STRUCTURE OF THE SOUTH MOCCASIN LACCOLITH, FERGUS COUNTY, MONTANA.

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Central Montana is a region of transition between the Rocky Mountains and the Great Plains physiographic provinces. Although mostly a plains region there are a number of outlying mountain groups, such as the Judith, Highwood, and Bearpaw Mountains. West of the Judith Mountains and near the headwaters of Judith River are two small laccolithic masses, the North and South Moccasin Mountains. The South Moccasin Mountains may be reached from Lewistown, the seat of Fergus County. They cover an area about five miles in diameter. The maximum elevation is slightly over 5,800 feet above sea-level, or 2,200 feet above the general level of the surrounding plains.

The South Moccasin Mountains have a laccolithic core of rhyolite porphyry, the intrusion of which has disturbed strata from the Cambrian to the Upper Cretaceous. Small areas of undisturbed travertine and terrace gravel lie on the flanks of the mountains and are believed to be of Quaternary age.[1] The porphyry crops out here and there in an area of about two square miles.

Uneven doming by the laccolithic intrusion produced an unsymmetrical topography on which many of the streams developed. Diehl Creek, the chief stream, has opened up the interior of the laccolith, leaving a horseshoe-shaped rim. The outward-dipping heavy bed of sandstone in the Kootenai formation (Lower Cretaceous) makes a prominent hogback which extends most of the way around the mountains but makes striking gateways where it is crossed by the radial streams. The massive Madison limestone (Mississippian) makes even more imposing gateways. Tilted, triangular masses of Madison limestone occupy the interstream slopes of the main mountains and are visible for great distances.

* Abstract of a portion of a dissertation submitted in partial fulfillment of the requirements for the degree of Doctor of Philosophy, Yale University.

[1] W. C. Alden in a recent paper (Physiographic Development of the Northern Great Plains, Geol. Soc. Am., Bull. Vol. 35, pp. 385-423) places the terrace gravel in the Miocene or Pliocene. It is suspected, but not proved, that the travertine is older than the gravel.

Three types of stream courses may be recognized. First, the various subsequent tributaries to the headwaters of Diehl Creek, which are centripetal or radially inward flowing. Second, the lower course of Diehl Creek and other centrifugal or radially outward flowing streams which were consequent upon the original laccolithic uplift. Third, subsequent streams which have worked back from the consequent streams and have opened up small areas of weak Mesozoic rocks on the inner side of the Kootenai hogbacks. Their courses are tangential to the roughly circular ground plan of the mountain group.

The South Moccasin Uplift.—The South Moccasin Mountains are bounded on the east by a lowland area of nearly horizontal sedimentary rocks five miles wide which separates them from the Judith Mountains. An area that is similar in extent and structure, except for a group of short faults of small throw, separates the South and the North Moccasin Mountains. On the south ten or fifteen miles of plains lie between the South Moccasins and the Big Snowies. To the west the plains of Judith River Basin extend much farther.

The South Moccasin laccolith, like many others, is far from symmetrical. The purpose of the present paper is to describe its form and offer an explanation for it.

Little can be known of the floor of the South Moccasin laccolith, as erosion has exposed no part of it. The floor is certainly not a single flat surface, because in some places the Devonian beds and a little of the Cambrian have been raised by the intrusion; whereas elsewhere these strata have not been disturbed and the intrusion took place at the top of the Devonian or within the Mississippian beds. Thus the floor consists of several horizontal or subhorizontal surfaces which lie at different elevations and are separated by scarps. Some of the blocks that are found as big inclusions in the porphyry may have been stoped from the floor instead of the roof, thus increasing the irregularity of the floor.

The sedimentary rocks have been tilted so that they dip away from the mountains on all sides, the dips decreasing in general as the distance from the mountains increases.

The structure contour map (fig. 1) and the stereogram (fig. 2), from both of which the dikes and other minor apophyses are omitted, show with considerable accuracy the upper surface of the laccolith. Eight structure sections along critical lines across the laccolith were constructed on the basis of numerous dips and strikes

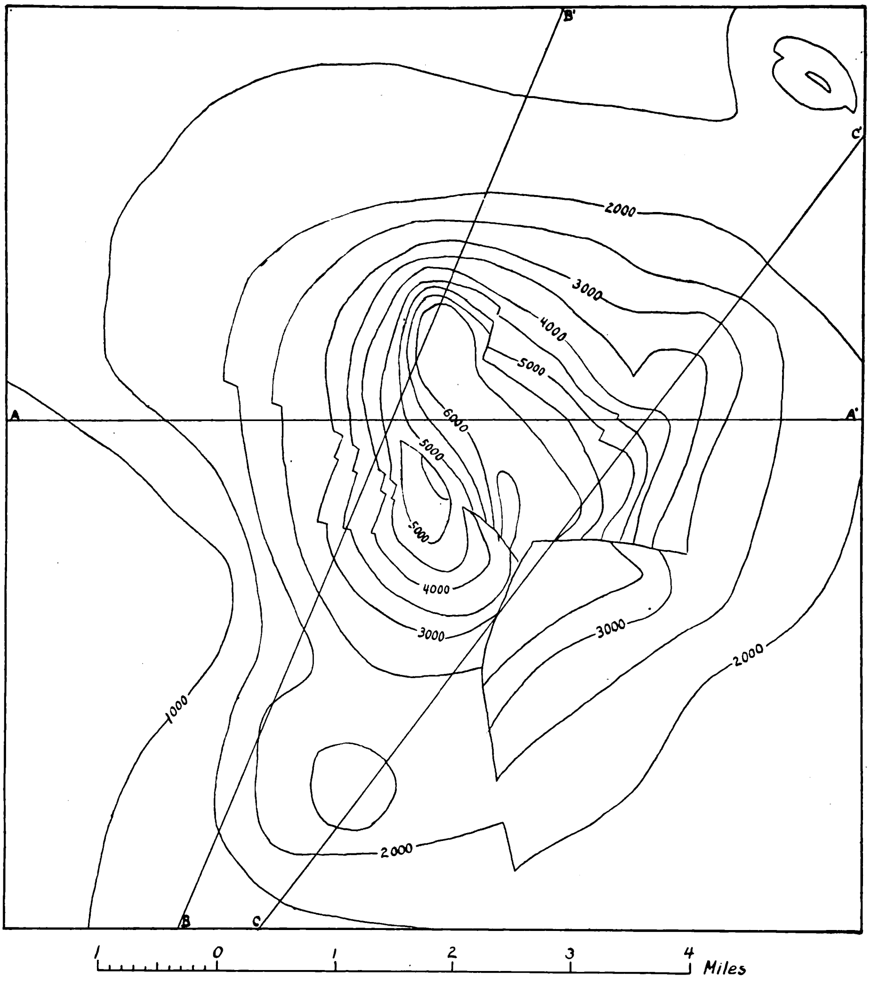

Fig. 1.—Structure-contour map of the South Moccasin laccolith. The contours are drawn on the upper surface of the porphyry mass.

observed in the field and the data given by the topographic and geologic maps, which were made with plane table and telescopic alidade. From these structure sections, three of which are reproduced in fig. 3, the struc-

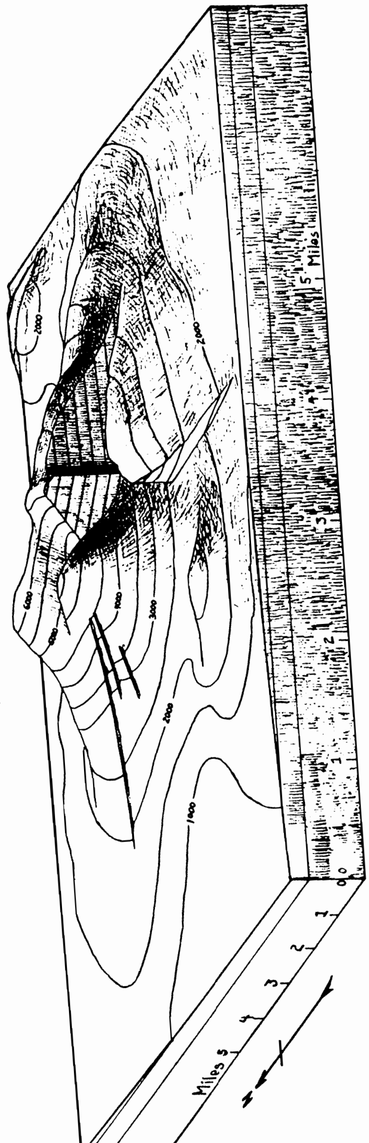

Fig. 2.—Stereogram of the South Mountain laccolith, drawn on the same surface as the structure-contour map. Minor intrusions and apophyses are omitted.

ture contour map was made. The stereogram was prepared from the structure contour map, the line of sight being inclined at 15° from the horizontal and bearing N. 17° E.

As shown by either the structure contour map or the stereogram, the roof of the laccolith is divided roughly in half by a pair of faults, one of which extends west-northwest, and the other east from the center outward. The south half is further divided into quadrants by a southward extending fault, the Diehl Creek Fault. The northern half is less markedly broken by two smaller faults which are concealed in the stereogram. Three more minor faults run about parallel to and a little south of the west-northwest fault.

The southeast quadrant is a blunt, northwest-pointing wedge in ground plan. The roof dips southeast or outward over most of its area, but at the point of the wedge the dip is northwest or inward. The north edge is also bent down so that the dips along it are northward or toward the east fault.

The southwest quadrant includes "South Peak Dome" and, farther south, "Hanover Dome." Hanover Dome is a smooth-topped, symmetrical dome, nearly two miles across and with a spring of about 1,500 feet. South Peak Dome is about three miles across and has a spring of 3,200 feet. It is rather symmetrical, but is cut on the north and east by faults. The lower western slopes blend with those of the northwest quadrant. The fault between the northwest and southwest quadrants is of the scissors type. Opposite South Peak the south side has been raised about 1,000 feet whereas farther east it has dropped 5,000 feet.

In short, the South Moccasin laccolith has a dome shape, consisting of a number of lesser domes which in part merge into one another and in part are separated by faults.

The volume of the intruded rock is estimated to have been 1,077 x 10^9 cubic feet, or 7.3 cubic miles, when it had cooled fully but before any had been removed by erosion. When still molten the volume would have been a little greater—1,090 x 10^9 cubic feet, or 7.4 cubic miles. The weight of the porphyry, including that removed by erosion, is estimated at 89 x 10^9 tons. The laccolith covers an area of about 952 x 10^6 square feet, or 34 square miles, which is equivalent to a circle with a diameter of 34,800 feet, or 6.6 miles.

Various minor intrusive bodies are related to the laccolith. None was definitely identified in the east half of the mountains. Two phacoliths were found on the slopes of South Peak Dome; one extending north and south at a low elevation on the Diehl Creek side, and one extending northwest-southeast at a higher elevation on the southwest slopes. At its southeast end the latter turns northward and then continues downward as a dike. A sill 8 to 10 feet thick crops out here and there for a mile along a wavy line in the trough between Hanover and South Peak domes.

On the crest of the west rim of the mountains the west-northwest fault fissure becomes filled with a broad agglomerate dike. On the lower west slope of the northwest quadrant are three sills and on the north slope there are two dikes.

Although the contact between the porphyry and the sedimentary rocks is in general concordant, there are many places where it cuts across the bedding. For the most part the contact is near the base of the Madison limestone, but in places it is in or below the Devonian or even in the Cambrian strata. Intrusion has had very little contact-metamorphic effect on the enclosing rocks, and the inclusions of sedimentary rocks in the porphyry are likewise very little altered.

Proof of Laccolithic Character.—As the floor is nowhere exposed, it is impossible to prove that the South Moccasin intrusive body is injected and not subjacent. The belief that it is injected is supported by two arguments. It is probable that this intrusive body has the same habit as those of the Judith and other neighboring mountain groups; these are associated with the same sedimentary formations and the intruded igneous bodies in many of them have been demonstrated to have floors. Secondly, if the igneous mass of the South Moccasin mountains were the top of a subjacent body, that is, one which extends downward to an indefinite depth, it would probably have exerted more exomorphism, and furthermore the ground-mass of the porphyry would probably have been much smaller in amount and much coarser.

Mode of Intrusion.—Aggressive intrusion takes place when the energy in the magma reservoir is sufficiently great to force the molten matter into position. Permissive intrusion occurs when stresses originating in or transmitted by pre-existing rocks are sufficient to arch, or otherwise distort them so as to make a region of reduced rock pressure into which the molten rock moves in obedience to hydraulic laws.

Most primary stresses in the earth's crust are either nearly vertical (radial) or nearly horizontal (tangential), though either sort may cause secondary, oblique stresses. Vertical stresses, unless produced by igneous intrusions, are rarely if ever restricted to such small areas as the South Moccasin Mountains. Horizontal stresses are generally produced by the interaction along the edges of adjoining segments of the earth's crust. The segments are relatively large so that the horizontal stresses are developed along rather long lines or in elongated zones and not against a point or small area. It is difficult to conceive a mechanism by which centripetal, horizontal compression might converge so as to make a small, quaquaversal dome. Horizontal compression habitually causes thrust faults or long folds. Therefore it seems certain that the South Moccasin intrusion was the result of aggressive, vertical igneous forces and not of horizontal stresses that made a dome beneath which the magma might flow by permission of reduced rock pressure.

Faults resulting from centripetal compression would be thrust faults and therefore presumably of low angle. Aggressive intrusion would apply to the roof, vertical stresses, which by shearing strain would give rise to steep faults. The faults of the South Moccasin mass appear to be fairly steep and therefore due to vertical rather than horizontal stresses.

Permissive intrusion may take place when some stress or combination of stresses tends to separate strata, thus making a region of reduced rock pressure. Such stresses may be developed on the flanks of folds where differential movement between the various strata is favored. Less extensive stresses might arise similarly on the flanks of dome-shaped intrusions. The hypothesis that the Moccasin Mountains bore this relation to the larger

Judith uplift was considered but seems untenable. In the first place, it is unlikely that the stresses would be effective after being transmitted through five to eight miles of strata from so small a master structure. They would tend to permit of intrusion at less distance. In the second place, such stresses would probably result in elongated intrusions with their long axes paralleled to the edge of the master structure or in a series of intrusions arranged along such a parallel line. They would not be likely to give rise to intrusions of subcircular ground plan like the Moccasin laccoliths.

Presumably the two phacoliths in the southwest quadrant and some of the other minor intrusions of the South Moccasin Mountains were made by permissive intrusion and are satellites of the main, aggressively intruded laccolithic body.

Gilbert's studies in the Henry Mountains[1a] indicate that the trachyte of those laccoliths had an average specific gravity of 2.61 and was intruded beneath strata whose average specific gravity ranges from 2.16 to 2.36, depending on the depth at which intrusion took place. The inference drawn by Gilbert is that the lighter roof material was hydrostatically floated up by the heavier intrusive material. Gilbert made his determinations of the specific gravity of the trachyte samples in the usual way but weighed the more or less porous sedimentary rock samples first in water after some soaking and then made his weighings in air before the water could drain out. The results are from one-seventh to one-fourteenth lower than would have been obtained by the usual procedure and are believed by Gilbert to measure the weight of the rocks at the time of intrusion.

The specific gravity of the holocrystalline equivalent of each of types of South Moccasin porphyry was computed according to the "normative specific gravity" method of Washington.[2] The various values were then weighted according to the estimated abundance of the various types of porphyry, and the average found to be 2.69. The actual specific gravity of the porphyry is somewhat less than this figure, which is for the holo-

[1a] Gilbert, G. K., Report on the geology of the Henry Mountains, U. S. G. & G. S. R. M. R., 1880, p. 74.

[2] Washington, H. S., Isostasy and rock density. Geol. Soc. Am., Bull., Vol. 33, part 2, pp. 375-410, 1922.

crystalline equivalent. However, we can step from the holocrystalline equivalent to the magma, which is the thing to compare with the sedimentary rocks.

Daly[3] has computed the specific gravity of melts of various rocks at 1,000° C. and higher temperatures. The specific gravities of granite and gneiss, which are 2.60, 2.70, and 2.80 at 20° C., become 2.31, 2.40, and 2.49, respectively, at 1,000° C. The losses are 0.29, 0.30, and 0.31. Applying the average loss, 0.30, to the specific gravity of the holocrystalline equivalent of the South Moccasin porphyry, we find that the specific gravity of the South Moccasin magma would have been about 2.39 at 1,000° C. Judging from Daly's tables, heating of the magma from 1,000° to 1,300° C. would have reduced the specific gravity to 2.37.

A large number of specimens of the sedimentary rocks overlying the porphyry were weighed in air and reweighed in water after soaking for twenty-four hours. Corrections were introduced later for the effect of voids in lightening the rock. The specific gravities thus determined were weighted according to the thickness of the beds or formations they represent and the average of the whole column of overlying rock was found to be 2.56. On the assumption that the sandstones have an average porosity of 20 per cent and the limestones and shales an average porosity of 5 per cent, the average for the whole column becomes 5.5 per cent.[4] If the pores were filled with air, the net specific gravity would be reduced to about 2.42, or if filled with water to about 2.47. Much of the pore space was probably filled with water at the time of intrusion. In order that the net specific gravity of the sedimentary rock overburden should reduce to 2.39, the assumed specific gravity of the magma, we would have to assume a porosity of 6.6 per cent if the pores were air filled, or 11 per cent if water filled.

In short, it appears that the average specific gravity of the overburden was greater than that of the magma, though only a little greater. If the values taken are fairly accurate, or if both err in the same direction, we

[3] Daly, R. A., Igneous Rocks and their Origin, p. 202, 1914.

[4] The values assumed above are somewhat larger than those used by M. L. Fuller in getting at the average porosity of all sedimentary rocks. See "Amount of free water in the earth's crust," U. S. Geol. Survey Water-Supply Paper 160, p. 61, 1906.

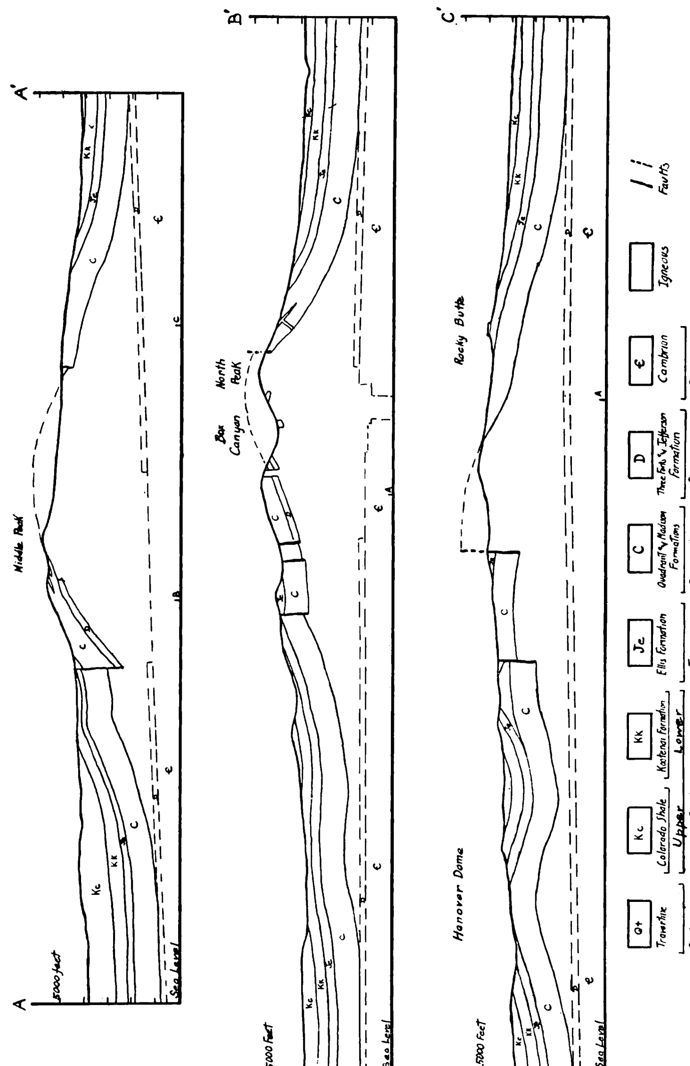

Fig. 3.—Structure sections drawn across the South Moccasin laccolith.

may conclude that the lifting of the cover of the laccolith was not due to hydrostatic floating on the magma. It seems more probable that the massive Madison limestone presented a mechanical obstacle to the ascent of the magma and so determined the horizon at which the magma should spread; and further, that the hydraulic pressure of the magma was sufficient to cause the doming.

Accommodation in the Roof.—Gilbert,[5] in his classical study of the laccoliths of the Henry Mountains, pointed out the fact that "when a circular portion of a continuous level stratum is lifted into a quaquaversal arch—there must be stretching or fracture." In the Lesser Holmes Arch he found a lengthening of 300 feet in three miles, and assigned this lengthening to thinning by compression by the intrusive rocks.

In order to calculate the lengthening of the strata over the South Moccasin laccolith some hypothesis must be assumed as to the form of the roof. It is clear from the structure sections given in figure 3 that to consider the roof as a part of a sphere or to consider a line across the roof as the arc of a circle does violence to the facts. However, this is the only hypothesis capable of simple mathematical treatment and it is therefore adopted with the belief that it will give the correct order of magnitude of the stretching of the roof rocks. The diameter of a circle of the same area as the estimated base of the laccolith is 34,800 feet. A spherical segment having this base area and a volume equal to that of the laccolith is assumed for calculation. There are two cases; one is the volume before and the other the volume after solidification and cooling of the magma. The rocks overlying the porphyry, on this hypothesis, would have been stretched from an arc length of 34,800 feet to one of 35,199. The actual lengthening then must have been of the order of 400 feet. The subsequent shrinkage would have decreased the arc length to about 35,188 feet, or by 11 feet.

A blister is analogous to a laccolith in that it consists of an upper layer which has been stretched and curved by a fluid forced beneath it. The analogy is defective in that though skin has a high limit of elasticity the roof

[5] Op. cit., pp. 74-78.

rocks of a laccolith have a low limit of elasticity, and must yield either by fracture or flow. Some of the hypotheses suggested to explain how the roof rocks behave are as follows:—

(1) By cracking of the roof into blocks which would be variously tilted and would be separated by wedge-

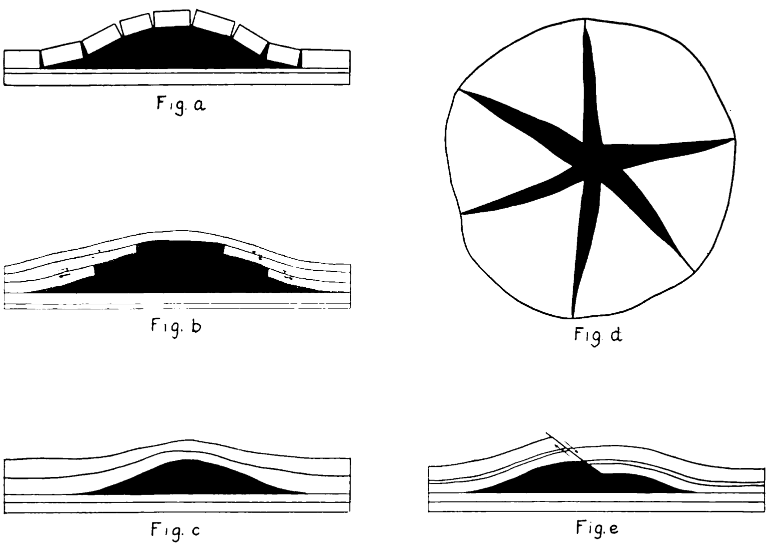

Fig. 4.—Methods of accommodation of stretching in the roof of a laccolith.

a. Roof broken into blocks separated by gaping fractures.
b. Differential movement between layers of roof.
c. Thinning by flowage of roof rocks over greater area.
d. Roof broken radially into sectors.
e. Movement along an inclined fault.

shaped openings. Those on top of the laccolith would gape upwards, and those around the base would gape downwards (fig. 4-a). On this hypothesis the upper surface of the laccolith would consist of a number of plane or sub-plane surfaces separated by apophyses, rather than of a system of curved surfaces.

The volcanic breccia that constitutes the dike filling on the west rim of the South Moccasin Mountains may be interpreted as the filling of one of these wedge-shaped openings between blocks.

(2) By faulting along bedding planes which dip away

from the center of the laccolith (fig. 4-b). Such faulting should be visible in radial valleys if it had occurred, but none was found in the South Moccasin Mountains. Inward movement of the upper layers over the lower ones seems improbable as it would involve tension around the margin of the laccolith which would start arcuate faults. Such faults would break the roof into blocks like those of the first hypothesis.

(3) Laccoliths intruded into relatively plastic rocks might thin them by vertical compression and thus spread them over larger areas (fig. 4-c), as suggested by Gilbert for the Lesser Holmes Arch in the Henry Mountains. It seems probable that the shale members of the Mesozoic formations overlying the South Moccasin laccolith were thinned and stretched in this way, but since the heavy, rigid Madison limestone seems to have yielded in large part by faulting, it is probable that the Mesozoic rocks also yielded in part by faulting, the faults of the Madison limestone having been transmitted into them. Probably the faults died out in the Mesozoic beds, which have a great total thickness. Proof of thinning by compression would have to be made by comparing the thickness of the formations above the laccolith with the thickness in nearby regions. This, however, cannot be done, as erosion has removed the evidence.

(4) By radial faulting, dividing the roof into sectors which are spread apart at the center of the dome where they are most raised, as indicated in figure 4-d. If the radial faults were vertical the spaces between them would be filled by intrusive rock or by an agglomerate such as that of the dike on the west rim, referred to under the first hypothesis. If the radial faults had considerable hade, differential uplift might keep the fault surfaces essentially in contact, the accommodation being due to the heave of the fault. With an inclined fault the hade, throw, and heave are connected by the following formula:—

$$\frac{\text{heave}}{\text{throw}} = \text{tan. hade.}$$

Assuming the heave to be 400 feet and substituting various values for the angle of hade and solving, we get the following table:—

Throws and hades corresponding to 400 feet heave.

Throw	∞	11500	5720	3810	2850	2270	1490	1100	860	690	400
Hade	0°	2°	4°	6°	8°	10°	15°	20°	25°	30°	45°

From this table we see that the order of magnitude of throws in the South Moccasin faults is sufficiently great to have accommodated the stretching of the roof by the heave resulting from faults with no greater hade than 5° to 15°.

Probably no one method of accommodation occurs at all laccoliths and generally the accommodation of the roof at a single laccolith is by two or more of these methods. Beds of different character might well yield in different ways; the massive sandstones and limestones by one of the faulting processes, the more plastic shales and marls by flowing under compression. Thus the Paleozoic rocks of the South Moccasin laccolith yielded chiefly by faulting, both radial and tangential, and the Mesozoic shales by flowage. Perhaps the massive Kootenai sandstone was broken into blocks around which the more plastic enclosing shales flowed. Such blocks would probably have been restricted to the upper parts of the laccolith dome which have now been removed.

Time Required for Injection of the Laccolith.—How long a time was taken up by the process of intrusion cannot be ascertained but because of the analogies between hypabyssal injection and volcanic eruption it is probable that the times taken by each are of like order of magnitude.

Monte Nuovo, near Naples was built to nearly its full height in about 12 hours, according to Bonney.[6] Grabau[7] gives the circumference of the base as 8,000 feet and the total height as 440. Using these data and assuming it to be a symmetrical cone, the volume is calculated to be 0.005 cubic miles. At the rate of this small eruption, between two and three years would be needed to discharge a volume comparable to that of the South Moccasin laccolith, which is 7.3 cubic miles or 40 billion cubic yards.

In view of the fact that the porphyry was able to lift the great weight of over half a mile of sedimentary

[6] Bonney, T. G., Volcanoes, p. 11, 1899.
[7] Grabau, A. W., Textbook of Geology, vol. I, p. 13, 1920.

strata, the energy involved in the South Moccasin intrusion would be more comparable to a major eruption than to such a minor one. Winchell[8] gives data on the volumes discharged at several great eruptions. That of Coseguina on the Bay of Fonseca, Central America, in 1835, lasted only a few days but threw into the air 65½ billion cubic yards of pumice and ash. This volume is over 60 per cent greater than the volume of the South Moccasin porphyry, but the mass cannot have been much different on account of the fragmental and vesicular character of the ejectamenta. Skaptar Jökul in Iceland, in 1783, discharged 655 billion cubic yards of lava, or about 16 times the volume of the South Moccasin porphyry. The eruptions were somewhat spasmodic and lasted from early June to late September, or less than 120 days. Very likely most of the lava was extruded in a fraction of this time if the quiet interludes are omitted. The data for Coseguina, an explosive acidic eruption, and for Skaptar Jökul, a basic one, indicate that a magma reservoir might well supply molten matter fast enough to build the South Moccasin laccolith in a few days.[9]

Another indication of the brevity of the action is that some of the pre-existing rocks yielded by fracture. If the stress had been applied slowly, the deformation might well have been by flowage.

It is reasonable to suppose that the injection of the South Moccasin laccolith occurred in two or more spasms, for the porphyritic core comprises two rather easily distinguishable rock varieties. This does not, of course, necessarily imply that the time between the episodes of injection was long.

HONOLULU, HAWAII.

[8] Winchell, Alexander, Walks and Talks in the Geological Field, Chap. XV.

[9] Assuming a cover 3,900 feet thick, with an average specific gravity of 2.56 and a base area of 34 square miles, to have been lifted 1,150 feet (the average thickness of the South Moccasin porphyry) in one day, the average rate of work would have been about 14 billion horsepower. If the time had been a week the horsepower would be about two billion.