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PARAGENETIC CLASSIFICATION OF THE MINERALS OF FRANKLIN, NEW JERSEY

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SUMMARY

A list is given of 137 species of minerals which are found in the region near Franklin, New Jersey. It is shown that these may be classified genetically into five groups of varying importance. Of the whole number of species, 111 are found in the zinc ore-bodies and 98 in these only; 13 are found in granite pegmatites; 18 in iron ores of pegmatic origin; 26 in the Pre-cambrian limestone and 5 in the Paleozoic limestone. These five paragenetic groups are described, those of less importance first and then the main group of the zinc-ore minerals. A paragenetic table for this group shows four main subdivisions viz:

1. Primary Ores: 2. Pegmatite Contact Minerals, (a) Skarns and Recrystallization Products; (b) Pneumatolytic Products: 3. Hydrothermal Vein Minerals: 4. Surface Oxidation Products.

Each of these groups is described with examples of characteristic mineral associations.

The origin of the zinc ores is discussed. The author's theory is that metasomatic deposits of hydrated oxides and silicates of iron, manganese and zinc were formed by replacement in the white limestone and that these ore-bodies were changed to their present mineral composition during the Pre-cambrian regional metamorphism simultaneously with the recrystallization of the enclosing limestone. Subsequent intrusions of pegmatites produced recrystallization of the primary minerals near contacts, and formed skarns by interaction of ores and magmatic materials. Pneumatolytic products of the pegmatite magma also reacted with the primary ores to produce numerous vein minerals and as the temperature fell hydrothermal veins of great variety were formed in the ore-body. These products of pegmatite intrusion are extremely diverse mineralogically but of minor importance compared to the great mass of the primary franklinite-willemite-calcite-ores.

The zinc mines of Franklin are located in the New Jersey Highlands, about fifty miles northwest of New York City. The region is readily accessible by three lines of railway and by excellent motor roads. There are two similar ore deposits, one on Mine Hill at Franklin (formerly known as Franklin Furnace), and the second about three miles southwest of Franklin, on Sterling Hill near the town of Ogdensburg.

The geological relations of the Franklin ore deposits have been described by A. C. Spencer in the Franklin Furnace Folio, No. 161, of the Geologic Atlas of the United States, published in 1908.

The characteristic rocks of the region are Pre-cambrian, probably Grenville in age, including limestone and gneisses of both sedimentary and granitic origin. With these are minor masses of granite pegmatite and a few basic dikes. Superposed upon this older series are stratified formations ranging in age from Cambrian (Hardyston quartzite) to Devonian (Kittatinny limestone) which are folded, faulted down into the Pre-cambrian and cut by dikes of probable Triassic age. Glacial deposits of various kinds mask the bed-rock geology of considerable areas.

In the Folio there may be found full details of the structure and composition of the ores and enclosing rocks, with maps and sections showing the distribution and form of the formations and ore deposits as known in 1908. Little has been published since regarding the geology and no detailed description has been given of the extensive mining developments of the last twenty years. But reference will be made to two papers by Ries and Bowen, and by Spurr and Lewis which contain important new facts. Their titles will be found in the references at the end of the paper.

The two main ore deposits are essentially alike in form and composition. Both are warped, tabular bodies with hookshaped outcrops. Both are wholly enclosed in the white limestone and their folds pitch to the northeast in sympathy with the general gneissic structure of the Highland region. In both the principal mineral constituents are four in number, franklinite, willemite, zincite and calcite; the first three being the ores of the metals zinc, manganese and iron for which the deposits are valuable, the fourth the sole important gangue.

Normally these minerals are intimately intermixed in granular form; the grains of the ore minerals are in general noticeably rounded and the interlocking calcite grains form a paste or matrix to the whole mass. Generally also a marked banding is visible in the mass of the ore, due to the greater or less concentration of one or more of the ore minerals in adjacent layers, parallel roughly to the walls of the deposit.

The mineralogical and chemical character of the average ore, established by long continued mill and assay tests, may be approximately stated in the following figures.

MINERALOGICAL COMPOSITION OF FRANKLIN ORE*		CHEMICAL COMPOSITION OF FRANKLIN ORE	
	Percentages		Percentages
Franklinite	43	ZnO	31
Zincite	1	FeO	25
Willemite	26	MnO	10
Other Silicates (garnet, rhodonite, etc.)	5	SiO ₂	9
Calcite	25	CaCO ₃	25

In contrast to the very simple mineral composition of the ore bodies as a whole stands the complexity of the following list of the minerals found at Franklin, shown in Table I. The chief purpose of this paper is to attempt to analyze this list so as to show the various genetic assemblages of which it is composed.

TABLE I
LIST OF MINERALS OF THE FRANKLIN REGION.

The significance of the letters following each name is as follows: A, Zinc Ores; B, Pegmatite; C, Iron Ores; D, White Limestone; E, Paleozoic Limestone.

Actinolite	A	Bornite	A	Cuspidine	A
Albite	A, E	Bustamite	A	Datolite	A
Allacite	A	Cahnite	A	Desaulesite	A
Allanite	B, C	Calamine	A	Descloizite	A
Anglesite	A	Calcite	A, D, E	Diopside	C, D
Anhydrite	A	Calcium-larsenite	A	Dolomite	A, D
Anorthite	D	Celestite	A	Edenite	D
Apatite	A, B, C, D	Cerussite	A	Epidote	B, C
Apophyllite	A	Chalcocite	A	Epistilbite	A
Aragonite	A	Chalcophanite	A	Fluorite	A, D, E
Arseniosiderite	A	Chalcopyrite	A	Franklinite	A
Arsenopyrite	C, D	Chloanthite	A	Friedelite	A
Aurichalcite	A	Chlorophoenicite	A	Gageite	A
Axinite		Chlorite	A	Gahnite	A
Ferroaxinite	C	Chondrodite	D	Galena	A, B, E
Manganaxinite	A	Clinohedrite	A	Ganophyllite	A
Azurite	A	Clinozoisite	A	Garnet	A, B, C
Barite	A	Copper	A	Glaucochroite	A
Barysilite	A	Corundum	D	Goethite	A
Bementite	A	Crocidolite	A	Graphite	D
Biotite	C	Cuprite	A	Greenockite	A

* The figures of the first column were kindly supplied by the New Jersey Zinc Company, with permission to publish them. The chemical composition was calculated from them and is not exact since much of the iron and some of the manganese are in the sesquioxide state.

Gypsum	A	Marcasite	A	Schefferite	A
Hancockite	A	Margarosanite	A	Serpentine	A
Hardystonite	A	Mcgovernite	A	Siderite	A
Hedyphane	A	Microcline	B, C	Silver	A
Hematite	A, D	Millerite	A	Smithsonite	A
Hetaerolite	A	Molybdenite	C, D	Sphalerite	A, B, E
Heulandite	A	Muscovite	B	Spinel	C, D
Hodgkinsonite	A	Nasonite	A	Stilbite	A
Holdenite	A	Neotocite	A	Sussexite	A
Hornblende	A	Niccolite	A	Svabite	A
Hyalophane	A	Norbergite	D	Talc	A
Hydrohetaerolite	A	Pectolite	A	Tennantite	A
Hydrozincite	A	Phlogopite	C, D	Tephroite	A
Ilmenite	D	Prehnite	A	Thomsonite	A
Jeffersonite	A	Psilomelane	A	Thorite	B
Larsenite	A	Pyrite	A, C, D	Titanite	B, C, D
Lead	A	Pyrochroite	A	Tourmaline	D
Leucaugite	D	Pyrrhotite	D	Tremolite	A, D
Leucophoenicite	A	Quartz	A, B, D	Vesuvianite	
Limonite	A	Rhodochrosite	A	var. Cyprine	A
Löllingite	A	Rhodonite	A	Willemite	A
Magnetite	A, B, C, D	Roebingite	A	Zincite	A
Malachite	A	Roeppeite	A	Zinc-schefferite	A
Manganite	A	Rutile	C, D	Zircon	B, C
Manganophyllite	A	Scapolite	C, D	Zoisite	B
Manganosite	A	Schallerite	A		

Of the more than one hundred and thirty minerals composing this list, slightly more than one hundred are found in the zinc-ore deposits and nearly one hundred are found there only. In order to eliminate the groups of less importance and concentrate the discussion on the main issue, the associated mineral deposits of the region will be taken up first.

PEGMATITE INTRUSIONS

Granite pegmatite forms an important part of the Pre-cambrian complex, appearing both in extensive mapable areas and in dikes of moderate and small size. It is later than the gneiss and limestone, both of which it cuts; and some at least of the pegmatite is later than the zinc deposits. It is probable that the pegmatites continued to be intruded through a long period of time. Spurr and Lewis (2) have pointed out that in various places in the limestone, pegmatite dikes have been drawn out into lenses or even broken into isolated blocks; and that these blocks have reacted on their

whole periphery with the surrounding limestone. It seems improbable that a degree of movement sufficient to dissect these dikes so effectively should not also have dislocated the ore-bodies which were close at hand but now show unbroken continuity. It seems more reasonable to suppose that the ore was introduced after the first pegmatite intrusions and their deformation. The later pegmatites cut the ore deposits and do not show extensive deformation.

The composition of the pegmatite is granitic, with relatively little quartz. It consists essentially of microcline, oligoclase and quartz with occasional accessory minerals including apatite, muscovite, titanite, epidote, allanite and much more rarely thorite and zircon. Magnetite is rarely wholly absent and may be dominant as described under the next heading. Galena and sphalerite are often found in minute grains in the pegmatite and are believed to be original constituents. Zoisite occurs as an alteration of microcline. At the contacts of pegmatite with both the limestone and the zinc ore-bodies groups of reaction and pneumatolytic minerals are generally developed which will be described under later headings.

MAGNETITE DEPOSITS

Magnetite in mineable bodies is found in various parts of the Franklin region. The magnetite ores occur in both limestone and gneiss and are so intimately associated with pegmatite that there can be little doubt of their genetic relation. It is noteworthy that zinc and manganese compounds are lacking in these iron ores although minute traces of both metals have been detected in the magnetite. The minerals composing the iron ores, most of them except magnetite present in small amounts or very locally developed, include magnetite, microcline, diopside, epidote, allanite, biotite, phlogopite, scapolite, iron-axinite, iron-garnet iron-spinel, apatite, pyrite, arsenopyrite, molybdenite, rutile, titanite and zircon. This association of minerals reflects the relationship to pegmatite shown in the field by the iron ores.

THE FRANKLIN LIMESTONE

The limestone is a coarsely crystalline rock, known commonly as the white limestone from its typical color. It varies in composition from a practically pure calcium carbonate to a magnesian carbonate with almost the proportions of dolomite, the variation

being very irregular and not affecting its appearance or degree of crystallinity. Near the ore deposits the limestone becomes manganesian and weathers black. This limestone has been largely quarried as a flux both at Franklin and Sterling Hill and to the north at Rudeville so that it is well exposed and has been a fruitful collecting ground for mineral seekers. It is characterized by a group of minerals, all devoid of both zinc and manganese, which are unknown to, or extremely rare in, the zinc deposits. Sometimes these minerals are in close proximity to pegmatite bodies or more basic dikes which probably caused their formation by interaction; in a larger number of occurrences, however, the minerals are quite isolated in the limestone and either represent products of its recrystallization during metamorphism, or the presence of new elements introduced by the intrusives which have migrated far from their source.

The minerals found in the limestone at pegmatite contacts include amphiboles, chiefly tremolite and edenite; pyroxenes, especially diopside and leucaugite or aluminous pyroxene; scapolite; green and brown, magnesian tourmaline; chondrodite and norbergite, intergrown or separate. The writer has never seen garnet in the limestone away from the zinc ores although Spurr and Lewis (2) describe it from the wall of the ore body. It may be noted that except for pyroxene all the minerals of this group contain some "mineralizer" such as hydroxyl, chlorine, boron or fluorine, a condition which hardly agrees with the statement of Spurr and Lewis that these minerals are due to simple heat reactions without the presence of gas.

The minerals found in the limestone in isolated crystals or grains include all the foregoing and in addition graphite, molybdenite; chalcopyrite; pyrite; pyrrhotite; arsenopyrite; fluorite; quartz; corundum; hematite; ilmenite; magnetite; spinel; rutile; anorthite; phlogopite; titanite; and apatite.

This group of limestone minerals is typical for such highly metamorphosed limestones; it could be duplicated with very minor changes for the well known mineral occurrences of Orange County, N. Y., which are in the same band of Franklin limestone a score of miles to the north; and for many other limestones. It clearly owes nothing in its formation to the agencies which produced the ore bodies.

PALEOZOIC LIMESTONES

The Paleozoic sediments have not been notably metamorphosed or mineralized. They have, however, been intruded by dikes of camptonite and nephelite syenite; and have been profoundly faulted, both events probably to be assigned to Triassic time.

Spurr and Lewis (2) record "irregular subsequent impregnations of fluorite, arsenopyrite, pyrrhotite, sphalerite, galena, and many other minerals" associated with such a basic dike in limestone. In the limestone in a number of places are seen irregular cavities on whose walls are crystals of fluorite, quartz, calcite, albite and sphalerite.

These occurrences are of minor importance in the mineralogy of the region but are of interest as showing the presence of sulphide-bearing solutions during the post-paleozoic deformation. It is quite possible that to such solutions are due the small and infrequent veins of carbonates, quartz, pyrite and sphalerite which are found cutting the ore deposits and which will be described on a later page.

THE ZINC ORES

There remain for consideration the minerals found in the zinc deposits, by far the most important as they are by far the most numerous minerals of the whole list. The classification of these minerals into genetic groups here offered is of course hypothetical but seems to simplify the description. It should be stated that most of the conclusions here presented are based primarily on the study of hand specimens. No detailed examination of the ores in place has been made by the writer, nor so far as he is aware, by any geologist or mineralogist among the hundreds who have visited or written about these deposits.

The minerals will be grouped under the following four headings, it being clearly recognized that the groups merge more or less insensibly.

Minerals of the Zinc Ores

1. Primary Minerals
2. Minerals of the Pegmatite Contact Zones
 - a. Reaction and Recrystallization Products—"Skarn"
 - b. Pneumatolytic products
3. Minerals of the Hydrothermal Veins
4. Minerals resulting from Surface Oxidation, etc.

Table II exhibits these groups, each mineral being accompanied by its chemical formula in order the better to bring out the chemical nature of the groups.

1. PRIMARY MINERALS

The four minerals certainly to be regarded as primary are those that make up the great mass of the two ore bodies at Franklin and Sterling Hill. These are franklinite, willemite, zincite and calcite. The proportions in which they are present in the average ore have been stated on a previous page.

There are frequent wide departures from the average. Franklinite, alone or with calcite, may form large masses of ore. Zincite has been segregated in certain bands almost to the exclusion of the other minerals. Willemite is in rare cases the only ore mineral in the calcite gangue. But the typical ore is a banded mass of all four minerals in rather coarse grains. To these may be added tephroite as an occasional rare accompaniment of willemite, probably of primary nature.

The relative age of these ore minerals has been determined by Ries and Bowen (1) through the study of thin sections of the ores. They show that tephroite and willemite are oldest followed by franklinite and zincite, but with more or less overlap.

Of these minerals which are the main ores at Franklin, only tephroite and willemite have been found elsewhere and then only as subordinate constituents of manganese and zinc deposits. The exceptional mineralogical character of the deposits is convincing evidence of unusual conditions determining their deposition.

2. MINERALS OF THE PEGMATITE CONTACT ZONES

This group is the most complex of any found at Franklin and includes the greater number of those species peculiar to the locality.*

* The following 24 minerals were first found at Franklin (F) or at Sterling Hill (S) and are as yet not known elsewhere:

cahnite	(F)	glaucochroite	(F)	leucophoenicite	(F)
calcium-larsenite	(F)	hancockite	(F)	mcgovernite	(S)
chalcophanite	(S)	hardystonite	(F)	roebblingite	(F)
chlorophoenicite	(F)	hetaerolite	(F)	roepperite	(S)
clinohedrite	(F)	hodgkinsonite	(F)	schallerite	(F)
franklinite	(F, S)	holdenite	(F)	sussexite	(F)
gageite	(F)	jeffersonite	(F, S)	zincite	(F, S)
desaulesite	(F)	larsenite	(F)	zinc-schefferite	(F)

In addition to these, margarosanite and nasonite, first found at Franklin are only known besides at Långban.

There is unfortunately a great lack of detailed observations in the mines to support the conclusions drawn from the chemical nature of the minerals. But in that part of the Mine Hill deposit known as the Trotter Mine the relations were definite and conclusive.

It is clear that the intrusion of pegmatite produced local high temperatures which not only effected recrystallization of the primary minerals of the ore but initiated a vigorous interaction between the ore minerals and the magmatic constituents at and near the contacts. Moreover, the pegmatites were in some cases rich in volatile constituents which varied from place to place, and were capable of combining with the ore minerals in a variety of new compounds. These reactions apparently continued through a considerable period of falling temperature, merging ultimately with purely hydrothermal processes whose products are placed in a separate group.

The pegmatite contact minerals have been divided into two groups which are not sharply separable. One, for which the convenient Swedish mining term "Skarn" has been employed, includes silicates and oxides which are conspicuous, especially at Franklin by reason of their abundance and brilliant color. Most of them are direct reaction products between ores and the silica and alumina of the pegmatite. The second group is termed pneumatolytic for it includes mostly minerals in which magmatic volatiles are present or some metal clearly derived from the magma.

(2a) SKARN AND RECRYSTALLIZATION PRODUCTS

The skarn silicates as shown in the table, column 2, are chiefly characterized by the presence of zinc or iron or manganese or all three. Rhodonite* is particularly abundant at Franklin and may be seen in great masses crystallized against calcite. At Sterling Hill the principal skarn was composed of jeffersonite with gahnite. There too, roepperite was locally very abundant and a manganese hornblende was found in very large crystals. The cyprine variety of vesuvianite is found at Franklin intergrown both with pegmatite and with rhodonite. Hardystonite, known only from Franklin, seems to form a transition to the next group as it always contains traces of lead minerals.

* Rhodonite is always zinc-bearing at Franklin and should be termed fowlerite in exact usage.

Often with the skarn and again in independent areas, the primary ore minerals occur in coarse aggregates or large, well-formed crystals. Franklinite in octahedrons or dodecahedrons up to six inches in diameter; willemite, particularly the manganese-rich variety troostite, in large stout hexagonal prisms a foot or more long; and zincite in broad plates as much as six inches across are examples of these recrystallizations. Their association with skarn indicates that they are related to the pegmatite intrusions. But there is often no visible relation with intrusives and in fact the most notable occurrence of this sort was found in the early workings at Sterling Hill where pegmatite is less abundant than at Mine Hill. In such cases local accumulations of water may have become an active solvent through heating due to remote intrusions.

In a few cases recrystallization seems to have been accompanied by a certain degree of breaking down of the original minerals. As examples may be noted the occurrence of manganosite, MnO , a molecule generally only present here in franklinite and in solid solution in the zincite; and hematite in the remarkable cube-like parting masses intergrown with franklinite which may be due to the separation during recrystallization of some of the iron of franklinite.

(2b) PNEUMATOLYTIC PRODUCTS

This group includes a great variety of minerals, chiefly silicates, in which some element is present not normally found in either ore or pegmatite. These "mineralizer" elements include hydroxyl, lead, chlorine, fluorine, boron, arsenic and sulphur. A number of metallic sulphides are placed in this group with considerable doubt. The mode of occurrence of these minerals is various; they may constitute irregular masses mingled with skarn minerals which they seem to replace; or again they fill very definite veins in ore or skarn, along whose walls more or less replacement of the older minerals has occurred. The detailed paragenesis is almost infinitely variable and but a few examples will be mentioned. The group is practically confined to Franklin.

During the early development of the Trotter Mine at Franklin a pegmatite was revealed notable for the presence of green microcline and allanite. About it at the surface was an abundance of garnet skarn, and throughout the mine rhodonite and manganese-

axinite were very abundant. Niccolite and chloanthite occurred here in considerable masses mingled with sphalerite and purple fluorite.

The Parker Shaft, sunk near the north end of the Mine Hill deposit cut through great masses of garnet-rhodonite-axinite skarn, associated with which were many lead silicates. Here were first found nasonite, margarosanite, roebblingite and hancockite and with them the hydroxylsilicates leucophoenicite, clinohedrite, pectolite and prehnite. Fluorine appeared there in fluorite, cuspidine and apatite, and copper in the native form and in cyprine.

Much the same suite of minerals was found in the replacement veins containing the recently found lead silicates larsenite and calcium-larsenite.

Cahnite, a calcium boro-arsenate, was found in cavities of axinite or in veins with willemite, hedyphane and datolite or in open vugs in rhodonite veins.

Veins with the succession garnet-tephroite-willemite-barite-calcite seem to belong in this group. Hodgkinsonite and leucophoenicite, the latter especially apt to be associated with sussexite, are widespread both as replacement and vein minerals. Willemite in particularly fine, complex crystals is characteristic of the group and franklinite, when found in open veins, takes on a rare cubical habit.

The metallic sulphides of this group occur mostly in ill-defined masses apparently replacing normal ore. They rarely show any relation to pegmatite and may be of much later introduction. As typical examples of their grouping may be mentioned chalcocite, surrounding octahedrons of magnetite and separated from them by films of native silver; films of native copper and of native lead in axinite-willemite-barite veins; and granular aggregates of galena, chalcopyrite, bornite, pyrite, löllingite and sphalerite, alone or variously mingled. It should be said that these occurrences of sulphides are small and rare.

There is no sharp delimitation between the pneumatolytic veins and those of the next or hydrothermal group. Some minerals occur in both but in the latter there is less evidence of replacement in the walls, the veins being in general clearly fissure veins.

3. MINERALS OF THE HYDROTHERMAL VEINS

The complexity of this group is scarcely less than that of the last into which it shades by imperceptible gradations; on the

other hand, however, it includes many occurrences obviously formed at lower temperatures, either at greater distance from pegmatite intrusions or at a later period of fissuring. The vein form is characteristic, the walls clean-cut, the fissure either wholly filled or open and crystal-lined.

The veins are generally small and of no great linear extent. A width of a few inches is the rule and many of them are mere seams, less than an inch wide. Thus, although in places very numerous, their total bulk is insignificant in comparison with the great mass of the ore bodies. Their most notable characteristic is extreme variability of mineral content.

Here also space permits the description of but a few of the very numerous examples supplied by collections.

As a typical example of the veins transitional between pneumatolytic and hydrothermal may be cited the paragenesis, garnet-leucophoenicite-gageite-clinozoisite-willemite-zincite-pyrochroite-calcite. A similar type is seen in the combination, hodgkinsonite-willemite-hetaerolite-calcite.

Rhodonite, friedelite, schallerite and mcgovernite are each found as the sole filling of numerous fissures. Friedelite is often followed by barite and calcite. Willemite is very common as a vein filling, especially the light green or white fibrous variety, low in manganese and highly phosphorescent. Zincite is only known in crystals from vugs in calcite veins while the form known as calcozincite is a mixture of granular zincite with fibrous calcite, generally coating slickensides in ore.

The arsenates hedyphane, allactite and holdenite are found in veins with calcite while chlorophoenicite occurs with gageite and acicular willemite.

The zeolites ganophyllite, and heulandite are found in veins with rhodonite or sulphides; the other zeolites of the list are minor vein minerals.

Sussexite is typically a vein mineral, its asbestiform fibres filling narrow cracks or coating slickensides in ore. It is closely simulated by veins of fibrous tremolite mixed with calcite.

Another type of vein very common at Franklin consists dominantly of some carbonate, often strikingly banded parallel to the walls. The filling may be calcite with or without fibrous willemite; sometimes it is siderite or an intermediate calcium-magnesium-iron carbonate; again rhodochrosite or smithsonite. Dolomite is

the filling of a few veins with open vugs lined with crystals of dolomite, calcite, albite, quartz, or sphalerite and more rarely with millerite, marcasite or the oxides goethite, manganite or hematite. Pyrochroite and chalcophanite are also found in calcite veins. Aragonite coats cracks with radiating rosettes of needles.

Quartz in compact form, alone or with massive sphalerite or pyrite forms narrow, clean-cut veins and at times shows crystals on free surfaces. On the whole it is very rare at Franklin.

The parageneses calcite-sphalerite, and calcite-sphalerite-quartz-willemite-crocidolite are common and conspicuous vein formations. In fact it is in these veins alone that sphalerite appears in any noteworthy amount at Franklin if we except the mass described above at the Trotter Mine.

Bementite and the closely related manganese serpentine are not uncommon as vein fillings, alone or more commonly with a carbonate such as rhodochrosite or smithsonite.

It is highly probable that the carbonate and quartz veins carrying sulphides belong to the much later, post-paleozoic deformation as suggested in an earlier paragraph.

4. MINERALS RESULTING FROM SURFACE OXIDATION, HYDRATION, AND CARBONATIZATION

With one important exception this group of minerals is of minor interest at Franklin and Sterling Hill. Manganese serpentine forms pseudomorphs after silicates such as rhodonite; the nickel-rich genthite known as desaulsite has replaced niccolite and chloanthite at the Trotter Mine. Quartz, hematite and limonite form gossans on a few pyritic veins at Franklin and in the gossans of sphalerite veins there are found small amounts of calamine and hydrozincite. The ordinary copper oxidation minerals form about the rare copper sulphides and descloizite, cerussite and anglesite were the alteration products of galena in a pyroxene skarn at Sterling Hill.

The exception noted was so remarkable, however, that it requires special description. Reference is made to the great bodies of calamine which during the "seventies" constituted the chief zinc ore mined at Sterling Hill. They occurred in two deposits lying in the angle between the two legs of the vein and shown as mines on the map in the Folio. In 1906 their place was occupied by irregular conical excavations, apex down, separated by a wall

of barren pegmatite. When mining began this part of the area was a shallow water course and mining reached a depth of more than forty feet below the original level. The bare limestone walls remained in 1906 just as they were left by the stripping operations and the detail of surface clearly indicated that they were solution surfaces, probably the result of long continued action by underground waters. These exposures have been long since caved by the modern mining at Sterling Hill and the Noble and Passaic Mines exist now only as names on the Folio map.

Mr. O. J. Conley, Superintendent of the Noble Mine in 1878, very kindly went over the ground with the author and described the deposit of which no contemporary account was published. According to him the calamine formed a layer directly on the limestone, six inches or a foot in thickness. The principal filling of the excavated mass was more or less fragmental, consisting of sand, clay, and limestone fragments with loose and broken crystals of franklinite, willemite, garnet and the like. All was much stained by iron and manganese oxides. Separating this loose material from the calamine layer on the north side of the pit was a layer up to four inches thick of a greasy black mud very rich in manganese, which was the cause of dangerous slides in the pit. On the south side, in a similar relation to the calamine were found the deposits of chalcophanite and hydrobetaerolite which were so characteristic for this locality. Magnificent specimens of this calamine are preserved in collections and almost all the specimens examined show a considerable amount of harsh, brown or yellow clay adhering to the under surface. The clay is rich in zinc and has been named vanuxemite.

The relations of these calamine deposits, as described by Mr. Conley, to the ore-bed sufficiently establish their secondary nature. There is, however, further direct evidence in the presence, among the fragmental materials from the pit, of crystals of willemite still preserving their form but wholly covered with manganese-stained needles of calamine; and of deeply corroded franklinite crystals, surrounded by and imbedded in calamine. These zinc and manganese deposits resulted from the destruction of a certain portion of the outcropping ore-bed, the products of solution being carried to a lower position where they replaced the limestone with the zinc silicate and zinc, iron and manganese hydrous oxides. The reason for describing this deposit at such

length is that it seems to throw some light on the origin of the major deposits as will be shown in the next section.

ORIGIN OF THE ZINC-ORE DEPOSITS

The vexed question of the origin of these unique ore deposits has been often discussed and it is not proposed to attempt here a full treatment of the matter. In the paper by Ries and Bowen (1) already referred to there is an excellent summary of the various theories which have been proposed and this may well be reproduced with some comments.

Among the theories which have been advanced the following are outstanding:—

1. **IGNEOUS INJECTION.** First offered by Rogers in 1840. Suggested by Spencer in the *Folio* in 1908 as the best alternative. Rejected by Ries and Bowen in 1922 on the ground that it would not account for the admixture with the ore minerals of grains of Franklin limestone. Advocated by Spurr and Lewis, in 1925, the ores being regarded as igneous veins of sulphide magma which have lost their sulphur by later oxidizing roasting at a temperature above that of fusion. How the required oxygen was supplied is not revealed.

To the author the best argument against the theory of igneous injection is the mineral and chemical character of the ores.

2. **SEDIMENTARY DEPOSITION.** The zinc ores are supposed to be contemporary with the enclosing limestone and to have been metamorphosed with it. First proposed by Kitchell in 1855 and maintained by the geologists of the New Jersey Survey as late as 1896. It is difficult to establish because there is no way of determining whether the banding of the ore is parallel to the original bedding of the limestone. Neither does it explain the structure of the Sterling Hill deposit as now developed.

3. **CONTACT METAMORPHISM.** First proposed by Nason in 1890 and advocated by Kemp in 1893 who misinterpreted the evidence of the then poorly exposed pegmatite intrusions. Rejected by Ries and Bowen on evidence similar to what has been given in preceding pages as to the intrusive relation of pegmatite to ore.

4. **DEPOSITION BY MAGMATIC WATERS BY A PROCESS OF REPLACEMENT OF THE LIMESTONE.** This theory is accepted by Ries and Bowen, their only question relating to whether the replacement preceded or followed the folding of the limestone. They

believe that it preceded the folding and that the "primary minerals," willemite, franklinite and zincite were deposited directly as such in that order, from magmatic solutions

To the author the nature of the primary minerals is such as seems unlikely to have resulted from the action of magmatic solutions. In all cases known to him where zinc ores have indubitably been deposited by magmatic solutions it is the sulphide which is formed and the absence of sulphides is one of the marked features of these ores.

5. AUTHOR'S THEORY. It is believed that the ore bodies were metasomatic replacements formed in the limestone in Pre-Cambrian time before its regional metamorphism; that they were deposited near the surface under oxidizing conditions and probably consisted largely of the hydrous zinc silicate, calamine, together with hydrated oxides of iron and manganese, and perhaps carbonates of zinc and manganese. The depositing solutions are believed to have derived their metallic contents from the products of oxidation of a previously existent mass of mixed sulphides.

It is believed that these oxidized minerals were laid down in more or less well banded masses whose form may well have been determined by a preceding folding of the limestone which initiated structures and controlled the flow of the depositing solutions. The present minerals constituting the deposits are, on this theory, the result of dehydration and recrystallization effected during the profound and long continued metamorphism of the whole Pre-Cambrian system of rocks. Thus were impressed upon the minerals of the ore deposits the identical texture and structures of the enclosing limestone, so marked a characteristic. The established sequence in the age of the minerals, oxides following the silicate, seems entirely consonant with the suggested mode of origin.

The metasomatic deposition of these ore bodies was suggested to the writer by the descriptions of two deposits of zinc minerals having a related origin. The first of these is a small-scale illustration which has the advantage of being located on the spot—the calamine deposits at Sterling Hill, described on a previous page. There had been accumulated a rich ore deposit consisting of parallel bands of calamine, smithsonite, zinciferous clay and iron and manganese hydrates; the banding followed the walls of the cavity in the limestone by whose solution place for the new ore was formed. The source of this ore was the near-by franklinite-

willemite mass; and the new ore was constituted in such a fashion that had it and the surrounding limestone been subjected to a vigorous and deep-seated, high-temperature metamorphism, there might well have resulted from its dehydration and recrystallization a new deposit closely analogous to the parent mass.

The second illustration is drawn from the published description of the well-known zinc deposits at Moresnet, Belgium. Here there are vast sphalerite replacement deposits in Paleozoic dolomites. These have undergone a profound oxidation; the soluble products have been transferred to the adjacent dolomite and have there accumulated in synclinal folds which halted the circulation. Extensive deposits consisting principally of calamine, with some smithsonite and limonite have thus been formed in bodies whose form, while determined in general by the structure of the dolomite, is independent in detail of anything except the solvent action of the depositing solutions. It does not seem unreasonable to think that in these Belgian deposits of desulphurized zinc and iron ores we have in all respects, except the absence of manganese, a good presentment of the New Jersey zinc ores before the great metamorphism.

This metasomatic hypothesis of ore emplacement seems to account for the observed facts without essential conflict. The localization in the limestone is necessary, the duplication not remarkable. The form of the ore bodies may be quite independent of sedimentary structure. The pitching synclines are conformable in attitude to the general structure of the gneiss but how much of the folding may have been effected during metamorphism we have no means of determining. The hypothesis is indifferent in this matter since the original form of the deposits may have been anything from a simple layer to a mass whose form was not unlike what we now see. The identical texture of ore and country rock; the banding of the ore; the sudden transition from ore to barren limestone; the dying out of the ore along the strike, northwards at Mine Hill; the occasional occurrence of disseminated ore in the limestone within the fold at Sterling Hill; all these characters are satisfactorily accounted for by the suggested process. The chemical character of the ore is unusual chiefly in the association of zinc with both iron and manganese; but we know of metamorphosed metasomatic deposits of iron and manganese and the addition of the third metal marks simply an unusual set of original

conditions of accumulation. The mineral composition is conformable to the theory; for willemite we have no comparable example, but franklinite is a spinel and therefore to be expected as a product of the assumed mode of formation. Light is thrown on the presence of zincite by Magnusson's (3) recent study of the Långban deposits where manganosite, MnO , and periclase, MgO with a trace of ZnO , are shown to have been formed from manganese and magnesium carbonates by a high-temperature metamorphism. So zincite may have been formed by the breakdown of smithsonite in these deposits.

The modifications which have affected the ore bodies after their primary crystallization in present form are relatively unimportant and have been sufficiently illustrated in the foregoing paragenetic study. The only clear evidence of direct introduction of magmatic materials is to be found in the contact zones about the pegmatites which were certainly far later than the ore deposits themselves.

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Discussion of the foregoing paper would be welcomed by the author and editor and any comments or criticisms received will be printed in a future number of the Journal.—The Editor.