THE SIOUX QUARTZITE
AND CERTAIN ASSOCIATED ROCKS

BY

SAMUEL WALKER BEYER.

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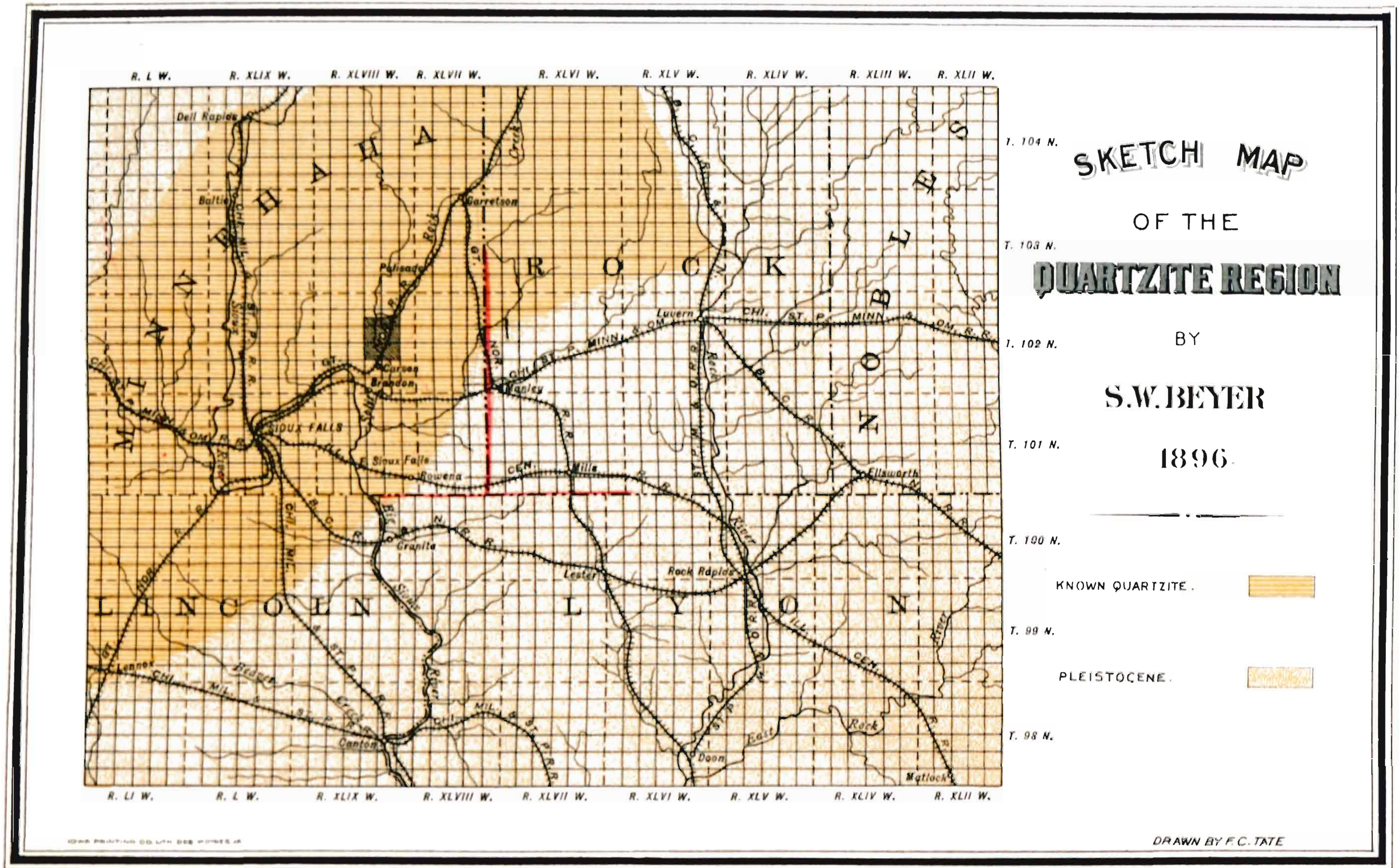
CONTENTS.


SKETCH MAP
OF THE
QUARTZITE REGION
BY
S.W. BEYER
1896.
KNOWN QUARTZITE.
PLEISTOCENE.
R. L W.
R. XLIX W.
R. XLVIII W.
R. XLVII W.
R. XLVI W.
R. XLV W.
R. XLIV W.
R. XLIII W.
R. XLII W.
R. LI W.
T. 104 N.
T. 103 N.
T. 102 N.
T. 101 N.
T. 100 N.
T. 99 N.
T. 98 N.
MINNEHAHA
ROCK
NOBLES
LINCOLN
LYON
Dell Rapids
Baltic
Garretson
Palisade
Corson
Brandon
Sioux Falls
Rowena
Luverne
Manley
Mills
Ellsworth
Granite
Lester
Rock Rapids
Lennox
Canton
Doon
Matlock
DRAWN BY F.C. TATE

INTRODUCTION.

AREA.

The Sioux quartzite is a southwestward prolongation of "Minnesota Point."* It extends across the northwestern corner of Iowa and underlies about equal areas in South Dakota and Minnesota. Its extreme eastern limit of outcrop is marked approximately by Redstone, at the junction of the Cottonwood and Minnesota rivers, while its most westerly exposure is near Mitchell on the James river. It has a maximum width of sixty miles extending from Flandreau, its

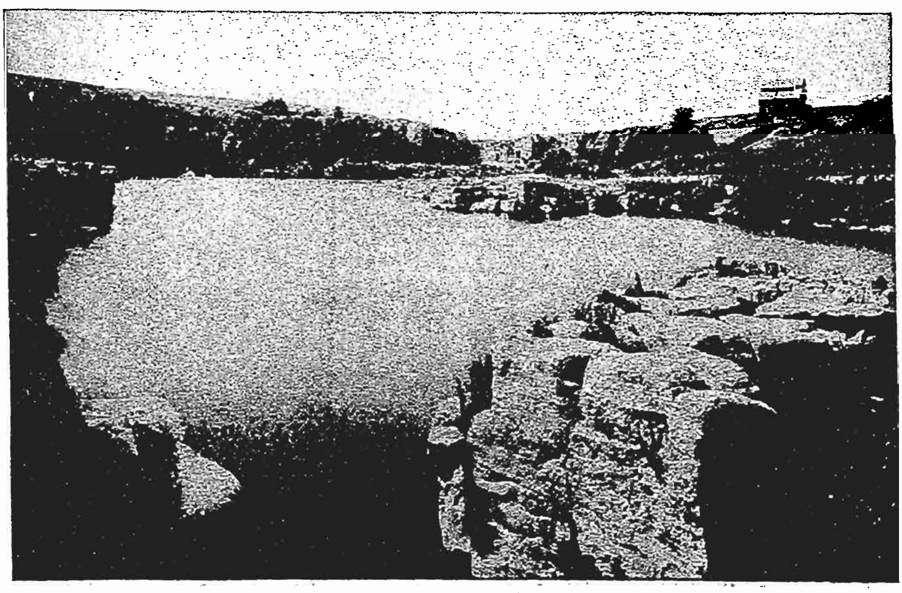


FIG. 20. Canyon on Split Rock creek at the Palisades.

northern limit, to Canton, just within its southern boundary. The formation, although generally concealed by glacial debris and by scattered patches of Cretaceous, probably extends over an area of more than 6,000 square miles.†

*Geology of Wisconsin, Vol. IV, p. 533. 1873-1879.

† For a historical resume of the literature on the Sioux quartzite, see Geol. and Nat. Hist. Sur. Minn., Vol. I, pp. 537-543. Also Iowa Academy of Sciences, Vol., II, pp 218-222.

TOPOGRAPHY.

A southwestward extension of the "Couteau des Prairies" traverses the quartzite area at right angles, a short distance east of its middle, forming a watershed for the tributaries of the Mississippi and Missouri drainage systems. The crest of the Coteau, at its middle point in the quartzite area, has an elevation of nearly 2,000 feet above sea level. There is a gentle slope westward to the James river, which, in the vicinity of Mitchell, has an altitude of about 1,200 feet. The eastward slope inclines rather more rapidly toward the Minnesota river, where, near the mouth of the Cottonwood, the elevation is considerably less than 1,000 feet. The divide which separates the Red river valley from the valley of the

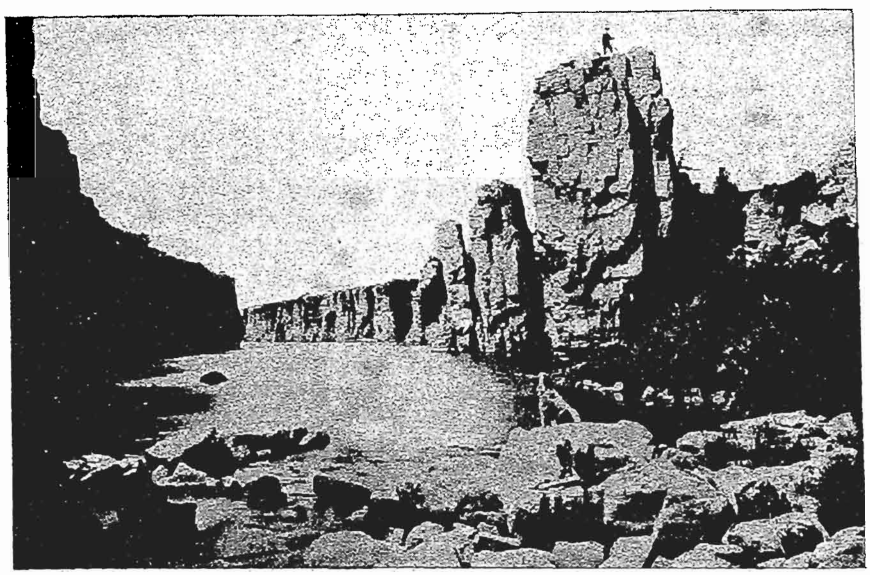


FIG. 21. Vertical cliffs of quartzite at the Palisades.

Big Sioux lies some distance to the north of the quartzite belt, so that the surface of the formation as a whole pitches southward at a low angle. The Big Sioux river, with its tributaries, drains the major portion of the area covered by the quartzite in Dakota.

The streams have high gradients, and have deeply incised the region. Rapids and falls are not uncommon. The flood plains are narrow, and in some instances, as along Split Rock creek at the "palisades" and the Big Sioux at Dell Rapids, there are canyons whose vertical walls range from fifty to seventy feet in height. In both of the above cases, canyon cutting is not confined to the main stream, but is being performed by the side branches as well. As an illustration of the sculpturing done by the short lateral branches, may be mentioned a case which occurs about one mile north of the Palisades. At this point a gulch makes off at right angles from the main stream and extends eastward more than a mile.

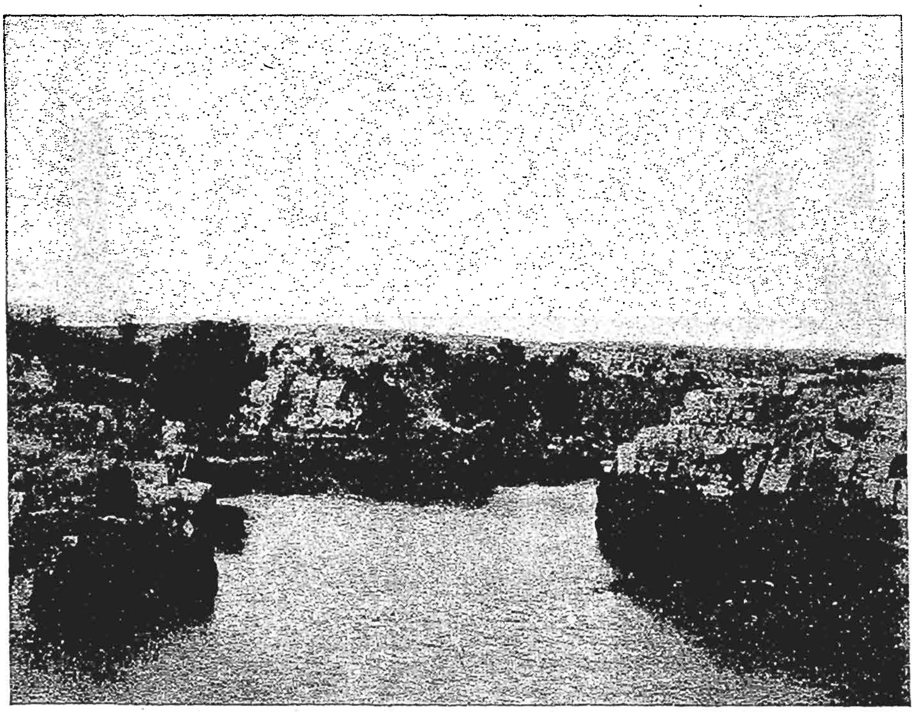


FIG. 22. Jasper pool, near the northwestern corner of Lyon county, Iowa.

It is a narrow gorge which, in places, has reached a depth of from seventy-five to nearly 100 feet. This appears the more striking in that the surface features of the prairie give no indication of the presence of the gorge until one is in close proximity to its edge. The erosion forms developed in the quartzite area are well shown at Jasper pool in Lyon county, Iowa.

SPECIAL AREA CONSIDERED.

In the following paper is given an account of the structural relations existing between the Sioux quartzite and associated rocks as found exposed in sections 10, 11, 14, 15, 22 and 23, Tp. 102 N., R. XLVIII W., Minnehaha county, South Dakota. Detailed petrographical descriptions of the rocks outcropping in the region are also given. From the description of this area, which may be considered typical for the whole formation, it is hoped that there may be established a more substantial basis for the correlation of the beds occurring within the district with formations of other areas of known age.

The special area in question is located about twelve miles northeast of Sioux Falls. Corson station, on the Great Northern Railway, is just within the southern limit of the area and is a central point in the greater quartzite region. Split Rock creek, a tributary of the Big Sioux, meanders through the area from north to south and is flanked on either side by a chain of hills, the summits of which rise to a height of nearly 100 feet above the channel of the stream. The valley of this stream, measured from crest to crest, is about one mile in width. Near the northeast corner of the northeast quarter of section 15, an isolated hill, Keyes knob, rises within the valley and is the most prominent topographic feature in the vicinity.

GEOLOGICAL FORMATIONS.

NIOBRARA.

Originally, the Niobrara probably formed a continuous mantle over the older formations in the region; but, on account of the readiness with which it succumbs to weathering and erosive agencies it has been removed largely or so thoroughly worked over and incorporated into the drift that only a few, small, isolated areas have maintained their identity. Exposures of the chalk beds of this terrain occur at certain points where the creek impinges on one side or the other of its flood plain. The maximum elevation of the chalk is not more than twenty feet above the stream channel. The remnants probably mark out the position occupied by the river valley during pre-Cretaceous times.

The "chalk rock" is, when fresh, a dirty gray color, but soon whitens upon exposure. It is of a porous nature and percolating waters easily circulate through it. The rock often becomes cavernous as a result of the removal of the calcium carbonate, and cherty concretions, present in all the rock, become then a more prominent feature. The chalk is thinly bedded. The weathering agencies have in many instances almost obliterated bedding planes, so that it is impossible to determine dip and strike with any degree of certainty; but in all probability, the planes of stratification do not depart far from the horizontal.

At the point marked Bx on the map the chalk is exposed horizontally a distance of about 200 yards on the east side of Split Rock creek, and presents a maximum vertical exposure of about sixteen feet. The overlying drift contains fragments of spotted slate.

QUARTZITE.

The quartzite, as already mentioned, forms a base upon which the later sediments have been deposited and through which the diabase (to be described later) must have broken. There is an almost continuous exposure from a central point on the north boundary of section 26 to the center of section 11. No quartzite was found *in situ* on the west bank of Split Rock creek, nor west of the line AB. (See plate iv.) This line marks a ravine which almost connects the two limbs of the large bend in the creek. The dip of the rock varies from 3 to 7 degrees, in a southwesterly direction. At the points A and F are vertical scarps rising about twelve feet above the water in the creek. The quartzite at A is capped with "chalk." At H on the map, the quartzite outcrops in the open prairie and is exposed over a superficial area of some twenty acres. It also forms a low escarpment along the ravine previously mentioned. Along this ravine the quartzite breaks into large cuboidal or trapezoidal blocks, as a result of the presence of two systems of vertical cracks which are nearly at right angles to each other and conform closely to the cardinal points of the compass. These two sets of joints are common throughout the formation and to them are due the vertical-walled canyons and square-faced escarpments which form such characteristic features in the Sioux quartzite topography. The exposed surface of the rock is often beautifully wind polished* not unlike the mirror-like surfaces presented by the Mountain sandstone which caps many of the summits of the Blue Ridge mountains.

Catlin* in describing the quartzite at Pipestone, Minnesota, wrote as follows: "The quartz is of a close grain and exceed-

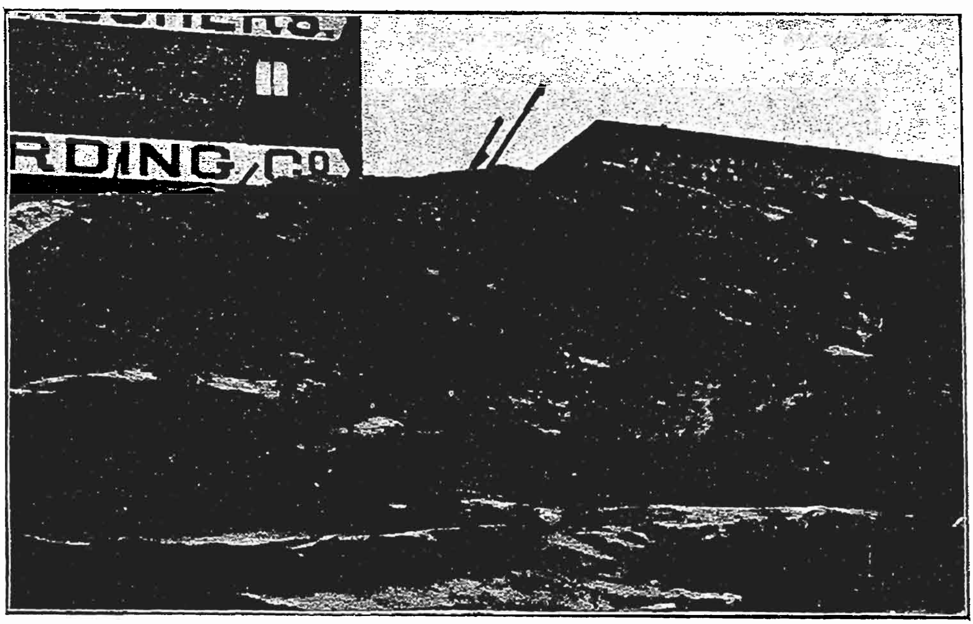


FIG. 23. Cross-bedding in the quartzite at Sioux Falls. An exposure near the Chicago, Milwaukee & Saint Paul railway station.

ingly hard, eliciting the most brilliant sparks from steel, and in most places where it is exposed to the sun and air its surface has a high polish entirely beyond any result which could

* For a full discussion of wind polishing, see G. K. Gilbert, Proc. Am. As. Adv. Sci., Vol. XXIII, Hartford Meeting. 1875. Von Walther, Einleitung in die Geologie, S. 589 et seq. 1893 and 1894.

* Am. Jour. Sci., (1), Vol. XXXVIII, p. 1840.

have been produced by diluvial action, being perfectly glazed as if by ignition."

Beach phenomena are not uncommon in the quartzite, being expressed in ripple marks and false bedding. The best example of false bedding observed is at Sioux Falls near the Chicago, Milwaukee & St. Paul railway bridge across the Big Sioux. Here the normal strata are nearly horizontal or inclined slightly toward the south, while the overlying false beds are tilted at an angle of about 30° to the north. (See figure 23.) At Fort James this same phenomenon occurs on a small scale and is rendered beautifully apparent by alternations of red and pink layers.

SLATES.

About 200 yards north of the exposure of chalk marked Bx on the map, a purplish black slate outcrops on the edge of a low ridge which marks the eastern limit of the flood plain of Split Rock creek. At this point a prospect hole put down in the hope of finding coal, revealed a thickness of about ten feet of slate, which was immediately underlain by weathered diabase. The diabase, which offered little resistance to removal, was penetrated nearly ten feet, when further prospecting was discontinued.

The slate also outcrops along the north bank of Split Rock creek in the Se. ¼ of section 10, and Sw. ¼ of section 11, near the wagon road. The outcrop along the creek continues eastward to within 300 yards of the quartzite escarpment at F, but presents a maximum vertical exposure at E of about ten feet. In all of the outcrops of slate observed true slaty cleavage is absent, but partings along the bedding planes in conjunction with vertical joints making various angles with each other, facilitate the ready removal of the rock in tabular blocks from two or three to six inches in thickness. The rock, wherever exposed, presents a curiously mottled aspect due to the irregular distribution of light colored spots throughout its mass. These spots appear to be wholly independent of the structural features of the rock, and their color is not unlike that presented by weathered surfaces along joints.

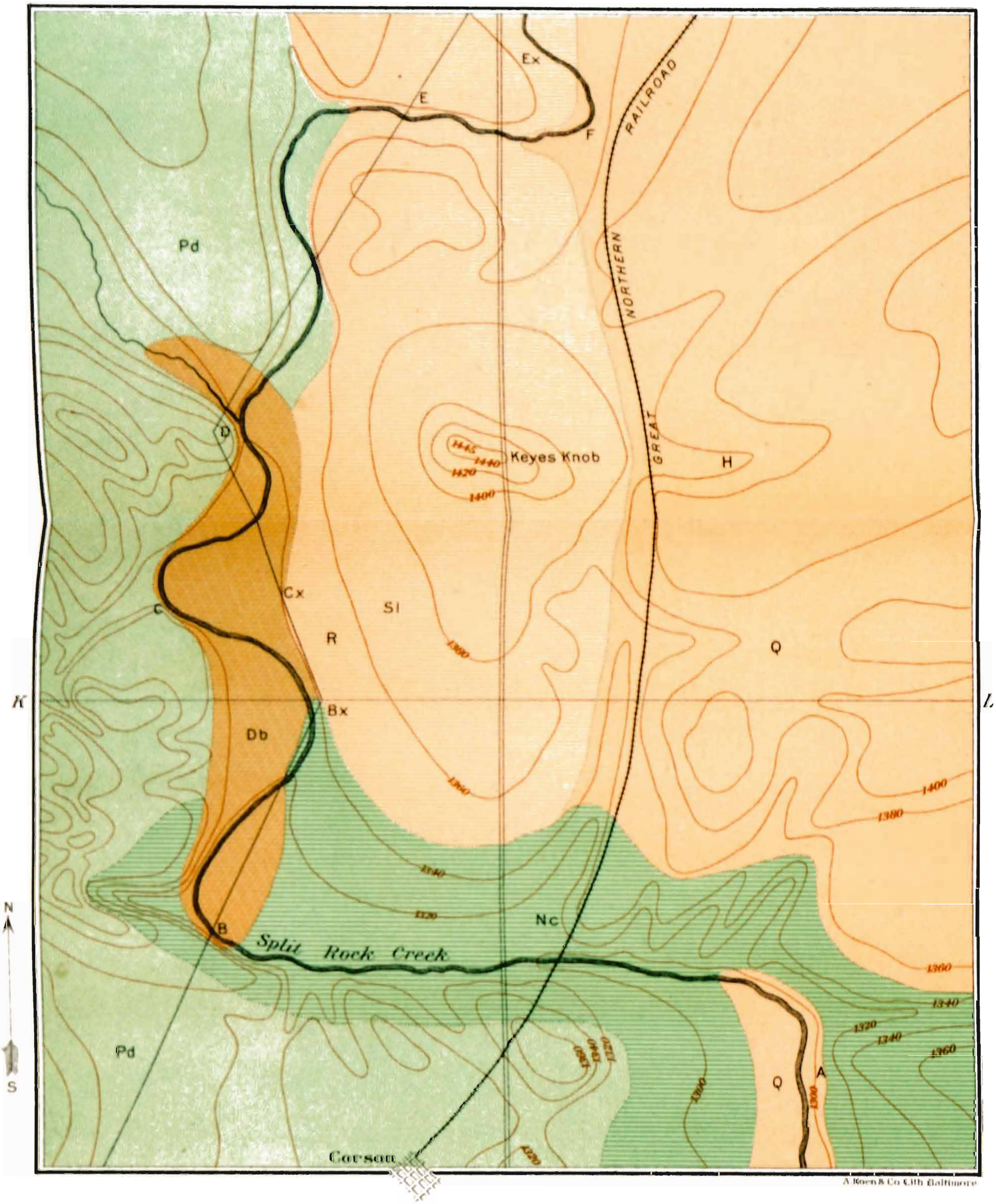
RELATION OF SLATE TO QUARTZITE.

As the slate and quartzite are not represented together in any exposure within this area, it is necessary to go beyond its border for positive evidence regarding their relationship. At the Palisades, about four miles to the northeast, slate is exposed in perfect conformity with the quartzite, often interbedded with the upper quartzitic layers, and sometimes grading into them. The spots, which were always present in exposures further south, are typically developed at the Palisades, while the texture and composition of the slates at the two localities are very similar, so that their correlation seems to be perfectly justifiable. Moreover, a legitimate inference would be that the slates are an upward extension of the quartzite formation, and that they have been removed in large part, owing to the greater readiness with which they would yield to erosive agents.

THICKNESS OF THE QUARTZITE FORMATION.

Irving* in his preliminary report upon the Archean formations of the northwestern states, estimated the thickness of the Sioux quartzite to be from 3,000 to 4,000 feet. This estimate was based upon the section along Split Rock creek from the Palisades to Corson, and the assumption that the average dip was about seven degrees. The shortest distance between the two areas measured perpendicular to the strike (which is nearly north and south) is about two miles, and the change in altitude is 140 feet. The slates have been shown to be practically identical at the two points and therefore the assumed dip value is far too great. The average inclination of the strata between the outcrops cannot be more than one degree. It is evident that the dip is far from constant, and that the relatively high dips at the termini of the above section must be counterbalanced by dips at very low, or even

*Fifth Ann. Rept. of the U. S. Geol. Surv., p. 201. 1885.

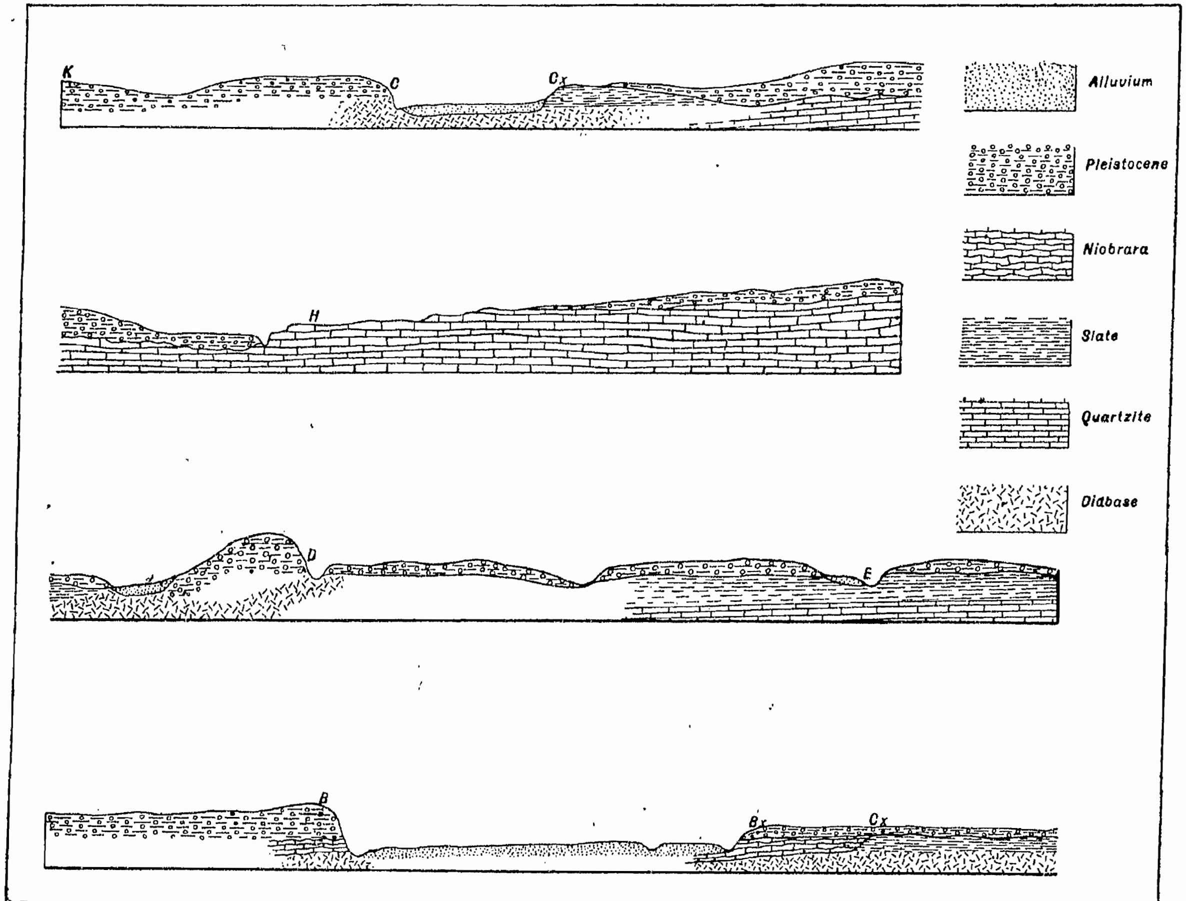


MAP OF THE DIABASE AREA NEAR CORSON, S.D.

BY S.W. BEYER.

SCALE 3 INCHES = 1 MILE. CONTOURS 20 FEET.

PLEISTOCENE	NIOBRARA	SLATE	QUARTZITE	DIABASE
Pd	Nc	Sl	Q	Db



CROSS-SECTIONS THROUGH DIABASE AREA.

reversed angles. That the dip is not constant, is evident from the field relations of the strata a few hundred yards to the north of the Palisades, where the beds are inclined in the opposite direction. It would appear that any estimate of the thickness of the formation must of necessity be little more than a guess, and Todd's* estimate of 1,500 feet would seem to be, in the opinion of the writer, a very liberal one.

DIABASE.

Diabase extends from a point near the center of section 22, almost due north, a distance of about one mile and a quarter and exposures are afforded wherever the creek impinges upon its western bank. The maximum vertical exposure is about twenty feet at D (see plates iv and v). At this point the diabase appears to be composed of completely weathered material. Fresh diabase in place occurs only as a low ridge extending across the creek at the point mentioned. It forms a slight fall in the creek and the outcrop continues southward along the east bank a distance of some 250 yards to the point Dx, but the rock never rises more than two feet above low water level. There are continuous rapids between the two points D and Dx. The exposure at C is in large part a duplication of the one just described; but since the structural features are here better expressed, it will be treated as the typical exposure. The diabase, although so completely weathered that a pick can be driven into it without difficulty, maintains a vertical wall some fifteen feet in height on the west bank of the creek, and the characteristic ophitic texture is perfectly preserved. The jointed structure, which is characteristic of massive rocks in general, is especially prominent owing to the filling in along the joint planes by vein material which offers greater resistance to disintegrating forces than the wall rock. Three systems of joints may be readily distinguished, of which the first is horizontal, while the second and third are vertical and approximately at right angles to each other. In certain places a fourth series of joints may be observed which

*South Dakota Geol. Surv., Bul. No. 1, p. 35. 1895.

is inclined at an angle of 45° to the horizon. Many of the blocks which are found in the stream channel and on the flood plain faithfully represent the above jointing in their rectangular, trapezoidal and wedge-shaped forms. The prismatic or columnar structure, which so often characterizes the basic igneous rocks that have solidified near the surface, is entirely wanting; and the amygdaloidal structure, which more strongly

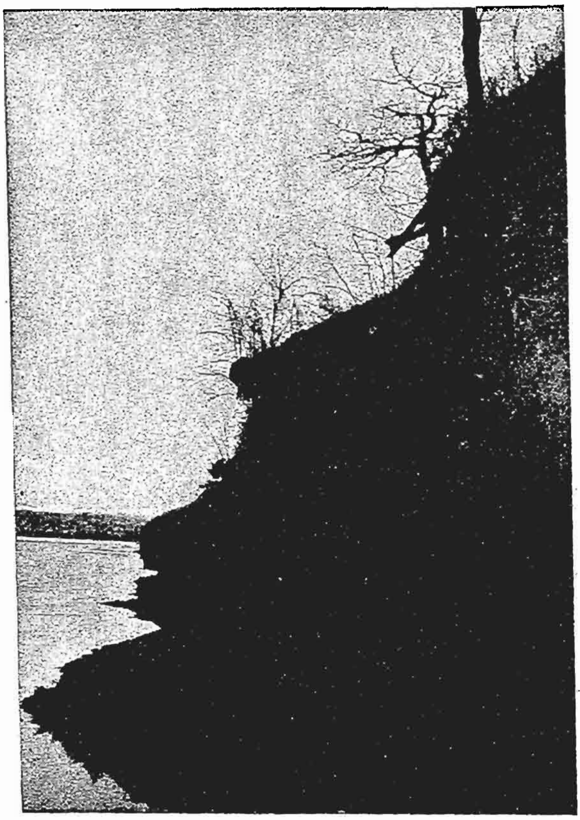


FIG. 24. Diabase ledge at Risty's.

bespeaks surface conditions of cooling, is not represented. The rock is thoroughly holocrystalline and its coarse texture, considered in connection with the absence of glass, may be taken as evidence of its slow rate of cooling.

The vein material effervesces freely when treated with hydrochloric acid, and seems to be in large part a calcareous substance much stained by iron oxide. It is probably of secondary origin, having been deposited by percolating waters which derived their load from some extraneous source, or from the decomposing diabase itself.

The extreme width of the diabase outcrop is best shown by the map, plate iv. The diabase at B is capped with chalk, a layer of residual clay two or three inches in thickness separating the two. There is no evidence here of contact metamorphism, either of an exogeneous or endogeneous nature. At C and D the diabase is immediately overlain by drift. At the latter place a layer of sand and gravel, which forms the contact zone, has been cemented in many places into a pudding stone. At Cx, as has been mentioned, slate conceals the igneous rock; and, as the contact zone cannot be observed, it is impossible to say definitely whether or not there has been any contact action. Here as in other exposures, the diabase is greatly weathered, and the structure is perfectly preserved and normal. Judging from the material excavated it gives no evidence of endomorphic action.

Perhaps as Culver* has pointed out, "the most prominent field characteristic of this rock is the profound decomposition it has suffered. How much of it has been removed by erosion it is impossible to say, but the whole exposure, from its upper surface down to the bed of the stream, a distance of twenty-five feet seems to be thoroughly disintegrated. It apparently maintains its vertical position now only by the support of a network of thin quartz veins which ramify through it in all directions." (This last statement has not been verified during the present investigation.)

In regard to the amount of pre-Cretaceous weathering† we have no measure; but that conditions have been favorable to rapid weathering during post-Cretaceous time appears evident; the rate being determined by the geological structure of the region and the texture of the rock. The dike coincides with a well-marked depression, probably constructional, which

* Wis. Acad. Sci., Arts and Letters, p. 207. 1891.

† It has been suggested by Prof. C. R. Van Hise, that in order to account for the great amount of weathered material it is not necessary to assume that all of the weathering has been done during post-Cretaceous times, much less since the glacial epoch. That in both cases, the deposits were laid down gently and would not necessarily have disturbed even a badly weathered surface.

has been sought out by Split Rock creek; moreover its contacts with the porous chalk and the sandy gravel layer of the drift would form natural water courses. Its relation to the slate cannot be definitely stated, but it appears quite probable that the diabase is intruded between the bedding planes of the slate, and even here the conditions may be favorable to the active circulation of the universal solvent. Weathering is facilitated also by the coarse texture of the rock and its complicated systems of jointing.

PETROGRAPHIC DESCRIPTION OF THE ERUPTIVE ROCKS.

OLIVINE DIABASE.*

MINERALOGICAL COMPOSITION.

The eruptive rocks of this area are confined, so far as known, to a single type, which is composed essentially of a lime soda feldspar, a monoclinic pyroxene and olivine. This rock is very similar in general appearance to the olivine-gabbro forming the axis of Pigeon Point as described by Bayley.† It also bears a very close resemblance to Törnebohm's "Åsby-type."‡ It is a coarse-grained rock and exposed surfaces present a peculiarly pitted aspect due to the relatively greater readiness with which the ferro-magnesian constituents, as compared with the feldspar, succumb to atmospheric agencies. The perfectly fresh diabase is black, with a greenish-yellow tinge, and an oily lustre which depends on the amount of olivine present. In the unaltered rock the feldspar is extremely fresh and glassy, and on account of its transparency, almost escapes notice. One of the most marked effects of weathering, even in its incipiency, is to bring the feldspar into prominence. As weathering proceeds the oily lustre of the olivine is lost, and the surface soon becomes rough. When the weathered portion is protected

* G. E. Culver has given a brief account of this occurrence accompanied by a petrographic description of two thin sections of the rock by Prof. W. H. Hobbs. (Trans. Wis. Acad. Sci., Vol. VIII, p. 206. 1892)

† Bul. 109. U. S. G. S., p. 32, et seq. Washington, 1893.

‡ Über die wichtigeren Diabase u. Gabbro-Gesteine Schwedens. N. J. B., p. 268. 1877.

from removal, the rock passes into a rusty-gray residuum in which its characteristic structure is preserved, even when the resultant product can be reduced to a powder between the fingers. This lustreless mass finally breaks down into a yellowish-red soil. The work of the atmospheric agencies is facilitated by the triple system of joints which separate the rock into more or less rectangular blocks, so that nearly all of the rock accessible is much altered, save the dislocated blocks lying upon the flood plain of the creek.

The feldspar is the most prominent constituent, occurring in large divergent laths, some of which are nearly an inch in length and having twin lamellæ easily seen with the unaided eye. The pyroxenes are less clearly defined and sometimes tend toward porphyritic development, measuring an inch or more in length, with feldspar laths as inclusions or forming embayments. At other times the rock becomes more or less granular through contemporaneous development of feldspar and pyroxene.

Feldspar.—Microscopically the feldspar occurs as laths parallel to crystallographic a or assumes the tabular form parallel to the clinopinacoid. In either case it is idiomorphic with respect to the augite, though generally influenced by the olivine. Sometimes the feldspar develops equally in all directions and then is allotriomorphic with respect to the augite; when such is the case, the rock assumes a granular structure.

When fresh the feldspar is colorless or water-colored, often perfectly transparent, seeming to similate the microtine habit, but when even slightly altered it rapidly loses its transparency and becomes white or grayish, and, as alteration progresses, may assume a green, yellow, reddish or brown hue.

The cleavage is not so pronounced as in orthoclase, but in sections cut favorably, two cleavages can be recognized readily according to P and M. The basal pinacoidal cleavage is usually the more perfect.

The laths are generally albite twins, composed of but few lamellæ, seldom more than four, and often only two. Twinning according to the Pericline law is also quite common and manifests itself in its characteristic cross-hachuring; which, when observed between crossed nicols, appears as fine striæ nearly normal to c. One or both of the above laws occasionally appear in conjunction with the Carlsbad law.

The extinction angle when measured against the composition face in the zone P-M, according to Pumpelly's* modification of the Des Cloizeaux' method was found to reach a maximum of 30° at which point the laminæ extinguished symmetrically. It was also found that certain individuals under similar circumstances presented an extinction angle of only 16 or 17°. On submitting the feldspar powder to Thoulet's solution it was found that a portion dropped when the solution was reduced to a specific gravity of 2.702, and another portion when the solution was still further reduced to about 2.65. This would indicate the presence of at least two feldspars; one a labradorite and the other an oligoclase. The first, according to Max Schuster,† would correspond to the $ab_3\ an_4$ molecule with a theoretical sp. gr. of 2.703 and the second to $ab_4\ an_1$ molecule whose theoretical sp. gr. he determined to be 2.652. The above results accord very well with the observed optical angles. Senfter‡ states as a result of his work on the diabase of Nassau, that an alkali feldspar, oligoclase, is regularly present; it being usually accompanied by a calcium feldspar, apparently labradorite. G. W. Hawes§ in his study of some Jersey City diabase, proved the presence of at least two feldspars. By means of Thoulet's solution he separated the feldspar constituent into two parts; the first having a specific gravity above 2.69 and containing 52.84 per cent of $Si\ O_2$ and the second with a sp. gr. less than 2.69 was found

*Geol. Wisconsin, Vol. III, p. 30. 1873-9.

†Ueber die Optische Orienterung der Plagioklase. T. M. P. M., Vol. III, p. 153. 1880.

‡Zur. Kenntniss des Diabases. N. J. B., p. 698. 1872.

§On the Mineralogical Composition of the Normal Mesozoic Diabase upon the Atlantic Border. Proc. U. S. Nat. Mus., p. 131. 1881.

to contain 60.54 per cent Si O_2. Dathe records a similar occurrence in the diabase dike at Ebersdorf.* Barrois † mentions labradorite and oligoclase as essential constituents of the olivine free diabase of the Menez-Hom.

The relation of the two feldspars in the South Dakota diabase seems to be normal. They occur in zonal growths, the central zone being the more basic and increasing in acidity peripherally. They also occur as distinct individuals.

The feldspars often show pressure phenomena, and at times evidence of mechanical deformation; attested to by undulatory extinction, bent laminae and broken crystals. These results cannot be ascribed wholly to protoclastic influences, for the other constituents have been effected in a similar manner though in less degree, and a legitimate interpretation would seem to be, that deformation took place subsequent to the consolidation of the magma.

Undulatory extinction may be due in many cases to zonal growths; but there are numerous instances in which the

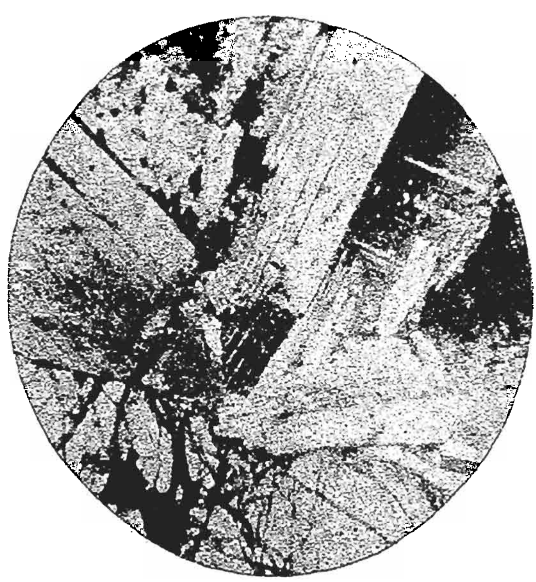


FIG. 25. Secondary twinning in feldspar due to mechanical deformation. Micro-photograph taken in polarized light.

cleavage lines are distinctly bent and these suggest the true cause to be mechanical and external rather than molecular

*Diabasgang im Culm bei Ebersdorf; Jahrb. pr. Geol. Landst Anst. für 1881. p. 307.

†Memoire sur les Eruptions Diabasiques Siluriennes du Menez-Hom, Finistere. Bul. d. Serv. d. l' Carte géol d. l' France, No. 7, p. 11, 1890. Paris.

and internal. Where distortion has exceeded the limit of cohesion of the crystals, rupture occurs, and one or both of the broken ends show the development of extremely fine secondary twin lamellæ which seldom persist the entire length of the individual. In such cases, when rupture has relieved the strain in the crystal, undulatory extinction is not noticeable.

Von Werweke,* in his study of the Olivine norites of Pauls Island on the coast of Labrador, and also in the case of the feldspar of the olivine gabbro from Store Bekkafjord, Norway, was the first to call attention to this phenomenon. He believes deformation and the consequent twinning to be of a secondary nature and the result of pressure.

A review of the literature of the subject shows a considerable number of observations, which tend to confirm Von Werweke's work. Lehman† proves that dynamic agencies have been efficient in producing secondary twinning in the plagioclase of the gabbro from the Saxon Granulitgebirge. Teall‡ in his study of the metamorphosis of dolerite into hornblende-schist says: "Optical anomalies due to strain are frequently recognizable. The extinction shadows sweep over the sections as the stage is rotated under crossed nicols. The lines separating adjacent twin lamellae are frequently curved, and sometimes, where the limit of elasticity has been exceeded, a crystal is seen to have been fractured. The twin lamellae often show a great want of persistence in one and the same crystal and sometimes they appear to be related to the fractures in such a way as to suggest that they may be in part of secondary origin."

Judd,§ in his study of the plagioclases of the "Older Basic Rocks of Scotland," shows that twin lamellae are not essentially a primary character, but are dependent in large part on conditions of cooling; or may be superinduced by mechan-

* Eigenthümliche Zwillingsbildung in Feldspath und Diallage. N. J. B., II, pp. 97-101. 1883.

† Untersuchungen ueber die Entstehung der Altkrystallinischen Schiefergesteine, etc., p. 196, Bonn. 1884.

‡ On the Metamorphosis of Dolerite into Hornblende-Schist. Quar. Jour. Geol. Soc., Vol. XLI, p. 136. 1885.

§ On the Tertiary and Older Peridotites of Scotland. Quar. Jour. Geol. Soc., Vol. XLI, p. 365. 1885.

ical means. Similar observations have been recorded by Stecher,[1] Bergt,[2] Doss,[3] Williams[4] and Adams.[5] Rosenbusch[6] considers undulatory extinction, mechanical deformation and the development of secondary twin lamellæ as the results of dynamo-metamorphism. From an experimental standpoint Fouque and Lévy* have demonstrated by their synthetic experiments with the plagioclase feldspar that twin lamellæ are not necessarily a primary characteristic but may be developed artificially. Foerstner† also proved the same thing to hold true in nature, by developing artificially, twin striæ on the untwinned crystals of feldspar from Pantellaria.

Aside from the earliest secretions of the magma, such as magnetite, olivine and some apatite, the feldspars contain relatively few primary inclusions. Gas inclusions are not uncommon, but generally seem to be of a secondary nature. Chloritic aggregates which probably represent devitrified magmatic glass inclusions, were noted. A few crystals seemed to be charged with reddish-brown dust particles which gave a brownish tone under low power. In such instances the adjoining pyroxenes often showed a similar effect.

ALTERATION OF THE FELDSPAR.

The first evidence of the alteration of the feldspar is commonly seen in the presence thoughout its mass of nearly colorless scales of a micaceous mineral giving high interference colors between crossed nicols. The mineral is probably sericite or kaolin. Incipient alteration begins along the

[1]Contacterscheinungen an schottischen Olivindiabasen. T. M. P. M., Vol. IX, p. 155, et seq. 1888.

[2]Beitrag zur Petrographie der Sierra de Santo Monta. etc. T. M. P. M., Vol. X, pp. 342, 333. 1889.

[3]Die Lamprophyre und Malaphyre des Plauen' schen Grundes bei Dresden, Vol. XI, p. 31. 1890.

[4]The Greenstone Schist Areas of the Menominee and Marquette Regions of Michigan. Bul. 62, U. S. G. S., p. 225. 1890.

[5]Ueber das Norian oder Ober-Laurentian von Canada. N. J. B., B. B., VIII, p. 433. 1893.

[6]Mik. Phys. d. Mas. Ges., Zwelte Auf., Bd. II, p. 155. 1887.

*Reproduction des Feldspaths par Fusion et par maintien prolongé a une température voisine à celle de la fusion. Comp. Rend., LXXXVII, No. 191. Nov, 1878, p. 700. Ref. N. J. B, p. 412. 1879.

†Ueber Künstliche physikalische Veränderungen der Feldspäthe von Pantellaria. G. Z. f. K., Bd. IX, pp. 333 et seq. 1884.

cracks which traverse the crystals in every direction and sometimes, as remarked by Dathe,* proceeds most rapidly parallel to the principal cleavages and the composition face. Series of lozenge-shaped cavities, which may or may not contain liquid inclusions, arranged with their major axes parallel to each other, anticipate the appearance of the micaceous mineral. The first effect of alteration is the gradual obliteration of the twin lamellae; and the whole individual becoming more or less opaque and showing aggregate polarization. The process is accompanied by the separation of calcite and free silica. A second alteration of the feldspar leads to patches filled with rounded granules which, from their high index of refraction and moderate double refraction, are probably zoisite; but in this rock this is not a prominent feature in its alteration. The aggregate thus formed would correspond to Cathrein's† definition of "saussurite." A third alteration takes place when the feldspar comes in contact with olivine. Here tufts of a greenish, slightly pleochroic mineral, project into the feldspar and seem to be the result of an interaction between the two minerals. This mineral was identified as chlorite. In many cases the outer zone of a feldspar has been completely changed, while there still remains a central core of perfectly fresh material.

Augite.—The augite is almost always allotriomorphic and occurs filling large wedge-shaped areas between the feldspars or sometimes as large porphyritic crystals‡ more than an inch in length, in which numerous feldspars are imbedded. When the feldspars are more or less isomerous, and the rock tends toward a granular structure, the augite individuals often appear as idiomorphic crystals, and present their characteristic eight-sided cross-section, bounded by the prism and the two vertical pinacoids. Prismatic cleavage is clearly defined in sections cut perpendicular to c, but in inclined sections is not

*Mikroskopische Untersuchungen ueber Diabase, Z. d. D. G., Vol. XXVI, p. 5.

†Zeitschrift für Krystallographie, Vol. VII, p. 234. 1883.

‡Such an augite would correspond to the "ophitic plate" of Teall. British Petrography p 58. London, 1888.

pronounced. Sections favorably cut often show traces of a clino-pinacoidal cleavage, which manifests itself as a series of cracks which tend to wedge. The extinction c to c is about 41°. Twins, with the ortho-pinacoid ($\infty P \bar{\infty}$) as twinning plane are not uncommon.

In one instance, the polysynthetically twinned individual was observed in a section showing but a single system of

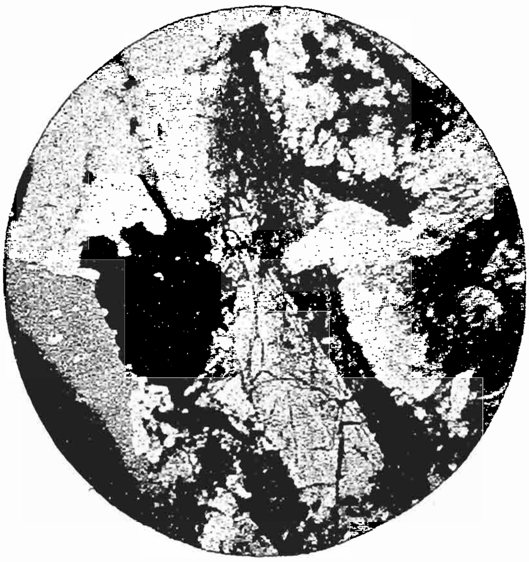


FIG. 26. Augite twin according to $\infty P \bar{\infty}$. Microphotograph taken in polarized light.

cleavage cracks with the twin striae inclined to them at an angle of 26°. This might at first glance be thought to indicate a new twinning law, as was actually suggested by Cohen,* who described a strikingly similar occurrence. Klein, from data furnished by Cohen, calculated the new twinning plane to be ∞P_2. Becker† in his study of the Washoe District observed the same phenomenon but thought it an example of twinning according to the common law, where $\infty P \bar{\infty}$ is the twinning plane. He "considers it to be a section making a considerable angle to the principal axis; and cutting a prismatic face nearly parallel to the edge OP, ∞P. The second system of cleavage does not appear in this instance, because it cuts the section at a very low angle."

*Geognostische Beschreiubung der Umgegand von Heidelburg, p. 69, 1881, und Sammlung-M ik. Pho., T. XXVIII, Fig. 4, 1889.

†Monograph III, U. S. G. S., p. 113, pl. iv, Fig. 28. Washington, 1882.

F. Becke* re-examined Cohen's original preparation and through an elaborate mathematical demonstration proved conclusively that no new law was necessary; reaching thus practically the same result as that previously attained by Becker. Rosenbusch†, in the third edition of his Mikroskopische Physiographie, accepts Becke's results. Becke's solution, with respect to the proper reference of the twinning-plane seems to apply perfectly in the case under consideration. The reason for the non-appearance of the second cleavage may merit a brief explanation. It is a well known fact that cleavage depends upon an inherent property of the crystal. In general, crystalline substances tend to break more readily in one direction than in another; i. e. they possess directions of cohesions maxima and minima; and the so called cleavage planes are normal to cohesions minima, and are only made manifest when the crystals have been subjected to sufficient external force to overcome said cohesions minima. This efficient force may be any of those natural forces which have to do with the deformation of rock masses, or in case of thin sections, may be the power used in cutting the sections. That the process of manufacturing thin sections is efficient in developing cleavage cracks is evidenced by the fact that thin sections show cleavage lines much better than thick ones. In minerals where the difference between cohesions maxima and minima is not great, as in the pyroxenes, it is clear that if the plane normal to cohesions minima makes a very low angle with the plane of the section, as in the case of the "second cleavage" alluded to above, the conditions would be unfavorable for the manifestation of the cleavage lines; because the resistance to development would be represented by the hypothenuse of a right-triangle the base of which would be the plane of the section and the altitude its thickness. Moreover, the applied force would act practically parallel to the plane of the section, and according to the

*Ueber Zwilling's verwachsungen gesteinbildener Pyroxenes und Amphibole. T. M. P. M., Vol. VII, pp. 93-107. Wien, 1886.

†Mik. Phys. d-Min. und. Ges., Dritte Auf., Vol. I, p. 251. Stuttgart, 1892.

parellelogram of forces, the component tending to develop the "second cleavage" would be insignificant as compared with the component which would tend to produce fractures perpendicular to the plane of the section and to accentuate the "first cleavage." A glance at figure 25 will show the development of fractures nearly normal to cleavage lines.

The color of the augite in incident light is black or greenish-black; in transmitted light it is a light purplish-brown. Pleochorism is pronounced in all save clinopinacoidal sections; the ray vibrating parallel to $\mathfrak{a}$ is an olive brown; parallel to $\mathfrak{b}$ a reddish-brown; and parallel to $\mathfrak{c}$ is a light olive brown. The depth of the color depends, in a measure, upon the thickness of the section.

Zonal structure is not uncommon, and in general the outer zone is the darker, although this arrangement is at times reversed. As augite is the youngest of the essential constituents, inclusions of the earlier secretions of the magma are extremely abundant, especially apatite. Gas and fluid inclusions are not numerous and when present seem to be of secondary origin, as they are confined to areas which show incipient alteration.

ALTERATION OF THE AUGITE.

Augite and hornblende are so closely associated that it is often difficult to determine whether they are true intergrowths or whether the hornblende is an alteration product of the augite. The hornblende not only occurs as a rim around the augite, but also in scattered areas through the pyroxene individual. There seems to be a sharp gradation from one to the other, and in those augites which are more or less idiomorphic the characteristic pyroxene cross-section is preserved. Such occurrences appear to indicate a secondary origin for the amphibole.*

The hornblende is readily identified by its strong absorption, characteristic prismatic cleavage making an angle of

*In regard to the primary or secondary nature of hornblende intergrowths with pyroxene See Bul. 62, U. S. G. S., pp. 53 et seq. 1890.

about 125° to each other in cross-section and low extinction angle. Its orientation* is such that b and ċ are common for the two minerals.

In some instances the compact brown hornblende is further altered into the fibrous hornblende† (Uralite‡); the fibers are prisms with small cross-sections and are elongated parallel to crystallographic ċ. The compact hornblende is subject to a change in color; often assuming a bluish-green color peripherally and accompanied by gradual loss of pleochorism probably due to the reduction and hydration of the iron. This change may be considered the incipient stage of chloritization.

Augite also changes to biotite.§ Scales of biotite occur scattered through the augite area, as well as in what appear to be parallel growths. These are very similar in distribution to and very intimately associated with the hornblende; though readily distinguished from that mineral by its characteristic "birch-bark" sheen just before extinction. The cleavage cracks of the biotite are approximately parallel to those of the augite in the prismatic zone. This alteration is generally accompanied by the separation of magnetite.

A third alteration of augite is to a chloritic aggregate, which often assumes the form of a rosette or spherulite. The spherulites show a black cross when observed in parallel light between crossed nicols. The individual scales or fibers exhibit a low index of refraction and low interference colors. They are of a light greenish color in transmitted light and are decidedly pleochroic. The ray vibrating parallel to the fibers is green, while the ray vibrating at right angles is a straw yellow. These chlorite aggregates seem oftentimes

*G. H. Williams; Paramorphism of Augite and Hornblende, Am. Jour. Sci. (3), Vol. XXVIII, p. 259. 1885.

†Bergt, in his study of the rocks from Columbia, South America, says that pyroxene, in passing to fibrous hornblende passes through the compact brown hornblende stage. T. M. P. M., Vol. X. p. 288, 1889. Williams (G. H.). in his work on the Greenstone Schists of Michigan, considers the compact brown hornblende to be, in many cases, an intermediate stage between the pyroxene and fibrous hornblende. Bul. 62, pp. 72, 211. Doss records the same cycle of changes in the pyroxene of the lamprophyres and melaphyres of the Plauen'schen Grundes bei Dresden. T. M. P. M., Vol. XI, p. 47. 1890.

‡Bul. 62., op. cit. pp. 52 et seq.

§For full discussion and literature references, see Bul. 109, U. S. G. S., p. 42.

to be imbedded in a matrix of calcite. A fourth product which probably owes its origin to the pyroxene, is that occurring in triangular areas, in the form of radiating, unterminated, light green prisms which generally diverge from a fragment of augite or magnetite. Numerous quadratic grains of magnetite are scattered among the prisms and the whole is imbedded in a matrix of calcite. The crystals show high relief and also high interference colors, and have an extinction angle of about 17° to the prismatic face. Poussin and Renard* in their study of the gabbro of the Hozémont have described and figured a similar occurrence and determined the mineral to be actinolite. It is probable that the mineral in the present case is the same.

Olivine.—This mineral is the oldest secretion and hence seldom contains the other constitutents as inclusions. When seen under the microscope it tends towards six-sided cross-sections which are often more or less rounded, the latter being due to magmatic corrosion. In such cases the mineral is surrounded by a black rim. Olivine also occurs in irregular grains without characteristic outlines. In relatively rare instances individual olivines are allotriomorphic toward the feldspar. In some cases idiomorphic feldspars project into, or, at times are entirely included within the olivine. This would indicate that the feldspar commenced to separate out from the magma before the close of the olivine period of crystallization. As an essential constitutent olivine seems to play a reciprocal role with the augite. In those sections showing most pyroxene, olivine is least abundant; the converse is also true. A similar relationship is noted by Zirkel† in the case of olivine and an orthorhombic pyroxene.

The cleavage is usually poor, but traces of that parallel to the clinopinacoid may sometimes be observed. In sections these striæ divide the crystal into a number of wedge-shaped areas, which are broken by irregular cross-fracturing. The

*Mém. Sur. les Caracteres Mineralogiques et Stratigraphiques des Roches Dites Plutiniennes d. la Belgique et d. l' Ardenne, Francaise. p. 74. Brussels, 1876.

†Lehrbuch der Petrographie, Zweite Auf., Vol. II, p. 633. 1894.

color is a pale yellow and the mineral is sometimes faintly pleochroic in tones of that color. Both index and double refraction are high, showing the characteristic shagreen surface in ordinary light and colors of the second and third orders between crossed nicols.

Inclusions in olivine are not uncommon; the most prominent being inclusions of magmatic glass, now represented by chloritic aggregates containing grains of magnetite and in some cases scales of biotite, derived through devitrification. These inclusions are characterized by black rims similar to those which surround the olivine crystals; and are probably of the same origin. Other inclusions are unimportant.

ALTERATION PRODUCTS.

Olivine is the least resistant to weathering agencies of all the essential constitutents of the diabase. The numerous cracks which traverse the crystals in all directions afford easy access for the circulating water and it is along these that alteration begins. The cracks become accentuated by trails of magnetite grains set in a matrix of a greenish chloritic or serpentinous, felty material which oftentimes contains needles of hornblende. (Pilite according to Becke.*) Serpentine seems to be rare as an alteration product in the Dakota diabase, but probably occurs in limited amounts, when it is likely to be confused with chlorite. Williams† in his study of the greenstone schist areas of the Menominee and Marquette regions of Michigan, was able to distinguish two classes of such secondary products, and suggested the following criteria for their separation: "First, such as are more or less fibrous in structure, without pleochroism, and have a decided action upon polarized light; and second, such as are scaly in structure, with pleochroism and so weakly polarizing as to appear isotropic." The first class embraces substances allied to serpentines; the second, those which more or less closely resembly chlorite. According to

*T. M. P. M., Vol. III, pp. 330-350 and 450. 1882.

†Bul. 62, U. S. G. S., p. 55, 1890. Here will be found an elaborate discussion of Chloritization with full literature references.

the above criteria, chloritization is much more common than serpentinization in the case under consideration; the necessary alumina being furnished by the plagioclase. This kind of alteration may present complete pseudomorphs of the olivine, which oftentimes, are stained a deep yellowish-brown, are non-pleochroic, and have but little effect upon polarized light. Biotite* is rather common as an alteration product of the olivine in this rock. Flakes of biotite which are readily recognized by their intense absorption, are scattered through the slightly weathered portion of the mineral, along fractures, forming irregular areas. According to Julien,† both biotite and hornblende are supposed to be due to the action upon the olivine of alkaline waters emanating from the plagioclase.

Biotite.—Biotite, aside from being an alteration product of augite and olivine, also seems to occur as an original constituent. Rosenbusch‡ says: "All olivine diabase contains brown biotite and hornblende as original constituents." Ch. Barrois,§ in his memoir on the diabases of Menez-Hom, remarks that the mica is original when olivine is present. Wadsworth,‖ in discussing the origin of biotite in the gabbro of Minnesota says: "This biotite is evidently formed from the magnetite with associated feldspathic material during the process of alteration." Again in describing Figure 1, plate vi, he continues: "The biotite is supposed by the writer to be the result of alteration and a reaction between the magnetite and the feldspar. The clear, feebly polarizing, greenish substance of an unknown character is probably an early stage in the formation of biotite." Zirkel¶ mentions magnesian mica as the constant companion of hornblende in the coarser grained diabase.

Biotite occurs in allotriomorphic flakes, commonly in close connection with magnetite, as inclusions in skeleton crystals,

*See Bul. 109, U. S. G. S., p. 39, 1893, for full literature references (2) Geology of Wisconsin, Vol. III, p. 235.

†Geology of Wisconsin, Vol. III, p. 235.

‡Der Massige Gesteine, Zweite Auf., p. 217. 1887.

§Bul. d. Services d. l' Carte géol. d. l' France, p. 4. 1890.

‖Minn. Geol. and Nat. Hist. Surv., Bul. 2, p. 87. 1887.

¶Lehrbuch der Petrographie, Zweite Auf., Vol. II, p. 631.

and filling the hackley indentations of the same, or surrounding magnetite grains. It is usually of a deep reddish-brown color but sometimes fades into a light green, or may become almost colorless as a result of hydration and leaching of the iron. The absorption is very strong, even in the lighter varieties, and is expressed in the absorption formula $\mathfrak{b} \geqq \mathfrak{c} > > \mathfrak{a}$ determined by a study of fresh material. The pleochroism is not marked except in shades of brown and yellow. The optic angle is small; as the hyperboles scarcely separate on revolution of the stage. The bisectrix $\mathfrak{a}$ is very slightly inclined to OP; foron a cleavage flake, the interference cross remains almost absolutely in the center of the field on revolving the stage.

The alteration of biotite to chlorite takes place readily; so that what Wadsworth denominates the first stage of biotitization would seem to be the first stage of the alteration to chlorite in the present case.

Hornblende.—Though hornblende, like biotite, appears to occur as an alteration product of the augite and olivine, it deserves notice as a primary constituent. As an original mineral, hornblende shows characteristic six-sided sections bounded by the prism and clinopinacoid. Prismatic cleavage is perfect, the prismatic angle being about 125°. The extinction angle is about 15°. The color is brown, with the periphery, in many cases a blue-green, as previously mentioned for the secondary hornblende. Absorption is strong for brown hornblende but less marked in case of the green, according to the formula $\mathfrak{c} > \mathfrak{b} > > \mathfrak{a}$. The hornblende in turn, alters to chlorite.

Apatite.—Apatite is very abundant in certain portions of the rock and is especially prominent in weathered areas. The latter fact might lead one to infer that it is of secondary origin, as has Wadsworth* in his study of the "Gabbros and Diabases of Minnesota," where he says: "This mode of occurrence, with the increasing abundance in proportion to

*Bul. No. 2, Geol. and Nat. Hist. Surv., p. 68. 1887.

the alteration of the rock, and its being found in known secondary minerals like quartz, indicates that in the majority of its occurrences, if not in all, it is a product of alteration in the rock and is due to the aggregation of the phosphate of lime in the rock during the general process of rock alterations." The apatite in the Dakota diabase, although most abundant in weathered areas, does not lend confirmation to the above view, but rather emphasizes its primary nature. Its presence in any mineral seems to give easy access to the weathering agents, for apatites are often surrounded by rims of much altered material, and the outer portion of a feldspar crystal filled with apatite is oftentimes completely altered, while a central core remains perfectly fresh. It occurs in extremely long hexagonal prisms, showing here and there the characteristic cross-jointing. As evidence of its primary character it may be mentioned that it occurs in abundance in unaltered augite and in the outer portion of feldspar crystals; but even in extremely altered areas, one end of a prism generally extends into the unaltered feldspar or augite. Sometimes single crystals of apatite penetrate two or more crystals of the other minerals. In section 11 an apatite passes through an augite and projects into a feldspar at either end. Inclusions in the apatite crystals are numerous and are often so arranged as to give the prisms a reed-like appearance. It is difficult to determine the nature of the inclusions. In some instances the cavities seem to be empty, in others they contain magmatic glass which has since devitrified into a chloritic aggregate, and sometimes scales of biotite are present. Skeleton crystals similar to those figured and described by Bayley* in his study of the diabase of Pigeon Point are common.

Magnetite.—Magnetite is extremely abundant, and as in the case of apatite its abundance seems to vary directly with the alteration of the rock. As a primary constituent it is one of the earliest to crystallize and occurs in idiomorphic crystals—

*Bul. 109, U. S. G. S., p. 47. 1893.

octohedra, presenting quadratic cross-sections. It also occurs as irregular grains and finely divided particles in the form of inclusions in all of the other constituents. Magnetite also originates as a secondary product from the decomposition of the ferro-magnesian constituents, and in such instances may occur as small crystals or grains widely scattered throughout the altered areas, or in large idiomorphic skeleton forms, some of which are more than one-fourth square inch in area. Tests for titanium failed to disclose the presence of that element. Barrois* states that the olivine disease of Menez-Hom contains pure magnetite while the non-olivine-bearing rocks contain titanium magnetite, ilmenite, and its decomposition product, leucoxene, are rare. Section No. 7 shows rhombic plates of a light gray color, more or less opaque, which may be altered ilmenite. Magnetite gives rise to the other oxides and hydrates of iron, through oxidation and hydration. In numerous instances pyrite was noted in close relationship to the magnetite.

In section 7 diamond-shaped crystals of sphene were observed. The obtuse angle was about 135° and in some instances the margins of the crystals were darkened through magmatic corrosion, testifying to their primary character. Pleochorism is pronounced. The ray vibrating parallel to the long dimension is a pale yellow, while the ray vibrating at right angles to this is a reddish-brown.

GENERAL ALTERATION OF THE ROCK.

All of the principal constituents tend to alter, directly or indirectly to a chloritic aggregate, "viridite" and kaolin. The most prominent by-products in this general process of chemical adjustment, are the iron ores, calcite, and free silica. In the breaking down of the feldspars to micaceous or chloritic minerals $Ca\,O$ and $Si\,O_2$ are constantly in excess; the former becomes fixed as calcite, the percolating waters furnishing the necessary carbon dioxide, while the latter crystallizes out as quartz.

*Bul. d. Services d. l' Carte géol. d. l' France, p, 179. 1890.

In all of the changes to which the ferro-magnesian minerals are subject, iron seems to be in excess and makes its appearance in the form of magnetite crystals and grains, hematite scales, ochreous stains, and earthy material. These products often wander out into the feldspar areas.

The secondary quartz sometimes occurs in large irregular areas, which, when viewed between crossed nicols, break up into sectors composed of convergent fibres. The fibres are positive in character (developed parallel to c) and corresponding closely to Miche-Lévy* and Munier-Chalmas' "quartzine."

The final alteration is accomplished by the leaching out of the soluble constituents and the reduction of the rock to a yellowish-gray residual clay.

CHEMICAL COMPOSITION.

A chemical investigation of the South Dakota diabase tends to confirm the work of the microscope. In order to obtain a representative analysis, samples were taken from a number of boulders and from the fresh diabase ledge and, after being powdered, were thoroughly mixed. A portion of the composit product was analyzed with the following results.

$Si O_2$	42.85
$Ti O_2$	Trace
$Fe_2 O_3$ / $Fe O$	13.66
$Al_2 O_3$	20.23
$Ca O$	6.85
$Mg O$	3.42
$K_2 O$	1.90
$Na_2 O$	5.78
$H_2 O$	0.88
$P_2 O_5$	Trace
Total	100.57

But few comments on the above analysis are necessary. The low percentages of silica, lime and magnesia, and the relatively large amounts of iron, alumina, potash and soda are interesting facts, highly confirmatory of the microscopical

*Comp. Rend., March 24, 1890.

determinations of the mineralogical constitution of the rock. The specific gravity is high, the average being about 3.1.

STRUCTURE.

Structurally the diabase is holocrystalline, hypidiomorphic; varying from a true ophitic* to a more or less granular structure. The expression of these structures is the direct result of the relative ages of the feldspar and pyroxene. In the first case, the feldspar is always idiomorphic with respect to the pyroxene and hence the earlier to crystallize. The habit of the feldspar in this instance is prismatic according to a, or tabular after the clinopinacoid. In the second case where there is a tendency toward the granular structure, both constituents approach isomerism (become equi-dimensional) in development. Sometimes the feldspar is idiomorphic with respect to the augite, and sometimes the augite is idiomorphic toward the feldspar; which means in terms of age, that in the one case the feldspar is the older, and the augite in the other. As both cases may be observed in a single section, a legitimate inference would be, that both minerals were crystallizing simultaneously in slightly separated areas.

When we compare the above structures with the purely granular structure in the plagioclase-pyroxene rocks, a third relationship between the plagioclase and pyroxene is observed. In those rocks possessing a strictly granular structure, the feldspar is never idiomorphic with respect to the pyroxene, while in numerous instances when the two minerals are in juxtaposition, the pyroxene shows more or less idiomorphism, proving that it was the first to crystallize. In this case the two constituents are equi-dimensional. In the study of the holocrystalline plagioclase pyroxene rocks, no exceptions have been observed, and, so far as the writer is aware, no observations have been recorded which are not in accord with the above statements. Hence, it seems clear that we

*Structure ophitique of Fouque and Lévy, diabassischkörnig, of Rosenbusch or divergent-strahlig-körnig of Lossen.

have a series of structures which are the direct expression of the relative ages of the two principal constituents. To summarize, we have, in terms of feldspar relations to pyroxene:

Feldspar, idiomorphic, older than the pyroxene; habit columnar or tabular ....Ophitic Structure.

Feldspar, idiomorphic or allotriomorphic; contemporaneous with the pyroxene and approaching isomerism...... ....Intermediate Structure.*

Feldspar, allotriomorphic, younger than the pyroxene; equidimensional..........................Granitic Structure.

PETROGRAPHIC DESCRIPTION OF THE QUARTZITE AND SLATE.

QUARTZITE.

Macroscopically the quartzite varies in color from the various shades of gray in the leached upper layers, to pink and red, or dark purplish-brown in the lower beds. Some of the slightly argillaceous portions assume a deep, brick-red color, and are usually thin-bedded. In general the massiveness as well as the color increases with the depth, but certain exposures show remarkable variations in texture and compactness, both horizontally and vertically. These changes are often extremely abrupt; a layer of perfectly compact, vitreous quartzite, with conchoidal fracture, and responding with an almost metallic ring when struck with the hammer, may be followed by a layer of incoherent sand, and this, in turn, by firmer rock. The sand layers are commonly of but slight thickness; rarely exceeding a few inches in the section observed in the area about Sioux Falls, though Merriam has recorded observations made about twenty miles to the west, in which the sandy layers often reach a thickness of several feet. Where the rock is not thoroughly quartzitic, it breaks around the integral grains instead of through them; so that freshly broken surfaces glisten in the sunlight, by virtue of

*Prof. W. C. Brogger in his work "On the Basic Eruptive Rocks of Gran" recognizes this transitional structure in the name "Olivine-Gabbro-Diabase," which he gives to one of his rock types. Quar. Jour. Geol. Soc., Vol. I, p. 18. February 1, 1894.

the numerous crystal-faced quartz grains. Such surfaces present a sugary appearance.

The size of the grain is an extremely constant factor over nearly the whole area. At the Palisades a large boulder of quartzite conglomerate was observed, but the parent ledge could not be found. In this boulder the conglomeratic pebbles varied in size from that of a pea up to that of a walnut. They consisted of vein quartz and were imbedded in a quartzitic matrix. Similar occurrences have been noted by the Minnesota geologists* in their study of the northeastern continuation of this same formation.

A thin section of the quartzite, when viewed under the microscope in ordinary light, is seen to be composed essentially of rounded quartz grains, the outlines of which are delicately traced by circlets of iron oxide, imbedded in an almost transparent matrix of interstitial quartz. In some of the most ferruginous varieties the interstitial cement takes on a jaspery appearance and becomes opaque.

The completely vitreous quartzite, when observed between crossed nicols, breaks up into numerous irregularly bounded areas which are oftentimes dove-tailed together in a very intricate manner, often forming a quartz mosaic. The interstitial quartz is found to be, in large part, in perfect optical accord with the original quartz grains.† In the Sioux quartzite the quartz grains often show the action of pressure as manifested in undulatory extinction and fractured grains. The cracked grains are readily detected by the slight displacement of some of the parts and their failure to extinguish as a unit. Several instances were noted in which the parts were slightly faulted and in one instance the fault-fissure was filled with sericite. Faulting was especially noticeable where a quartz grain contained so-called "quartz needles," the discontinuity of the needles emphasizing the displace-

*Final Report of the Geol. and Nat. Hist. Surv., of Minn., Vol. I, p. 541. 1894.

†Vid. Irving and Van Hise "On Secondary Enlargements of Mineral Fragments in Certain Rocks." Bul. No. 8, U. S. G. S. 1884.

ment. The movement of one grain upon another was in a few instances accompanied by a slight peripheral granulation.

Inclusions are extremely common, especially small, dark-colored dust particles and irregular gas cavities. Liquid inclusions are abundant in certain specimens and often contain movable bubbles. Fluid inclusions are, at times, arranged in more or less parallel lines and these lines extend across more than one individual and hence are of secondary origin.

Of the individualized inclusions, zircon and "quartz needles" (rutile) are most abundant. The zircons are often doubly terminated and show beautiful zonal growths (No. 6916). The ratio of length to breadth is generally about 1:3. The zircons* themselves, commonly contain inclusions arranged parallel to c and centrally located. In some instances the zircons are slightly iron-stained and their crystal angles are occasionally rounded. Aside from occurring as inclusions in the quartz grains, they are not infrequently located in the interstices.

The most interesting of all the inclusions are the so-called "quartz needles" of Hawes (Lithology of New Hampshire), which are very abundant.

It is comparatively easy to trace the stages from the indeterminate hair-like forms to bodies whose optical characters, so far as can be observed, are identical with those of rutile. Section 4863 shows all gradations. Certain of the quartz grains containing "quartz needles" are slightly altered and the needles are much jointed; considerable space intervening between consecutive segments. The segments are larger than the ordinary fibers; many of them so large that a distinct, pale yellow color could be distinguished, and they show strong relief and high double refraction; which is considered presumptive evidence of their identity as rutiles. The linear arrangement of the fragments suggest that they

* Von Crustschoff considers zircons which generally have a rounded form, with more or less characteristic crystal form and a central, very dark brown opaque single inclusion, or at times a group of inclusions, to be characteristic in a high degree for gneisses and related Archæan rocks. T. M. P. M., Vol. VII, p. 410. 1886.

were once integral portions of a continuous needle. Romberg,* in his study of the "Argentine Granites" proves the so-called "quartz needles" to be optically positive. In another instance a well developed rutile crystal in the interstitial area immediately adjoining the quartz grains was accompanied by another individual of pyramidal habit, probably anatase. Both crystals are of secondary origin and were derived perhaps from the rutilated quartz. No. 4849 shows comparatively large rutiles, as single individuals and as geniculate and polysynthetic twins similar to those described by Sauer† as occurring in the Adorf phyllites. All of these crystals are located in interstitial areas and hence are secondary. Other occurrences of anatase‡ were noted. As to the source of the titanium it must be said that one is hardly warranted in supposing that the "quartz needles" would be an all sufficient source, but it is a fact worthy of mention that in nearly every case, the individualized interstitial rutiles are in close proximity to the rutillated quartzes and strongly suggest as their source, the "quartz needles." It is quite probable that some titanium has been furnished by the biotite, which was undoubtedly present in small amounts, but which has given place to muscovite or to epidote (4859). Sagenite webs have often been recognized in biotite from other localities, while Thürach proved the presence of titanium in biotite, even when it did not manifest itself as individualized rutile. Hexagonal plates of hematite often accompany the rutile needles. Apatite was rarely noted as an inclusion in quartz and when present, the cross-gashing is never prominent.

Besides quartz, traces of orthoclase remain. Certain quadratic areas which have given place completely to sericite were probably of orthoclastic origin. In some instances the

*N. J. B., B. B. VIII, p 250. 1892.

*A. Sauer, Rutile als microscopische Gemengtheil in der Gneiss und Glimmer-schiefer formation, sowie als Thonschiefernädelchen in der Phyllit-formation, N. J. B., Vol I, p. 273. 1881.

*Vid. Thürach on the distribution of Anatase in Clastic Rocks. Verhand. der phys-medic. Gessell zu Würzberg, Bd XVIII.

sericite takes the form of rosettes, assuming a more or less radial arrangement.

Section 4867, from the James river, contains a considerable amount of plagioclase which shows the characteristic twin lamellæ and is remarkably fresh. Some of the individuals present very irregular outlines and show dynamic effects, as evidenced in bent laminæ and the development of fine twin striations. The same section shows certain light green, pleochroic, scaly particles, of slight relief and low double refraction, which were identified as chlorite. The plates occur bent around the quartz grains, and probably have resulted from the alteration of biotite or the interaction of the feldspar and the iron ores.

Section 6920 contains epidote in large amount, which probably originated from plagioclase.

SLATES.

The slates vary in color from a brick-red to a purplish-black, and weather to a light-gray or pinkish-gray. True slaty cleavage is absent, but parting may be readily effected along the bedding plane. These are not true slates in the common acceptance of the term, but correspond very closely to the quartz-slate of Irving and Van Hise.* Their specific gravity varies from an average of 2.65 in the slightly carbonaceous, purplish-black slates near Corson, to 2.83 for the deep-red, ferruginous slates of the Palisades. They vary in texture from the extremely fine-grained homogeneous "pipestone" to arenaceous slates or argillaceous quartzites. At the Palisades, as has been previously mentioned, the slates are interbedded with the quartzite, and there are insensible transitions from the pipestone to a vitreous quartzite.

Microscopically considered, the slates are composed essentially of quartz, a micaceous mineral, the iron ores and more or less carbonaceous material. They differ from the quartzite, in that the quartz grains are smaller and more angular,

*The Penokee Iron-Bearing Series; Tenth Annual U. S. G. S., p. 370 et seq. 1890.

and in the presence of a large amount of argillaceous material, which has crystallized as sericite or kaolin, or in some instances, chlorite; and in the increased percentage of iron. The angularity of the quartz grains seem to vary inversely as their size. Hence, in general, the smaller the grains, the sharper are their angles. When the amount of interstitial material is relatively great, the quartz grains seldom have definite boundaries, but seem to fade out at the edges, and often the peripheral portions of the grains are charged with very finely divided particles of iron and carbonaceous material. This rim is undoubtedly of "secondary growth." When observed between crossed nicols, siliceous matrix is seen to be in optical continuity with the original grain, as in the quartzite, although the result is more obscure.

Inclusions in the original grains are the same as in the quartzite.

In the finer grained varieties the micaceous scales are often bent or disturbed in various ways, being forced to adapt themselves to the quartz grains. In many instances

FIG. 27. Crushed quartz grain in slate from the Palisades.

the scales become more or less fibrous and are radially arranged. In the slates at the Palisades large flakes of mica are arranged parallel to the bedding and noticeably increase the fissility of the rock. The quartz grains and mica scales testify to horizontal movement in the rock,—shearing on a miscroscopic scale.

The iron oxide is abundant in the unaltered rock and occurs as indefinite grains in the interstices and also as inclusions in the peripheral portion of quartz grains and to some extent in the mica. It generally appears black or brownish-black and lustreless, but in the more ferruginous varieties some shade of red is the prevailing color. Van Hise ascribes the source of the iron in the graywackes of the Penokee-Gogebic iron-bearing series, to pyrite, marcasite and ferrite. This is probably true of the rock under consideration, so evidenced by the blackened areas, which are not unlikely the remnants of iron pyrites.

THE SPOTTED SLATES.

The slates over the whole district present peculiar markings in the form of circular spots which, seen in three dimensions, are spheroidal, with the major axis parallel to the

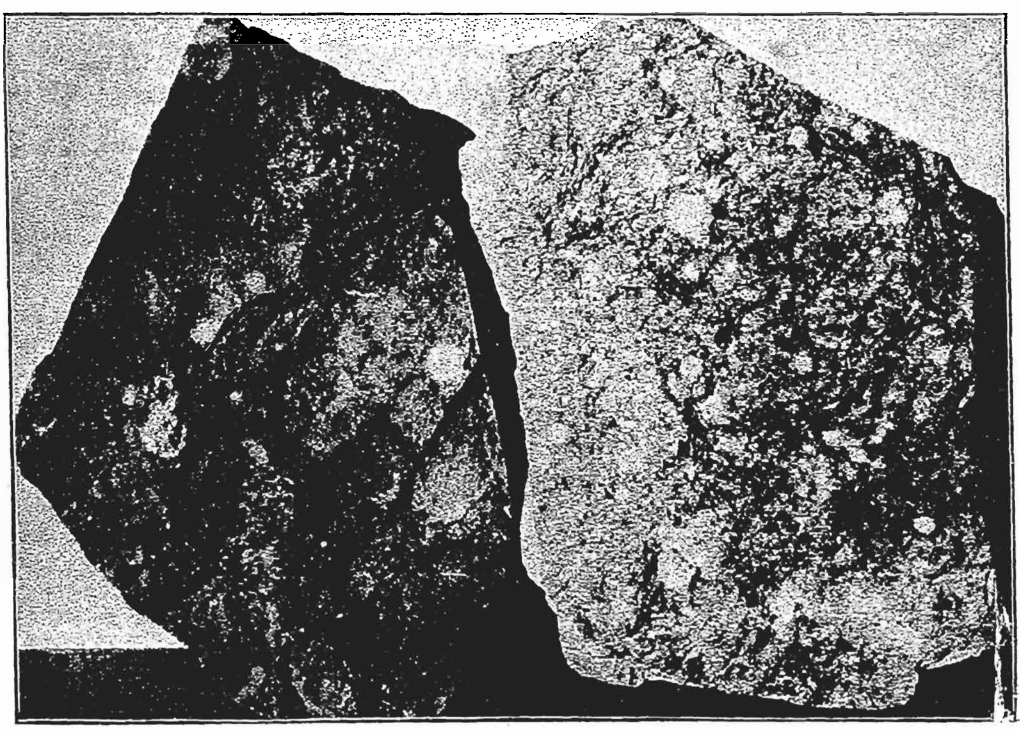


FIG. 28. Spotted slates near Corson, S. D.

bedding plane and present extremely sharp contours. These spots vary in size from a centimeter in diameter down to mere specks. They are always of lighter color than their matrix and commonly show a concentric arrangement of color in alternating yellowish-gray and pink shells. This alternation is rarely repeated more than three times; the series from the outside in generally being gray, pink, and gray center. In the smaller spots there may be but a single alternation. The matrix, in immediate contact with the spot, is usually of deeper color than the mass of the rock and thus tends to heighten the contrast. As to disposition of the spots, there seems to be no law controlling their arrangement. They sometimes occur along joint and bedding planes, but are quite as numerous in other positions.

Microscopically, the spots are essentially the same as their matrix, save that they contain less of the iron constituent and seemingly more of the micaceous mineral, which probably owes its increased prominence to the increase in transparency due to loss in iron. That the difference in color does not arise from the change in the state of combination, but from the withdrawal of the iron constituent, has been proved by numerous chemical analyses of related occurrences. Maw,* in his studies "On the Disposition of Iron in Varigated Strata," carefully separated the material composing the light colored spots from their deeply colored matrices, in sandstones, shales and slates, and demonstrated by an elaborate series of chemical analyses, that the bleaching is due to the removal of the iron.

The general appearance of the spots both microscopically and macroscopically, is almost if not wholly identical with the decolorized areas along joints and exposed surfaces where the present state can be definitely referred to the action of weathering agencies. In both cases the resultant product owes its origin to the removal of its iron constituent; but the anomalous arrangement of the spots and their entire independence of joints, fractures and bedding planes, precludes their reference to any external agency. The active principle in the leaching process must have originated within

*Quar. Jour. Geol. Soc., Vol XXIV, pp. 351-400. 1868.

themselves. Iron as a coloring agent in rocks is generally in the form of the insoluble ferric oxide (Sesquioxide) and according to Dawson* the leaching process is inaugurated by the reduction of the sesquioxide, through the action of organic matter, to the soluble protoxide, which is then readily removed by the percolating waters. The verity of this process has been confirmed by many observers, and has come to be widely recognized in the theory of the bog-iron ore accumulation. Diligent search was made for any trace of organic remains in the spots under consideration but without success; yet no other explanation of their origin appears tenable.

ORIGIN OF THE QUARTZITE AND SLATES.

Sorby,† in his second presidential address before the Geological Society of London, considers it probable that "the cohesion of the grains in hard and compact quartzites" was due to the deposition of interstitial quartz, but it was left to Irving and Van Hise‡ to transform a probability into a demonstrated reality and to make manifest the true geological significance of the process.§

Irving,‖ in his summary of general conclusions regarding the genesis of the Huronian quartzites, says: "All the true quartzites of the Huronian are merely sandstones which have received various degrees of induration by the interstitial deposition of siliceous cement, which has generally taken the form of enlargements of the original quartz particles, less commonly of chalcedonic or amorphous silica, two or even all of the three forms occurring at times in the same

*Quar Jour. Geol. Soc., Vol. V, p. 25. 1848.

†Quar. Jour. Geol. Soc., p. 62. 1880.

‡Bul. No. 8, U. S. G. S. 1884.

§The relation of the interstitial silica to the original quartz grains was correctly interpreted by A. Knop (Ueber Kieselsaure-Abscheidungen ünd Oölithbildung, N. J. B., p. 281, 1884) After giving a careful description, he says: "Jedes dieser Quarzkryställchen ist nichts Anderes, als das Product des Fortwachsens obgerundeter und individualister Quartzkörperchen in einer Kieselsaurelosung und Art lhrer Aggregation, das gegenseitige Abstossen der Krystalle mit Contactflachen, sowie der Mangel solcher Contactflachen an den rundlichen Kornern selbst beweisen, dass die Regeneration dieser zu Krystallen. nach der bereits erfolgten Ablagergung der Sandkorner auf eine noch fur uns rathselhafte Weise vor sich ging, denn keinerlei Einwirkung hoherer Temperatur, weder at den Gesteinselementen, noch an dem Bindemittel lasst sich mit Sicherheit constatiren." Inostranzeff fully explains the origin of quartzite by metasomatic growth. Studien uber metamorphisirte Gesteine im government Olonez. Die Entstehung der Conglomerate und Quartzite u. s. w. Leipsig, 1879.

‖Bul. No. 48, U. S. G. S. 1894.

rock. There may have been, in some cases, some solution and redeposition of the original quartz material, but in the main these rocks are still made up of the fragmental constituents that composed them before induration, the fragments retaining for the most part their original contours."

"It also appears that besides the true quartzites, ... other rocks of the Huronian, e. g., the graywackes, in which quartz is merely subordinate, or at least not the principal ingredient, have been affected by the same sort of siliceous induration, the indurating silica occurring both as enlargements of the quartz fragments and independently of them. Accompanying this induration there has been at times replacement of feldspathic material by quartz, and the alteration of feldspar to chlorite occurring both as a pseudomorphic substance for the feldspars and independently crystallized in the interstices. * * * By one or more of these processes, rocks have been changed so as to present macroscopically and microscopically the appearance of more or less complete original crystallization, and yet they are made up almost entirely of the original fragmental material, the alteration which they have undergone having been merely metasomatic, and not 'metamorphic' as the term is generally understood."

The facts observed in the study of the Sioux quartzite and slates are in complete accord with the above conclusions. That the original sand grains served as nuclei, around which the interstitial silica was deposited is a matter of simple observation. The source of the silica, however, is not so self-evident. An arkose or feldspathic sandstone, undergoing alteration, would give up a considerable amount of free silica when the feldspar changed to mica or chlorite and this might in some instances be sufficient to cement the rock. But the Sioux quartzite bears evidence of but little original feldspar and hence it becomes necessary to seek another source for the added silica. Irving (Ibid. p. 49) speaks of the percolating silica-bearing waters, but does not specify the origin of their load. Newton* in discussing the probable origin of the interbedded quartzites of the Black Hills, ascribes the source of the silica to diatoms, sponge spicules, etc., which were original constituents of the formation. This view has been elaborated by Crosby† in his study of "Quartzites and Siliceous Concretions.". As no evidence of organic life could be found in the Sioux formation, and it is improbable that the rock has been able to furnish sufficient silica to cement itself, the natural inference is that the percolating waters received their silica burden from some extraneous source. The exact source can only be conjectured with the data at hand, but it is not impossible that the quartzite has been covered by a highly feldspathic deposit which has long since been removed.

AGE OF THE QUARTZITE FORMATION.‡

The Sioux quartzite has been referred to the Huronian by Hall, White, Kloos, Irving and Van Hise in their respective writings upon the subject. Hayden approached the area from the southwest and believed the formation to be possibly Cretaceous, while the Minnesota geologists assert with equal positiveness its equivalency with the Potsdam of New York. Todd, in a preliminary report on the geology of South Dakota, follows Hall in his treatment of the quartzite formation.

The present investigation leads to the reference of the formation to the pre-Cretaceous times for the following reasons:

I. Character of its inclusions.

a The coarse, holocrystalline diabase and the absence of pyroclastics argues strongly in favor of intrusion under high temperature and pressure. In other words the diabase is of deep-seated origin.

b The Mesozoic diabases of the Atlantic slope are close textured and in nearly all instances carry more or less glass.

*Geology and Resources of the Black Hills of Dakota, pp. 92 and 93. 1880.

†Technology Quarterly, pp 397, 407. May, 1888.

‡See Geol. and Nat. Hist. Surv. of Minn., Vol. VII, pp. 533-561; also Iowa Acad. Sci., Vol. II, pp. 218-222.

II. Lithological character of the formation. Much of the slate and quartzite is thoroughly indurated. The induration is due in large part, to metasomatic infiltration. So far as the writer is aware, no instances have been recorded of Mesozoic arenaceous deposits in undisturbed areas becoming completely indurated according to the above process.

III. Geological structural relationships. The Niobrara overlies the quartzite formation unconformably. According to Irving* there is reason to believe that the Sioux quartzite underlies unconformably the Saint Croix as exemplified by the exposures in the vicinity of Mankato and New Ulm. The Minnesota geologists concur in this view.

The following facts may be adduced in support to Hall's reference to Huronian.

1. As has been emphasized by Irving, the lithological characters of the quartzite are almost identical with those of the Baraboo quartzite in Wisconsin. The latter formation has been referred with some degree of confidence to the Huronian by both Irving and Van Hise.

2. The diabase near Corson in South Dakota and the quartz-porphyry† discovered at Hull in Iowa are strikingly similar to the intrusives which are peculiar to the Huronian in the Lake Superior region.

ACKNOWLEDGMENTS.

Prof. C. R. Van Hise kindly placed at the writer's disposal the note books of R. D. Irving and W. N. Merriam on the Sioux quartzite area. The note books were illustrated by forty-four thin sections of quartzite and related rocks made from specimens collected by the above investigators.

The laboratory work was carried on under the personal supervision of Dr. E. B. Mathews, and to him the writer desires to express his hearty appreciation for many valuable suggestions.

Above all the writer takes this opportunity to acknowledge his great indebtedness to the late Prof. G. H. Williams, to whose influence and teaching is due anything that may be found of merit in the paper.

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* Fifth Ann. Rept. U. S. G. S., p. 202.

† Iowa Geol. Surv., Vol. I, p. 165. 1892.