T H E

AMERICAN JOURNAL OF SCIENCE

[F O U R T H S E R I E S .]

ART. XXXIX.—*The Geology of Pigeon Point, Minnesota;*
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Introduction.—During the summer of 1916 the writer, in company with Professor Charles Palache of Harvard University, spent six days in a field examination of the intrusive body which has become celebrated through the able memoir by Bayley, entitled "The Eruptive and Sedimentary Rocks of Pigeon Point, Minnesota, and Their Contact Phenomena."* With the kind assistance and personal guidance of Professor F. F. Grout of the University of Minnesota, the point was found to be easily accessible. Leaving the regular steamer from Duluth to Port Arthur at Grand Portage, six miles west of the point, the party there boarded the motor-boat of Mr. P. Gagnon and were soon comfortably camped in Little Portage Bay, an excellent center for the study of the whole eruptive area, especially

* W. S. Bayley, Bulletin 109, United States Geological Survey, 1893.

because transportation by the motor-boats of resident fishermen could be secured.

The objects of the visit were to secure personal acquaintance with the rocks so admirably described by Bayley, and to collect structural and petrographical material bearing on the origin of the local "red rock," which represents one of the main problems of Minnesota geology and, yet more significantly, falls under the general question regarding the origin of the world's granites.

The red rock has been called "quartz keratophyre" and also "soda granite." It is a highly micropegmatitic or granophyric rock, chemically very similar to many common granites, but locally it has a chemical composition much like a quartz syenite. The red rock passes gradually into "intermediate rock," that varies, chemically, from a monzonite-like type to a diorite-like type. The intermediate rock, always in small volume, in turn grades into gabbro. The latter is much the largest component of the main Pigeon Point intrusive. It has olivine-rich and olivine-free phases. Though possessing a somewhat low content of alkalis, the gabbro has nearly normal characters. For the full petrography of the eruptive and sedimentary rocks of the point, the reader is referred to Bayley's memoir.

Short as the field study was, it permitted a revision of the geological map and structure sections published in Plate XVI of Bayley's paper. A map showing necessary changes in the lines of contact is given in the accompanying fig. 1. So far as the outcrops allow a decision, the main intrusive appears to be a sill cutting the local Animikie sedimentaries, rather than a dike, as stated by Bayley. The red rock is concluded to be a gravitative differentiate from the magma which filled the sill chamber. As Bayley and others proved long ago, the origin of that magma is a question involving the possibility of the fusion of the Animikie quartzites and metargillites by primary gabbroid magma. While Bayley showed the probable reality of this melting-up, its absolute proof, here as so commonly at eruptive contacts, is obscured by the processes of differentiation.

A special novelty discovered is the existence of minute igneous bodies which are hereafter described under the name "linear or ribbon injections."

Professors Palache and Grout have greatly aided in the collection of facts and in clarifying the discussion, but neither should be held responsible for the theoretical views hereafter expressed.

Revised Map.—Pigeon Point is a peninsula stretching eastward from the main shore of Lake Superior, 150 statute miles (240 kilometers) northeast of Duluth. The peninsula is six

miles (10 kilometers) long; its maximum width is a little more than one mile. Its area is small; yet, on account of a dense growth of moss and trees over much of the interior, a correct delineation of all significant contacts of the rocks must take much time. The scant six days spent on the point did not suffice for a complete field review of the geology, but it was possible, with the liberal and highly expert help of Professor Palache, to trace most of the contacts in the eastern third of the peninsula, an area of about 2 square kilometers; and to run

FIG. 1.

FIG. 1. The eastern part of Pigeon Point. Animikie sediments, left blank; 1, gabbro; 2, intermediate rock; 3, red rock. Diabase and gabbro dikes in solid black. Sediments and sill (1-3) dip about 15° in a direction somewhat east of south.

a few cross-sections in the broader part of the peninsula, to the westward.

In general, the maps of the western two-thirds of the peninsula, shown in Bayley's Plates XIV and XV, were found not to need any essential change: The eastern third is likewise accurately mapped by Bayley so far as the shore zones are concerned. Close study of the less well-exposed interior showed, however, the necessity of significant changes in the mapping of contacts, though no vital improvement can be offered on his remarkably thorough diagnosis of the kind of rocks occurring in the area.

The most important alterations of the geological map are noted in the isthmus at Little Portage Bay ("E" in fig. 1) and

to the eastward thereof. The red rock of the isthmus has throughout a general east-west contact with the mass of the intermediate rock and gabbro, and not a north-south contact, as indicated on Bayley's map. The patch of red rock and intermediate rock mapped by him, in a narrow band stretching south toward "*D*" from the little bay at "*B*," fig. 1, does not exist. Finally, the southern edge of the gabbro locally extends farther south, both to east and west of Little Portage Bay, than as drawn on Bayley's map. Special care was taken to be sure of these necessary changes and, in general, fig. 1 is believed to be essentially correct, in spite of the fact that the upper part of the gabbro carries some interstitial micropegmatite and is thus not always to be distinguished with ease from the intermediate rock.

It is seen that the map is distinctly simplified by these changes. The main gabbro is continuous and not cut across by any large body of red rock. The red rock is nearly continuous, lying between the main gabbro on the north and the quartzite-metargillite series of the south. The intermediate rock is nearly as continuous; it lies between the gabbro and the red rock, again with persistent trend of outcrop directed nearly east and west.

Main Intrusive a Sill.—R. D. Irving and Bayley considered the main intrusive to be a dike. In a letter N. H. Winchell has stated his belief that it is a sill.* The decision between the two views is not obvious, on account of the few exposures of the Animikie sediments along the northern side of the eruptive mass. So far as the evidence goes, however, the sill hypothesis should be preferred. The matter is so important that some of the detailed field observations are worth stating.

Narrow dikes of red rock respectively cut the sediments, the main gabbro, the intermediate rock, and even rock phases which themselves closely approximate red rock in composition; nevertheless, every one must agree with Bayley and Winchell that the main gabbro, the intermediate rock, and the main body of red rock are transitional into one another, forming a single geological unit. The case is strikingly parallel to the associations of silicic, mediosilicic, and subsilicic rocks in the intrusive sheet at Sudbury, Ontario, in the (Moyie) sills of the Purcell mountains of British Columbia, and in several sills and laccoliths of South Africa. Since the red rock and the gabbro belong to one rock body, the contact of each with the Animikie sediments should be questioned concerning the structural relation of the intrusive.

The actual contact of the gabbro with the sediments is exposed at very few places. One of these is described by

* See this Journal, vol. xx, page 200, 1905.

Bayley in the following words (page 23 of his paper): "On the north side of the point, at the mouth of Pigeon river, are slates and quartzites, capped by an overflow of a fine-grained variety of gabbro." Professor Palache and the writer visited that locality and found a dip-section as illustrated in fig. 2. It happens to be situated where two or more dikes of relatively fine-grained gabbro merge upward into the main gabbro mass, which itself, at least locally, has a concordant, sill contact with the quartzite-metargillite series. In the face of a steep cliff, 300 meters east of the fig. 2 locality and in the line

FIG. 2. Section of floor contact of sill, near mouth of Pigeon river. Gabbro dikes (dotted) pass upward into the sill gabbro (dotted). Q, Animikie sediments. Observed contacts shown by continuous lines; inferred contacts, by broken lines.

of Bayley's north-south section "*a-b*," the exact contact was again found, about 20 meters above lake-level. It could be traced for about 25 meters along the strike. Throughout this stretch the contact surface dips gently southward, rigorously parallel to bedding in the sediments except for strictly localized and quite minute transgressions, such as are common at most sill contacts.

At the only other area of sediments exposed in the peninsula, north of the main gabbro ("*A*" in fig. 1), the surface of contact cannot be located within a stratigraphically vertical interval of about 3 meters. On the small headland the quartzites have their regional, southward dip of 10° to 15° . They are cut by several trap dikes, one of which is composite.* A few meters

* The well-exposed composite dike runs north and south. The older component is a fresh diabase porphyrite, free from both olivine and quartz. Its width measures about 2 meters over all, that is, including the enclosed

south of the most southerly outcrop of quartzite, the main gabbro appears in a low cliff. Here the gabbro bears feldspar phenocrysts ranging from 2 to 5 centimeters in length. These are commonly parallel, as if arranged by flow in the magma, and lie parallel to the bedding planes of the adjacent strata. The same parallelism of orientated feldspars to the regional dip-plane of the Animikie sediments was observed in the gabbro at several other localities. Such repetition in the arrangement of the gabbro phenocrysts, where that rock is distinctly porphyritic, is inexplicable on the dike hypothesis. As Bayley hints (page 23), the phenomenon rather suggests that the gabbro was injected after the manner of a typical sill.

FIG. 3.

FIG. 3. Section of roof contact of sill, made east of "C," fig. 1, and similar to other roof sections to the west. Q, contact-metamorphosed Animikie quartzite with metargillitic interbeds; 2, intermediate rock; 3, red rock. Blocky character of upper contact illustrated diagrammatically.

Again, the gabbro, especially near its northern contact, has a principal system of joints or rift, dipping 5° to 20° southward, the other joint systems being roughly perpendicular to that rift. These structural details are also consonant with the sill hypothesis.

The contact of the red rock with the sedimentary rocks is much better exposed. With a few short interruptions, quartzites and interbedded metargillites extend all along the southern

younger component. After the consolidation of the porphyrite, this older dike was split, on a nearly-central plane, and a red granite dike was injected along that plane. The granite dike is a little over one meter in width; so that the whole composite, as far as visible, is composed of porphyrite and granite in nearly equal proportions. The porphyrite shows chilled edges. The granite does not, but is coarse-grained throughout and locally even pegmatitic. The granite, almost wholly made up of quartz and alkaline feldspar, has been much kaolinized and otherwise altered, as if hydrothermally. Its original structure was the hypidiomorphic-granular; no granophyric intergrowth is found in the thin section.

The geological relation of this good example of composite dikes to the sill, only a few meters distant, could not be determined.

shore of the peninsula. At many places their contact with the red rock, for distances of from one to ten or more meters, measured down the dip, is seen to be clearly accordant (fig. 3). In general, the surface of contact dips southward, under the quartzites, at angles of from 5° to 20° , averaging about 15° . Parallel to that general direction is an unusually well developed system of rift joints in the red rock (see fig. 8 in Bayley's memoir). These are also parallel to a distinct, though less conspicuous, rift system in the adjacent intermediate rock; and roughly parallel to the main rift system in the gabbro, as already implied. Assuming that these rifts are parallel to the

FIG. 4.

FIG. 4. Dip-section of the Pigeon Point sill through "A," fig. 1, where the sill is relatively thin. Q, Animikie quartzite with metargillitic interbeds; D, diabase and gabbro dikes; 1, gabbro; 2, intermediate rock; 3, red rock.

original cooling surface of the complex intrusive—a probable interpretation—the conclusion that the intrusive is a sill is again indicated.*

Nevertheless, the upper contact of the intrusive is by no means always concordant with the bedding of the roof quartzites. In the low cliffs of the south shore the red rock may be seen at some points to cross-cut the sedimentaries at high angles. There the red rock fills blocky re-entrants in the roof. The maximum observed degree of cross-cutting is a couple of meters, measured at right angles to the bedding of the sediments, but it may be locally several times that amount. Thus, in spite of the fact that bedding of the roof rock and the contact surface are on the whole roughly parallel, the roof exhibits re-entrants which seem to be small-scale analogues of those depicted in Barrell's study of the intrusive stock at Marysville, Montana.† As at Marysville such sharp-angled embayments

* The wonderfully perfect rift in the red rock is clearly a primary structure and in no way related to relief of load by erosion or to the present topography. This Pigeon Point case strongly suggests that the rift in batholithic granite is similarly related, in a genetic way, to the forms of the corresponding batholithic roofs. For these larger granitic bodies also the explanation of the nearly flat rifting through cooling contraction still seems to be the best.

† J. Barrell, Professional Paper 57, U. S. Geol. Survey, 1907, page 72 and plate II.

in the country rock are best explained as due to its dislocation along fractures, accompanied by downstopping of the blocks immersed in the magma. At other points along the contact, much more intense shattering of the sedimentary rocks is in evidence, and swarms of quartzitic xenoliths show that magmatic stoping has, once again, been "caught in the act."

In summary, the field facts seem to show that the Pigeon Point body is a sill (fig. 4), modified, as to the detailed form of its roof, by heat shattering and moderate overhead stoping. So far as could be observed, the lower contact is more perfectly concordant with the Animikie beds, the cross-cutting there proved being restricted to rare local offsets of a few centimeters.*

Tilting after Injection of the Sill.—Almost all of the many diabase and gabbro dikes cutting the sediments follow master joints, developed at right angles to bedding. The east-west dikes therefore now dip about 75° northward (see fig. 4), since the quartzites dip about 15° in a southerly direction. It is simplest to assume that the joints were formed when the strata lay flat; and that the dikes, some of which merge into the gabbro at its lower contact and thus seem to represent feeders for the sill, were injected before the Animikie beds were tilted. If so, the great sill was injected before being turned up into its present position. Yet absolute proof of this hypothesis has not been found. (See page 446.)

During or after the tilting the sill and sedimentaries have been affected by a few dip-faults of small displacement. One fault has offset a trap dike cutting the main gabbro at the extreme end of the point. Some of the irregularities in the ground-plan of the complex eruptive may, perhaps, be explained by similar faults.

Stratiform Structure of the Sill.—Bayley's view that the principal intrusive of Pigeon Point is a practically vertical dike, does not agree well with his explanation of the red rock as the product of the contact fusion of the sediments by the primary gabbro. Except for a few dikelets, the red rock is restricted to the southern side of the main gabbro. If the gabbro were injected as a dike, there is no apparent reason why the sediments along the northern contact should not be fused in the same way.

* The time spent in the field did not permit of full study of the relations between the small patches of gabbro mapped by Bayley on Plate XV, to the southward of the red rock. The patch on Fisherman's Point is clearly a thick dike with normal chilled contacts. The other three patches may represent one or more other dikes older than the sill, or they may be residual chill phases of the sill magma, analogous to those observed locally at the roof of the Duluth laccolith. A dip fault may explain the offset of the red-rock band in the area mapped on Plate XIV of Bayley's memoir. These uncertainties do not seriously affect the conclusion that the main eruptive is a sill.

On the other hand, the asymmetry of the complex presents no mystery if the whole igneous mass is, in essence, a sill dipping gently southward. (See figs. 1 and 4.) Many direct field observations, as well as numerous homologies among the sills of British Columbia, Ontario, South Africa, etc., indicate that the gabbro of the Pigeon Point body forms a thick layer at the sill floor; and that this is, in succession, overlain by much thinner layers of intermediate rock and red rock. The principle of gravitative differentiation is obviously suggested.

Segregation of Red Rock through Gas Tension.—Gravity has not been the sole control in the separation of the red rock magma. Narrow, short dikes of red rock cut the intermediate rock, the gabbro, and the quartzites underlying the sill gabbro. The dikes seen in those quartzites appeared in all cases to peter out within a distance of about 10 meters below the lower contact of the sill, and to be, in a sense, apophyses from the sill. The existence and location of these dikes imply that the red rock differentiate was fluid longer than the gabbroid differentiate; and that the red rock magma was injected into the sill floor, into the roof, or into the already solidified gabbroid phase, by virtue of strong gaseous tension in the red-rock magma.

That this magma was charged with gas in large amount is shown by the great development of miaroles or drusy cavities in the red rock of sill and dike. Similar miaroles were observed in the intermediate rock, but never in the gabbro. The unusual driving force which must have been resident in the red-rock magma is suggested also by the lengths of numerous, exceedingly thin veins of red rock in the sediments of the roof.

"Ribbon Injections."—A very striking proof of enormous tension in the red-rock magma was found in other minute, though locally numerous bodies, which may be called "linear injections" or, perhaps better, "ribbon injections." On the south shore, immediately west of the little bay marked "C" in fig. 1, the roof of the sill consists of micaceous and feldspathic quartzites enclosing thin, originally argillaceous beds. Into two different layers of the argillite, separated by about 12 decimeters of quartzite, the red rock has been injected in the form of nearly straight, flattened needles, or thin, narrow ribbons of relatively great lengths. The exposures in three dimensions here happen to be almost perfect, so that one can make out the form and relations characterizing this novel kind of intrusive body.

The smaller ribbons are one millimeter or less in thickness, 5 to 10 millimeters in width, and of various exposed lengths of 10 centimeters to one meter. The largest ribbon seen is

one to two centimeters in thickness, 4 to 8 centimeters wide, and 2.5 meters in ascertained, minimum length. These lath-like bodies all lie in the bedding planes of the argillite. The low side walls of each ribbon are usually sharp and are perpendicular to the bedding. None of the smaller ribbons appears to have uparched the overlying sedimentary rock, or to

FIG. 5.

FIG. 5. Cross-sections (*a*, *b*, *c*) and partial ground-plan (*d*, *e*) of ribbon injections of red rock (dotted), cutting thin metargillitic layers (2), between beds of micaceous quartzite (1). Figs. *d* and *e* represent the two extremities of an observed ribbon seen in plan. With other ribbons the kind of termination shown in *d* is the more common. All drawings are to natural scale. Diagram *c* refers to the largest observed ribbon.

have caused the slightest depression in the rock underlying the ribbon. The cross-section is here conspicuously rectangular (fig. 5, *a* and *b*). On the other hand the largest ribbon has decidedly arched its roof (fig. 5, *c*). At their extremities the ribbons either thin out to sharp points (fig. 5, *d*) or end abruptly

at master joints in the country rock, with a square termination, like that of a commercial lath (fig. 5, e).

The injection mechanism of the largest ribbon is, in appearance, much like that of a laccolith with a lateral conduit. The thinner ribbons are not so obviously explained. They seem to follow joints in the argillite, and to have made room for themselves by crowding aside and compacting the argillaceous material on each side. No other feasible interpretation of the rectangular cross-section has yet been imagined. Where erosion has exposed the top of a ribbon as well as the argillaceous layer on each side, the ribbon looks like the filling of a sun-crack in the sediment. However, the cross-section of the same ribbon always shows normally bedded sediment immediately below the red rock; so that any genetic connection with sun-cracks is improbable. The explanation by lateral crowding presents patent difficulty. Each shale lamina concerned may have been prepared for the required sudden condensation through preliminary contact metamorphism; the main contact of the great sill is not more than about 10 meters below these gently dipping metargillites. Perhaps the heating of water, specially abundant in the shale, prepared the material for sudden condensation under great stress.

Some of the probable feeders of the ribbon injections are visible in low cliffs along the shore. The feeders are true dikes or veins, always very thin (one millimeter or less to three millimeters in maximum thickness) and often of capillary dimensions. They are interrupted and some seem to peter out, both above and below, in the cliff sections. None of these dikelets could be traced with certainty into a ribbon. The ribbons regularly cross the planes of the dikelets at high angles. In none of the observed ribbons is the immediate roof or floor diked by red rock. Hence the ribbons cannot be parts of co-terminous dikelets abruptly widened at shaly horizons. Each ribbon chamber appears to have been forced open by magma which entered from one end. The forcing of a nail into wood by very strong, steady pressure is an analogy, though the injected red rock was, of course, not rigid. The viscosity of the ribbon magma must rather have been of an extremely low order.

Time Relations of the Magmatic Phases.—Because the Pigeon Point gabbro is cut by dikes of the red rock, a few observers have argued that all of the red rock here belongs to a magma distinctly younger than the gabbro magma. Accordingly, the intermediate rock has been explained as the product of the fusion of the older gabbro and its peripheral intermingling with the red-rock magma. This view has little to commend it. The irregular main layer of red rock averages

probably less than 30 meters in thickness; it is hard to believe that its original content of heat could have sufficed to melt and impregnate the gabbro to the extent demanded by the hypothesis. The contact of the two chief phases has not the character of that between two members of the normal composite sill in other parts of the world. This hypothesis also fails to account for the practical restriction of the red rock, except for the small dikes above noted, to the upper contact of the gabbro. It fails to explain the micropegmatitic (red-rock) material often seen, under the microscope, to fill the interstices of the feldspar-pyroxene fabric in the gabbro, scores of meters stratigraphically below any level which could have been seriously affected by the hypothetical red-rock injection. Finally, this hypothesis fails to account for the local development of the intermediate rock between the main gabbro and the roof quartzites, with no red rock present in the cross-section at all; the intermediate rock, here as usual, passing gradually into the gabbro.

These objections have great cumulative weight. One is compelled to assume that at one stage much of the gabbro and much or all of the red rock were simultaneously molten; that the gabbro froze first and the red rock froze last, so as to be capable of diking both gabbro and intermediate rock.

In summary, the writer considers the main body of eruptive rock in the peninsula to be a unit, a sill which has been differentiated under gravity. The intermediate rock represents a shallow layer marking incomplete differentiation between the gabbro below and the red rock above. Because of special concentration of gas in the red rock, its temperature of consolidation was relatively low, and small tongues of its magma were driven down, into the gabbro, as well as upwards, into the sedimentary roof, because of the abnormally high gas-tension.

Differentiation necessarily Postulated.—At the close of his paper (p. 118), Bayley stated that the red rock "is only the final stage in the alteration of the slates and quartzites by the gabbro." In other words, he regards the red rock as the crystallized product of a secondary magma. Apparently he nowhere mentions the principle of differentiation in connection with the problem, but considers the red rock as sedimentary-rock material which has been fused *in situ*. Yet his average analyses of red rock and sedimentaries are systematically contrasted, as shown in the accompanying Table I, taken from p. 113 of his paper. The red rock is poorer in iron and magnesia, and, as distinctly, richer in soda and potash.

TABLE I.

	1	2	3	4	5
SiO ₂	74.00	72.42	70.31	73.64-74.22	59.71
TiO ₂	.34	.40	tr.		tr.
Al ₂ O ₃	12.04	13.04	12.81	10.61-11.25	18.32
Fe ₂ O ₃	.78	.68	7.26	6.24- 7.45	8.11
FeO	2.61	2.49	.88	.77- 1.04	.85
MnO	.05	.09	----		none
MgO	.42	.58	2.03	1.48- 1.57	3.54
CaO	.85	.66	.60	.36- .56	1.05
BaO	.12	.15	----		----
SrO	tr.	tr.	----		----
Na ₂ O	3.47	3.44	2.19	1.67- 3.04	1.93
K ₂ O	4.33	4.97	1.90	1.08- 1.65	3.43
Li ₂ O	tr.?	tr.	----		----
H ₂ O	.86	1.21	2.22		3.24
P ₂ O ₅	.06	.20	----		----
Cl	tr.	tr.	----		----
	99.93	100.33	100.20		100.18

- 1.—Analysis of the powder of three specimens of porphyritic red rock.
- 2.—Analysis of the powder of seven specimens of granular red rock.
- 3.—Mean of the analyses of three unaltered quartzites and one, slightly altered, metargillite.
- 4.—Range of oxides in three quartzites free from contact metamorphism.
- 5.—Analysis of one specimen of unaltered metargillite.

The present writer's field and microscopic study has led to the belief that the systematic differences are typical of red rock and sedimentary rock throughout practically the whole outcrop of the sill roof. Hence the mere fusion of the sediments by the heat of the gabbro magma probably cannot explain the red rock as now constituted. If part of the quartzite-metargillite roof has been simply fused *in situ*, without being dissolved in the gabbro, the red-rock magma could have originated from the fused product only if the latter had undergone some differentiation. Still more clearly, the red rock cannot be assumed to have originated from a solution of sediments in the gabbroid magma, unless the resulting hybrid magma has been differentiated. Competing with both of these hypotheses is a third: that the red rock and gabbro are the two poles of differentiation in a primary magma, which has never been affected by assimilation. In any case differentiation has to be reckoned with and it is this feature that, more than anything else, makes the genetic problem difficult.

As a preparation for further discussion it is well to note the approximate relative amounts of red rock and gabbro in the sill. Taking 15° as the average dip, the thickness of the exposed part of the sill varies from 125 meters to 200 meters

or perhaps a little more, with an average of about 160 meters. Of the exposed mass, nearly one-eighth by weight is red rock; the remainder is gabbro, associated with an almost negligible proportion of intermediate rock.

Nature of the Magma Differentiated.—If the red-rock material were a differentiate of a purely primary magma, and if the actual weight ratio of red rock to gabbro is given by the surface exposure, the composition of the assumed parent solution (neglecting volatile substances which have escaped from the sill chamber) may be roughly calculated. The result is shown in Column 3 of Table II. Columns 4, 5, and 6 give respectively the average composition of diabase, gabbro, and basalt as world types.

TABLE II.

	1	2	3	4	5	6
SiO ₂	49.88	72.42	52.70	50.12	48.24	48.78
Al ₂ O ₃	18.55	13.04	17.86	15.68	17.88	15.85
Fe ₂ O ₃	2.06	.68	1.89	4.55	3.16	5.37
FeO	8.37	2.49	7.64	6.73	5.95	6.34
MgO	5.77	.58	5.12	5.85	7.51	6.03
CaO	9.72	.66	8.59	8.80	10.99	8.91
Na ₂ O	2.59	3.44	2.70	2.95	2.55	3.18
K ₂ O	.68	4.97	1.22	1.38	.89	1.63

1.—Analysis of mixed powders of five fresh specimens of Pigeon Point gabbro.

2.—Analysis of mixed powders of seven specimens of granular red rock.

3.—Calculated composition of the mean rock of the sill, giving "1" the weight of seven and "2" the weight of unity.

4.—Mean of analyses of 20 typical diabases.

5.—Mean of analyses of 41 typical gabbros.

6.—Mean of analyses of 161 typical basalts.

The calculated mean composition of the sill is seen to be not far from that of the average diabase, gabbro, or basalt of the world. The result would be little affected by considering also the volatile matter that has escaped from the chamber. Hence one must seriously entertain the hypothesis that the red rock has been differentiated from a gabbroid or diabasic magma essentially like that represented in the narrow, and therefore quickly chilled, dikes of Keweenaw age in Minnesota.

However, there are two chief objections to that view. Though red rock is similarly associated with gabbro or diabase in the Logan sills farther north, and in the gigantic Duluth laccolith to the west, many of the thick Keweenaw injections are constituted wholly of gabbro or diabase without any red-rock phase. In other regions, many comparatively thick sills and dikes, of dates varying from the pre-Cambrian to the Tertiary, contain no acid differentiate which is comparable in purity

and relative volume to the red rock at Pigeon Point. One or more special conditions must, therefore, be assumed in order to explain these remarkable Minnesota bodies, if due to pure differentiation. No such condition has yet been deduced from the field facts; until some are found, the pure-differentiation idea must remain in the realm of speculation.

On the other hand, specially rapid and thorough differentiation of an originally basic magma might be thought to have been induced by its absorption of much water from the walls of its conduit. The Pigeon Point magma rose through a great thickness of Animikie strata before reaching the level of the sill chamber. The sediments were then hydrous, probably more so than now. If the original gabbroid magma absorbed some water from them, the temperature of consolidation was lowered and the magmatic life thereby lengthened. Any tendency to spontaneous differentiation would become more effective merely because of the longer time available, and the resurgent water itself might be an independent cause of magmatic differentiation.

If this were true for the sill, similar differentiation might be regularly expected in the thick Keweenawan dikes cutting the upper Animikie sediments; since dikes, crossing the bedding, are favorably situated for the absorption of connate water. As far as known, the thicker Minnesota dikes show no special tendency to extreme differentiation.*

Evidences of Assimilation.—The second objection to the pure-differentiation hypothesis is more telling. There is an unmistakable consanguinity between the red rock and the Animikie siliceous sediments, just as there is between the micropegmatitic phases of the Moyie sills of British Columbia and the quartzites invaded by them. The consanguinity is both mineralogical and chemical. In neither respect are sediment and red rock identical; yet qualitatively the two formations are closely parallel, and one cannot rest in the belief that their similarity is accidental. On the contrary, their qualitative likeness suggests that the red rock is the result of syntexis *plus* differentiation.

For a distance of from 5 to 20 meters, measured at right angles to the roof contact of the sill, the quartzites and metagillites have been strongly metamorphosed by the magma. Their maximum alteration is like that in the many xenoliths close to the shattered roof. Nearly always the contact between red rock and sedimentary rock is sharp and the bedding planes

* Other things being equal, the volume of water absorbed by an ordinary dike would be less than that entering the magma of a conduit to a great sill, so that the postulated differentiating influence of water might be more conspicuous in the sill than in the dike; yet some effect should, by the hypothesis, be illustrated in visible thick dikes.

of the latter are usually evident. The originally gray or greenish quartzites become of a deeper and deeper red tint, according to the degree of their metamorphism. When most changed the quartzites have a color nearly identical with that of the red rock.

More locally, drusy cavities, lined with well-terminated quartz and feldspar crystals, are developed in the roof quartzites. These are of habit similar to that of the yet more abundant druses in the red rock.

Both the reddening and the formation of drusy cavities in the roof rocks might be regarded as effects of water-gas and other emanations from the red rock, in which the same features were developed because of its own content of these gases. By this hypothesis the color change is attributed to the chemical influence of the gas; the existence of the cavities, to its high tension. Thus, the two characteristics mentioned would be considered to have no significance in the problem of the red rock.

Yet some mode of origin for the emanating gas itself is demanded. A critic of the foregoing hypothesis may reply that it puts the cart before the horse, holding that the magmatic gas involved was largely water-gas derived from the sediments, as really implied in Bayley's theory of the red rock.

The consanguinity of red rock and sedimentary rock is more clearly suggested from the fact that each bears indigenous micrographic intergrowths, composed of quartz and feldspar. Some of this material has doubtless been introduced into the roof sediments, through impregnation, from the red-rock magma, but careful microscopic study shows this explanation to be unacceptable for much of the micropegmatite developed in the sediments.

The original quartzites and metargillites contain quartz, feldspar, sericite (also paragonite?), chlorite, biotite, and iron oxides. In an early stage of the contact metamorphism the quartz grains are seen to have been embayed by minute tongues of their alkaline and aluminous cement. These minute, but relatively long and narrow, tongues can only be due to mutual solution of quartz and feldspar, or quartz and general cement, aided by connate fluids. Where the mutual solution has not gone beyond the incipient stage, the product is generally obscure. In a slightly more advanced stage, most or all of the tongues in an attacked quartz grain are filled with alkaline feldspar, mixed with accessory material. The feldspathic parts of the tongues commonly extinguish simultaneously under the microscope. With further metamorphism this new feldspar is found to be intergrown micrographically with quartz, indicating a *quite local, but complete*, mutual solution. The micro-

pegmatite so formed is indistinguishable from that in typical red rock, of which micropegmatite forms an essential part. The thin sections in which this series of changes can be traced show no sign of fracturing and no indication of any channel through which magmatic material has been introduced. In other words, the micropegmatite has apparently been formed of material original in the sediment, without importation.

Professor Grout, in a personal letter, has raised the question whether the intergrowths in the metamorphosed sediment have been produced through the agency of juvenile water-gas emanating from the magma. Of this there is no evidence in the thin section. On the other hand, chemical analysis of the sediments collected where they have not undergone any contact metamorphism proves that they now bear a relatively high percentage of connate water. In Keweenaw times these beds were less affected by regional (static) metamorphism and were, as above noted, probably even more hydrous. That the connate water must have acted as a solvent in the highly heated sediments is an obvious fact; to attribute the visible solution to the influence of juvenile gas is a speculative assumption, unsupported by facts won from a study of the thin sections. The matter is admittedly delicate, but the present writer prefers to dwell on the simpler inference from observed facts.

The indigenous character of the micropegmatite observed in the contact aureole is further suggested by its occurrence in the floor quartzites, next the gabbro, in which the granophyric material is almost or quite absent, and where, to judge from the actual mineralogy of the rocks, magmatic gases were never greatly concentrated.

The problem is identical with that studied in connection with the micropegmatite of the Moyie sills of British Columbia. There the roof aureoles are sometimes richly charged with typical micropegmatite, distributed through the bedded quartzites. Chemical analysis shows that little or none of this quartz-feldspar intergrowth is to be explained by emanation of feldspathic material from the magma.* According to Professor Grout the same chemical relations hold at Pigeon Point.

While, then, feldspathization in many other contact aureoles is not to be doubted, that principle seems not to account for much of the micropegmatite in the country rocks of the Pigeon Point sill.

Nor is it likely that the close field association of micropegmatite in the red rock with micropegmatite in the metamorphosed sediments is a pure accident. The material is of a nature too specialized for that. The preferable explanation is probably to be found in the principle of "ultra-metamorphism,"

* Cf. Memoir 38, Geological Survey of Canada, 1912, page 243.

the red-rock material having been chiefly derived from dissolved quartzite and metargillite.

Red-rock Shells Surrounding Xenoliths.—One set of field observations made by Bayley and repeated by the present writer at first sight appear to corroborate that theory most emphatically. In gabbro, in intermediate rock, and in red rock alike, are xenoliths of quartzite which are completely enclosed in shells of typical red rock. These small masses of red rock thus, in the field, look like direct contact fusions of the sediment. The shells vary from one centimeter to 50 centimeters or more in thickness. In general their contacts with the enclosed quartzite and with the enclosing igneous rock are fairly sharp. The quartzite of the xenolith often shows clear bedding and always a texture different from that of the surrounding red rock, so that there is seldom much doubt as to the limiting surface of the non-magmatic material. Just east of the little bay marked "C" in fig. 1, a large group of these shelled xenoliths is exposed along the shore. In the group a series of xenoliths can be found, wherein the relative thickness (and volume) of the red-rock shell increases, the volume of the respective xenoliths decreasing, until thick shells of red rock are seen to enclose mere shreds of quartzite. Finally, at the end of the series, no quartzite is seen, the whole, roughly globular mass being composed of red rock. All of these bodies lie in a general matrix of intermediate rock. The masses of pure red rock, one or two decimeters in diameter, have the appearance of being "ghosts" of completely fused xenoliths. That explanation would seem the more probable since xenoliths of feldspathic gabbro (torn from a dike older than the sill) have no such envelopes of red rock; thus a genetic connection between sedimentary rock and red rock is the more readily credited.

Lawson found quartzite xenoliths in the diabase of the Logan sills, north of Pigeon Point, and noted the reddening of the diabase in their vicinity.*

The importance of the red-rock shells first came to the writer's attention in the course of a personal discussion with Professor Grout. He seems to have been the first to see clearly that mere fusion of the xenoliths *in situ* is not the whole explanation of the red-rock shells. He has made a special study of the large rimmed xenolith in the intermediate rock at the locality mentioned on page 110 of Bayley's memoir. After a detailed microscopic and chemical investigation of this xenolith and its red-rock shell, Professor Grout has concluded that the shell is much richer in alkalis, especially potash, than

* A. C. Lawson, Bulletin 8, Geological and Natural History Survey of Minnesota, 1893, page 30.

the quartzite of the xenolith. The writer has confirmed his view by microscopic study of the same and of other rimmed inclusions in the intermediate rock. As shown by the thin sections, each shell contrasts with its xenolith in carrying at least twice as much potash and also more soda. Moreover, the shells examined are nearly uniform in composition and therein are equivalent to the main mass of typical red rock of the sill; while the xenoliths vary considerably in their original content of alkalis. As Professor Grout has pointed out, the differences of alkaline content between the shells and xenoliths are of the same order as those between the alkali content in the average analysis of the main red rock and the alkali content of the average Animikie sediment of the region. (See Table I.)

(1) Assuming the red-rock shell to have resulted from the fusion of the xenolith, without addition of material from the general magma, a large amount of silica, iron, and water must have been expelled from the secondary melt. It is conceivable that one or more compounds of iron and silica, aided by the water, might rapidly diffuse into the general magma, leaving behind the less volatile feldspar and some free silica. By such differential diffusion feldspar would be more concentrated in the shell than in the original quartzite. As yet no compelling evidence either for or against this hypothesis has been found; however, one may well doubt the quantitative value of the imagined process.

(2) Is the red-rock shell rich in alkalis because these have been, as it were, sweated-out from the hot interior of the xenolith? The connate water of the inclusion must have attained high gas-tension, which might be conceived to have led to the expulsion of a water-feldspar-quartz solution, analogous to an ordinary, low-temperature pegmatitic magma. This second guess as to the cause of the concentration of feldspar in the shell at once meets the difficulty that certain shells have volumes greater than their respective enclosures.

(3) On the whole, it seems more probable that, while some fusion of each xenolith has taken place, some of the soda and potash, and perhaps alumina, concentrated in the red-rock shells have been derived from the general magma. How this was accomplished is a residual question, as yet without adequate answer. At least half of the soda and potash in the feldspar of the average shell must, apparently, have been imported, the remainder being the alkalis of the xenolith fused *in situ*. If the oxides of sodium, potassium, and aluminum, in the presence of water, were highly diffusible in the roof phase of the general magma, those oxides might conceivably have been fixed, both in chemical combination and in position, by the free silica of the partly melted xenolith. The mystery as to the phases

actually present in a natural magma and as to their capacity for diffusion is so profound that this third speculation cannot be profitably discussed.

Difficulty of explanation cannot alter the fact that the red-rock shells appear to be due in part to separation of material from the general magma. These envelopes are, therefore, not direct proofs of an origin of the main red-rock mass in mere contact fusion of the Animikie sediments. Nevertheless, the discovery of indigenous micropegmatite in the contact-metamorphosed sediments shows that *some* red-rock material has been generated by contact fusion.

Magmatic Stopping.—As Bayley noted, the roof rock of the sill is locally much shattered. Besides the isolated xenoliths, evidence of the disruptive action is given in comparatively thick breccias of roof quartzite, now cemented by subordinate amounts of red rock. Xenolith and breccia block still remain near or at the roof, evidently because the magma was nearly frozen when the enclosure of roof fragments took place. During the long preceding magmatic period, other shattering must have occurred, and, because of the smaller magmatic viscosity then ruling, the roof blocks sank into the heart of the sill.* As in the case of the normal batholith, the efficiency of fusion and syntaxis can here be estimated only after the fate of the sunken blocks is considered. In all batholiths the deeper levels are never exposed, so that the subsequent history of downstopped blocks can only be inferred. The outcrops of the Pigeon Point intrusive are sufficiently continuous to warrant the statement that xenoliths are very rare at depths greater than 20 meters below the roof. If the initial, hot magma did actually shatter and stope more effectively than the nearly frozen magma, one is compelled to believe the older xenoliths to have been melted and more or less completely dissolved in the primary gabbro magma. If this "abyssal" assimilation strongly supplemented any assimilation at the roof, some differentiation must be postulated, for the gabbro has been cleansed from nearly all the material which is not present in normal gabbro. The actual stratiform structure of the sill implies, as already noted, gravitative control in the separation, which would presumably progress simultaneously with the stopping and internal solution of blocks.†

*The lighter shales would float in the initial gabbro. Practically all xenoliths would sink in the acidified magma. Blocks of the dominant quartzites would probably not sink all the way to the sill floor, but would come to rest at intermediate levels. There high temperature was long maintained, with the result that the blocks would tend to be completely dissolved or fused.

†On the shore, east of the bay marked at "C" in fig. 1, the red rock cuts an older, nearly vertical dike of coarse anorthositic gabbro. For a distance of about 30 centimeters from their contact, the red rock is charged with

The probable importance of stoping is indicated by the pronounced irregularity of the sill roof. The reader will recall that, at many places, the red rock sharply cross-cuts the roof strata for several meters, the eruptive occupying blocky reentrants in the roof. One result is the development of local, dike-like contacts, some of which were emphasized by Bayley.* (See fig. 3.) On the other hand, the floor contact, where seen, is that characteristic of a typical sill, with observed cross-cutting to the extent of only, at most, a few centimeters, measured at right angles to bedding. Correspondingly, the eruptive at the floor, nearly the normal gabbro in composition, has a continuous chilled contact and shows little or no evidence of having there shattered or assimilated the sedimentary rock. Since roof and floor originally matched, the roof must have been roughened by some kind of magmatic activity; that roughening is most readily ascribable to stoping.

The reason for the practical restriction of stoping to the upper contact is discussed in a following paragraph.

Capacity of the Original Magma for Assimilation and Contact Fusion.—The syntectic theory is very commonly dismissed from sympathetic consideration by those who emphasize the "enormous" amount of latent and other heat required to fuse or dissolve rock. For the present case, as for many other debated cases, the heat demanded may be regarded as "enormous" in absolute measure but as small when compared with the initial heat supply.

In the Pigeon Point area, trap dikes and sills only a few centimeters thick were observed. Such thinness, combined with great length, demonstrates some superheat in their diabasic or gabbroid magma. The main sill itself, less than 200 meters thick and probably more than 10 kilometers long, could not have been emplaced unless it were somewhat superheated. The temperature of its magma would be raised by

large plagioclase individuals which seem to have crystallized from a hybrid magma, formed by the solution of the gabbro in the invading red-rock magma. This contact phase of the red rock is specially dark in color because of the abundance of a femic mineral, now completely chloritized. Thus the red-rock magma was capable of performing some assimilation, even at a late stage in its history. If that deduction is correct, it tends to fortify the assumption that hydrous, feldspathic quartzite, related to red rock in composition could be wholly dissolved by the initial, hot, gabbroid magma.

*The "gabbro" (really a coarse porphyrite) shown in fig. 3 of Bayley's paper belongs to a thick dike, which is certainly older than the red rock and probably older than the main gabbro. The cross-cutting quality of the red rock at this point may be explained either by stoping or by local up-faulting of the sill roof along the contact of the massive, strong dike. In any case the section does not invalidate the conclusion that the main eruptive is a sill.

friction in the very act of injection, if that magma were initially nearly frozen and therefore highly viscous. Superheat to the extent of 100° or perhaps 200° C. can be safely assumed for the melt when the main injection took place. On any hypothesis of origins this original magma was gabbroid in composition. Its temperature at the time of emplacement was probably at 1100° C. or higher. The freezing temperature of the red rock is not known; but, on account of its richness in water, was doubtless well below 1000° C., if not as low as 800° . Taking the masses of the gabbro and red rock as seven to one, and assuming fair values for the latent and specific heats involved, one may roughly calculate the initial superheat required for the assimilation of the sediments in volume sufficient to furnish the observed amount of red rock. The result is to show that the thermal problem is not so portentous as it is thought to be, in such cases, by certain petrologists.

Assimilation in the Sill Conduit.—But there is no necessity of assuming all the solution or fusion of the Animikie sediments, corresponding to the volume of the red rock, to have taken place in the visible sill chamber itself. The Pigeon Point eruptive rose through nearly the whole thickness of the great Animikie series. Those rocks are quartzites and metargillites like those exposed in the peninsula. Some solution of the sediments during the uprise of the initial, hot magma must be regarded as not impossible. The sill injection may have been a single act, the magma rising, through one or more simple dike-passages, from the earth's deep interior. Or the magma may have occupied one or more temporary sill chambers before reaching the horizon of the visible sill. The two modes of injection may be briefly described as respectively *legato* and *staccato*. If the injection were *staccato* in quality, some assimilation in the temporarily occupied chambers might have been brought about. Material then dissolved would tend to be mixed through the original gabbroid magma, because of the later movements; the final separation of the solute occurring in the chamber finally occupied.

Whether the eruption was *legato* or *staccato*, the rising gabbroid magma doubtless received an accession of water, which was thermally expelled from the Animikie sediments, then possibly wetter than now. Such resurgent water, added to that absorbed from xenoliths and main contacts in the visible sill chamber, would become concentrated at the sill roof. Through the consequent depression of its freezing temperature, the magma at the roof was not quickly chilled, as was that at the floor; but was able to continue stoping and also some marginal solution of country rock. Stoping and vertical currents inci-

dental to differentiation must have stirred the upper layer of magma and prevented rapid chilling at the roof.

To this rather bold sketch of the probable events, objection may be urged that the magmatic gas, so clearly forming an original part of the magma of the drusy red rock, may have been purely juvenile and in no degree resurgent. Such a speculation is founded on a difficult thesis, for it denies the efficiency of gas tension to drive connate water into the initial magma from the hot walls of the conduit. Some petrologists will have it that gas can move centrifugally from an intrusive body, but never in the reverse direction, into the intrusive magma. They think of the contact surface of the magma as a one-way gate. This remarkable conception surely needs critical examination. The gas moves because of differential pressure. In contact aureoles developed in relatively impervious, hydrous sediments, the steam pressure must, in very many cases, rise enormously. If the pores of the sediments were originally full of water, such pressure might be very much greater than that of the initial magma at the level concerned. To explain dehydration in such contact aureoles, it is quite gratuitous to assume that all the water moves centrifugally. The certainty of pegmatitic emanation in the late magmatic stage proves nothing at all regarding the direction of migration for gases during the long preceding stage of higher temperatures and gas pressures. In the present case the conditions, including the existence of many horizons of impervious shales in the Animikie series, seem to imply the necessity of expulsion of much water-gas from the wall-rocks into the gabbroid magma.

Further, no good reason is in sight for crediting this particular body of magma with a much higher proportion of juvenile gas than that fairly attributable to many Keweenawan injections in Minnesota. On the other side, no one can doubt that the Animikie sediments, especially the shaly beds, were during Keweenawan time rich in water. So true is this that it would not be utterly absurd to regard the abundance of gas, probably water-gas, in the red rock as another suggestion of consanguinity between that formation and the Animikie sediments.

Again, the heat producing gas tension in the wall-rocks of the conduit, and also aiding in the preparation of the temperature suitable for solution of their solid material in the magma, was not merely magmatic heat. Before the gabbro eruption, the lower beds of the Animikie series and the unconformably underlying rocks had been heated because of their burial under the thick, upper part of the Animikie series, perhaps already covered by early-Keweenawan lava flows. General earth heat had thus begun the process of superheating the connate water,

with the final development of steam pressure which tended to expel the water from the wall-rock into the conduit magma. How great this effect was cannot be estimated without a knowledge of the geothermal gradient in the Keweenawan period. That it was steeper than now is indicated by the efficiency of static metamorphism in pre-Cambrian time. Possibly the conduit walls of the Pigeon Point eruptive, where passing through the wet sediments, had a general temperature of 200° C. or higher. Experiments have shown the ample power of water, at temperatures little above 200°, to promote the solution of siliceous materials.

Herein, perhaps, is an explanation of the fact that very many of the known gabbroid sills and laccoliths bearing acid, granophyric differentiates, have pre-Ordovician, if not pre-Cambrian, dates of intrusion.*

Before leaving this subject, one other speculative point may be noticed. The Pigeon Point eruptive is precisely *en axe* with the Duluth laccolith, which in its essential petrography, in its gravitative differentiation, and in its general structural relations is a colossal replica of the sill under discussion. The known outcrops of the two bodies are separated by little more than 30 kilometers. Is the sill an apophysis from the 200-kilometer laccolith? Was some syntexis accomplished in the vaster chamber before the offshooting sill forced a way eastward as far as Pigeon Point? In the face of this possibility, is it safe to deny the efficiency of magmatic assimilation simply because of facts observed at the visible contacts of the sill?†

Summary on the Origin of the Red Rock.—Assimilation of the Animikie or underlying rocks had three possible loci: in the sill conduit, including one or more dikes and perhaps laccolithic or sill enlargements; at the main contacts of the visible sill chamber; and in the heart of the sill, where downstoped blocks are concerned.

Differentiation of the syntectic material had two possible loci: in the conduit, and in the visible sill chamber. The actual differentiation, implied by the existing rock types in the sill, had two phases: that controlled directly by gravity, and that controlled by gas tension.

* Compare list in the writer's "Igneous Rocks and Their Origin," New York, 1914, pages 230 and 344 ff.

† Elsewhere (Memoir 38, Geological Survey of Canada, 1912, page 250) the writer has described a mechanism by which syntectic magma, formed in one sill chamber, may be injected into a new, higher sill or dike chamber, where differentiation unaccompanied by further assimilation of country rock is possible. The country rocks of the second chamber may be chemically little related to those of the chamber where the assimilation occurred, or to any differentiate in the second chamber. The origin of the red rock in the Duluth laccolith is not here specially considered, but the size of that body warrants a sympathetic reception for the syntectic theory when applied to its red rock.

The observed characters and geological relations of the sill were established *after* both assimilation and differentiation had been completed.

In view of so many complexities, it is not astonishing that the problem of the red rock still awaits definitive solution. The solution must, of course, depend on a patient application of the principle of inference from known facts. Of these the most significant, in the writer's opinion, is the development of indigenous granophyric intergrowths of quartz and feldspar in the contact-metamorphosed sediments. The typical intergrowth has properties identical with those of the abundant micropegmatite of the red rock. That the red-rock material was derived from dissolved or fused sediments is further suggested: by the thorough reddening of the Animikie strata where strongly metamorphosed; by the discovery of isolated druses, like the druses of the red rock, in the same strata; and by the unusual abundance of gas, presumably water-gas, in the red rock. Some genetic, though not easily deduced, relation between red rock and quartzite is implied by the presence of red-rock shells around quartzite xenoliths and their absence at xenoliths of the older gabbro. Supplemented by the principle of differentiation, Bayley's idea of contact fusion seems to give one essential element in a valid explanation of the progressive, and ultimately complete, replacement of quartz xenoliths by red rock.

The principal difficulty with the assimilation-fusion hypothesis is the higher alkali, especially potash, content of the red rock, as compared with the Animikie sediments already analyzed. Bayley states that individual strata carry 75 per cent of feldspar, but such beds must be rare, and it is unsafe to assume for the average sediment a percentage of alkalies as large as that characterizing the red rock. The alkalies concentrated in the red rock may, in part, have been derived from the gabbroid magma. Combining with the silica and alumina of the Animikie shales, these juvenile alkalies may have risen to the sill roof during the general differentiation. The analyzed gabbro has, in fact, proportions of soda and potash which are abnormally low for gabbro. The same feature appears in other instances where granophyric and gabbroid rock have differentiated from each other.*

As the proximate mode of origin for the red rock, differentiation must be assumed. Both syntexis and mere fusion *in situ*, though probably important, have been masked by differentiation. The mechanism of magmatic separation represents an unsolved problem. Specifically, future investigation may well be devoted to the question as to how the feldspar molecules

* R. A. Daly, *Igneous Rocks and Their Origin*, New York, 1914, page 320.

have been concentrated in the red-rock envelopes surrounding xenoliths and in the red-rock layer, thin or thick, between the main gabbro and the sill roof. Until that mechanism is understood, a final decision concerning the origin of the red rock must be delayed.* Nevertheless, the facts now in hand seem to show the origin of the red rock to lie in both assimilation and differentiation, rather than in the differentiation of a wholly primary magma. In any case, be the fate of past and present speculation what it may, Pigeon Point will long engage the profound interest of petrologists, for its mysteries are the mysteries of igneous rocks in general and at but few other localities are the rocks representing the two commonest magmas—the basaltic and the granitic—better or more suggestively exposed.

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* While fully believing in fractional crystallization as a cause for the diversity of igneous rocks (see *Journal of Geology*, vol. xvi, 1908, pp. 401-420), the writer finds much difficulty in applying that principle as the sole explanation of the Pigeon Point differentiation. The matter is not here discussed.