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THE NATURE AND ORIGIN OF THE AMPHIBOLE-ASBESTOS OF SOUTH AFRICA

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CONTENTS

I. INTRODUCTION AND ACKNOWLEDGMENTS

Concluding a description of a mineralogical curiosity, a specimen of the blue asbestos from the Cape of Good Hope, Hausmann wrote nearly a century ago: "Should the asbestiform *krokydolith* from

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South Africa be available in greater quantity, then, on account of its property of ready separation into the finest threads of relatively remarkable strength, useful applications . . . . might perhaps be found for it" (1831, p. 1597, *trans.*). Today the asbestos deposits of South Africa rival in importance those of Canada and their economic value lies largely in the divisibility and consequent spinning property of the fibre.

Although the results of a number of studies of the South African asbestos have appeared, the chemical and optical data of the asbestiform amphiboles are still scanty and conflicting, and explanations of the origin of the deposits are not yet wholly satisfying. Therefore, at the suggestion of Professor Charles Palache, the writer undertook a study of the extensive amphibole-asbestos collection made under Dr. Palache's direction by the Shaler Memorial Expedition to South Africa in 1922. This collection contains some choice specimens donated by Dr. A. L. Hall and others, and is accompanied by a full range of thin sections.

The work was conducted in the Department of Mineralogy and Petrography of Harvard University, and the writer wishes at once to express his thanks to Dr. Palache for the privilege of studying this valuable material, for outlining the nature of the problem and fruitful lines of attack, and for generous provision of funds for chemical analyses. The writer is also indebted to Professor R. A. Daly for an instructive conversation on the genetic problem, and to Professor E. S. Larsen for some assistance in making optical determinations.

II. THE OCCURRENCE AND DISTRIBUTION OF ASBESTOS IN THE UNION

Although no new field observations are to be offered in this paper, the adequate treatment of the present subject, especially the genetic discussion, demands a brief statement of the geological relations of the asbestos-bearing beds. This will be derived from the comprehensive accounts by Hall (1918 A, B), the recent general text by Du Toit (1926), and the new geological map of the Union by the Geological Survey of South Africa (1925).

The useful asbestiform minerals fall into two groups: serpentine-asbestos and amphibole-asbestos. Although varieties of the former group still constitute the major share of the world's output of asbestos, amphibole varieties are gaining in importance. In South

Africa both types of asbestos are represented; but the deposits of asbestiform serpentine are small compared with the enormous reserves of fibrous amphibole, blue crocidolite, and recently to an increasing extent ash-gray amosite. The present study is concerned only with the amphibole-asbestos.

On the map accompanying Hall's monograph (1918 B, pl. xvi) ten asbestos localities are indicated. Of these the Cape Belt, yielding crocidolite exclusively, is by far the largest. The Lydenburg and Pietersburg Belt in the Transvaal, where both crocidolite and amosite are mined, comes next in size. The remaining regions are relatively small, and with the exception of Zeerust whence amosite is doubtfully reported, they yield only serpentine forms of asbestos.

The Cape Belt stretches northwards from about 25 miles south of Prieska to about 35 miles north of Tsenin in Kuruman, a distance of 240 miles. The width of the belt varies from a maximum of about 30 miles down to about 3 miles. This belt is formed by the outcrop of a series about 3000 feet thick of magnetic jaspers and siliceous ironstones with very subordinate sandstones, limestones and cherts. These beds form the lowest member of the Griquatown Series which in turn represents the uppermost of the three subdivisions of the Transvaal System in Griqualand West.

The Lydenburg and Pietersburg Belt extends west from the neighborhood of Penge to Chuniespoort, a distance of 160 miles, with a mean width of about 10 miles. This belt is formed by a series of ironstones similar to those of the Cape Belt and at the same stratigraphic horizon. As shown in Table I which is drawn from Du Toit (1926, p. 83), both asbestos belts overlie a series of dolomites.

Towards their base the asbestos-bearing ironstones are rather severely folded, especially to the west of the Gamagara Ridge in the Cape Belt. Farther up in the series signs of disturbance decrease and finally vanish. Whereas the Lydenburg and Pietersburg Belt is definitely within the contact aureole of the Bushveld Igneous Complex, no visible igneous body of comparable proportions has affected the Cape Belt.

Table I. Geological Relations of the Asbestos-Bearing Ironstones of South Africa

	TRANSVAAL		GRIQUALAND WEST	
TRANSVAAL SYSTEM (Pre-Devonian)	Pretoria Series	Magaliesberg Group Daaspoort group including the Ongeluk Volcanic Series Timeball Hill Group (with the Lydenburg and Pietersburg Asbestos Belt near the base)	Griquatown Series	Upper Griquatown beds Ongeluk Volcanic Group Lower Griquatown Beds (with the Cape Asbestos Belt)
	Dolomite Series		Campbell Rand Limestones and Dolomites	
	Black Reef Series		Black Reef Series	

III. THE GENERAL CHARACTER OF THE HAND-SPECIMENS

1. The Ironstones

The asbestos seams invariably lie parallel to the bedding in hard, banded ironstones. In color these rock vary from the darkest brown, through brown, purple and red, to ochre, depending on the degree of peroxidation and hydration of the iron content. In 13019[1] from Kliphuis an half-inch band of small pyrites cubes has developed in dense, dark ironstone. The texture grades from finely granular to densely compact. Within the limits of the hand-specimens the bands, which are defined by sharp changes of color rather than of texture, have widths ranging from a mere hair's breadth to one inch or more; bands of the latter width are rare, however. Sometimes the banding of the ironstones shows little or no disturbance; often the bedding is mildly warped together with the asbestos seams. In an exceptional case, such as 13073 from Warrendale near Daniels Kuil, severe contortion is displayed accompanied by a coarsening of grain and a development of siliceous bands.

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[1] This and subsequent specimen numbers refer to the catalogue of the Mineral Collection of Harvard University.

2. THE NATURE OF THE ASBESTOS SEAMS

Broadly surveying the hundred specimens constituting the present collection it is clear that the dominant material, apart from the enclosing ironstone, is a blue, fibrous mineral occurring in persistent, concordant, cross-fibre seams. Occasionally, as in 13070 from Koegas and 13072 from Warrendale near Daniels Kuil, the fractured face of the fibrous mass presents a deep-blue, smooth, compact, faintly undulating, silky-lustrous surface, corresponding perhaps to a mass effect of minute unit prism faces of similarly oriented amphibole fibres. In the majority of cases, however, the fractured surface across the seams is lavender blue, non-lustrous and fluffy. In either case bundles of fibres can be readily detached with the fingers and indefinitely disintegrated into threads of unlimited fineness.

Several specimens, such as 13016 and 13017 from Kliphuis and 13047 from Keikamspoort, have bands of acicular brown amphibole arranged in the cross-fibre manner characteristic of the asbestos. The presumption that this acicular amphibole is a morphological variant of the blue fibre is confirmed by later chemical evidence. Thus this coarser material is of particular interest as it permits fuller optical study than can be made with the fine fibres.

Occasionally crystalline structure fails entirely in the blue bands. In 13018 and 13025 from Kliphuis and 13071 from Westerberg the blue bands present a dull, amorphous appearance, and the belief that these bands represent incipient or potential asbestos is again justified by chemical analysis.

In one example, 13067 from Kalkfontein in the Prieska district, the rich blue color is lacking, the seam consisting of greenish gray fibres otherwise similar to the blue fibre. In other specimens, notably 13083 from McBean's Loc and 13092 and 13093 from Penge in the Transvaal, the fibre is silvery, ashy or reddish gray. This is the material for which Hall proposed the name amosite (1918 A, p. 8); and the few specimens in the present collection show that the white fibre tends to much longer development than the blue material, with little loss of flexibility and divisibility.

Some specimens show a transition from the usual blue fibre to a hard, inflexible, golden fibre which can sometimes be crumbled with the fingers with the formation of an ocherous powder; 13033 from Keikamspoort is an example. With increase in the relative amount of the golden fibre, the seams assume a rich, golden, lustrous fracture-surface whose beauty is enhanced by the variety of reflections resulting from corrugations in the fibres; 13033–13037 and 13039 from Keikamspoort illustrate various phases in the development of this so-called "golden asbestos." With the complete suppression of blue fibre the golden seams assume a still greater hardness and lustre, which, when combined with an undulatory fibrous growth, result in "tiger's eye" with the chatoyant lustre prized by the lapidary; 13066 is a beautiful example of this stone.

3. The Structure of the Asbestos Seams

The blue fibre seams vary in width from a small fraction of an inch to two inches. Hall states that the Cape fibre rarely exceeds three inches in length, while fibre three-quarters of an inch in length represent 80 per cent of the output of the Westerberg and Koegas workings in 1917 (1918 B, p. 18). Five-eighths of an inch may therefore be taken as a fair average length of the blue asbestos fibre. Golden asbestos and tiger's eye occur in seams of similar width. In the present collection the white fibre, amosite, reaches a length of nearly 11 inches. According to Hall this is a maximum length for amosite; an output of fibre 4 to 7 inches long can however readily be maintained (1918 B, p. 20).

Although some of the thinner asbestos seams are essentially parallel-sided, some irregularity in width is much more common. A frequent structure is one in which a seam is bounded by one plane contact, the other being undulating or corrugated. Sometimes a seam may be twofold, bounded top and bottom by plane contacts and enclosing a wavy medial band of ironstone, as in 13083 from McBean's Loc. In 13072 from Warrendale, near Daniels Kuil, both contacts of the asbestos seam are undulatory and complementary, the seam being thus divided into pod-like bodies connected by mere filaments.

The cone structure described by Hall is exemplified in 13074 from Kuruman. It results from conical protuberances from the enclosing rock into the asbestos seam, and it is best seen where the specimen has parted along the junction between the asbestos and the wall.

Generally the fibres are oriented normal to the bedding, but occasionally they may assume a notably oblique position. In some cases the fibres are curved, being nearly normal to one wall and oblique to the other.

IV. OPTICAL AND CHEMICAL STUDY

1. QUARTZ

Quartz occurs in the asbestos-bearing ironstones in three phases which are distinct in grain, in texture and in age. The first mode of occurrence is represented by exceedingly small and indefinite individuals forming the major constituent of the colorless and cloudy bands of the more compact and banded rocks. This is the earliest quartz, evidently representing the almost unaltered siliceous component of the original sediment.

The second type of quartz forms the colorless bands of some of the less cherty and compact ironstones. The individuals are clear, fresh and equigranular, forming interbedded mosaic bands whose granularity averages 0.05 mm. These mosaic bands appear to be the more siliceous bands of the original sediment crystallized under mild metamorphic conditions.

The third quartz phase is clearly the latest. It appears in delicate veinlets of mosaic or fibrous structure sometimes traversing the section with no regard to the bedding direction; sometimes appearing in fine mosaic streaks forming, along with more abundant magnetite, a selvage to the cross-fibre asbestos seams; and sometimes forming massive cross-fibre seams through which is distributed a variable amount of concordant fibrous asbestos. In larger specimens this association results in the "tiger's eye" already described in a previous section. Although it might be held that the fibrous quartz in such specimens has replaced fibrous asbestos, the impression gained from the sections is that the two minerals grew concurrently. It is noteworthy that the quartz fibres in these rocks extinguish under crossed nicols at all angles to their direction of elongation, and that, therefore, they have no tendency to elongate along their principal axes. Precisely the same peculiarity was recently observed by Richards in veins of fibrous quartz and chlorite from Rhode Island (1925). It would thus seem that when quartz either replaces another fibrous mineral or grows concurrently with it, the elongation of the fibres is determined solely by the fortuitous orientation of the first quartz to crystallize, and is independent of the usual prismatic habit of quartz.

Qtz after Crocidolite
also to habit.

2. IRON ORES

Next to quartz, iron ores are the most abundant constituents of the ironstones. The sesquioxide, usually somewhat hydrated, appears to be the earliest and most abundant ore. Magnetite is prominent in many slides and tends to idiomorphism with the appearance of later crystallization.

The ferric oxides are nearly always amorphous. Their color grades from nearly black, through the usual shades of red and brown, to light brown. Often silica and hydrous ferric oxide form a perfectly homogeneous, brown aggregate giving no reaction in polarized light; sometimes ferric oxide is irregularly associated with amorphous magnetite. Rarely ferric oxide occurs in fibres showing pleochroism and parallel extinction. This structure is displayed in sections of the conical protuberances of ironstones which often project from the wall-rock into an asbestos seam. At first sight it might appear that these cones were unaltered relics of ironstone, but their fibrous structure, accurately oriented parallel to the axis of the cone and to the adjoining cross-fibre asbestos, and therefore wholly unlike the unoriented ferric oxide which makes up the unaltered ironstone, clearly indicates a later molecular rearrangement probably contemporaneous with the asbestos formation. Finally ferric oxide occurs in deep-red, translucent patches at the margins of partially reoxidized magnetite grains.

Magnetite is an ever present constituent of the ironstones, and an infallible associate of the asbestos seams. Grains of magnetite show a strong tendency to coalesce into opaque bands which give the banded appearance to the hand-specimens. Euhedral outlines are common and various sections of the octahedron and perhaps the dodecahedron sometimes simulate rhombohedral shapes. Magnetite crystals never have the appearance of detrital grains, and thus it is clear that they must have formed *in situ* by the partial reduction and crystallization of the earlier ferric oxides. Associated with the asbestos seams magnetite may occur in irregular black bands of coalescing grains at the contacts between the asbestos seams and the wall-rock; or it may form undulating bands of discrete grains distributed with some regularity through the asbestos seams; or it may occur as a quite irregular scattering of idiomorphic grains.

In a few rocks magnetite bands appear disposed in a manner which at first sight seems inexplicable. In such rocks the bedding as defined by magnetite bands at some distance on either side of an asbestos seam, is perfectly flat. In the neighborhood of the seam, however, but still within the wall-rock, the magnetic bands assume a wavy shape in sympathy with the wavy contact of the asbestos seam with the wall-rock. No tectonic influence could reasonably be invoked to produce this selective distortion, and thus one is driven to the conclusion that during the development of the asbestos seams the entire rock in the neighborhood of the plane of alteration acquired a kind of molecular mobility resulting in the regular disposition of the various materials when the change was complete. Although at first sight perhaps somewhat hypothetical, this molecular mobilization of the ironstone around the asbestos seams is precisely what must have happened in the caseof the cones of ferric oxide described above. In other words, the structural relations of asbestos seams and magnetite grains indicate that these minerals formed contemporaneously.

A typical fine-grained, barren magnetite-quartzite and a representative sample of the cryptocrystalline ferruginous chert adjoining a crocidolite seam were analyzed with the results given in Table II. In the appended deduced mineral constitutions the monohydrates of alumina and ferric oxide have been formed for the sake of simplicity. Phosphoric and carbonic acids have been combined with magnesia and small proportions of manganous oxide and magnesia are combined in the spinel of I which is, however, still essentially magnetite.

These analyses confirm the optical observations which indicated that the ironstones consist almost wholly of quartz and variously peroxidized and hydrated oxides of iron. The small amount of aluminium hydrate and the minute proportions of carbonates and phosphates indicated chemically are not detected by the microscope. It is significant that neither in the barren ironstone nor in the ironstone immediately adjacent to a crocidolite seam were lime or the alkalis found in determinable amounts. In the degree to which iron is peroxidized and hydrated the two analyses differ widely, in full accord with the microscopic observations. In I, which is largely a fine-grained crystalline mosaic, considerable reduction has taken place giving about 18 per cent of magnetite, while water is present in sufficient amount to give about 22 per cent of monohydrates of the sesquioxides. In II, on the other hand, which is largely an uncrystallized aggregate, iron oxide is entirely in the ferric state, and there is enough water present to produce 54 per cent of monohydrates of ferric oxide and alumina.

TABLE II. NEW ANALYSES OF IRONSTONES FROM SOUTH AFRICA

	I	II
SiO_2	45.50	43.85
TiO_2	trace	trace
Al_2O_3	1.52	1.44
Fe_2O_3	44.16	47.88
FeO	4.63	trace
MnO	0.57	0.00
MgO	0.42	0.35
CaO	trace	trace
Na_2O	trace	trace
K_2O	trace	trace
H_2O+	2.30	5.55
H_2O-	0.60	0.35
P_2O_5	0.05	0.06
SO_4	0.00	0.00
CO_2	0.12	0.35
S	0.00	0.00
	99.87	99.83
SiO_2	45.50	43.85
$Al_2O_3 \cdot H_2O$	1.80	1.67
$Fe_2O_3 \cdot H_2O$	20.11	52.33
Fe_2O_3	13.60	0.80
$FeO \cdot Fe_2O_3$	17.90	0.00
$MgO \cdot CO_2$	0.24	0.67
$MgO \cdot P_2O_5$	0.09	0.10

I.—Banded ironstone, 13001 (fine-grained, barren, magnetite-quartzite), from Prieska Kopje. Analysts, W. H. and F. Herdsman.

II.—Ironstone, 13010 (cryptocrystalline, ferruginous chert adjacent to crocidolite seam), from Kliphuis. Analysts, W. H. and F. Herdsman.

3. CROCIDOLITE

PREVIOUS WORK. Optical and chemical study of the blue, fibrous amphibole-asbestos, the dominant mineral in the collection, yielded a number of additions and contradictions to the existing data of crocidolite; a brief review of previous work is, therefore, desirable.

The Cape crocidolite has been analyzed a number of times and several attempts have been made to establish its chemical constitution. In Table III previous analyses have been arranged in chronological order together with two analyses of crocidolite from Cumberland, Rhode Island.

The first work was done by Klaproth (1815) who published a short description of a new, non-fibrous, massive, blue mineral collected by Lichtenstein at the Orange River near Prieska in the Cape. Klaproth gave an analysis (I), and proposed the name *Blau-Eisenstein* for the material.

Some years later Hausmann and Stromeyer (1831) described a blue, fibrous mineral from the Cape whose chemical identity with Klaproth's *Blau-Eisenstein* they established by two analyses (II, III). To avoid confusion with the pre-existing term *Blau-Eisenerde* Hausmann suggested the apt name *Krokydolith* for both materials, recommending that the fibrous material be called *asbestartiger Krokydolith* to distinguish it from the massive variety. *Krokydolith* is derived from κροκίς, meaning "fluff" or "woof."

Much later Doelter (1880) analyzed the Cape crocidolite (IV) and showed for the first time that the mineral contained abundant

Table III. Previous Analyses of Crocidolite From South Africa and Rhode Island

	I	II	III	IV	V	VI	VII
SiO_2......	50.0	50.81	51.64	52.11	51.89	52.13	51.03
Al_2O_3.....	....	.....	.....	1.01	.....	.....	.....
Fe_2O_3.....	....	.....	.....	20.62	19.22	15.93	17.88
FeO......	40.5	33.88	34.38	16.75	17.53	21.25	21.19
MgO.....	....	2.32	2.64	1.77	2.43	0.22	0.09
CaO......	1.5	0.02	0.05	.....	0.40	.....	.....
MnO.....	....	0.17	0.02	.....	.....	.....	.....
Na_2O.....	5.0	7.03	7.11	(6.16)	7.71	6.26	6.41
K_2O......	....	.....	.....	.....	0.15	.....	.....
H_2O......	3.0	5.58	4.01	1.58	2.36	3.95	3.64
	100.0	99.81	99.85	100.00	101.69	99.74	100.24

I.—Blau-Eisenstein, Cape of Good Hope. Analyst, Klaproth. Ref. Klaproth, **1815**.

II, III.—Krokydolith, Cape of Good Hope. Analyst, Stromeyer. Ref. Hausmann and Stromeyer, **1831**, p. 1585.

IV.—Krokydolith (Blau-Eisenstein), Cape of Good Hope. Analyst, Doelter. Ref. Doelter, **1880**, p. 40.

V.—Krokydolite, Cape of Good Hope. Analyst, Renard. Ref. Renard and Klement, **1884**, p. 537. Summation given, 101.71.

VI, VII.—Crocidolite, Beacon Pole Hill, Cumberland, Rhode Island. Analyst, Chester. Ref. Chester and Cairns, **1887**, p. 109. Summation of VII given, 99.94.

trivalent iron; lack of sufficient material to permit direct determination of the alkalis, however, renders this analysis somewhat unsatisfactory. Doelter believed that the water of the analysis is unessential, and concluded that crocidolite might be a fibrous form of arfvedsonite.

Soon after this Renard and Klement (1884) made the first attempt to establish the chemical constitution of the Cape crocidolite. Their analysis (V) leads to the formula: $H_2O \cdot 2Na_2O \cdot 4FeO \cdot MgO \cdot 2Fe_2O_3 \cdot 14SiO_2 + H_2O$, with tolerable agreement between the found percentages of the oxides and those demanded by the formula. Finding that their analysis gave 15 basic molecules and 14 molecules of silica these authors concluded that one molecule of water was uncombined. As the serious error represented by the high summation might well be concentrated in one of the smaller constituents, the results of these authors cannot be regarded as conclusive. This appears to be the last chemical work to have been done on crocidolite from the Cape.

Shortly after the above work Chester and Cairns (1887) gave an account of crocidolite from Cumberland, Rhode Island. Duplicate analyses (VI, VII) result in another formula: $2H_2O \cdot Na_2O \cdot 3FeO \cdot Fe_2O_3 \cdot 9SiO_2$, in which magnesia is neglected as unessential and water is regarded as entirely basic. In spite of the imperfections of the previous analyses of the Cape material it is clear that the mineral from Rhode Island differs somewhat from the Cape crocidolite in that the iron is in a lower state of oxidation, the magnesia is vanishingly small, and water is notably higher.

For crocidolite the sixth edition of Dana's *System* adopts a simplified formula: $Na_2O \cdot 2FeO \cdot Fe_2O_3 \cdot 6SiO_2$, which is accepted by Iddings (1911) and by Larsen (1921); this formula omits both water and magnesia and does not agree well with available analytical data.

In a recent paper Gordon (1927) regards crocidolite as a fibrous form of riebeckite to which he attributes the ideal formula: $R_2O \cdot R_2O_3 \cdot 4SiO_2$, where R_2O is chiefly soda with some water, and R_2O_3 is mainly ferric oxide.

Previous chemical work has thus shown that crocidolite is a metasilicate of soda, ferrous oxide and ferric oxide, with some water and magnesia. In detail, however, there is lack of agreement in the available analyses and consequently in the derived molecular constitutions.

Apparently the first published optical data on the Cape crocidolite are contained in a note by Johnson (1910). Assuming that he was dealing with fibres extended parallel to *c* Johnsen observed deep-blue absorption $\parallel c$ and light gray-blue $\perp c$. From this he inferred that $Y=c$, that X and Z, and therefore the axial plane, are perpendicular to *c*, and that the mineral is optically positive. This author also gives $2V=56°$ to $90°$.

Gordon (1927) gives the following data for crocidolite from Orange River, South Africa: $\beta=1.70$; $\gamma-\alpha=0.005$; $X\wedge c$, low; X (near *c*), bluish green; Y (near *a*), bluish gray; Z ($=b$), bluish gray. This orientation disagrees with that of Johnsen.

The works of reference, including Rosenbusch-Mügge (1926), have all adopted for crocidolite the following data by Lacroix (1890) for material from Templeton, Canada: $\gamma-\alpha=0.025$; optically positive; $X\wedge c=18°$ to $20°$; $2E=95°$. No analysis of this material seems to be available, and it is very probable, as Gordon says, that Lacroix's material "is undoubtedly some other amphibole" (1927, p. 193).

Thus optically as well as chemically there is discordance in the published data of crocidolite, and therefore a full restudy of the type material from South Africa is desirable.

New Observations. A sample of the finest blue fibre, 13008, from Kliphuis in the Cape Belt, fairly representing the dominant material in the collection, was studied optically and chemically. Even the finest strands were readily separable into still finer fibres and therefore microscopic observations refer to bundles of fibres in which the optical units are oriented with their *c* axes only in common. The following were observed: color in ordinary light, lavender; absorption $\parallel c$ indigo, $\perp c$ (presumably the mean of the two specific absorption colors perpendicular to *c*), pale gray-blue; extinction sensibly parallel to *c*; refractive indices between 1.695 and 1.705 with double refraction less than 0.010[2]; elongation negative, and therefore $c=X$ or Y. The fibrous nature of the material coupled with its deep color and low birefringence made further exact observations impracticable. On many bundles of fibres an apparently good biaxial interference figure was obtained; but this figure was regarded as unreliable being no doubt due to the mineral acting uniaxially in bundles of fibres, and thus giving a flash figure in the plane of the principal axis.

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[2] These and subsequent refractive index measurements were made by the immersion method with a probable error not exceeding plus or minus 0.003.

With the expectation of obtaining fuller optical data, the rarer acicular phase, 13016 from Kliphuis, was studied. The thin section shows elongated tablets, needles and fibres of deep-blue amphibole forming a cross-fibre seam in ironstone of the usual appearance. Late ferruginous alteration films roughly follow basal planes and also planes making 30° with the trace of the perfect prismatic cleavage. A single basal section showed intersecting prismatic cleavages less clearly than is usual in amphiboles. The angle of intersection is 54°. Observations on many cleavage fragments of the tabular amphibole gave the following results: $\alpha=1.698$, $\beta=1.699$, $\gamma=1.706$; X=indigo, Y=yellow, Z=indigo; $X \wedge c=0°$, $Z=b$; whence the birefringence is 0.008, and the elongation is negative. Every attempt to obtain an optical figure failed owing to the strong absorption and weak birefringence of the mineral; and therefore the value of 2V, which should be small according to the indices, and the orientation could not be checked. Also the extreme closeness of α and β rendered the directions X and Y indistinguishable. The pleochroism scheme and the orientation given are the more probable of two possibilities; X and Y may, however, require to be interchanged.

The non-fibrous, incipient or potential crocidolite, 13023 from Kliphuis, agrees with the two specimens just described in every respect except in the size and shape of the optical units. The blue seam is composed of minute, pleochroic, somewhat rounded units arranged either at random or in a crudely stellate manner. Ferruginous films traverse the seam at right angles to its length imparting a transverse structure.

In Table IV the new optical observations on crocidolite have been entered together with other recent data of crocidolite and riebeckite from various localities. It will be seen that the optical constants of the two minerals are impressively concordant, and therefore, in view of their chemical similarity, there can be no doubt that crocidolite is a fibrous form of riebeckite. Considering the data of crocidolite alone it will be seen that $X \wedge c=0°$ in the examples from Kliphuis and Narsarsuk, and that therefore as far as the immersion method shows, crocidolite is orthorhombic. But until measurable crystals are found or synthetically prepared it is preferable to preserve crystallographic unity among the soda-amphiboles and retain crocidolite as a monoclinic mineral in which the extinction angle is zero.

TABLE IV. OPTICAL CONSTANTS OF CROCIDOLITE AND RIEBECKITE

Mineral and locality	α	β	γ	$\gamma-\alpha$	Pleochroism			Orientation	Ref.
					X	Y	Z		
Crocidolite, Kliphuis, S. Africa.	1.698	1.699	1.706	0.008	Indigo*	Yellow*	Indigo	$X^* \wedge c = 0°$ $Z = b$	New data
Crocidolite, Orange R., S. Africa	.....	1.70	.....	0.005	Bluish green	Bluish gray	Bluish gray	$X \wedge c$ low $Z = b$	Gordon, 1927, p. 204.
Crocidolite, Quincy, Mass.	.....	1.699	.....	0.005	Deep bluish green	Bluish yellow	Bluish gray	X near c $Z = b$	"
Crocidolite, Narsarsúk, Greenland.	.....	1.701	.....	0.005	Methyl blue	Straw yellow	Pale Medici blue	$X \wedge c = 0°$ $Z = b$	"
Riebeckite, Cumberland, R. I.	.....	1.695	.....	0.005	Deep bluish green	Yellow	Greenish gray	$X \wedge c = 5°$ $Z = b$	Gordon, 1927, p. 202.
Riebeckite, Quincy, Mass.	.....	1.701	.....	0.005	Bluish smoky green	Olive brownish yellow	Dark smoky green	$X \wedge c = 5°$ $Z = b$	"
Riebeckite, Narsarsuk, Greenland.	.....	1.701	.....	0.005	Grayish blue	Yellow	Dark gray	$X \wedge c = 5°$ $Z = b$	"

* With possible interchange of X and Y.

Chemical analyses of the three phases of crocidolite described gave the values in TABLE V.

TABLE V. NEW ANALYSES OF CROCIDOLITE FROM SOUTH AFRICA

	I	II	III
SiO_2	51.94	50.71	50.66
Al_2O_3	0.20	0.00	0.04
Fe_2O_3	18.64	20.45	22.64
FeO	19.39	17.41	17.05
MgO	1.37	2.28	1.99
CaO	0.19	0.15	0.01
Na_2O	6.07	5.75	5.15
K_2O	0.04	0.07	0.09
H_2O+	2.58	2.50	2.62
H_2O-	0.31	0.96	0.15
	100.73	100.28	100.40

I.—Fine, blue, fibrous crocidolite (13008) from Kliphuis, 8 miles N. of Prieska, Griqualand West. Analyst, H. E. Vassar.

II.—Incipient or potential crocidolite, slightly iron-stained (13023) from the same locality. Analyst, H. E. Vassar.

III.—Acicular crocidolite, slightly iron-stained (13016), from the same locality. Analyst, H. E. Vassar.

Clearly these three materials, whose optical characters so closely agree, have essentially the same chemical composition. The only noteworthy discordance appears in the values for ferric oxide; but the somewhat higher values for this constituent in II and III are at least partially accounted for by the ferruginous staining in those specimens.

In TABLE VI the same three analyses in the same order have been treated as follows: In each case moisture has been deducted and the remaining oxides have been calculated to 100 per cent. Then the molecular proportions obtained from these figures have been divided by integers chosen to produce approximately constant factors. With exception of the excess of ferric oxide which becomes increasingly larger from I to III, and the slight deficiency of soda in III, the factors show tolerable constancy. As analysis I represents material quite free from visible oxidation we may derive from it the following formula for crocidolite: $3H_2O \cdot 2Na_2O \cdot 6(Fe, Mg)O \cdot 2Fe_2O_3 \cdot 17SiO_2$, in which MgO is very subordinate to FeO, H_2O is wholly basic, Fe_2O_3 reacts with its full valency, and SiO_2 is present in sufficient amount to produce an accurately balanced metasilicate.

TABLE VI. MOLECULAR PROPORTIONS FROM THE ANALYSES IN TABLE V.

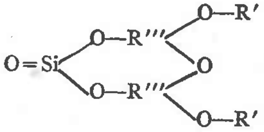
	I		II		III	
SiO_2	.862	=17(.051)	.851	=17(.050)	.842	=17(.050)
Al_2O_3	.002	=2(.059)	.000	=2(.064)	.000	=2(.070)
Fe_2O_3	.116		.129		.141	
FeO	.269	=6(.051)	.244	=6(.051)	.236	=6(.048)
MgO	.034		.057		.050	
CaO	.004		.003		.000	
Na_2O	.098	=2(.049)	.093	=2(.047)	.083	=2(.042)
K_2O	.000		.001		.001	
H_2O	.143	=3(.048)	.140	=3(.047)	.145	=3(.048)

TABLE VI shows, however, that the found proportions of Fe_2O_3 exceed that required by the formula by amounts which cannot be wholly related to impurity of material and analytical error. This anomaly has frequently been noticed in analyses of amphiboles carrying notable amounts of the sesquioxides; and it is recognized again in Gordon's recently proposed general expression for members of the arfvedsonite-riebeckite group (1927, p. 205), which may be written thus:

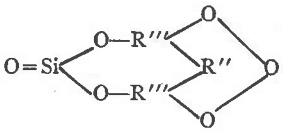
$$\begin{array}{ll} l & R_2O \cdot 3RO \cdot 4SiO_2 \\ m & R_2O \cdot R_2O_3 \cdot 4SiO_2 \\ n & R_2O_3. \end{array}$$

Some authors have attempted to obtain better equivalence between the bases and silica by assuming that H_2O is wholly or partially unconstitutional; but in view of the essential rôle played by the volatiles in the formation of amphibole, and the severe ignition required to liberate combined water, this assumption is unwarranted.

A better explanation is that of Penfield (1907) who concluded that the sesquioxides in amphiboles react with subnormal valency. From the fact that very close equivalence of bases and silica was displayed in a series of careful amphibole analyses when water was included with the bases and the sesquioxides were neglected, Penfield inferred that R_2O_3 combined with hydroxyl, fluorine, the alkalis, lime and magnesia, in that order of preference, to form radicles which require only one molecule of silica to satisfy them, thus:



and



But the application of this method of interpretation to the present analyses of crocidolite, and to a series of other amphibole analyses to be discussed later, results in an excess of silica. We must therefore conclude that the sesquioxides act partly with subnormal valency in the manner suggested by Penfield, and partly in the normal trivalent manner. Accordingly in TABLE VII the average values of the molecular proportions of the three new crocidolite analyses have been combined to form the following molecules:

$R_2O_3 \cdot RO \cdot SiO_2$ (Penfield's molecule)
$R_2O_3 \cdot RO \cdot 4SiO_2$ (Gordon's ideal riebeckite molecule)
and $RO \cdot SiO_2$ (general amphibole moelecule)

where RO embraces R″O and $R_2'O$. The distribution of R_2O_3 between the first and the second molecules is obtained by the simple equation:

$$T = s + 4(S - s) + R - S$$

where T = total silica, R = total bases including water but excluding the sesquioxides, S = total sesquioxides, and s = sesquioxides in Penfield's molecule.

TABLE VII. INTERPRETATION OF THE AVERAGE OF THE THREE NEW CROCIDOLITE ANALYSES

	Ratios	$R_2O_3 \cdot RO \cdot SiO_2$	$R_2O_3 \cdot RO \cdot 4SiO_2$	$RO \cdot SiO_2$	
SiO_2	.852	.024	.424		.404
Al_2O_3	.001				
Fe_2O_3	.129	.024	.106		
FeO	.250			.250	.404
MgO	.047			.047	
CaO	.002			.002	
Na_2O	.091			.091	
K_2O	.001			.001	
H_2O	.143	.024	.106	.013	

As H_2O fulfils the "RO"-requirements of the first and second terms, and as Al_2O_3, CaO and K_2O are negligibly small, we may write the constitution of crocidolite as follows:

$$\begin{aligned}&l\ Fe_2O_3 \cdot H_2O \cdot SiO_2\\&m\ Fe_2O_3 \cdot H_2O \cdot 4SiO_2\\&n\ (Fe, Mg, Na_2)O \cdot SiO_2\end{aligned}$$

which neglects the insignificant replacement of a small amount of Na_2 by H_2 in the third term.

In view of the smallness of the coefficient l this method of interpretation may be regarded as unjustified; but it will be shown presently that this term becomes relatively large when the same method is applied to the orthorhombic amphiboles.

4. AMOSITE

PREVIOUS WORK. The name *amosite* was proposed by Hall (1918 A, p. 8) for the long, ash-gray fibre which is abundantly developed in the Lydenburg and Pietersburg Belt in the Transvaal. The term is derived from the initial letters of "Asbestos Mines of South Africa." Hall described amosite as a white, pale-brown, silvery-gray, ash-gray, or very delicately greenish, monoclinic iron-amphibole, which may perhaps form a local variety of crocidolite without the characteristic blue color, or represent a fibrous phase of the cummingtonite—grünerite group of amphiboles. The extinction angle given is from zero to 20°, commonly between 10° and 17°. The following analyses are given by Hall (1918 A, p. 16, and 1918 B, Appendix):

These analyses were evidently made for commercial purposes and much of the material analyzed was evidently not fresh; they indicate that amosite is essentially a ferrous silicate with rather widely varying amounts of alumina, ferric oxide, magnesia, lime, soda and water.

Wherry (1921) examined a specimen of amosite and found that it showed within the limits of error the exact optical properties of ferroanthophyllite; and as Hall's analyses show that amosite is chemically close to grünerite and ferroanthophyllite Wherry concluded that amosite comprises these two species. The description of ferroanthophyllite with which Wherry compared amosite is one by Shannon (1921) of material from Idaho. This mineral has the optical and chemical properties listed under II in TABLES IX and X respectively.

TABLE VIII. PREVIOUS ANALYSES OF AMOSITE FROM THE TRANSVAAL

	I	II	III	IV	V	VI	VII
SiO_2......	49.72	53.34	50.24	49.10	36.20	49.48	47.68
Al_2O_3.....	5.72	9.35	.....	.....	.....	0.68	trace
Fe_2O_3.....	.....	.....	7.80	.....	12.08	8.16	4.84
FeO......	37.00	34.35	32.00	43.86	24.27	30.09	36.00
MgO.....	3.77	.74	3.96	6.14	8.50	6.77	6.20
CaO......	1.65	1.59	trace	0.46	5.56	0.88	trace
Na_2O.....	.....	.....	2.12	.....	0.15	0.20	0.28
H_2O+....	2.29	.....	3.00	.....	4.70	2.74	4.50
H_2O-....	.....	0.62	.....	.....	.....	.....	.....
CO_2......	.....	.....	.....	.....	8.40	0.56	0.21
	100.15	99.99	99.12	99.56	99.86	99.56	99.71

I, II.—Third-grade, brownish asbestos from near the surface, Penge. Analyst, Hahn.

III.—Best quality "white" asbestos, fourth level, B section, Penge. Analyst, C. Gardthausen.

IV.—Second quality asbestos, Streatham. Analyst, Hahn.

V, VI, VII.—Amosite, Penge. Analysts, Gulick, Henderson & Co.

NEW OBSERVATIONS. The collection contains several large specimens of typical amosite from Penge in the Lydenburg district of the Transvaal. One large mass, 13092, consists of curved, cohering fibres which maintain a length of 4 inches. The coherent mass is pale greenish-yellow in color and somewhat unctuous to the touch. Where the mass has frayed out the fibres are silver-gray and perfectly flexible and divisible. Optical study of small bundles of straight parallel fibres oriented at random with their *c*-axes in common gave the data listed under III in TABLE IX. Chemical analysis of the material yielded the values under III in TABLE X. In addition to the ash-gray fibre just described the collection contains specimens of greenish-gray fibre sufficiently distinct to warrant separate description. This material is represented by a few specimens from Middelwater 10 miles S. of Griquatown, one from Keikamspoort, and one from Kalkfontein in the Prieska district. In hand-specimens the fibre is greenish-gray sometimes stained with iron solutions. The seams are usually less than half an inch wide, and corrugated structure is not developed. In a few cases shearing of the enclosing walls has resulted in oblique orientation of the fibres with respect to the walls. This greenish fibre has the optical and chemical properties under IV in TABLES IX and X respectively.

TABLE IX. OPTICAL CONSTANTS OF AMOSITE AND OTHER ORTHORHOMBIC AMPHIBOLES

Mineral and Locality	α	β	γ	$\gamma-\alpha$	Pleochroism			Orientation	Ref.
					X	Y	Z		
I. Anthophyllite, Franklin, N. C.	1.6288	1.6301	1.6404	0.0116	....	......	......	$Y=b$ $Z=c$	Penfield, 1890, p. 396.
II. Ferroanthophyllite, Idaho	1.668	......	1.685	0.017	Pale brownish green	....	Deep brownish green	$Z=c$	Shannon, 1921, p. 399.
III. Amosite, Penge, Transvaal, 13092.	1.675*		1.702	0.027†	Pale greenish brown		Pale brownish green	$Z=c$	New data
IV. Amosite, Kalkfontein, Cape Province, 13067.	1.663*		1.680	0.017†	Grayish green		Grass green	$Z=c$	New data
V. Gedrite, Fiskernäs, Greenland.	1.623	1.636	1.644	0.021	Not appreciable			$Y=b$ $Z=c$	Ussing, 1889, p. 609.

* $\frac{\alpha+\beta}{2}$

† $\gamma-\frac{\alpha+\beta}{2}$

Considering firstly Table IX, it will be seen that there is a strong general similarity in the optical properties of anthophyllite, ferroanthophyllite, amosite and gedrite; and that therefore, as far as optics go, amosite belongs properly to the orthorhombic amphiboles. In each case crystallographic *c* is the direction of highest refraction, and where data are given, of strongest absorption. The refractive indices and birefringence of the members of the series vary somewhat evidently in sympathy with chemical composition. Ferroanthophyllite and amosite, which have high iron-contents with correspondingly low magnesia, have systematically higher indices than anthophyllite and gedrite in which iron is very subordinate. From the optical data alone the validity of amosite as a distinct species cannot be judged as even such distinct species as anthophyllite and gedrite would be hardly distinguishable in small fragments.

In Table X are listed the analyses of the same five amphiboles. It will be seen that alumina increases progressively from nearly zero in anthophyllite to nearly 22 per cent in gedrite, while silica decreases antipathetically. The divalent bases vary widely and they must clearly be regarded as isomorphous in their relations to the amphibole acid. Ferric oxide varies from zero to about 3½ per cent while water fluctuates between about 1 and 2 per cent. The alkalis are represented only by a small amount of soda in gedrite.

The general molecular relations of the sesquioxides in these analyses are the same as those found and discussed in connection with crocidolite; and therefore the same method of interpretation devised for corcidolite has been applied to the orthorhombic amphiboles (Table XI).

Table X. New Analyses of Amosite with other Orthorhombic Amphiboles

	I	II	III	IV	V
SiO_2	57.98	49.30	47.35	47.04	46.18
TiO_2	.....	.....	trace	trace	.....
Al_2O_3	0.63	1.30	4.20	7.02	21.78
Fe_2O_3	.....	2.15	3.34	2.43	0.44
FeO	10.39	30.50	36.60	26.10	2.77
MnO	0.31	3.48	0.28	0.15	.....
MgO	28.69	0.66	5.80	4.96	25.05
CaO	0.20	10.73	0.77	10.84	.....
Na_2O	.....	.....	trace	trace	2.30
K_2O	.....	.....	trace	trace	.....
H_2O+	1.67	2.13	1.25	1.05	1.37
H_2O-	0.12	0.18	0.35	0.45	.....
P_2O_5	.....	.....	0.04	trace	.....
S	.....	.....	0.05	0.05	.....
SO_4	.....	.....	0.00	0.00	.....
CO_2	.....	.....	trace	0.10	.....
	99.99	100.43	100.03	100.19	99.89

I. Anthophyllite, Franklin, N. C. Analyst, S. L. Penfield. Ref. Penfield, **1890,** p. 396.

II. Ferroanthophyllite, Tamarack-Custer Mine, near Gem, Coeur d'Alene district, Idaho. Analyst, E. V. Shannon. Ref. Shannon, **1921,** p. 399.

III. Amosite, Penge, Transvaal (13092). Analysts, W. H. and F. Herdsman (new analysis).

IV. Amosite, Kalkfontein, Cape Province (13067). Analysts, W. H. and F. Herdsman (new analysis).

V. Gedrite, Fiskernäs, Greenland. Analyst (?) N. V. Ussing. Ref. Ussing, **1889,** p. 609.

TABLE XI. INTERPRETATION OF ANALYSES IN TABLE X

Numbers corresponding to Table X		Ratios	$R_2O_3 \cdot RO \cdot SiO_2$	$R_2O_3 \cdot RO \cdot 4SiO_2$	$RO \cdot SiO_2$	
I	SiO_2	.966	.005	.004		.957
	Al_2O_3	.006	.005	.001		
	FeO	.144			.144	
	MnO	.004			.004	
	MgO	.717			.717	.956
	CaO	.004			.004	
	H_2O	.093	.005	.001	.087	
II	SiO_2	.822	.019	.028		.775
	Al_2O_3	.013	.019	.007		
	Fe_2O_3	.013				
	FeO	.424			.424	
	MnO	.049			.049	
	MgO	.017			.017	.774
	CaO	.192			.192	
	H_2O	.118	.019	.007	.092	
III	SiO_2	.789	.046	.064		.679
	Al_2O_3	.041	.046	.016		
	Fe_2O_3	.021				
	FeO	.508			.508	
	MnO	.004			.004	
	MgO	.145			.145	.678
	CaO	.014			.014	
	H_2O	.069	.046	.016	.007	
IV	SiO_2	.784	.070	.056		.658
	Al_2O_3	.069	.070	.014		
	Fe_2O_3	.015				
	FeO	.363			.363	
	MnO	.002			.002	.657
	MgO	.124			.124	
	CaO	.194	.012	.014	.168	
	H_2O	.058	.058			
V	SiO_2	.770	.217			.553
	Al_2O_3	.214	.217			
	Fe_2O_3	.003				
	FeO	.039		....	.039	.561
	MgO	.626	.104		.522	
	Na_2O	.037	.037			
	H_2O	.076	.076			

By allotting three molecules of SiO_2 to each molecule of R_2O_3 it will be seen that a deficit of silica would result, this deficit becoming progressively greater throughout the series, I to V. In the interpretation given, however, a balance between silica and the bases is maintained by introducing the Penfield molecule, $R_2O_3 \cdot RO \cdot SiO_2$ in appropriate amount. The fact that in gedrite (V) close equivalence is obtained with R_2O_3 combined wholly in the Penfield molecule supports the choice of this combination.

We thus see that the orthorhombic amphiboles, like crocidolite, are expressible as balanced metasilicates in the form:

$$\begin{array}{l} l\ R_2O_3 \cdot RO \cdot SiO_2 \\ m\ R_2O_3 \cdot RO \cdot 4SiO_2 \\ n\ RO \cdot SiO_2 \end{array}$$

in which RO again includes R_2O. In anthophyllite (I) l and m almost vanish, and as RO in the third term is mainly MgO, the accepted formula, $MgO \cdot SiO_2$, results. In gedrite (V) m vanishes and the formula, $l\ Al_2O_3 \cdot (H_2, Na_2, Mg)O \cdot SiO_2 : n\ (Mg, Fe)O \cdot SiO_2$, is obtained. In ferroanthophyllite (II) and amosite (III, IV) the terms l and m are both present in notable amounts, and ferric oxide becomes conspicuous in R_2O_3. It will also be seen that in II and III, H_2O is sufficient to satisfy the "RO" requirements of the first two terms; in IV, however, a small proportion of lime requires to be introduced.

Amosite evidently belongs to the orthorhombic amphiboles; but on account of the intermediate amount of sesquioxides carried by this mineral, and the fact that these constituents apparently link themselves partly in the subvalent gedrite manner and partly with full valency, amosite cannot be properly identified either with anthophyllite, ferroanthophyllite or gedrite. And therefore, if we are justified in retaining crocidolite, which differs from riebeckite only in its fibrous structure, then there are even better grounds for retaining amosite as a mineral species.

V. GENETIC DISCUSSION

1. The Origin of the Ironstones

An attempt to solve the problem of the origin of the asbestos deposits involves a consideration of several distinct groups of evidence; and therefore it seems desirable to discuss these groups in a selected order, progressively bringing the various conclusions reached to bear on the ensuing considerations. Previous explanations have usually emphasized chiefly one or another of the several aspects of the problem which seem to demand consideration; therefore, in preference to first reviewing these explanations, published opinions on the various points will be referred to in their appropriate connections.

In South Africa massive ironstone formations occur in the Swaziland System, in the Witwatersrand System, in the Transvaal System, and to a very limited extent in the Karoo (Maufe, 1920, pp. 20, 21). In other parts of the world, notably in the Lake Superior region, somewhat similar ironstone formations are known; these always occur in the oldest geological systems. It is now generally agreed that these ironstone formations are of aqueous origin, and furthermore that they originated, not as accumulations of detrital material, but as chemical precipitates. The complete absence of recognizable detrital grains in the many thin sections examined, and the uniquely simple chemical composition of the ironstones revealed by the new analyses both point to the same conclusion. It is true that a fine, compacted, argillaceous sediment is probably microscopically indistinguishable from an indurated chemical precipitate of the same composition; but from the fact that the ironstones contain only $1\frac{1}{2}$ per cent. of alumina we may conclude, not only that these rocks do not represent argillaceous sediments, but that the accumulation of silica and iron oxides, constituting together with water more than 97 per cent of the ironstones, took place outside the range of mechanical sedimentation and therefore remote from land. It might be thought that the ironstones represent ancient deep-sea deposits similar to the red clay now slowly accumulating in the deepest parts of the oceans; but red clay is composed essentially of finely divided, profoundly altered basic eruptive material including many vitreous and crystalline fragments and possessing a chemical composition much too complex to permit comparison with the ironstones. The ironstone formations of the Transvaal System carry occasional intercalations of detrital sediments; and therefore, while it is believed that the ironstones themselves are wholly of chemical origin, it is clear that occasionally the basin of accumulation became sufficiently shallow and restricted to permit mechanical sedimentation.

The origin of the ironstones of various parts of the Union has been briefly discussed by Rogers (1906, pp. 32–33), Maufe (1920, pp. 20–21), and Wagner (1921, p. 120). Emphasis is usually laid on the similarity of the South African ironstones and those of the Lake Superior region; and the explanations offered are clearly influenced by the conclusions reached by Van Hise and Leith in their exhaustive study of the genesis of the North American occurrences (1911, pp. 499–561). In briefest terms the hypothesis of Van Hise and Leith is as follows: soluble iron salts, supplied either directly by migrating solutions from contemporaneous basic eruptives, or produced by the action of sea-water or meteoric water on basaltic lavas either hot or cold, accumulated in the ocean. These salts were then precipitated in the ferrous condition mainly as carbonate (siderite) and as hydrous silicate (greenalite), some of which is still represented as siderite chert and greenalite rock, while some suffered further chemical changes.

While the South African ironstones are apparently to be explained as chemical deposits the direct application of the hypothesis of Van Hise and Leith is not feasible. Firstly, while the Lake Superior ironstones are directly associated with abundant contemporaneous basic eruptives often having the appearance of submarine extrusives, the South African ironstones, which rest on a formation of limestones and dolomites, carry only an intercalated series of volcanics lying above the main asbestos-bearing horizon. The several methods whereby iron salts are contributed to the sea-water on the Van Hise and Leith hypothesis are thus not directly applicable.

Again, descriptions of South African ironstones contain no compelling evidence of a previous ferrous condition of the iron minerals; and the material studied in the present paper shows no vestige of earlier siderite or greenalite. In the ferruginous cherts of the Lower Griquatown Series Rogers describes rhomboidal areas up to 1/50 of an inch long composed of chert, brown iron oxide and magnetite in various proportions (1906, pp. 32–33). The inference that these areas are replaced siderite is not beyond question. In the same rocks the present writer has observed polygonal microstructures some of which are rhomboidal in shape; with strong magnification and illumination, however, these structures prove to be due to minute, interlacing needles of iron ores crystallizing from the amorphous ferruginous chert. Also the rhomboidal shapes seen by Wagner in grains of iron minerals in the ironstones of the Rustenburg district (1921, p. 120) might be random sections of crystalline forms proper to the ores, and not relics of earlier carbonates. Greenalite has apparently never been observed in ironstones from South Africa. The view that these rocks are altered deposits of siderite and greenalite is thus apparently based more on analogy with the Lake Superior deposits than on convincing petrographic evidence. Without denying the possibility of complete obliteration of a previous carbonate condition, if a reasonably probable chemical process can be devised whereby deposits of ferric hydrate and silica could be formed, such a theory would accord more closely with the known petrographic facts.

And finally, Van Hise and Leith are not specific as to the nature of the acid radicle combined in the salts contributed to the sea. To be satisfying a theory involving the introduction of iron salts to the sea-water should specify the acid employed and give reasonable grounds for the choice.

Some assistance in removing these difficulties and thus arriving at a working hypothesis involving the only admissible kind of process, namely a chemical one acting remote from land, may perhaps be gained from a brief consideration of what may be a kindred problem, the origin of the vast body of chlorides in sea-water. In the main, marine chlorides may be regarded either as having condensed from a primitive atmosphere, or as having been "sweated out" of the body of the earth during the consolidation of the crust. Just as a quantitative consideration of the amount of water released during the consolidation of igneous rocks makes it perfectly permissible to relate at least a great bulk of the waters of the hydrosphere to a juvenile source, so a consideration of the amount of chlorine in igneous rocks and volcanic emanations forms the basis of a strong argument for the view that combined marine chlorine is juvenile in origin. Many modern volcanoes and fumaroles, especially the hottest ones as Suess has pointed out (1902, p. 520), emit abundant chlorine, hydrochloric acid and chlorides.[3] Becker has calculated that 1000 vents each 6½ centimeters in diameter continuously delivering hydrochloric acid vapor at 200° and 6.62 kilograms per square centimeter into atmosphere

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[3] Becker's statement, that the most probable origin of the chlorine of volcanoes and deep springs lies in the possible product of decomposition of lawrencite in deeply buried siderolites (1910, pp. 8, 9) seems more difficult to accept than the simple reasonable assumption that chlorine, like water-vapor, is more abundant in igneous magmas than in igneous rocks, and is therefore partially released during the consolidation of igneous rocks.

at 0° would suffice to saturate all river-borne sodium (1910, p. 8). Such a supply of chlorine would surely not be difficult to realize, and therefore, without delaying further with this question which is beside the main issue, we may adopt the already widely held view that marine fixed chlorine was emitted from the body of the earth, and conversely, that the amount of this chlorine gives a rough measure of the amount emitted by volcanoes and fumaroles both subaerial and submarine.

At ordinary temperatures and pressures hydrochloric acid has little action on most silicates; but at 400° and the corresponding pressure dilute hydrochloric acid will convert rock silicates completely into chlorides.[4] Submarine volcanoes certainly exist and therefore submarine fumarolic action undoubtedly also takes place. To be expelled submarine fumarole vapors must be at a higher pressure than that defined by the overlying column of water; and at some depth in the crust below the sea floor the vapors would probably be at temperatures of several hundred degrees. Water vapor charged with hydrochloric acid, commonly observed in the gases of fumaroles, would therefore cause extensive decomposition of the walls of the fissures traversed by submarine fumarolic and volcanic vapors. Chlorides of all the common bases, iron, alumina, lime, magnesia and the alkalis would thus be formed with concurrent liberation of silica, and the periodic nature characteristic of volcanic and fumarolic action would ensure the transference of these chlorides to the sea-water. On account of the readiness with which ferrous solutions peroxidize to the ferric condition in presence of oxygen, and the fact that sea-water is known to contain notable amounts of dissolved air even at great depths, the iron chlorides formed in the manner suggested would undoubtedly be rapidly converted mainly to ferric chloride.

If the emission of an alkaline reagent be now postulated the desired effect of selective precipitation of iron and alumina as hydrates would be effected; the sea-water would become essentially neutralized as it is now; lime and magnesia would remain in solution to be precipitated later most likely as carbonate and phosphate; and alkaline chlorides would persist in solution as at present. Ammoniacal vapors known to be emitted from some volcanoes and to react with hydrochloric acid vapor to produce clouds of am-

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[4] The success of the Jannasch method of decomposing rocks for analysis depends on this fact.

monium chloride, and soluble alkaline silicates formed in the manner proposed by Van Hise and Leith, suggest themselves as possible available alkaline reagents. In this way silica, ferric hydrate with some aluminum hydrate according to the amount taken into solution by the acidic vapors, would be precipitated almost free from other constituents. With subsequent upheaval of the basin of accumulation this heterogeneous precipitate would become largely dehydrated and indurated to give a rock corresponding substantially to a ferruginous chert.

A full discussion of the origin of the ironstones is outside the scope of the present paper; and therefore the many questions and difficulties attending the admittedly speculative hypothesis offered must be left undiscussed. In view of the relatively slight attention which the genetic problem of the South African ironstones has received even a sketch treatment may be of some value in possibly affording a clue to the true mechanism whereby rocks of such unique chemical and petrographic character may have been formed.

2. The Origin of the Constituents of the Asbestos Seam

The asbestos seams were manifestly formed after the deposition of the ferruginous cherts in which they occur; and thus the chemical components of crocidolite and amosite may be accounted for in one of the following three ways: (1) by deposition of entirely foreign material from travelling solutions; (2) by reaction of the ferruginous cherts with travelling solutions carrying some component part of crocidolite or amosite; or (3) by molecular reorganization *in situ* of pre-existing materials entirely without introduction of foreign matter.

The first of these modes of origin has apparently never been seriously advocated, although it is virtually implied by Taber's general theory of vein formation, to be considered later. In view of the strong general chemical similarity existing between the asbestos seams and the enclosing ironstones; the fact that occurrences of iron-asbestos are rigorously restricted to ferruginous sediments, just as serpentine asbestos occurs only in ultra-basic igneous rocks of similar composition; and the entire absence of transgressive relations between the asbestos seams and the bedding of the ironstones; a theory of origin involving the introduction of wholly foreign material either in open spaces or by injection along planes of weakness is in the highest degree improbable.

Considering crocidolite first, it will be recalled that this mineral consists essentially of silica, ferric oxide, ferrous oxide, soda and water in descending order of abundance, with magnesia in small amount and alumina, lime and potash in negligible proportions. The ironstones consist of silica, ferric oxide, ferrous oxide and water, with small amounts of alumina and magnesia, and negligible proportions of the other constituents, including soda. The main constituents, silica and iron oxides, are common to both, and the petrographic evidence favors the obvious conclusion that the silica and the iron oxides of the crocidolite seams represent components of the ironstones reorganized *in situ*. This is also the view advocated by Hall (1918 B, p. 125).

Magnesia in crocidolite is about four times as abundant as in the ironstones. Hall suggests that this constituent was derived from solutions ascending from the dolomite formation which underlies the ironstones (1918 B, p. 120); and this view is supported by the rather consistent restriction of crocidolite seams to the lower horizons of the ironstone formation. At the same time the postulate of rising solutions transgressing the bedding offers some difficulties; and since a simple concentration of the magnesia in belts four times as wide as the respective crocidolite seams would be adequate—and the ironstones in the neighborhood of the asbestos seams commonly exhibit a leached appearance—the writer is inclined to explain magnesia in crocidolite to local concentration, and to refer the greater abundance of crocidolite seams in the lower reaches of the ironstone formation to the higher temperatures which probably obtained at the lower horizons.

To explain the presence of about 6 per cent. of soda in the crocidolite seams is perhaps the most difficult part of the genetic problem. Throughout the investigation this question was constantly kept in mind, but no really positive evidence was obtained. Again there are three possibilities: soda may have been a foreign constituent introduced by travelling solutions; or the crocidolite may occupy the place of pre-existing soda-rich bands; or soda may have been uniformly distributed throughout the ironstones and subsequently concentrated in certain bands. The fact that the two ironstone analyses show that these rocks now carry only traces of alkalis is compatible with each hypothesis and therefore does not assist in a decision. In this connection, perhaps the most significant features of the crocidolite seams are their sharp demarcation as relatively thin planes of great lateral extension, and their constant concordant relation to the bedding of the ironstones. If soda were concentrated by a comprehensive leaching of the ironstones presupposed to have contained sufficient evenly distributed soda, it seems very unlikely that these features would be developed in the resulting crocidolite seams; and therefore we may regard this hypothesis as the least probable of the three. Hall inclines to the postulate of pre-existing soda-rich bands (1918 B, p. 120), and suggests that these may be related to deposition in brakish water. Du Toit adopts a similar view (1929, p. 107) and mentions submarine zeolite formation as a possible mechanism for effecting concentration of soda along certain bedding planes. As the ironstones were probably laid down mainly beyond the zone of mechanical sedimentation Hall's suggestion, implying crystallization and occlusion of soda salts in shallow water, does not seem to be supported; and similarly Du Toit's proposal is frankly hypothetical and lacks petrographic corroboration.

The view that soda was introduced by hydrothermal solutions derived from some igneous mass was proposed by Lambert in an unpublished study of the present material. While it is conceivable that injected solutions would invariably follow the bedding of the ironstones, late veinlets of quartz and calcite are frequently found transgressing, and it is probable that alkali-bearing solutions and the consequent crocidolite seams would do likewise if soda were introduced by hydrothermal solutions. Again, Hall (1918 B, p. 120) and Du Toit (1926, p. 107) agree that an adequate igneous source is not known in the Cape Province; and in any case, in the Transvaal where asbestos is developed definitely within the contact aureole of the Bushveldt Intrusion, alkali-free amosite of great fibre-length is developed just where we would expect an alkali-rich product on Lambert's hypothesis.

Thus each alternative is fraught with difficulties. On the whole the postulate of soda-rich bands seems to account best for the structural relations of the crocidolite seams, and while the mechanisms suggested by Hall and by Du Toit to explain such local concentration of soda along certain bedding planes do not appear very plausible, a wholly satisfactory alternative explanation does not suggest itself. During the accumulation of the igneous solutions believed to have reacted with precipitation of silica and ferric hydrate, sodium silicate solution may have occasionally been emitted in considerable excess and have become occluded in horizontal zones in the accumulating chemical sediment. With subsequent dehydration and regional metamorphism the soda in these zones would be concentrated and might enter into some combination with the other constituents to form interbedded soda-rich bands which subsequently developed into crocidolite seams. This possibility receives support from a laboratory experiment in which the supposed precipitation of ferric hydrate by sodium silicate was imitated, and abundant soda obtained in the precipitate. While admittedly speculative this suggestion is put forward *faut de mieux* in the hope of stimulating critical interest in the difficult problem.

With regard to water, the last constituent to be considered, the analyses show that even the rather strongly metamorphosed magnetite-quartzite still contains about 3 per cent of water, while the ferruginous cherts adjoining the crocidolite seams contain about 6 per cent of this constituent. Crocidolite itself holds around 3 per cent of water. As the ironstones have undoubtedly been losing water since their deposition as chemical sediments, we may conclude with safety that interstitial water was present in the ironstones in amply sufficient amount to account for the proportion of water now combined in crocidolite. We are thus lead to the conclusion that all the chemical components of crocidolite pre-existed in the ironstones *in situ*; in the case of soda, however, the evidence is not strong, and the view that soda is a foreign constituent cannot be definitely dismissed

In regard to amosite the situation is different. Typical ash-gray amosite from the Transvaal is essentially a ferrous silicate with notable amounts of sesquioxides, magnesia and lime, less water than crocidolite and only traces of alkalis. Hall clearly shows that the amosite occurrences lie in the contact aureole of the Bushveld Complex (1918 B, p. 121), and it is impossible to resist the conclusion that the chemical dissimilarity existing between amosite and the country rock and the exceptional fibre-length exhibited by amosite are due to the fact that asbestos formation in the Transvaal was controlled by hydrothermal solutions emanating from the igneous mass after intrusion.

3. THE CONDITIONS ATTENDING THE FORMATION OF AMPHIBOLE-ASBESTOS

In the preceding section it was concluded that all the constituents of the crocidolite seams were present *in situ* in the ironstones; this implies the conclusion that the crocidolite seams were formed by molecular reorganization without essential transfer of material, following a change of physical conditions and a consequent displacement of chemical stability. To discover approximately what these conditions probably were we must be guided by the known conditions attending successful laboratory syntheses of amphibole, and by some geological considerations.

The difficult synthesis of amphibole was first achieved by Chrustschoff (1891) who obtained measurable prismatic crystals of hornblende by preparing the appropriate constituents chemically in the form of an aqueous gel which was heated in special stout exhausted glass bulbs for three months at about 550°C. Similarly Allen, Wright and Clement (1906) obtained minute fibres of amphibole with chemically prepared charges and water contained in a platinum crucible placed in a steel bomb and heated at 375–475°C for three to six days. These experiments show that the presence of water vapor is essential for the formation of amphibole, and that charges of the appropriate materials will combine at moderate temperatures and consequent pressures acting through periods negligibly short compared with geological time. They also show, as would be expected, that with lower temperatures and short runs fibres are formed, and that with higher temperatures and longer runs well developed crystals are obtained.

It is hard to estimate the quantitative effect of the time factor on the temperature required to effect such chemical changes. Certain it is, however, that given almost indefinite time the temperature at which the amorphous components of amphibole will combine will be very much lower than that required in a laboratory synthesis occupying only a few days. As crocidolite rarely develops beyond the fibrous condition we may further conclude that the temperature which obtained in the ironstones when the reorganization to crocidolite took place was near the lower extreme of the stability range of that mineral. Therefore, in view of the complete absence of evidence of severe thermal or contact metamorphism in the ironstones of the Cape Province, the very extensive and uniform nature of the crocidolite development, and the considerations just given, it seems probable that the development of crocidolite was accompanied by a very moderate rise of temperature, such as would be produced by simple burial to moderate depths.

In addition to elevated temperatures, pressures above atmospheric are essential for the production of amphibole. Hornblende is perhaps the most familiar product of metamorphism induced by directed stress in rocks of basic composition; but such conditions would have converted the entire ironstone formation into amphibolite. In the present case we are clearly concerned not with directed stress, but only with uniform pressure resulting from the load of superincumbent strata and with the hydrostatic pressure necessary to inhibit the escape of water vapor at the prevailing temperature. Water vapor at a few hundred degrees centigrade is undoubtedly a very penetrating fluid and one might well question the retention of interstitial rock moisture at such temperatures, and therefore the formation of amphibole in the manner suggested. But colloidal materials have the property io retaining water at considerable temperatures at atmosphercf pressure, a fact that was brought out in the laboratory experiment mentioned in connection with the origin of the ironstones. The colloidal precipitate obtained, even after heating to 350°C at atmospheric pressure, yielded over 3 per cent of water on ignition. Many rocks and minerals exhibit the same property.

We thus arrive at the conception of the crocidolite-bearing ironstone formation being buried under younger sediments, experiencing a consequently moderate rise of temperature and pressure greatest at the base and decreasing progressively upwards, and suffering a "sweating" process which resulted in molecular reorganization just sufficient to permit the union of amorphous silica, iron oxides, soda, magnesia and water dominantly in the lower horizons along bedding planes inferred to have been initially rich in soda. These conditions were also sufficient to promote some conversion of chert to quartz and amorphous iron oxide to magnetite, and occasionally to permit the growth of crocidolite to extend beyond the fibrous stage to an acicular condition.

4. The Origin of Cross-Fibre Structure

The familiar cross-fibre structure of asbestos seams presents a problem which has attracted considerable attention and has given rise to a variety of explanations. Minerals which assume fibrous form are also commonly found in well-developed crystals; thus when the fibrous condition is developed the explanation lies not in inherent habit but in special conditions of growth. To enquire into these conditions in the case of amphibole-asbestos and to ascertain if possible the cause of the typical common orientation of the fibres normal to the surfaces bounding the asbestos seams is the object of this section.

The beginnings of crystallization in amorphous media are marked by the development of crystallites so minute that their reaction to polarized light is inappreciable. Thus in acid volcanic glasses we find globulites, margarites, trichites and various plumose, arborescent and fibrous bodies representing incipient crystallization which was checked by the chilling of the glass. Similarly in natural and artificial glasses the inherent tendency to crystallize slowly overcomes the great viscosity of glass in the cold and devitrification proceeds with the development of similar fibrous crystallites. In palagonite, which is ideally the hydrogel of sideromelane (Author, 1926, p. 74), fibrous crystallites readily develop; and in general, minerals which crystallize from hydrogels, such as chalcedony and kidney ore, fibrous structure is displayed.

In the ironstones the beginnings of crocidolite formation are seen in the blue, sensibly amorphous bands which Klaproth called *Blau-Eisenstein*, and are referred to by Hall as *potential crocidolite*; these bands have been shown to have the same chemical composition as crocidolite. In the sections studied, every stage was seen from these unorganized blue bands to seams composed of wholly crystallized material ranging from the finest hairs to stout needles; and the conclusion is inevitable that the fibrous seams developed from sensibly amorphous, blue bands of incipient crocidolite. The fact that the fibrous condition is the dominant one, the incipient and acicular phases being now only slightly represented, may reasonably be taken to show that when crocidolitization had in the main reached the fibrous stage the conditions which promoted this change were withdrawn, and further integration of fibres to form stout needles was largely inhibited. As the products of crocidolitization display the structural features peculiar to the products of crystallization in many known amorphous media containing the necessary components *in situ*, the hypothesis that crocidolitization proceeded by molecular organization in a hydrated amorphous aggregate containing the necessary constituents in place receives support.

To explain the persistent orientation of asbestos fibres normal to the planes of the seams two principles, in general, have been invoked: first, that provided a growing crystal have restricted contact with the saturated solution from which it is growing, by virtue of the linear force of crystallization this crystal will continue to grow where it is in contact with saturated solution even against strong mechanical resistance; and second, that when a growing crystal wholly in contact with saturated solution meets mechanical obstruction as a result of its growth, the pressure developed at the contact increases solubility and checks further growth at that point, and the crystal continues to grow in the direction of least resistance.

The first principle is at the root of Taber's general theory of vein formation, based on experimental work on crystallizing salts, applied to the case of serpentine asbestos, and extended to cover the case of other minerals including crocidolite (1916; 1917; 1918 A, B; 1919; 1924; 1926). Taber partly immersed porous porcelain cups in concentrated solutions of various salts. Fibrous crystals commenced to grow from the walls of the cups and occasionally within the walls; in the latter case the growing crystals produced rupture with formation of cross-fibre veins. Incorporating these results, Taber's hypothesis is briefly as follows: " . . . . that all cross-fibre veins are formed through a process of lateral secretion, the growing veins making room for themselves by pushing apart the inclosing walls; and that the fibrous structure is to be attributed largely to the physical conditions which have limited crystal growth to a single direction" (1917, p. 1985). On this hypothesis the solution from which the vein mineral is growing reaches the mineral only through the walls of the vein. Thus, in spite of the tendency for the pressure developed at the terminations of the growing fibres to inhibit further growth in the direction of the walls, as solution reaches the fibres only from this direction growth will continue with forcible displacement of the walls providing the concentration of the solution be sufficiently increased to keep pace with the increase of solubility produced by this pressure.

Taber's hypothesis as applied to crocidolite has many implications which are irreconcilable with known facts. If crocidolite seams were formed by the forcible displacement of their walls then we would expect to find close sympathy in the irregularities of the two walls of a seam, especially in narrow seams. But when crocidolite seams are not bounded by parallel planes they are typically defined by one plane surface and one corrugated surface, so that in sections transverse to the bedding the crocidolite appears in short, sometimes almost disconnected, pod-like bodies; and within the space of a hand-specimen the bedding planes on either side will be perfectly straight. Such a structure cannot be explained by displacement of the walls. Again, if Taber's mechanism results in cross-fibre structure, then crocidolite seams should invariably have possessed this structure from the first; but many seams are still in the incipient, non-fibrous, unoriented condition, and there are good reasons for believing that all the cross-fibre seams originated in this condition. Furthermore, the basic postulate of Taber's hypothesis, namely of solutions of crocidolite migrating transversely to the bedding is difficult to accept. As far as we know, amphiboles cannot be taken into solution except under fusion conditions, and it is quite certain that such conditions never obtained in the ironstones which still consist largely of uncombined silica and iron oxides, materials which flux at moderate fusion temperatures. And finally, granting transversely migrating solutions of crocidolite, there is no evident reason why deposition should always take place along planes parallel to the bedding. For these reasons Taber's theory of cross-fibre vein formation is believed to be inapplicable to the South African crocidolite.

Other explanations of the cross-fibre habit of asbestos are directed mainly towards providing a means whereby a relief of pressure can be attained transversely to the seams, thus inducing the mineral to grow in a cross-fibre manner according to the second principle stated above. Merrill suggests that shearing action may account for the cross-fibre habit of asbestos in many cases (1895, p. 289). Differential movement of the walls in the plane of a growing asbestos seam would certainly produce the desired relief of transverse pressure with increase of lateral pressure, and tend to produce an oblique structure. In the present collection, however, seams with obliquely oriented fibres are exceptional, and in these cases the skew orientation is probably the result of later shearing. In the case of the chrysotile-asbestos of Black Lake, Thetford area, Quebec, Graham believes that the thermal contraction of the peridotite batholith may have been greater than the expansion due to concurrent serpentinization, and that therefore fractures in the mass tended to widen and thus to encourage cross-fibre growth of chrysotile (1917, p. 195). But such a mechanism is manifestly inapplicable to the sedimentary ironstones.

Hall infers that the South African crocidolite and amosite was first deposited in the mass-fibre condition. With continued growth favorably placed fibres would tend to thrust the walls apart thus encouraging the remaining material to develop fibres transverse to the plane of the seam; in addition, lateral pressure due to mutual interference of growing crystals, unequal pressures arising from volume changes, and unequal solution supply are suggested as contributing to the final cross-fibre structure (1918 B, p. 123). Thus, while recognizing that the transverse orientation of the fibres in amphibole-asbestos seams is not a primary property of the seams, Hall's explanation appears to rely at once on the power of a crystal to grow against mechanical resistance, and on the tendency for crystals to grow in the direction of least obstruction.

The tendency for crystallizing bodies to develop structures normal to their bounding surfaces is a common one. In the case of crystallization from igneous fusion this tendency is illustrated by the familiar columnar structure developed normal to the cooling surfaces of intrusive rock-bodies, and by the orientation of the dendrites which develop in steel ingots normal to the chill-surfaces of the moulds. Similarly certain salts, such as common salt, copper sulphate and potash alum, commonly develop cross-fibre structure on crystallization from aqueous solution in natural veins. The satin-spar varieties of gypsum and calcite and the mineral celestite frequently develop the same feature. Certain hydrous silicates, such as prehnite, stilbite and pectolite, and other minerals which have crystallized from gels rather than from solution, such as goethite, serpentine and chalcedony, commonly develop fibrous or platy structure in which the long axes of the crystalline units lie normal to the bounding surfaces of the mineral body. The perpendicular relation between fibrous structure and the bounding surfaces of mineral bodies possessing this structure is thus too consistent to be insignificant, and therefore we can hardly escape the conclusion that the bounding surfaces in some way exert a control over the orientation of the fibres.

In the case of minerals which crystallize from normal or colloidal solutions, crystallization is accompanied by loss of water. If this should take place in a totally enclosed cavity, or in an extensive vein completely filled with the solution or gel from which precipitation is taking place, the escape of water necessary to produce saturation and precipitation must ultimately take place through the walls of the cavity or vein. In this way the bounding surfaces of the mineral body become "drying-surfaces," strictly analogous to cooling-surfaces in their effect on precipitation and orientation of structure.

In the analyzed examples the ferruginous cherts in the neighborhood of crocidolite seams contain a total of 5.90 per cent of water; incipient crocidolite, inferred to be the earliest product of crocidolitization contains 3.46 per cent of water; the fine cross-fibre crocidolite believed to have resulted from further organization of the incipient material, carries 2.89 per cent of water; while the stout acicular material, representing further crystalline integration in fibrous seams, yields 2.77 per cent. of water. Crocidolitization is thus accompanied by a progressive loss of water, which must have escaped through the walls of the seams. The change from the incipient to the fibrous condition would thus take place first at the contacts of the seams with their walls. Just as crystals of ice grow out perpendicularly to the walls of a tank of water from which heat is being withdrawn, the first thin film of crocidolite changing from the incipient to the fibrous condition would arrange itself with its fibres normal to the controlling wall-surfaces. Where possible, crystalline accretion takes place in optical continuity with existing crystals of the same material; and therefore the lead set by the first thin layers of perpendicularly oriented fibres would determine the orientation of the remainder of the seam.

To conclude, although the ultimate nature of the force or reaction of forces, by virtue of which cooling- or drying-surfaces of a mineral body control the orientation of fibres developing at such surfaces, has not been found, the existence of this control cannot be gainsaid. On the theory of origin of crocidolite developed, the orientation of the fibres normal to the walls of the seams is believed to be an effect of this proved, although not fully understood, control.

VI. SUMMARY OF OBSERVATIONS AND CONCLUSIONS

1. Mineralogical

(a) The South African asbestos-bearing ironstones range from cryptocrystalline ferruginous cherts to fine-grained magnetite-quartzites in which detrital grains cannot be detected and crystalline structure appears to be secondary.

(b) Two new analyses show that the ironstones consist of silica, iron oxide largely or wholly peroxidized, and water, with less than three per cent. of other constituents.

(c) The dominant asbestos variety is blue crocidolite occurring chiefly in thin, extensive, cross-fibre seams conforming strictly with the bedding of the ironstones. To a subordinate extent crocidolite occurs also in a non-fibrous, "incipient" condition, and in seams of stout needles—the "acicular" condition.

(d) New analyses of the three phases of crocidolite conform tolerably with the metasilicate: $3H_2O \cdot 2Na_2O \cdot 6(Fe,Mg)O \cdot 2Fe_2O_3 \cdot 17SiO_2$, in which H_2O is wholly basic. To maintain a better balance between silica and the bases in these analyses, and in other analyses of amphiboles carrying notable proportions of sesquioxides, an interpretation in terms of the three molecules: $R_2O_3 \cdot RO \cdot SiO_2 \cdot R_2O_3 \cdot RO \cdot 4SiO_2$; and $RO \cdot SiO_2$ is advocated.

(e) The following new optical data were obtained for crocidolite: $\alpha = 1.698$; $\beta = 1.699$; $\gamma = 1.706$; X = indigo; Y = yellow; Z = indigo; $X \wedge c = 0°$; $Z = b$; X and Y may possibly be interchanged. Although sensibly orthorhombic crocidolite is regarded as a fibrous form of riebeckite and retained as a monoclinic amphibole in which the extinction angle is zero.

(f) The long-fibred, ash-gray asbestos, amosite, typically developed in ironstones within the contact aureole of the Bushveld Intrusion, proves to be an orthorhombic amphibole with ferrous oxide as the dominant base. Carrying sesquioxides intermediate in amount between the ideally sesquioxide-free anthophyllites and the highly aluminous gedrite, amosite is sustained as a mineral species. The composition of amosite is expressed in the same general manner devised for crocidolite (d). A greenish, short-fibred form of amosite carries about 11 per cent of lime.

(g) The following new optical data were obtained for typical ash-gray amosite: mean of α and $\beta = 1.675$; $\gamma = 1.702$; mean of X and Y, pale greenish brown; Z, pale brownish green; $Z = c$. Greenish amosite gave: mean of α and $\beta = 1.663$; $\gamma = 1.680$; mean of X and Y, grayish green; Z, grass green; $Z = c$.

2. Genetic

(a) On the grounds of typical non-detrital character and uniquely simple chemical composition, the ironstones are regarded as having originated as chemical precipitates deposited in an extensive marine basin. Occasional intercalations of detrital sediments are related to oscillations of the floor of this basin, varying its extent and occasionally bringing it within the range of mechanical sedimentation.

(b) It is shown that certain essential differences of constitution and geological relationship exist between the ironstones of South Africa and those of the Lake Superior region; and that therefore the hypothesis of Van Hise and Leith to explain the origin of the North American occurrences is not directly applicable to the South African problem.

(c) The view that marine fixed chlorine originated in igneous emanations is briefly advocated and adopted. From analogy it is argued that the action of hot, submarine fumaroles carrying hydrochloric acid would result, in addition to alkali chlorides, in the contribution of ferric chloride and gelatinous silica to the sea-water. Ammoniacal vapors and soluble alkali silicates are suggested as possible natural reagents to precipitate iron as ferric hydrate. On dehydration and induration the heterogeneous precipitate of silica and ferric hydrate would be converted into a rock substantially similar to a ferruginous chert.

(d) It is shown that, with exception of soda in the crocidolite belts, all the chemical constituents of crocidolite are present in adequate proportions in the ironstones. Of the alternate views: that crocidolitization was induced by soda-bearing solutions emanating from some postulated igneous source; or that crocidolitization took place along bedding planes inferred to have been initially rich in soda; the latter is adopted. The chief grounds for this decision are: that in the Transvaal, where asbestos formation was clearly induced by hydrothermal solutions from the Bushveld Intrusion, an alkali-free asbestos, amosite, is developed; that over the immense lateral extent of the crocidolite belts there is apparently little variation in the degree of crocidolitization; and that crocidolite seams unfailingly conform to the bedding of the ironstones while late veinlets of quartz and calcite frequently transgress.

(e) Crocidolitization is thus conceived as a mild, static, non-additive, metamorphic process resulting in the chemical union, along soda-rich bedding planes, of the necessary constituents already *in situ*. The process is described as a "sweating" action, facilitated by interstitial rock moisture, and induced by a moderate rise of temperature and pressure such as would result from simple burial of the ironstones to moderate depths.

(f) The unorganized, "incipient" condition, the typical fibrous condition, and the acicular condition, are regarded as progressive stages in the crystalline integration of crocidolitized bands. The transverse orientation of the fibres is therefore believed to have developed after crocidolitization was virtually completed.

(g) Taber's general theory of cross-fibre vein formation, involving deposition through the walls of the vein from solutions in the wall-rock, and forcible displacement of the walls by growing fibres, is shown to be inapplicable to the South African asbestos.

(h) The cross-fibre structure of the asbestos seams is related to the little-understood but undeniable control which bounding surfaces commonly exert on the orientation of the structure of fibrous minerals crystallizing from solutions or gels.

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VIII. EXPLANATION OF PLATES

Plate I

Fig. 1. Asbestos-bearing ironstones at Kliphuis, 8 miles north of Prieska, Cape Province. The dumps of the Kliphuis Mine are seen in the middle of the picture *Photo. by Charles Palache.*

Fig. 2. A closer view of the asbestos-bearing ironstones at Kliphuis, 8 miles north of Prieska, Cape Province. *Photo. by Charles Palache.*

Plate II

Fig. 1. Banded ironstone (13000) from Prieska Kopje. This rock, which consists essentially of finely granular quartz and magnetite, is a mildly metamorphosed facies of the normal, cryptocrystalline, ferruginous chert. Comparable with analysis I, Table II. Ordinary light; 20 diameters. *This and subsequent photomicrographs by the author.*

Fig. 2. Incipient crocidolite in ferruginous chert (13023), from Kliphuis. The dark areas are brown, cryptocrystalline ironstone, while the light areas are composed of minute units of blue crocidolite. These are unoriented, and therefore do not give the strong simultaneous pleochroism of similarly oriented fibres. Analysis II, Table V. Ordinary light; 20 diameters.

Plate III

Fig. 1. Crocidolite seam in bleached ironstone (13046), from Keikamspoort. The formation of crocidolite and magnetite in wavy bands has been accompanied by some extraction of iron from the enclosing chert. The magnetite is regarded not as representing pre-existing bands of ore displaced by the growing crocidolite, but as a contemporaneous product. Two ironstone "cones" are seen projecting into the asbestos seam. Ordinary light; 20 diameters.

Fig. 2. Seam of acicular crocidolite (13047), from Keikamspoort. This is the material from which the fullest optical data were obtained. Comparable with analysis III, Table V. Ordinary light; 20 diameters.

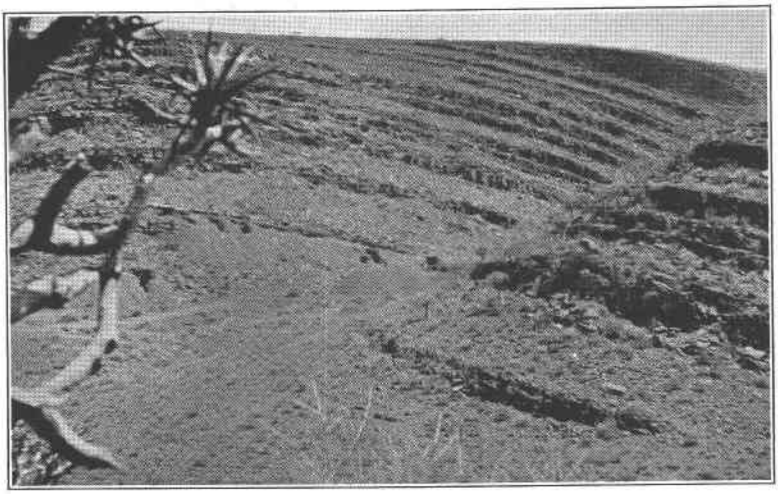

FIG. 1

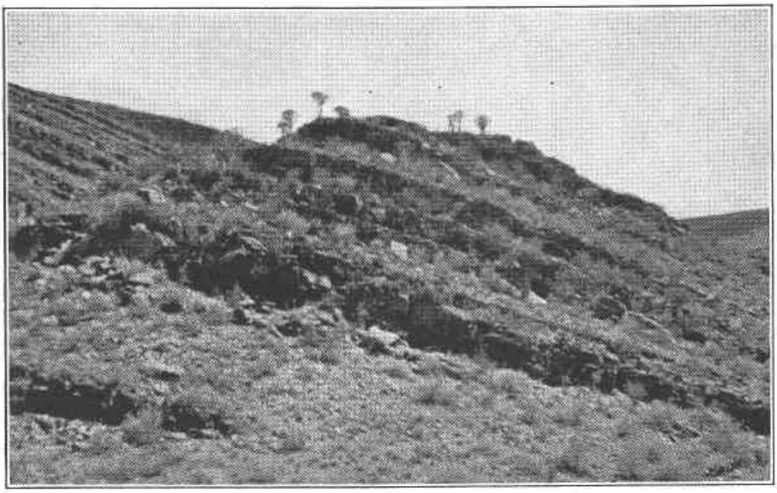

FIG. 2

PLATE I

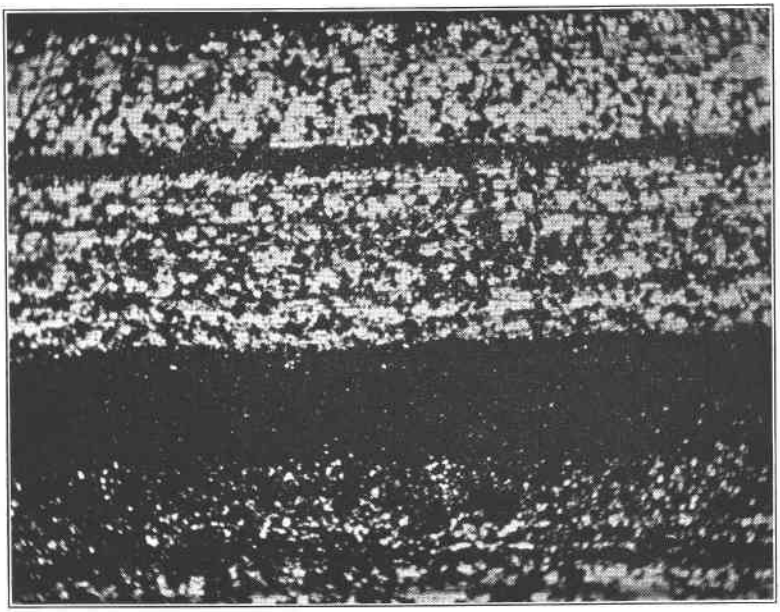

FIG. 1

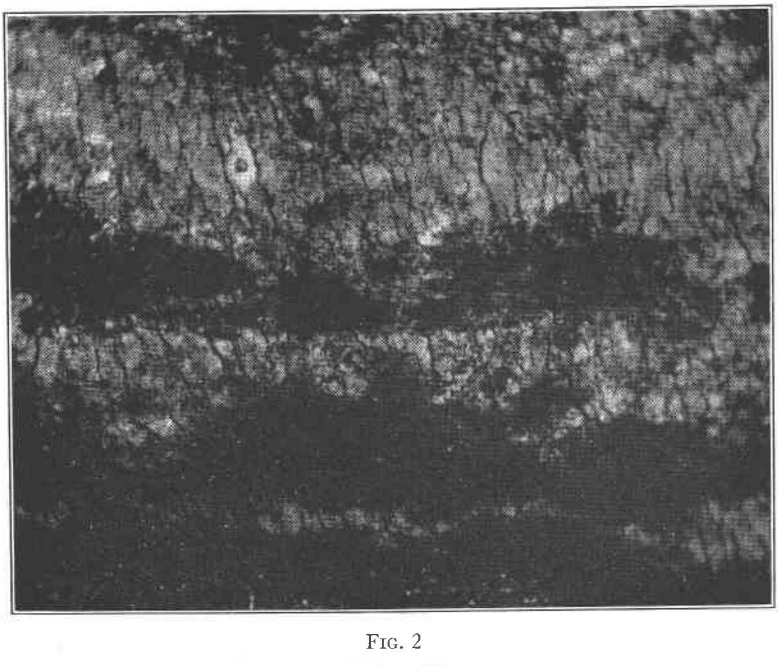

FIG. 2

PLATE II

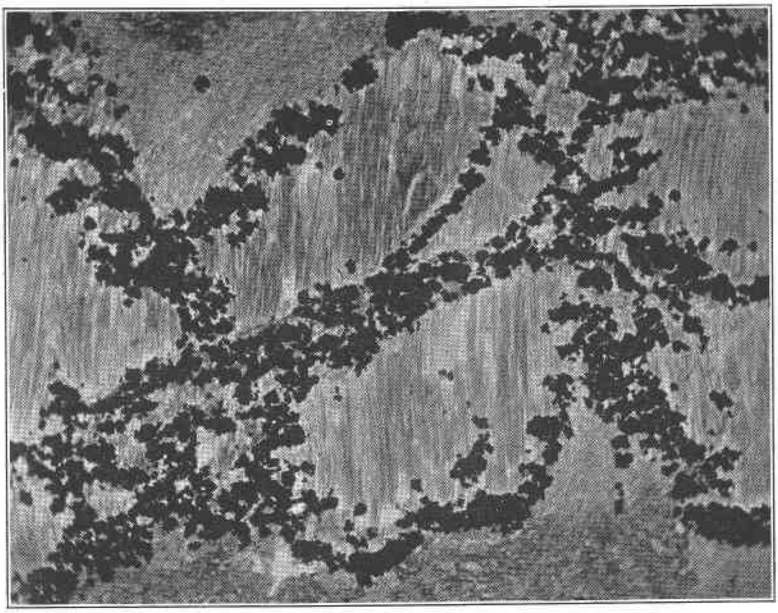

Fig. 1

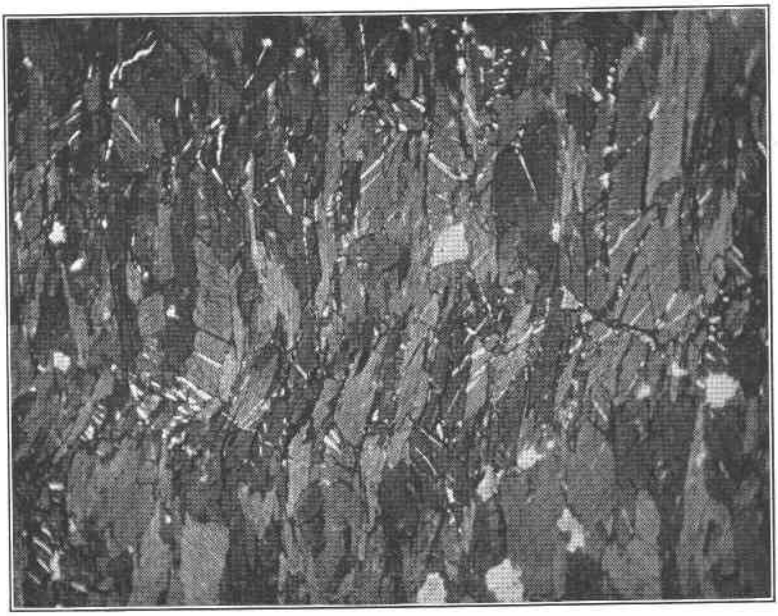

Fig. 2

Plate III