ART. XXVI.—*Structural Features of the Abajo Mountains, Utah*; by MALCOLM RUTHERFORD THORPE.¹

The Sierra Abajo, or "Blue Mountains," of San Juan County, Utah, occupy a roughly circular area of about 150 square miles nearly in the center of the Canyon Lands section of the Colorado Plateau physiographic province. They rise abruptly 3,000 to 4,000 feet above the encircling plain, presenting a prominent land mark from all directions. The Abajo Mountains comprise a group of laccoliths with associated sheets and dikes. The intrusive bodies composed chiefly of hornblende-latite porphyry show a remarkable similarity in mineral content and megascopic appearance and undoubtedly came from a common reservoir.

Detailed Structure.

The Abajo group will be divided into four sections, as follows: 1. Shay Mountain, northwest section; 2. Mt. Linnaeus, western section; 3. The southern area, including Abajo and South Peaks, and the region east of Johnson Creek, and 4. The northern area, comprising Horsehead, North and Twin Peaks.

1. *Shay Mountain* is essentially a dome of sedimentary rock. At its crest is an outcrop about 110 square yards in area of blue porphyry, identical in composition with the rock forming the main mass of the Abajo Mountains. This outcrop is probably a plug or short dike which has broken through the roof of the laccolithic chamber. The dimensions are approximately 50 feet north and south and between 15 and 25 feet in an east-west direction. Dakota sandstone is the highest formation now present in the area. Strata of McElmo and La Plata are exposed on the flanks in steep-walled ravines and canyons. The dip of the strata of the dome to the east is 12°, to the south 5°, to the west 9°, while on the north they dip 15° and then flatten out to 5°. It is thought that the magma insinuated itself between strata of the Chinle formation, but erosion has not cut deeply enough to prove this. A Dakota-capped synclinal ridge,

¹ The detailed geologic work on which this paper is based was done during the summer and fall of 1915 under the supervision of Professor Herbert E. Gregory; the complete report has been submitted for publication to the U. S. Geological Survey. This article is published with the permission of the Director of the Survey.

FIG. 1.

the axis of which runs east and west, joins Shay mountain and Mt. Linnæus. The pitch of the axis is toward the west and does not exceed 2° or 3° . The Dakota sandstone forms a dip slope on the south side of Shay Mountain and the same on the north slope of Mt. Linnæus.

2. *Mt. Linnæus* (fig. 3) is a partially uncovered laccolith. The Dakota sandstone overlaps the northeastern section, but no lower formation is exposed, whereas on the other sides of the mountain from 200 to 250 feet of upper McElmo are upturned beneath the Dakota sandstone, hence the horizon of intrusion is most probably middle McElmo, except on the northeastern side. If the lower Cretaceous and Upper Jurassic strata were projected

FIG. 2.

over the mountain in accordance with the dips now found they would form the cover of the laccolith with no difficulties. Patches of the roof rock are present in several places at all elevations on the mountains.

3. *The Southern Area.*—The Dakota and Upper McElmo formations flank the mountain sides to varying heights so that these peaks are by no means well exposed except near their summits. On the south and east sides the Dakota slopes up with a gentle but constantly increasing dip away from the mountains until it reaches well up their flanks. Here the Dakota and Upper McElmo formations unquestionably formed the cover at the time of intrusion. On the eastern side several prominent spurs extend outward and the dip of the strata flanking them is as high as 45° east, although dips ranging from 35° E. to 41° E. are common.

4. *The Northern Area.*—The horizon of intrusion in the case of North and Twin Peaks as well as the western part of Horsehead Peak was at or near the base of the

Mancos shale. Only on the east side of Horsehead Peak does the Dakota overlap the igneous rock. Fossils found in metamorphosed shale near the summit of North Peak, 11,350 feet high, were identified by Dr. Stanton as Middle Mancos. Isolated tilted blocks of Mancos shale lie at different altitudes, dipping in various directions and at different angles. At the mouth of North Canyon the Dakota and porphyry are in contact, the former dipping 80° northwest at the contact, decreasing to 16° E. about 200 feet from this point, and then sloping away for sev-

FIG. 3.

FIG. 3. Eastern slope of Mount Linnæus.

eral miles, gradually flattening out, and merging into the regional dip of the plain. The Dakota sandstone is apparently the floor of the laccolith except on the eastern side where the magma, instead of breaking through, arched up the sandstone as in the case of the southern half of the group.

Between Johnson and Recapture Creeks a large sheet of dacite outcrops. It is an offshoot of the magma forming the major intrusions. Its roof has been very nearly removed by erosion, but many isolated patches of Dakota sandstone as well as some strata of the McElmo still remain.

Faults.

In the Abajo area faulting is rarely found, whereas none was noted by Emery in the Carrizo Mountains of Arizona and but few faults were described by Gilbert as a result of his studies in the Henry Mountains. The most noticeable fault of the Abajo area is south of South Peak. It trends nearly north and south and hence lies at right angles to the main intrusion. The eastern wall of Recapture Canyon at this place is the steep western escarpment

FIG. 4.

FIG. 4. Upturned La Plata sandstone; south side of Abajo Mountains.

of the fault. This block is broken from similar strata on its southern boundary by another fault, trending at right angles to the major one and running parallel with the uplift. These faults form a block whose surface dips 12° to the east until it merges with the regional dip of 3° east. The maximum amount of throw was about 500 feet. Marginal faults may be seen in many places where blocks have been broken off and carried either up to the mountain summits or high up their flanks. Slickensided surfaces are common in the roof rock indicating a considerable amount of movement during the adjustment of the cover.

Structural Valleys.

The major stream channels, carved in sedimentary strata, have been determined by synclinal valleys. Near the head of Johnson Creek on the east bank, the Dakota sandstone dips $26^{\circ} \pm$ SW, strike N. 45° W., while in the bed of the creek near this point, the strata of the McElmo formation dip 6° S, strike E-W and on the west side of the creek the Dakota dips southeast at varying angles. North Canyon is another syncline, the floor of which is Dakota sandstone. On the east side of Horsehead Peak the strata dip to the east at high angles, slopes of 45° being common, while in the creek bottom they dip downstream and on the east side of the canyon are steep westerly slopes. Indian Creek has cut through the Dakota and McElmo formations along a line of weakness due to faulting caused by the uplift of North and Shay Mountains on opposite sides of the creek.

Floor.

The floor of the Abajo group is slightly visible in two localities; one in Hop Creek on the northwest slope of Mt. Linnæus and the other in Recapture Creek. Both of these exposures are very much obscured by talus and do not furnish sufficient data for a definite statement that the floor or floors is or are even or uneven, but in the writer's opinion they are uneven for the following reasons:

1. In this system there are a group of laccoliths, with both vertical and horizontal distribution, as determined from their position and structure. Hence part of the floor of one is the uneven roof of the laccolith next below.

2. The general structure of the region shows folding and faulting near the Abajo area and it is now generally agreed that very little, if any, of those phenomena have taken place since the uplift of the group.

3. Hayden, in a section through this area, constructed after his studies in 1876, drew an uneven floor with the west side much higher than the east.²

4. There is a difference in elevation between the same horizons on the west and east sides of the group of between 1,500 and 1,750 feet, the higher level being invariably on the west. Emery noted like evidences of the antecedent structures in the Carrizo Mountains.

² Hayden, F. V.: Geol. and Geog. Atlas of Colorado and portions of Adjacent Terr. 1877, Sheet XVII, sections to accompany Sheet XV.

5. Several monoclines south and southwest of the Abajo area are considered by Gregory to be of pre-Tertiary age, while the uplift of the mountains is regarded as having taken place in the Tertiary.

The above considerations offer two lines of argument in support of the theory of an uneven floor for this group. The first depends upon the irregular vertical and horizontal distribution of the laccoliths and the second involves the antecedent structures, existing on all sides of the area, which apparently underlie the superimposed igneous masses.

Roof.

The roof of the Shay Mountain laccolith is lower than the base of the La Plata, since this formation is involved in the doming. It is impossible to determine at what depth lies the horizon of intrusion for erosion has not cut sufficiently deep into the uplift. Upper McElmo and Dakota formations roof the southern and western sections of the Sierra Abajo, while the northern half was covered by Mancos shale. Since the crests of the mountains are either uncovered or still retain only isolated patches of the roof rock, the former configuration of this roof cannot be definitely known. From the shape of the igneous mass, which does not present any marked irregularities on its upper surface, and from dips of the sedimentary areas on and at the base of the uplifts, it is inferred that the roof was fairly regular and but slightly faulted as shown by the tilting to which some of the residual roof blocks have been subjected.

A considerable thickness of strata has been eroded from the cover of the laccoliths and only metamorphosed remnants of the roof now remain. From the data furnished by these residual masses it is evident that Dakota and McElmo strata and in all probability Mesa Verde sandstone also formerly covered the laccoliths. It remains to be demonstrated whether any Tertiary or later sediments were ever deposited over this area, for none now exist except alluvial deposits which were laid down since the intrusion. The lowest strata observed in contact with the intrusive rock are the McElmo (Jurassic), while the highest formation is the Middle Mancos (Benton). It is not known that the Mesa Verde (Upper Cretaceous) covered this area at the time of intrusion of the

magma, so that in estimating the thickness of the cover, the top of the Mancos shale will be used as the datum plane. Hence the depth of the cover over the Shay Mountain laccolith must have been not less than 2,750 + feet, while the depth over the northern area of the Abajo group was not less than 1,200 + feet and over the southern and western sections about 1,500 feet. In the Carrizo area Emery estimated a depth of between 2,000 and 5,000 feet for the depth of the cover over that mountain. Gilbert, in restoring the roofs of the laccoliths which comprise the Henry Mountains, found a depth of about 3,500 feet for the laccoliths of the upper zone and for those of the lower zone nearly 7,000 feet. Gilbert considered that all of the Cretaceous beds covered the laccoliths of the Henry Mountains. In all probability they also covered the Abajo group and in that case from 800 to 1,000 feet of strata must be added to the writer's estimate of the depth of the cover over that region.

Summary of proof of laccolithic origin for the Abajo group.

Criteria in support of the theory of laccolithic origin for the Abajo group have been carefully studied in the field and in the laboratory and the results will be briefly presented below:

A. Factors in the igneous mass of the Abajo group which tend to prove an intrusive origin.

1. Porphyritic texture is most common, indicating that the rock cooled at considerable depth to allow the phenocrysts to form in place, to assume their crystal forms and to attain considerable size. 2. Specimens of rock gathered at various horizons in the laccoliths and at different localities show a remarkable similarity both in composition and structure. 3. There is an absence of all extrusive characteristics, such as amygdaloidal and vesicular structures. 4. Laccoliths of this area are in association with dikes, sheets and other igneous bodies which have a crosscutting relationship to the sediments. The origin of these phenomena is clearly intrusive. Some of the dikes cut through the cover of the laccolith and hence the igneous mass must have been intruded.

B. Factors in the sediments associated with the igneous rock which point to an intrusive origin for the latter.

1. At every locality where the igneous mass is in visible contact with the sedimentary strata, the latter are meta-

morphosed. Not only is this true of the lower, but also of the upper contacts. 2. There is an entire absence of fragments of the igneous rock in the overlying sediments. 3. The strata which flank the mountain have unquestionably been disturbed since their deposition. 4. The presence of a floor in the Abajo group seems practically certain, although it is not entirely capable of proof, unless, from the two small areas where it is visible, it can be said to be characteristic of the whole mass. 5. The northern and northwestern sections of the group have been intruded at different horizons in the sedimentary strata than have the southern and eastern sections. 6. On the crests of the laccoliths masses of sediments, over 100 feet thick, dip at various angles from the horizontal and are highly metamorphosed.

C. *Factors not closely associated with either the intrusion or its cover, but which point to intrusion in the region.*

1. Distribution of the laccoliths in a group instead of in a system. This is characteristic of all laccolithic intrusions and is found in the Henry, Carrizo, La Sal and other mountains of this type as well as in the Sierra Abajo. 2. There is an entire absence of tuffs, breccias, lava flows, volcanic bombs, lapilli, etc., in fact all the phenomena which are so characteristic of extrusion. In conclusion all the phenomena are those of intrusion and no evidence has been found pointing to extrusion in this area.

Contact Metamorphism.

Contact metamorphism has taken place in the Abajo area to a very limited extent. The endomorphic effects have been very slight. In some cases the igneous rock becomes of finer grain near the contact; in others it is more porphyritic, both of which phenomena are indicative of more rapid cooling. There is no indication that new minerals have been developed. The exomorphic effects have resulted in baking and hardening the overlying and other strata in contact with the laccolithic masses. The sandstones have been changed to quartzites and the shales to hornfels and argillites, but still retain all of their original structures, such as crossbedding, bedding planes and conglomeratic and granular structures. Almost no mashing or distortion of the sediments in contact with the igneous rock could be observed. This hardening of the sedimentary strata has made them tougher than the igne-

ous rocks so that they resist erosion and stand out as revetcrags, ridges and other topographic forms. The effects of the metamorphism is felt from 10 to 200 feet from the contact, depending upon the size of the laccolith with which it is in association. The effect produced in the igneous rock is apparent only a few feet at the most from the contact. Megascopically, the three formations, McElmo, Dakota and Mancos, have neither gained nor lost any element in their mineral content other than being slightly mineralized in very thin bands close to the contact.

Cause of the lack of intense Contact Metamorphism.

It is apparent from the above discussion that contact metamorphism has not been an important factor in the geology of the Abajo Mountains. In the Carrizo area Emery states that the effects of metamorphism "are commonly not noticeable at a distance of more than three feet from the contact,"³ and Gilbert, in the Henry Mountains, found many instances where no difference could be detected between specimens collected at the contact and at the interior of the laccolith, while the original structures of the enveloping rocks have not been altered, although they have been indurated. This phenomenon is characteristic of laccoliths in the Southwest and Cross attributes it to the lack of the mineralizing agents, chlorine, fluorine and superheated steam in the magma.⁴ The conditions of metamorphism in the Abajo area are believed to be due to this cause.

Manner of Intrusion.

No evidences of stoping or assimilation have been found in this area, and from this and other facts above mentioned, it seems conclusive that the Sierra Abajo owe their origin to intrusion. The character of the hornblende-latite porphyry of the Abajo Mountains is very uniform and it seems reasonable to suppose that all of the laccolithic material came from a common reservoir. In regions where the strata are practically undisturbed except by intrusions, as in central Montana and south-eastern Utah, the magma must have been aggressive,

³ Emery, W. B.: this Journal, 4th Ser., vol. 42, p. 363, Oct., 1916.

⁴ Cross, Whitman, Spencer, A. C., Purrington, C. W.: U. S. Geol. Surv., La Plata folio, No. 60, Geol. Atlas of U. S., p. 11, 1899.

insinuating itself between and doming the strata to form a laccolithic chamber. From all of the data at hand, it is justifiable to call the Abajo Mountains a group of laccoliths, coming under the head of injected bodies in Daly's classification of intrusive igneous masses.

Age of Intrusion.

There is an unanimous opinion among all students of the laccoliths of the Southwest that they are Tertiary in age, most probably Early Tertiary in the Late Laramie time, and the Laramide Revolution was responsible for their intrusion. There are certain structures, such as the Comb Monocline, of pre-Tertiary age in this area and these have been magnified by the intrusions. Hence the Abajo laccoliths were formed subsequent to these antecedent structures and hence can not be earlier than Tertiary. Again the intrusions took place subsequent to the deposition of the Middle Cretaceous and there seems to be no valid reason to doubt that all of the Upper Cretaceous likewise covered the area at the time of intrusion. Further than this it is impossible to date the intrusion due to the lack of any Tertiary deposits over this area. The age of the individual laccoliths, sheets and dikes, with respect to one another, could not be determined as they were not observed cutting each other.

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