractured than the lower which appear to have sagged in the center, collapsing perhaps over an emptying reservoir. Magmatic differentiation is evident, and contact metamorphism is pronounced, especially in the upper beds.

Daly (1912) observed in a volcanic region, a laccolite about 60 feet thick and 480 feet long, covered by 440 feet of of basalt layers. The overlying layers, distinctly up-arched, and the contact effects, gave definite proof of its intrusion, which was recent.

Loughlin (1912) considers the Preston gabbro of Connecticut a possible laccolite. It is an immense sill-like intrusion, the floor of which has not been discovered. Metamorphism has taken place for some distance in the sedimentary cover. It is not typically a laccolite.

Hill (1913) gives some knowledge of the laccolites of the La Sal Mountains, but his interest is principally economic. They are described better by Gould.

Schwarz (1913) terms laccolitic a large intrusion in the Transvaal, the Quizyhote laccolite. This is a subordinate feature of the great Karroo laccolite, 700 miles long and 200 miles wide. He believes the dolerite has resulted from gradual assimilation of tremendous amounts of sediment by an originally small volume of magma, in a process of overhead stoping and absorption. Parallelism of this with the development of an andalusite crystal is made; that is, growth is by replacement, not displacement, of original material. Schwarz is extremely hypothetical and the statement of his convictions is more prominent than scientific treatment. Great intrusions like this are hardly to be treated as laccolites anyway.

Paige (1913) abstracted some interesting ideas on laccolites. He illustrates a perfect range in shapes from the

Skonkin Sag, through normal laccolites, to Iddings' Bysmalith. As a cause of the variability of form, the "progressive increase in viscosity of a magma" is resorted to, instead of the simple previous "difference in viscosity".

Emery (1916) gives an account of the Carriso Mountain intrusions, which include 6 volcanic plugs, arranged linearly and suggesting a line of weakness, and laccolitic sills. Over one of the latter at North Mesa, the sandstone cover had been pinched out apparently between the laccolite and the superincumbent strata. This seems to have been a shortening of the roof stratum due to intrusion and deformation, since Emery states that no evidences of assimilation or stoping blocks were found. Contact metamorphism generally extended less than 3 feet; below the Tisnabas sill, the adjacent sandstone exhibited scarcely any effects, while the overlying sandstone was cemented quite to a quartzite.

Grout (1918) calls the Duluth gabbro a "Lopolith", which differs from a laccolite in the sinking in of the central part of the floor. This intrusion is 150 miles long and probably somewhere from 12,000 to 50,000 feet thick. Associated with it are many smaller sheets.

Thorpe (1919) described the laccolitic structure of the Abajo Mountains. Great blocks of roof beds were in places torn loose and elevated by the intrusive so as to lie atop the laccolite, but disconnected with their native bed. At all contacts of sediment and intrusive, metamorphism was distinct, extending for 10 to 200 feet into the sediments, and changing some overlying beds to quartzite and hornfels.

Bowen (1919) believes that numerous domes of sediments in the Mussleshell Valley, Montana, represent laccolites, though no igneous rock is exposed.

Hobbs (1921) evolved a new theory for laccolite origin, which entailed doming caused by orogeny, so that the load is relieved beneath competent strata; when shales lie beneath, they fuse due to the release of pressure, and form the igneous core of a laccolite. Hobbs uses as arguments the preference of laccolites for shales, the absence of laccolite feeders, the likeness in composition of shales and the average igneous rock, and the distribution of laccolites in orogenic regions; he infers that the cover strata are neither fractured nor pinched out, that inclusions from lower horizons are not found, and that thermal contact metamorphism is not evidenced.

Collier and Cathcart (1922) gave an account of the laccolites in the Little Rocky Mountains, and found indications of others not exposed. They state that in one the roof cover was broken in tension so as to admit the magma to higher levels; in another, over the center of the laccolite, the cover stratum was entirely pinched out.

Reeves (1924) mentions two laccolites in the Bearpaw Mountains, but, since his main interest is economic, there is only meager data on the points in question.

McCarthy (1925) gave an excellent review of the laccolite theories, covering the work of Gilbert, Cross, Jaggar, Iddings, Weed and Pirsson, and others. McCarthy also made experimental investigations on the nature of intrusions of viscous liquids in stratified material. His list of conclusions constitutes the best summary of ideas on laccolites that the writer is aware of. Some of these will be later referred to.

Howe (1900) had previously published, in connection with Jaggar, results of his experiments along the same line. He made the following conclusions: thickness and plasticity of cover beds tends to cause centrifugal migration of sedimentary material so that the arching deformation is not carried into the highest beds; intrusion seeks the bedding of the most incoherent strata; thick incoherent beds favor the production of irregular sills; other things equal, especially viscosity, laccolites formed at great depth tend to be smaller; when the feeder is inclined, the laccolite is thicker on one side; radial and concentric fractures form, making way for dikes and peripheral sills; -- high viscosity and rapidity of intrusion both tend to make a higher, more arched laccolite.

Gould (1927) in the geology of the La Sal Mountains, describes several laccolites and stock-like intrusions of the same general composition. He found dikes, which were apparently feeders to the Mount Mellenthin laccolite, inclusions of conglomerate in the Mount Allen igneous mass, and many inclusions of shale which showed distinct contacts and no incipient absorption by the magma; contact metamorphism was prevalent but limited, and Gould accounts for its small extent by low temperature and lack of mineralizers in the magma. One of the igneous masses was so large that it seemed impossible of formation by intrusion alone, but that orogeny had functioned. Gould concluded in general that orogeny might have a hand in the formation of laccolites, acting perhaps as a rudder to direct the force of intrusion.

Grabau (1913) pictures and refers to numerous laccolites, and offers suggestions on conditions accompanying their formation, but does not enter the question of their origin or throw light on it.

Giekie (1913) mentions laccolites briefly, accepting Gilbert's theory, and states that sills are much more common intrusives in Great Britain.

Daly (1914) also shows the existence of all intergrading forms between laccolites and sills and calls attention to the pronounced low viscosity effects and differentiation in the Shonkin Sag laccolite. According to him petrography has no valid connection with the formation of laccolites, because of the great range of their composition. In the case of large laccolites in which the floor dips centripetally, he suggests the emptying of the magma chamber as a cause.

SUMMARY AND ANALYSIS OF THEORIES.

To abstract from the writings reviewed, the principal theories and new ideas connected with laccolite formation:

1. Gilbert believed:

(a) That intrusion was the sole agent of laccolite formation.

(b) That difference in densities of lavas and rocks was a prime factor in the selection of the intrusive horizon.

(c) That laccolites formed at great depths tended to be larger than those at lesser depths, due to the following: (hydrostatic conditions are assumed).

The force elevating the roof is proportional to the square of the diameter of the laccolite.

The resistance of the strata to doming is approximately proportional to the diameter and also varies with depth, at a power higher than 1.

Therefore the equality of lifting force to resisting force is maintained at greater depths only by laccolites of larger diameter.

2. Jaggar:

(a) The load may be lifted by orogenic forces, while the intrusion is a subordinate feature permitted by fracture.

(b) Large laccolites were formed at lower horizons, smaller at higher, due to:

Greater fluidity and volumes of magma at great depths.

Local differences.

(c) Size of laccolites is independent of load.

(d) Asymetry of the laccolite may be due to inclination of the conduit.

(e) Thinness of the roof is a cause of intrusion at that point.

(f) Thick, soft shales favor the formation of laccolites, large ones especially when beneath a competent bed; conversely, frequent intercalation of shales and hard beds favors the production of sills.

(g) Doming may be absorbed by thick soft beds, so that the strata at some horizon above the laccolite may remain undisturbed.

3. Cross

(a) The Henry Mts. laccolites were intruded.

(b) But orogeny was mainly responsible for intrusions in the Ten Mile District and the Mosquito Range.

(c) That density was a negligible factor in the determination of the intrusive horizon.

(d) Deformation of strata may fade out at higher levels.

(e) Due to similarity of texture of laccolite cores at different levels, showing like cooling conditions, the thickness of strata once covering the mass was so great that differences in level were negligible.

4. Weed and Pirsson:

(a) High viscosity favors convexity of laccolites or production of stocks, rather than flat laccolites or sills; and the converse is true.

(b) Rapidity of intrusion has the same effect.

5. Paige

That progressive increase in viscosity of the magma during intrusion is the item responsible for such convexity mentioned above.

6. <u>Hobbs:</u>

(a) That laccolite doming is caused by orogeny.

(b) That the igneous core results from fusion of shales on release of the load.

(c) That intrusion does not function in the formation of a laccolite.

7. <u>Schwarz</u> :

That the igneous rock of the Quizyhote laccolite results principally from the adsimilation of the country rock by a small amount of original magma.

8. <u>McCarthy</u> :

In agreement with most of the other workers, that the generally minor effects of contact metamorphism at laccolites were not commensurate with the same at other intrusions, relative to their sizes; and that this indicated a low temperature for the laccolite-making magma.

For the most diametrically opposed of the important theories, we might select those of Gilbert and Hobbs. It is logical that contact metamorphism, evidence of a conduit, absence of crustal folds, indication of tension or thinning in the covdr bed, and inclusion of fragments from lower horizons would support the Gilbert idea. On the other hand, the fusion theory would be upheld by evidence of fusion or gradation between the two, perhaps by the restriction of intrusion to the shale horizons, or an arrangement of the intrusions like that of orogenic folds. Each of these criteria will be examined.

CRITERIA.

Distribution of Laccolites. Laccolites as known today, in their best form and in abundance border the eastern fore ranges of the Rocky Mountains. They may be found often in regions of orogenic activity. Their placement in irregular clusters is usual, although in the Little Belt Mountains and in Cutch they followed linear arrangement. Also in the Carriso Mountains, stocks were found along one line. Such regularity might be explained as well by a line of weakness inviting intrusions, as by orogeny determining their location according to system. The parallelism between the elongation of the Henry Mountain cluster and the Water Pocket fold also suggests a dynamic correlation. The writer in Fig.2 supposes an arc of laccolites, but knows of no such occurrence in nature. Distribution seems insignificant of their manner of formation.

Horizon of Intrusion. Hobbs has pointed out that laccolites occur almost exclusively in shales and beneath a hard cover bed. In the Henry Mountains, in a stratigraphic section where sandstone existed with shale in a ratio of 24:49, 18 laccolites lay within the shale, and 5 probably in the sandstone. This shows a decided preference for the shales, since $24:49 > 5:18$. However, it does not necessarily aid the fusion theory, since magma would obviously intrude soft shales more readily than harder beds. And the selection of a hard sand or lime stratum for a cover might quite readily be explained by the obstruction to upward movement and the lateral spreading of an intruding magma on encountering such a bed. The predominance of laccolites in shaly horizons then may not add weight to either theory of their origin.

Forms of Laccolites. The type form, a quaquaversal arch, has been seen to vary from almost flat sills to stocks. Paige illustrates this gradation very well. It is obvious from a moments inspection that lateral compression in the sedimentary beds could never have elevated the roof of the Shonkin Sag Laccolite, the shape of which is much like that of a coin. The same is true for most sills. Also, the distinctly penetrated strata around stocks or the Holmes bysmalith could never have been so ruptured simply by orogeny. It appears that intrusion alone can account for these. That a laccolite of intergrading form should be similarly caused is quite natural. Furthermore, laccolites of the type shape, are so frequently associated with sills and stocks, often with close petrographic relations, that it would seem as though intrusion of a single magma had accounted for all the structures. Thus the varying forms of laccolites corroborate the intrusive theory of their origin.

Conduits. In few cases has the laccolite feeder been found, but Jaggar found three and Gould seemingly found one of them. Also Gilbert (1877) and Hills found possible evidence of the same thing. Such finds are very good evidence of the intrusive nature of the laccolite, although it might be argued that the conduit merely leads from an original fusion chamber to a subsidiary laccolite.

Inclusions. Inclusions are frequent in igneous laccolitic rock, and in some cases, as at the La Plata Mts., they take on gigantic dimensions. Gilbert (1896), Iddings and Weed, and Gould have all found inclusions of rock from lower horizons. In one case, they were not perceptibly metamorphosed; this should be interesting. In general they do show thermal effects but retain a distinct border and give no intimation of intergrading at the contact or of a genetic relationship with the igneous rock; in other words, they give negative evidence of assimilation or fusion in such cases.

Contact Metamorphism. Laccolites are prevailingly accompanied by the effects of contact metamorphism. As compared with stocks and batholiths, laccolites are said by most geologists to have very limited effects on the adjacent country rock. For this,reasons are given such as the low temperature of the magma, proximity of the temperatures of the magma and sediments, and dearth of mineralizers. Now if we assumed a liquification of rock by release of pressure, it must occur by some combination of fusion and solution. It is probable that the process would require latent heat during the transition, exclusive of that required for a mere rise in temperature. Daly (1914, p.172) gives the latent heat of fusion of basalt or gabbro as 20 - 25% of its total melting energy from 0 degrees centigrade. The source of such an influx of heat is difficult to imagine, expecially since some energy is lost in the release of pressure, as in an expanding gas. Probably no metamorphic thermal effects could be expected in the neighboring sediments as a result of this. Therefore, the unfailing presence of these, to some extent at least in all cases, strengthens the intrusion theory.

In explanation of the fact that contact metamorphism is frequently stated to be less than should occur about such intrusions, the writer has a suggestion. Comparison of the amount of metamorphism with the "size" of the intrusion is perhaps not fair. A laccolite might be of greater circumference than a stock, and yet in depth be comparatively small; while the laccolite might be supposedly connected with the nether regions by a small feeder, the stock might extend indefinitely downwards, with ever larger horizontal sections. The stock may then concentrate upon its upper side-walls, mineralizers and heat from a vast volume of magma, while from the laccolite small amounts of heat and mineralizers are scattered over a large contact area; these come from its very limited depth of magma since its conduit is probably too small to be of use in transmitting them.

In several cases, contact metamorphism around a laccolite has been described as greater than around its parasitic dikes, relative to the sizes. Effects from the laccolite are generally greater on the roof than elsewhere; and this is to be expected from the action of convection currents.

Chemical Composition. The similarity between the composition of igneous rocks and shales, as pointed out by Hobbs, is striking. An attempt is made to present further comparison on this subject in the table of (page 23A). Magmatic differentiation and its effects are entirely neglected. The writer supposes that a great mass of sediments of all sorts might fuse, and a possible resulting composition is given in column II where the writer has averaged the sediments in the proportion in which they probably occur in the earth's crust. It cannot be said that this more closely resembles the composition of the average igneous rock of column III than does column I. That is, if a laccolite fused from sediments, it does not appear that it would have fused rather from a combination of sediments than from shales alone, or vice versa. Closer agreement of silica, soda, and iron in one case, are offset by that of potash and lime in the other.

Now, if columns III and IV be compared with I and II, or with some sort of an average of I and II (it is conceivable that shales might fuse more readily than the other sediments, and that they might exceed their given ratio in a composite of fused sediments), it is quite apparent that column III approaches I and II more closely than IV does, in practically everything but silica. And if in column III, due allowance had been made for the preponderance of granites in volume throughout the earth's crust (as noted by Daly - 1914) the silica content of the average igneous rock would doubtless be sufficiently higher to complete the analogy just drawn. Thus it seems that fusion of sediments would tend to produce a magma agreeing more closely in composition with the average igneous rock, than with that of the cores of laccolites. But it appears to the

	I. Average shale	II. Average Sediment	III. Average Igneous rock	IV. Average Laccolite core rock	V. Range Range of Laccolite core rock
SiO_2	64.18	65.00	61.02	64.90	56.62 - 69.24
Al_2O_3	16.91	14.80	15.85	17.19	15.30 - 19.09
Fe_2O_3	4.44 } 7.49	3.90 } 6.50	3.92 } 7.50	2.61	1.19 - 4.94
FeO	3.05	2.60	3.48	1.98	0.69 - 3.29
MgO	3.07	3.10	3.60	1.59	0.65 - 4.08
CaO	3.41	6.30	5.24	4.36	2.17 - 7.39
Na_2O	1.39	1.20	3.96	4.27	3.19 - 6.70
K_2O	3.56	3.10	3.23	3.06	1.97 - 3.52
Total	100.01	100.00	100.00	99.96	

I. Composite of 134 shales - Hobbs (#18) p. 34.

II. Composite of sediments. From Hobbs, (ibid) were taken the average compositions of shales, sandstone, and limestone, and the ratio of the amounts of these in the earth's crust (19:3:1). The writer then computed the composition of the "average sediment", i.e. a composite of 19 such shales, 3 sandstones, and 1 limestone.

III. Average igneous rock from Hobbs, ibid.

IV. Average core rock of laccolites from 18 prominent localities. This was averaged from the compositions given by Cross (#5), p.227. The set there given as XVI was omitted, for Cross states that it is properly of a different series.

V. This gives the range in percentage of each oxide in the previously mentioned 18 laccolitic cores. As a composition, it obviously has no significance.

writer that, in accounting for a similarity in composition between the average igneous rock and the average sediment, another reason is as good as the supposed fusion of sediments; namely that the ultimate source of all sediments is igneous rock.

Iddings takes the view that the tracing of composition of an igneous rock to sedimentary origin by fusion, or even that it is influenced by assimilation, is unwarranted. To quote:" Moreover, it may be said that there are no igneous rocks having the composition of certain sedimentary rocks which would form molten fluids if heated to the temperature of some volcanic lavas. Assertations that igneous rocks have been derived from sediments by fusion ignore this simple chemical evidence to the contrary .... However, there are those who consider that a large part of the variation in the composition of lavas has arisen from the admixture of mineral matter by solution of rocks through which lavas have been erupted; a conception within the bounds of abstract possibilities, if magmas were sufficiently heated at the time of their eruption to permit of considerable melting, solution, and diffusion of the dissolved rock material , and if the chemical composition of the magma and of the rocks, supposed to have been dissolved, were such that their mixture would produce a lava having the composition of one for which such an origin has been claimed .... The chemical composition of magmas is such that they appear to have come from depths below any at which sedimentary strata exist".

The writer draws the following conclusions from this :

1. From analogies of chemical make-up, it seems that fusion of a mass of sediments would not tend to produee the characteristic core rock of laccolites in preference to igneous rocks of average igneous rock composition.

2. This correspondence of compositions does not necessarily suggest that such fusion has occurred, since it may be as readily explained by the igneous rock source of material, for sediments.

Doming.

The formation of a dome might conceivably occur in at least two ways; by intrusion or by orogeny, and perhaps others. That it can occur by intrusion is obvious from the existence of laccolites and from experiments (Howe and McCarthy). Doming resulting from orogeny is more difficult, and as McCarthy observed, "problematic to say the least".

If we assumed lateral compression with thrusting in horizontal strata as pictured in the plan of Fig. 1, we might possibly have the formation of a dome as shown in section A - B. This would relieve compression in the strata at the dome only, and relief on either side where compression should also exist could be taken care of plausibly by folding as shown in section C -D. This fold would not have to arch up as high as the dome, provided there was a high degree of curvature. Another section , E -F at right angles to these is shown. It is readily seen that

that this is not a true dome at all but a fold in which the manner of folding varies somewhat, so that a "doubly tailed" dome-like structure or anticline results.

Thus, lateral compression in an area, towards a line, has been represented. If we considered thrusting only in a line, towards a point, the "tail folds" of Fig. 1 would not be necessary, but, in order to allow absorption of compression along one line, the laterally adjacent stationary strata might have to be sheared from those in the line of thrust, so that extensive faulting parallel to the thrust line would result. This has not been witnessed, and the point application of pressure, to give thrusting along a single line, might be difficult to produce.

If now a second series of thrusts were applied in addition to those in Fig. 1, and at right angles to those, a more nearly even quaquaversal structure would probably result. To go to the extreme case, a circuit of centripetally directed thrusts should form a dome; but they would have to be applied directly at the base of the dome, and could not be transmitted through surrounding level strata without much warping and circumferential overthrusts. The possibility of such a situation certainly looks remote.

Hobbs (1921) advances a theory that a string of laccolites instead of a level-crested anticline, may constitute the festoon characteristic of many island arcs. Such a scheme is represented in Fig.2. An arc of domes is there shown, with intervening basins,

caused by radial compression along a gigantic arc.
At every point of contact between a dome and a basin there are strata which are thrown neither above nor below their normal horizon, and must therefore find relief, probably in puckerings as shown in section Q- R.

No structure in connection with laccolites, such as is shown in either of these diagrams is known to the writer. In view of the fact that some laccolites occur with steep wall cover (sometimes 80° inclination), and that many are neatly quaquaversal and truly dome-like, and isolated in otherwise undisturbed strata, it seems that no such structure could be formed by orogenic processes, although orogeny may build or aid in the building of assymetrical structures.

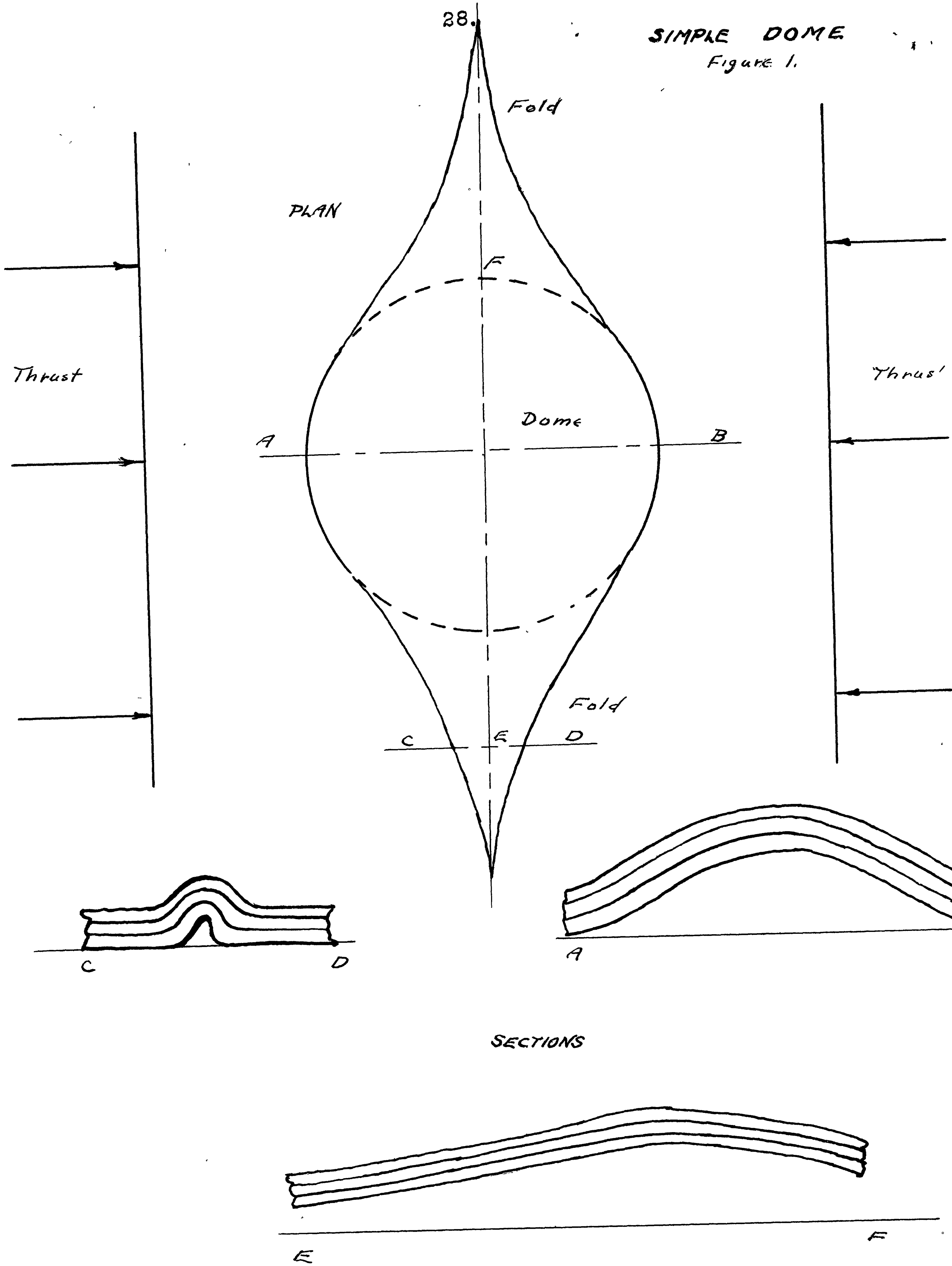
Fusion Following Release of Pressure.

There is at present little definite knowledge of the condition of magma deep within the earth's surface, since the conditions of pressure and perhaps temperature which exist there cannot be reproduced in the laboratory. However, we may state certain pertinent facts.

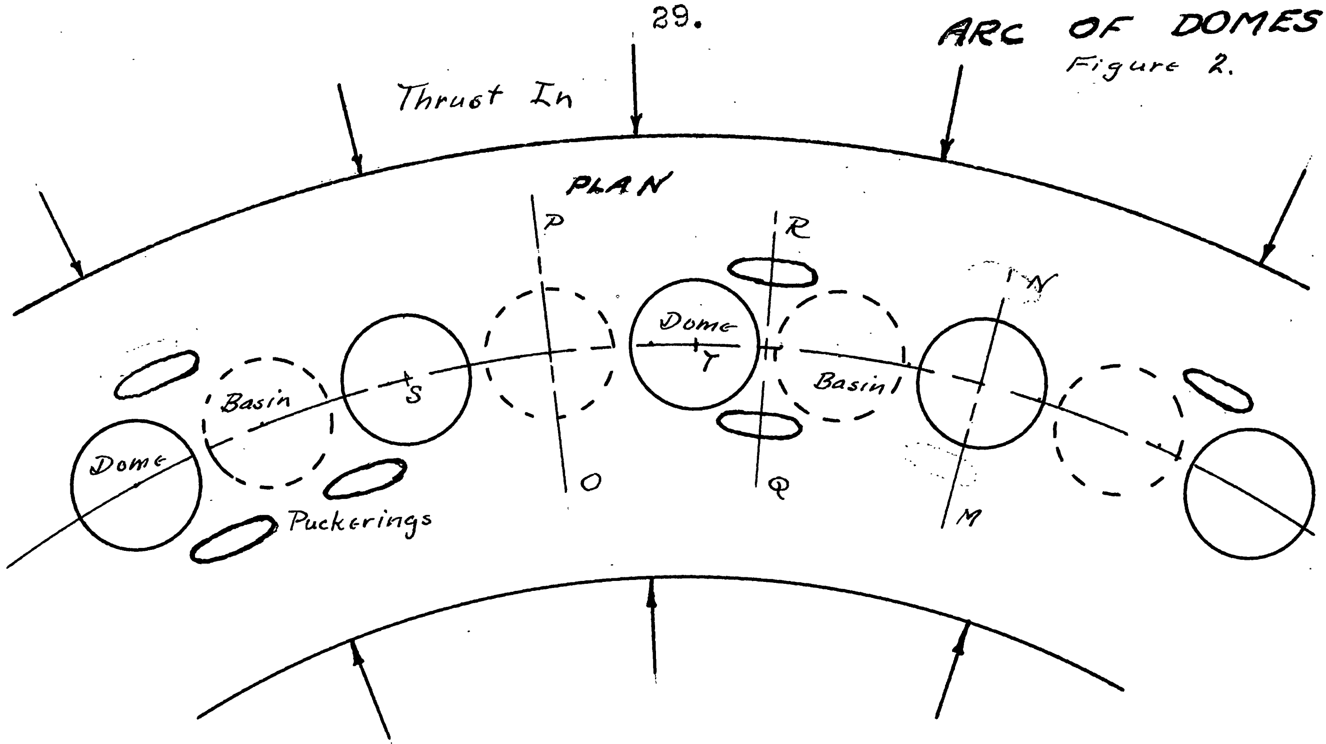
1. Molten rock is generally less dense than solid rock. This is known from the foundering of crust fragments in lava lakes, and from experiments on the fusion of rocks and rock minerals which expand.

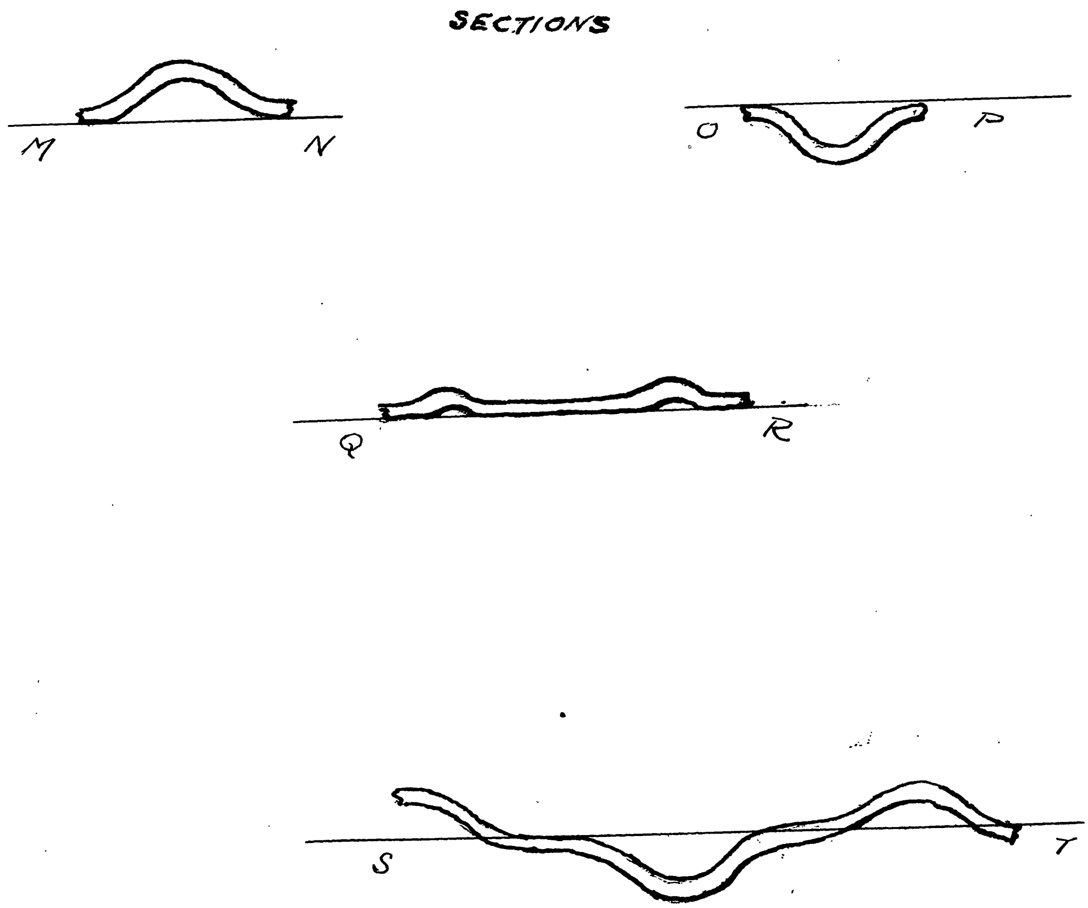
2. Solutions generally occupy a lesser volume than the total of the individual volumes of solvent and solute, and the same is true for alloys.

SIMPLE DOME
Figure 1.



ARC OF DOMES
Figure 2.





3. The liquidity of molten rock is generally conceded to be a result of solution rather than dry fusion because of the order of crystallization of the minerals from magma, following a sequence of increasing solubility rather than decreasing fusion temperatures.

Thus far, assuming that pressure would favor solution, we might believe that intense pressures would render rock at great depths more fluid, other things being equal. But a fourth fact prevents.

4. The interior of the earth, a zone of tremendous pressures, from which comes our molten rock, is known to be extremely rigid, since it is not daily distorted under the gravitative influence of the moon.

We might assume that, to explain the comparative volumes of rock and lava, the high temperature causing the expansion of the minerals, more than compensates the decrease of volume due to solution, so that the hot liquid rock, even though a solution, has a greater volume than the cold solid. Excessive pressure might than very plausibly cause greater viscosity or rigidity in a magma, by a reduction of volume, and decline of pressure would render it more fluid. It is known that the viscosities of wax and gasoline at room temperatures are much increased by high pressures. Iddings (1914) suggests as another possible cause of decrease of viscosity of magma with lowered pressure, the separation of water and other gases from chemical combination, so that they may act as solvents.

It is natural that pressure might increase with depth in the earth, and that very high pressures should exist at a small fraction of the greatest depth. It is also known that temperature rises proportionately with depth at a fairly constant rate up to known limits. It might be assumed that this rise of temperature continued to unknown regions where it would exceed known values and compensate the increase of viscosity of magmas due to pressure. But, the existence of such high temperatures is a matter of question, and is less probable than that of high pressures.

Indications are that water is abundant at great depths, and that fluidity of magmas should always occur by solution rather than by dry fusion. If rock were in such a zone that it would become fluid after relaxation of pressure, it is reasonable to believe that it existed there essentially as a solution since it would thus occupy probably less volume and be more stable, than in a crystalline state at such pressure. It might be rigid like glass or obsidian and at the same time fluid, and still a solution, however viscous it might be from the effects of pressure.

To quote Iddings (1914): "It is possible, then that there may be a zone at the base of the lithosphere consisting of material capable of fluid motion wherever there may be any change of stress due to shifting of overlying load through warping, and that this zone or base may consist of amorphous material; or of crystallized minerals in such a stage of equilibrium that they may pass into solution in one another upon the requisite change of pressure; or it may consist of a mixture of such crystals and amorphous substance, for in the nature of the case there should be very gradual transitions in all the physical characteristics of different parts of the earth's interior, and no abrupt changes ...."

To conclude, it appears that a mass of rock may become capable of liquifying upon release of pressure, only by entering a zone of the earth at great depth where a state of solution continually or intermittently exists, and that the rock mass could scarcely leave this zone with the same textural characteristics it possessed before entering it from above. Therefore it seems, that in laccolites which are surrounded by sediments of distinct identity, such as shales or sandstones, which probably never entered this zone, the core rock should have become liquid, not near the sediments, but at much greater depths, and should have been subsequently intruded into its final horizon.

Viscosity and Load.

The conclusion of Pirsson that a highly viscous magma renders a resultant laccolite more convex seems logical. It is well correlated with the high degree of differentiation in the Shonkin Sag Laccolite which is very flat and must have been formed by a very fluid lava. Paige's alternative offering of progressive increase of viscosity during intrusion is less useful when applied to the thin multiple sills which are so common and must cool rapidly as compared with larger masses of magma.

Jaggar's replacement of Gilbert's theory, to account for the greater laccolites abounding at greater depths, by simply different conditions of viscosity, etc., seems invalid. Gilbert's well derived "limital area" is sound and probably of importance in explaining this.

CONCLUSIONS.

It has been shown that the slightly systematic distribution of some laccolites, their horizons of intrusion, and their chemical composition may have ambiguous interpretations. More significantly, the variations in form of laccolites, the existence of conduits, inclusions from lower horizons, the persistent contact metamorphism, and the deformation of the roof strata, all argue that known laccolites have been formed by the intrusive theory of Gilbert. Furthermore, there appear to be improbabilities of acute doming by orogenic processes, and of fusion of some sediments while adjacent ones remain little altered, which would deny a possibility of formation according to the Hobbs theory.

A little light has been thrown also on some of the auxiliary theories. In brief, the following conclusions are offered:

1. The doming of sediments around laccolites is caused

by intrusion of magma and not by orogenic stresses, unless the form is not typically laccolitic (a perfectly symmetrical dome)

2. Orogeny may have been a more or less important factor in the development of asymetric forms of laccolites.

3. The resulting igneous core is derived entirely from injection of magma through a conduit, and not from fusion "in situ".

4. Assimilation of sediments in the region of intrusion is probably absent or negligible in all cases.

5. Contact metamorphism is always an accompanying feature, and may amount to all that could be expected.

6. The inclination of the conduit probably causes an asymetric thickening of the laccolite.

7. High viscosity of the magma and rapidity of intrusion both lead, separately or together, to the development of very convex laccolites or even stocks, instead of flatter laccolites or sills, and the converse of this is also true.

8. The tendency for large laccolites to form at greater depth is due probably to the relative values of the resistance and uplifting forces.

9. There are all gradations in form of laccolites, from sills to bysmaliths or stocks.

10. The energy for the formation of these intrusions must be adknowledged as one of the dynamic agents of vulcanism, though it is little known.

11. Horizons especially subject to laccolite intrusion are those of soft shales, underlying a competent bed which powerfully resists further rise of the intrusive.

12. There is a tendency, especially in perfect laccolites to stretch out the roof stratum. Sometimes it is actually thinned out over the intrusion, sometimes it is much fractured and torn apart and cut by dikes. The choice between these two deformations depends on dominance during adjustment, of lateral tension, or vertical compression.

13. Great deformation adjacent to the intrusion often disappears gradually above a thickness of cover beds.

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