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PETROGENY OF KYANITE DEPOSIT AT POWELL, WISCONSIN

by

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by

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First noted by Norwood.
See p 279 D D Owen
Geol Surv. of Wis., Ia., + Minn. 1852
He calls it "des Chêne".

LOCATION OF DEPOSIT

The kyanite-bearing gneiss occurs in Iron County, Wisconsin. The region is one of low relief and has a heavy cover of glacial drift. Numerous swamps and lakes make field work difficult. A dozen or so scattered outcrops are located in sections 28, 29, 32, and 33, T.42N, R.4E, and in section 5, T.41N, R.4E. (Maps 1, 2, and 2a) These outcrops were early described by Allen and Barrett (1914), and later in more detail by Ockerman(1938).

The gneiss is part of an infolded belt of undifferentiated Huronian sediments known as the Manitowish Range. (Map 1) Leith, Lund, and Leith (1935) have given a summary of probable age relations. The deposit is interbedded with even more ferruginous gneisses and schists, which are indicated by magnetic lines. The magnetic belts are known only from drill cores made for the F. I. Carpenter Syndicate and described by Allen and Barrett (1914).

Little is known of the intrusive granites which occur in and around this gneiss. They are pink to gray, contain both biotite and muscovite in considerable quantity, and are reported to have microcline. The granites are pre-Keweenawan in age according to work done by Marsden (1939).

GENERAL DESCRIPTION OF GNEISS

The important minerals in the gneiss are quartz, oligoclase, biotite, kyanite, almandite, and staurolite. The latter mineral is of minor consequence, although persistent. The rock may be termed a schist in part, but the general characters of coarse grain, coarse mineral-banding, and the occurrence of quartz lenticles and stringers in the plane of foliation make gneiss a more apt term.

The general strike of the banding is N 70-80°E. This is variable in any one outcrop. The dip is nearly vertical in the easterly outcrops. Outcrops in section 5, T.41N, R.4E, show a more gentle dip--about 20-40°N. There is alternation of coarse-grained with fine-grained bands. The latter are frequently lower in kyanite and higher in feldspar and garnet than the coarse bands. The banding is sometimes expremely contorted and takes the form of minor folds, whorls, and irregular patterns.

Lenticles, bands, and stringers of quartz occur irregularly throughout the gneiss. Their elongation lies in the plane of foliation. The biotite appears to curve around the quartz masses, but thin-sections show that it has developed in place. There is a tendency for grain size and kyanite content to increase in the vicinity of the quartz lenticles.

Pegmatites composed of quartz, feldspar, and muscovite occur as irregulat patches and lenses in the gneiss. The feldspar is largely plagioclase, but microcline is sometimes present. Occasionally the pegmatites cut across the gneissose structure, as in outcrop 13, where a dike one and one-half feet wide cuts sharply across the structure. It is probable that these represent the latest period of intrusion, whereas most of the other pegmatites were intruded before movement had entirely ceased. Andalusite and sillimanite, though rare, occur almost exclusively in the pegmatites.

There is, thus, considerable variation in the detail of the gneiss, but in the outcrops available for study the major mineral assemblage is surprisingly uniform.

LABORATORY TECHNIQUE

Optic properties of the minerals were determined from thin-sections and from grains mounted in Canada balsam. Refractive indices of grains were determined on the universal stage by the double variation method described by Emmons (1929). Grain slides and thin-sections were also mounted on the stage to determine exact optic angle, sign, and other properties. The X-ray analysis of garnet was made by E. J. Lyons in the X-ray laboratory of the Geology Department of the University of Wisconsin.

Determinations of composition and twin laws of the feldspar were made with a Bausch and Lomb universal stage. Thin-sections were mounted on the stage and compositions determined by the method described by Emmons (1934). Twin laws were then determined by the method outlined by Emmons and Gates (1939), a modification of the Federov and Rittman methods.

Mineral separations were made in acetylene tetrabromide, specific gravity 2.96. For lower gravities this was diluted with nitrobenzene. Centrifugation at moderate speeds aided in separations of the fine-ground powders. The rock was ground to various sizes and screened through meshes from 14 to 300 for different purposes. Magnetic separations of both heavy and light fractions aided in concentration of some of the minerals.

The presence of garnet and kyanite in the heavy concentrates masks the accessory minerals. It was found necessary to eliminate these for study of the accessories. To do this a separation was made of the rock which had been crushed and screened between 20 and 48 mesh. The light portion, which consisted of quartz, feldspar, and biotite, was then recrushed to pass 100 mesh. The heavies were concentrated in the usual manner. In some cases the biotite and the quartz-feldspar fractions were recrushed separately. It is believed that all minerals present in the rock are represented in these recrushed samples. In some cases it was necessary to boil the heavy concentrates in HCl to destroy apatite.

It was fou d impracticable to make Rosiwall counts of thin-sections to determine mineral percentage, due to the irregular distribution of the porphyroblasts of kyanite and garnet and the orientation of the biotite. For determination of the percentages of the major mineral constituents, grinding was so regulated as to produce as little as possible of sizes less than 100 mesh, but all the rock was ground to pass 14 or 20 mesh. This was necessary because of the tendency of biotite, and to a less extent kyanite and garnet, to concentrate in the coarser sizes, whereas quartz and feldspar tend to concentrate in the finer sizes. All the grains finer than 100 mesh were screened out to prevent particle size from greatly influencing the rate of settling.

The detailed proccedure for mineral percentage separations was as follows: A sample of approximately 40 grams of the powder was placed in a centrifuge tube. The tube was filled with acetylene tetrabromide and the contents stirred well. After standing 10 minutes the top portion was scraped out into a filter funnel. To this was added most of the liquid, which contained suspended biotite. This light fraction contained quartz, feldspar, and biotite. The kyanite and garnet had settled to the bottom with some of the biotite. Since the biotite is near the gravity of the liquid it remains in suspension, while the kyanite and garnet settle rather rapidly. It was possible, by repeated separations, to largely eliminate biotite from the heavy fraction.

The light and heavy fractions were separately washed in acetone and dried. Biotite was separated from the quartz and feldspar with the aid of an electro-magnet. Magnetic separation of the heavy fraction left a concentrate of kyanite. Staurolite was separated from garnet by varying the intensity of the magnetic field. Since staurolite forms considerably less than 1% of the average rock, it was discarded. Four fractions--quartz-feldspar, biotite, kyanite, and garnet--were then weighed and calculated to percentage.

The specific gravity of quartz is 2.65 and that of the average feldspar in the gneiss about 2.645. The presence of inclusions of graphite and the heavy minerals so offsets the true values that gravity separations gave light and heavy fractions which had no relation to the two minerals in question. Therefore, it was necessary to determine the ratio of quartz to feldspar by mechanical stage traverse in thin-section. About 400 mm. of these minerals were traversed in each section examined.

MINERALOGY

The minerals which have been identified are listed below in the approximate order of their abu dance. These are then described in detail, with special attention given to those of possible economic value or diagnostic importance.

- Quartz
- Biotite
- Feldspar
- Kyanite
- Garnet
- Staurolite
- Muscovite
- Sericite and chlorite
- Opaque minerals
  - Magnetite
  - Ilmenite
  - Graphite
- Apatite
- Rutile
- Anatase and leucoxene
- Zircon
- Monazite
- Sillimanite
- Andalusite
- Tourmaline

Quartz.

Quartz occurs abundantly and is seldom without strain shadows. These shadows are irregular in outline and quite distinct. Inclusions of all the other minerals occur in the quartz. The pegmatites contain some of the dark smoky variety. The quartz in the lenticles and stringers is colorless and rarely contains zircon, though the latter mineral is of frequent occurrence in the quartz of the gneiss groundmass and of the pegmatites.

Biotite.

The greater part of the biotite is a dark reddish-brown variety. It is entirely opaque in thick plates. Thin-sections cut parallel to the base transmit light. Color in these sections varies from light brown to dark reddish-brown. Pleochroism is strong in sections normal to the cleavage, with X pale yellow and Z dark brown.

There is some variation in the composition of the mineral, though this seems to be fairly constant. In heavy liquid separations the greater part of the biotite sinks, indicating a specific gravity somewhat higher than 2.96. Some of the mineral remains in suspension after centrifugation, and some small part rises to the top. The light fraction gives indication of being weathered or chloritized. The heaviest particles are clouded with heavy inclusions. It is probable that 3.08±.04 covers the gravity of the unaltered mineral. Pycnometer determination of a biotite concentrate gave 2.96.

Indices of refraction were determined on flakes from different outcrops. Complete data were obtained from only two of these.

#1. N_g 1.6435±.0002*

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*All indices here and below are reported for the D line.

N_m 1.6426±.0002

N_p 1.5950±.0005 (calculated from rotation readings)

N_g-N_p .0485±.0005

2V observed (-) 17°

calculated (-) 15½°

average (-) 16°±1°

#2. N_g 1.6429±.0002

N_m 1.6415±.0002

N_p 1.6013±.001 (calculated from rotation readings)

N_g-N_p .042±.001

2V observed (-) 13°

calculated (-) 20°

average (-) 16°±3°

Dispersion for N_g, F-C: .0172±.0002

Indices determined on cleavage flakes fall in the range from 1.6415 to 1.6435. These indices are either N_g or N_m.

The following values were chosen for determination of the approximate composition of the average biotite: N_g 1.6430, N_g-N_p .048. These values were plotted on Winchell's (1933) diagram of the isomorphous biotite system. The following molecular percentages are indicated.

Siderophyllite	54.4%
Eastonite	25.6%
Annite	13.6%
Phlogopite	6.4%

Approximate composition is: $20H_2O \cdot 10K_2O \cdot 35FeO \cdot 17MgO \cdot 18Al_2O_3 \cdot 52SiO_2$.

The biotite is replete with inclusions. Among these are zircon, magnetite, ilmenite, anatase, rutile, graphite, apatite, and monazite. Quartz, feldspar, staurolite, garnet, and kyanite are intergrown and may be included. Pleochroic halos occur around zircon, monazite, and apatite. The largest and most dense halos surround monazite. (Plate I-4) Apatite is encircled by only a faint dark ring. Zircons are abundant, and most of the biotite is peppered with minute grains, some as small as one micron or less, each with its dark halo. (Plate III-1,2,3,4) As many as 50 of these were counted in a single flake 0.2 mm. in diameter.

Chloritization has affected the biotite only rarely. This is accompanied by drop in birefringence to less than .0003, loss of pleochroism, and bleaching to pale greenish-yellow. Magnetite, or some other opaque mineral, has concentrated in cleavage traces and around the borders of this altered biotite.

Feldspar.

The gray feldspar throughout the gneiss is fairly uniform in composition from outcrop to outcrop. In the feldspars of any one thin-section, variations beyond the limit of error of the method used, about 2% An, may be as great as 2-3% in anorthite content. In 35 determinations from sections from various outcrops the anorthite content fell between the limits 20-30%. Thus all the feldspars are in the oligoclase group. Average composition is about 22% An. No potash feldspar was found in the gneiss itself.

A large crystal of microcline which was taken from a pegmatite mass in outcrop A was examined in detail. It has irregular intergrowths of plagioclase of ca. 37% An content. The andesine also occurs in narrow seams parallel to 001 cleavage. (Plate VI-1,2,3) This entire feldspar is a crystallographic unit. It thus resembles a perthite.

Twinning is more frequent in some thin-sections than in others. Probably as many as 30% of the feldspars are untwinned. Twin laws which are represented are pericline, albite, and acline A. Of these, the pericline and albite are about equally abundant. They occasionally occur together, though generally singly. Acline A occurrence is less frequent. Distribution of lamellae within a grain is sporadic, especially of acline and pericline twins. The pericline lamellae vary considerably in thickness and are frequently wedge-shaped or terminated.

Sericitization of the feldspars is present in all sections. This is largely confined to the narrower of the pericline lamellae, some of which are completely sericitized. The 001 cleavage in these grains generally shows no sericite. Albite lamellae which may occur in the same crystal are generally free of sericite. Where pericline lamellae are broad, the sericite occurs along the composition faces and criss-crosses only certain of these lamellae. (PlateV-3,4; Plate II-1,2,3) The cause of this selective sericitization is not known.

Inclusions in the feldspars are abundant; especially of the opaque minerals. Zircon, rutile, and apatite are of common occurrence.

Kyanite.

Kyanite occurs in crystals ranging from about 4 cm. to a few microns in length. The larger crystals are tabular, elongated in the c-direction, and have well developed 010 and 100 cleavages and 001 parting. The ends are generally unterminated. Color is variable, even in a single crystal. It is generally pale green-gray or blue-gray, but some crystals have streaks of dark blue parallel to the Z direction. These streaks are colorless in grains 0.1 mm. thick when X is parallel to the polarizer. Specific gravity determined by the pyncnometer is 3.63.

Optic data were obtained from five grains taken at random from concentrates from several scattered outcrops. These are quoted below.

#1. N_g 1.7298±.0002

N_m 1.7228±.0002

N_p 1.7150±.0005 (calculated from rotation readings)

N_g-N_p .0148±.0005

2V observed (-) 88°

calculated (-) 88°

average (-) 88°

Dispersion for N_g, F-C: .009±.001

#2. N_g 1.7295±.0002

N_m 1.7228±.0002

N_p 1.7167±.0005 (calculated from rotation readings)

N_g-N_p .0128±.0005

2V observed (-) 87°

calculated (-) 88°

average (-) 88°±1°

Dispersion for N_g, F-C: .010±.001

#3. N_g 1.7295±.0002

N_m 1.7223±.0002

N_p 1.7146±.0005 (calculated from rotation readings)

N_g-N_p .0149±.0005

2V observed (-) 89°

calculated (-) 88°

average (-) 88°±1°

Dispersion for N_g, F-C: .0085±.0005

#4. N_g 1.7298±.0002

N_m 1.7230±.0002

N_p 1.7152±.0005 (calculated from rotation readings)

N_g-N_p .0146±.0005

2V observed 90°

calculated (-) 86°

average (-) 88°±2°

#6. N_g 1.7293±.0002

N_m 1.7224±.0002

N_p 1.7152±.0005 (calculated from rotation readings)

N_g-N_p .0141±.0005

2V observed 90°

calculated (-) 89°

average (-) 89°±1°

Dispersion for N_g, F-C: .0085±.0005

The only noteworthy exception to the data which have been reported on kyanite by others is the high 2V in this material. The optic sign may be positive in some cases, as in #2 above.

Inclusions in kyanite are generally not very abundant. Some of the large crystals are poikiloblastic and intergrown with quartz, biotite, feldspar, garnet, and staurolite. (Plate V-1,2) The kyanite itself, however, contains few of the smaller inclusions. (Plate III-2) Zircon, apatite, rutile, ilmenite, anatase, magnetite, and graphite have been identified.

Garnet.

Garnet occurs throughout the gneiss and in the pegmatites. Pegmatites contain microscopic grains with well developed dodecahedral faces which are inclusion-free. (Plate I-3) The garnets of the gneiss are poorly formed, rarely have any good crystal faces, and are sometimes as high as 30% in inclusions. The outer portions of the garnets have fewer inclusions than the interior. In some grains the inclusions are arranged in patterns which may take the form of arcs or peculiarly curved whorls. These have no apparent relation to crystal boundaries or form. (Plate IV-3,4)

Crystals larger than 5 mm. in diameter are rare, and the majority are 1 to 3 mm. In thin-section they are colorless; pale pink in grains 0.1 mm. thick; brown to dark red in hand specimen. Where surface weathering has affected them they are brown, due to limonite stain in the fractures.

Optic data were obtained on grains from concentrates from various outcrops. Variation in indices in the garnets from a single hand specimen embraces the range found throughout the gneiss and pegmatites. Variation in indices within a single grain 0.1 mm. in diameter is nearly as great as that of the entire group. This indicates that zoning of some type is present.

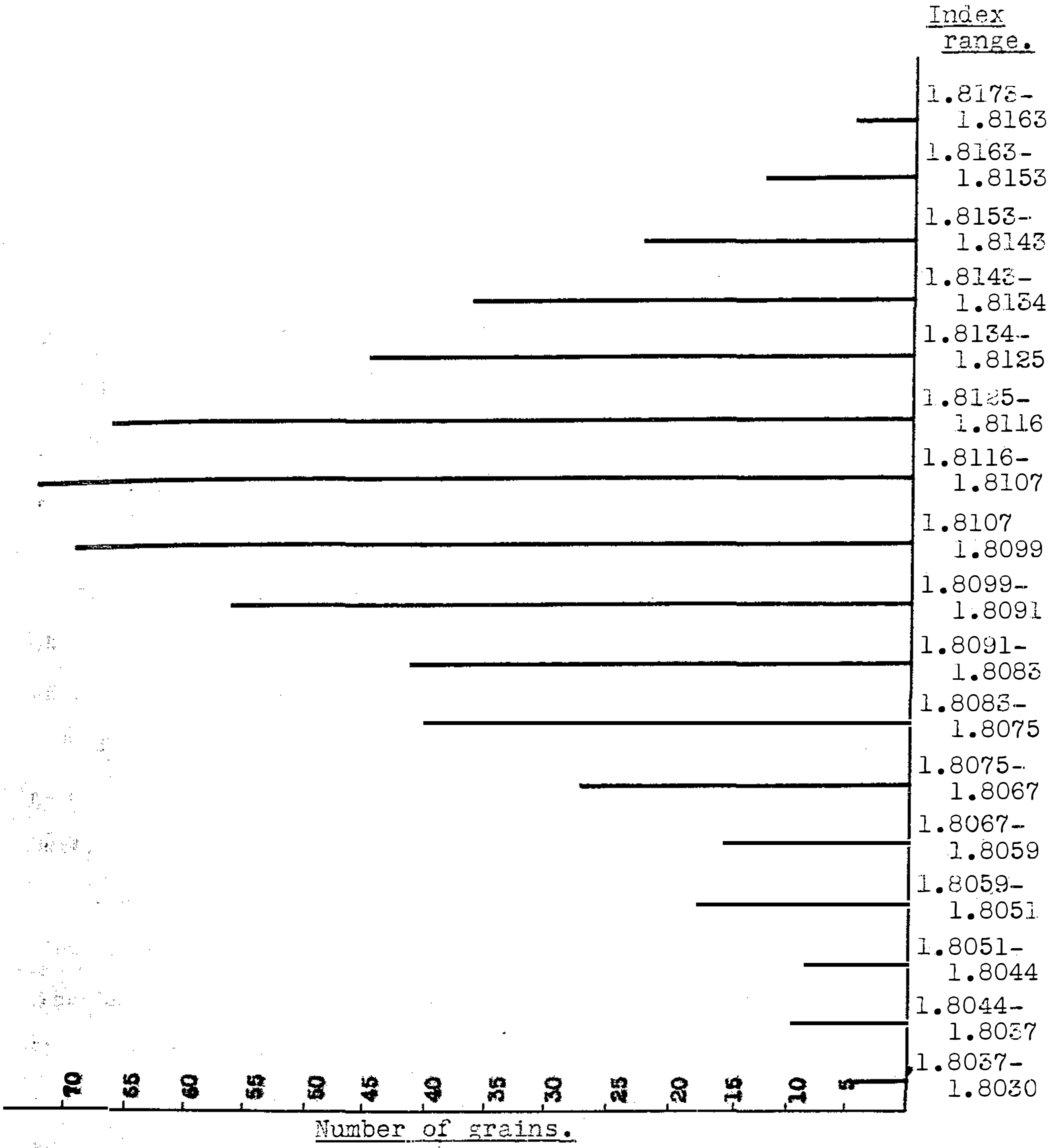
The liquid, ethyl di-iodo arsine, was found to embrace the index range at a constant temperature by merely varying the wave length of the light used. A dispersion curve for the liquid was constructed from refractometer readings by double variation. The dispersion curve of the garnet was determined from two grains by the same method. It was only necessary to obtain wave length readings at constant temperature and to plot these on the curves already determined.

The garnet is completely isotropic in thin-section. Indices fall in the range 1.8030-1.8171. Mineral dispersion for F-C is .0136. Index distribution for 557 grains is plotted in Table 1. The index of the greatest number is about 1.8110.

Specific gravity determinations by the pynonometer method were made of four garnet powder concentrates. Values are shown below:

#1	(Sized between 100 and 300 mesh)	4.04
#2	(Sized below 300 mesh)	4.04
#3	(Sized between 20 and 48 mesh)	4.07

Table 1.



#4 (Sized below 100 mesh) 4.13

The high admixture of ilmenite may account for the higher value of #4. Measured values of specific gravity have been found by Menzer (1926) and Stockwell (1927) to be always below the values calculated from chemical composition. It is probable that 4.1 is an average true value.

An X-ray picture was taken of one sample of garnet powder. (Plate VI-4) The length of the edge of the unit cube is 11.52±.02 Å. The intensity of the line 332 is extremely low. These two factors definitely place the garnet in the almandite-spessartite group of Stockwell (1927). Bead tests on powder show the absence of manganese, which eliminates spessartite. Therefore, almandite must be the dominant molecule. Using Stockwell's diagrams, the composition of the garnet appears to be 80% almandite and 20% pyrope plus grossularite and andradite. The latter molecule is probably very minor, otherwise the unit cube would be larger.

Chemical analyses were made of two of the garnet concentrates, #1 and #2 quoted on p. 13. Both contained very minor amounts of ilmenite, but they were otherwise free of admixtures and relatively free of inclusions. Both samples were washed briefly in HCl to dissolve limonite stain and admixed iron dust from the crusher. No determination was made of ferric iron. Therefore, what little is present is included in FeO. Results are given in Table 2.

Table 2.

Oxide	Sample #1 Percent	Sample #1 Molar ratio	Sample #2 Percent	Sample #2 Molar ratio
SiO_2	36.18%	602	32.86%	547
Al_2O_3	21.63	212	23.35	229
FeO	31.51	439	34.66	482
MgO	3.11	77	3.25	81
CaO	3.55	63	2.53	45
MnO	0.06	1	0.09	1
TiO_2	0.35	4	0.50	6
H_2O	2.00*		2.00*	
	98.39%		99.24%	

The TiO_2 was combined with FeO and eliminated from further calculations. The relations between SiO_2 and Al_2O_3 are interdependent, and therefore molecular ratios were determined from the bases--FeO, MgO, CaO, and MnO. Corresponding molecules are almandite, pyrope, grossularite, and spessartite.

	Sample #1	Sample #2
Almandite	75.5%	78.9%
Pyrope	13.4	13.4
Grossularite (and andradite)	10.9	7.5
Spessartite	0.2	0.2
Calculated specific gravity	4.07	4.10
(Observed gravity)	(4.04)	(4.04)
Calculated refractive index	1.803	1.807
(Observed index)	(1.811)	(1.811)

Approximate composition is: $23FeO \cdot 4MgO \cdot 3CaO \cdot 10Al_2O_3 \cdot 30SiO_2$.

These results closely check the observed values and earlier estimated composition. In view of the higher observed refractive index it is probable that andradite is present with grossularite. A small amount would raise the calculated index without affecting the specific gravity. It is apparent that X-ray patterns are valuable for determination of the composition of a garnet.

Staurolite.

Staurolite occurs in both small, well crystallized grains and large poikiloblastic masses. Small crystals are elongate in the c-direction and often have a rod-like appearance. Others are nearly equidimensional. (Plate III-3) The mineral is dark brown in hand specimen and pale yellow in thin-section. Pleochroism is distinct, from brown-yellow for Z to colorless or very pale yellow for X.

Optic data were not obtained.

Inclusions in staurolite are abundant in the large masses, but limited in the smaller crystals. Zircon, apatite, opaque minerals, rutile, quartz, biotite, and feldspar are all represented. The latter three are generally confined to the poikiloblastic masses.

Muscovite.

Muscovite occurs chiefly in the pegmatites, where crystals as long as one and one-half inches are not unusual. It is rarely found in the gneiss itself. The mineral is colorless, and it has 2V of (-) 47°±1°, as determined on the stage. This identifies it as iron-free muscovite.

Sericite and chlorite.

Sericite occurs as an alteration product in the feldspar. It is rare elsewhere, and especially absent in kyanite. Andalusite, where it occurs, contains sericite. Pegmatites are far more sericitized than the gneiss.

Chlorite occurs in association with biotite and garnet. Its occurrence is very limited, however. Its color is pale green-yellow. Birefringence is about equal to that of feldspar.

Opaque minerals.

Magnetite is present and occurs in euhedral crystals and irregular compact masses. It is scattered throughout the major minerals.

Ilmenite forms a large part of the opaque assemblage. It occurs most frequently in biotite in masses which have anatase crystals associated and intergrown with them. Other associated colorless, fine-grained, and highly birefringent material is probably anatase, but from lack of identification it is here called leucoxene. Leucoxene has been shown by Tyler and Marsden (1938) to be fine-grained anatase or rutile, and in some cases it may be brookite, though this has not been identified. The association of titanium minerals definitely distinguishes ilmenite from the other opaque minerals.

Graphite occurs in minute six-sided tabular crystals and in irregular compact masses. The mineral floats in liquid of specific gravity 2.50. Some of it is weakly magnetic and may contain admixed iron. It is opaque to transmitted light and steel gray in reflected light. The tabular crystals are recognized in thin-section as inclusions in quartz, feldspar, and biotite, especially.

No minerals other than those noted above have been recognized among the opaque group, though it is possible that some others may be present. The complete absence of pyrite in all of the concentrates is worthy of mention.

Apatite.

Apatite occurs most commonly as inclusions in the chief minerals. It generally exhibits euhedral form with elongation parallel to the c-axis. Ratio of length to width varies from about 1:1 to 5:1; it most commonly is about 2:1. There are six or twelve prism faces. Terminations are formed by a combination of pyramids, with or without bases. The mineral is colorless to pale gray.

No optic data were obtained.

Inclusions are extremely abundant in much of the apatite. These are largely opaque and are arranged in strings parallel to the c-axis.

Rutile.

Rutile occurs as inclusions in most of the other minerals. It is generally euhedral, and the crystal faces are a combination of many forms. In the majority of cases elongation is not pronounced. Color varies from nearly red through dark brown to dark gray. Pleochroism is distinct, from Z dark colored to X light colored. In thick grains the mineral is opaque.

Anatase and leucoxene.

Anatase is always associated with an opaque mineral, undoubtedly ilmenite, or originally so. This is true also of "leucoxene". The anatase is largely in rather thin basal plates, which may or may not have flat pyramids developed on them. Frequently the bases carry geometric patterns. When crystal form is developed the mineral shows square outline, but in some cases there are also prism faces. It is pale blue, pale yellow, or colorless. In heavy concentrates the basal plates give good uniaxial figures which have a negative sign.

Birefringence is higher than that of any of the other minerals except rutile. Relief is about equal to that of rutile and higher than that of any other mineral. Many of the minute "leucoxene" grains in the concentrates were oriented on the stage. All which were large enough to work with were identified as anatase.

Zircon, var. Malacon.

Zircon always occurs in euhedral grains as inclusions in almost all the other minerals. Its special host is biotite, in which it produces dark halos. Its color varies from brown-purple through yellow to colorless.

The maximum observed length was 0.12 mm. From this figure the size decreases to the resolution power of the microscope. The majority, however, are about 0.06-0.07 mm. long. Ratio of length to width varies from 1½:1 to 4:1; average is about 2:1.

In cross-section the grains are very nearly square. Terminations are by unequally developed pyramids--one, two, or three sets. Bases are sometimes present, though more often not. Thus the ends have a somewhat rounded appearance. The surfaces are etched or corroded, which gives the prisms indistinct edges in most of the grains. Frequently two crystals occur grown together along the prism faces. (Plate VII)

Determination of indices of refraction was found impracticable, except very roughly, due to great variation and indistinct Becke lines. Variation is considerable and probably ranges from 1.78 to 1.83 for E. Variation in a single grain is probably greater than this, inasmuch as the center often shows normal birefringence. The outer portions have birefringence of close to 0, or become completely isotropic. The indices have been shown by Chudoba (1937) to decrease with the birefringence. (For a discussion of the properties of the zircons of the Lake Superior region, see Marsden (1939)).

A goodly proportion of the malacons have high birefringent cores. (Plate VII-1,3) In some of the crystals the boundaries of the cores are distinct and give the impression of a zircon within a zircon, although crystallographic orientation is the same. In others the boundaries are quite irregular. There is no relation between size of zircon and occurrence of high cores. Some of the tiny grains have high cores, and yet some of the largest ones are completely low. Proportion of cored to uncored varies in the concentrates from different outcrops. In some slides most of the grains are cored, but in others only a small part shows this feature.

Monazite.

Monazite has been identified in thin-section as inclusions in biotite only, around which occur dense halos. (Plate I-4) It may occur elsewhere, however. Crystals are about 0.02 mm. in size or smaller. They appear to be euhedral, but they have so many crystal faces and forms that identification of them is impossible. The mineral is colorless in thin-section and pale yellow in grains.

Optic properties were determined largely on the universal stage, both in thin-section and in slides from heavy concentrates. Relief is about equal to that of the garnet, but certainly higher than that of staurolite. Birefringence is slightly less than that of anatase. One good cleavage is present, and most of the grains in the slides rest on this cleavage. The optic plane is nearly normal to the cleavage plane. Z and Y lie almost in this plane. The optic angle as determined by direct rotation on the stage is 12°-2° about the acute bisectrix, Z. Elongation is negative in thin-section. The mineral is generally free of inclusions, but a malacon was noted in one grain.

Sillimanite, var. Fibrolite.

Sillimanite occurs chiefly in the pegmatites. It is characterized by its needle-like form and aggregates of bundles and plumes. (Plate I-1,2) It was not recognized in thin-sections of the gneiss, but an occasional questionable grain is found in some of the heavy concentrates.

The mineral is pale colored to brown, has parallel extinction and positive elongation. It is slightly pleochroic, with Z darker than X. Optic data were not obtained.

Andalusite.

The only megascopic occurrence of andalusite was found in a hand specimen of pegmatite. Heavy concentrates show an occasional grain, but none was found in thin-sections of the gneiss itself. The pegmatite occurrence shows large crystals of about one inch maximum diameter. These are pale pink and have two good cleavages nearly at right angles. The mineral is colorless in thin-section. The grains found in the heavy concentrates are red-lavender parallel to elongation, which is X, and colorless for Z and Y. Extinction is parallel to elongation. Both the sign and sign of elongation are negative. Optic angle is about 84°, as determined from grains on the stage. Indices were not obtained.

Tourmaline.

The occurrence of tourmaline is limited and sporadic. The mineral is in long prisms which have negative elongation and strong pleochroism. Color is dark greenish-brown for O and pale yellow to colorless for E. In thick grains the O-direction is nearly, or quite opaque. Inclusions are rare, but apatite was noted in one grain.

MINERAL AND CHEMICAL COMPOSITION

Approximately 98% of the gneiss is composed of quartz, feldspar, biotite, kyanite, and garnet. Thus, calculation of chemical composition of the average rock will not be far in error if based on these minerals alone. The following determinations of percent mineral composition were made by heavy liquid separations.

Table 3.

Outcrop no.	%Quartz and feldspar	%Biotite	%Kyanite	%Garnet
2	62.52%	22.36%	10.69%	4.43%
3	65.51	23.45	5.75	5.29
4	69.45	20.73	4.31	5.51
5	54.44	31.00	7.70	6.86
6	57.94	26.46	10.96	4.64

7 and 8	56.59	34.11	5.55	3.70
9	65.50	24.25	4.71	5.54
10	55.25	32.32	7.05	5.38
11	53.44	40.88	1.85	3.83
Average	60.1	28.4	6.5	5.0

The samples of Table 3 are considered representative of their respective outcrops. They contain neither the highest nor the lowest values of any constituent in that outcrop.

Determinations of the ratio between quartz and feldspar were made in thin-section. Results are given in Table 4.

Table 4.

Slide no.	% Quartz	% Feldspar
2	78.9%	21.1%
3	37.5	62.5
4	35.6	64.4
5	50.9	49.1
6	50.5	49.5
A-4	77.8	22.2
A-7	61.5	38.5
B-6	23.1	76.9
B-8	65.7	34.3
B-12	37.3	62.7
B-13	58.3	41.7
B-14	74.0	26.0
Average	54.3	45.7

Specimens which are richest in kyanite have quartz predominant over feldspar, and where kyanite is low feldspar predominates over quartz.

Application of the quartz-feldspar ratio of the above table to the quartz plus feldspar percentage of Table 3 gives: 32.6% quartz and 27.5% feldspar. We then have the following composition:

Quartz	Feldspar	Biotite	Kyanite	Garnet
32.6%	27.5%	28.4%	6.5%	5.0%

Since this group represents approximately 98% of the entire rock, these values are reduced to:

Quartz	Feldspar	Biotite	Kyanite	Garnet	All others
31.9%	27.0%	27.8%	6.4%	4.9%	2.0%

The chemical composition of the gneiss can be calculated with the aid of the mineral formulae given on earlier pages. These are repeated below.

Quartz	SiO_2.
Feldspar (22% An)	$39Na_2O \cdot 22CaO \cdot 61Al_2O_3 \cdot 278SiO_2$.
Biotite	$20H_2O \cdot 10K_2O \cdot 35FeO \cdot 17MgO \cdot 18Al_2O_3 \cdot 52SiO_2$.
Kyanite	$Al_2O_3 \cdot SiO_2$.
Garnet	$23FeO \cdot 4MgO \cdot 3CaO \cdot 10Al_2O_3 \cdot 30SiO_2$.
Others	Compounds of TiO_2, P_2O_5, C, Fe_2O_3, ZrO_2, MnO_2, B_2O_3.

Although the last group is merely an approximation, it is felt that its effect on the analysis of the major rock forming elements is negligible. This oxide analysis is given in Table 5, together with analyses of two other aluminum-silicate-bearing schists, and with some pre-Cambrian slates of the Lake Superior region.

Composition of the gneiss corresponds to that of an average shale. It is not particularly high in alumina, but rather in iron oxides. The ratio of potash to soda is lower than in the other analyses quoted. The presence of sericite in the feldspar, which was not taken into account, would raise this ratio in a true chemical analysis. There is a close relation between the kyanite gneiss and the Huronian and Knife Lake slates.

Table 5.

Oxide	1*	2*	3*	4*	5*	6*	7*
SiO_2	62.4%	59.91%	58.18%	60.15%	58.15%	62.24%	60.88%
Al_2O_3	16.8	20.35	20.45	16.45	19.60	16.39	17.79
Fe_2O_3	9.2	1.21	.98	4.04	1.45	4.98	1.94
FeO		4.33	6.51	2.90	5.43	2.70	4.07
MgO	2.3	3.33	2.60	2.32	3.04	2.94	3.53
Na_2O	2.5	2.61	1.34	1.01	1.71	1.65	2.65
K_2O	2.3	3.85	5.00	3.60	4.12	4.23	3.16
CaO	1.4	1.47	.93	1.41	1.33	1.69	2.77
H_2O +	1.1	1.65	2.65	3.82	2.27	2.58	1.91
H_2O -			.05	.89	.37	.04	.13
TiO_2	p.	1.11	.93	.76	.85	.30	.62
P_2O_5	p.	.06	.15	.15	.11	.10	.19
MnO	tr	.08	.15	tr	.03	.06	
CO_2			.05	1.46			
C	p.			.88			
	98.0%	100.46%	99.97%	99.84%	98.46%	99.60%	99.02%

*Sources of analyses:

1. Approximate composition of Iron County, Wisconsin kyanite gneiss, calculated from mineral percentages and formulae.
2. Analysis quoted by Suzuki (1930) of a schist composed of quartz, feldspar (15-20% An), biotite, muscovite, garnet, staurolite, andalusite.
3. Analysis of kyanite schist facies rocks in Dutchess County, New York; from Barth (1936).
4. Composite analysis of 51 Paleozoic shales; from Clarke (1924).
5. Average of three composite analyses of little altered upper Huronian Virginia slate from northern Minnesota; from Grout (1933).
6. Average of two composite analyses of Rove slate of northern Minnesota; from Grout (1933).
7. Average of three composite analyses of Knife Lake slates of the Vermillion District, Minnesota; from Grout (1933).

PARAGENESIS OF MAJOR MINERALS

The mineral assemblage of the gneiss is characteristic of a high grade of metamorphism. One is handicapped in this region because of lack of outcrops, and it is not possible to trace the progress of metamorphism to less highly altered phases of the same formation. Only by inference can it be shown what mineral changes occurred and what the original rock probably was.

Idiomorphism among the most common minerals takes the following sequence: Almandite, staurolite, kyanite, biotite, oligoclase, quartz. The accessories are idiomorphic to all of these.

Staurolite.

The position of staurolite is difficult to interpret. It appears to be nearly stable with kyanite, but it occasionally occurs in knots of about one-half inch diameter and of extreme poikiloblastic texture. (Plate V-2) Associated with the staurolite are both almandite and kyanite, and also, of course, biotite, oligoclase, and quartz. The main mass of the knot forms an optical unit. It appears that the kyanite and almandite are growing at the expense of the staurolite. These relicts(?) of large staurolite crystals are interspersed throughout the gneiss, but one must search carefully for them.

Most of the staurolite occurs in microscopic euhedral grains. (PlateIII-3) Thus some of the mineral may have formed before or during development of the kyanite, and some of it may have given rise to other minerals.

Almandite.

Almandite has probably formed through a long range. Certain of the crystals contain inclusions which are arranged in arc-fashion, in straight lines, or in irregular curved forms. (Plate IV-3,4; Plate III-4) These have no apparent relation to crystal boundaries. The inclusions are largely quartz and opaque minerals, with minor amounts of biotite. Apatite is sometimes important. It is possible that biotite has contributed to almandite, accompanied by release of silica and potash. This would accou t for straight rows of inclusions which would represent the remains of the original biotite crystal. Where inclusions are curved it is possible that the garnets were rotated during growth. Harker (1932) describes and illustrates such garnets. Since all evidence of shearing has been obliterated, as shown by unbent biotite flakes, almandite was apparently still in the formative stage when this rotation occurred. The garnet frequently occurs in mere rims or shells which enclose quartz, biotite, and oligoclase. (Plate IV-1,2) The exterior portions of the crystals are generally nearly or quite free of inclusions.

The presence of zoning in the almandite indicates change in composition of material available during growth. It was not possible to determine what this zoning means in relation to chemical composition of the garnet, nor could it be determined whether the index rises toward the exterior or toward the interior. This study might be profitably pursued.

Feldspar.

Oligoclase shows evidence of having formed at an earlier stage and of later changing its composition. It very frequently shows strain shadows or undulatory extinction, though not to the extnet found in quartz. A conspicuous feature in all the thin-sections is a frequent rim of minute kyanite crystals between the feldspar grains. (Plate II) These are embedded in quartz and give the impression of having come from the feldspar, accompanied by liberation of silica. Small crystals of staurolite which are embedded in oligoclase are generally cushioned by a rim of quartz. It is possible these formed in a similar manner, taking the iron from inclusions in the feldspar.

Harker (1932) shows that increase in grade of metamorphism is accompanied by increase in the anorthite molecule of the feldspar. Since calcium is low in this gneiss, increase in the anorthite molecule of the feldspar could come about only by destruction of the albite molecule. This may account for the kyanite-quartz rims between feldspar grains. The released soda might well be taken up by the biotite, if insufficient boron were present to form tourmaline. Migration of silica might also afford a vehicle for removal of the base. This reaction is dependent upon chemical composition of the rock; specifically, a low calcium content.

The occurrence of potash feldspar--microcline or perthite--is confined to pegmatites which were formed later than the peak metamorphism of the gneiss. It probably represents material which has been contributed by the intruding magma.

<u>Biotite.</u>

Biotite appears to have a wide range of formation. There is a suggestion in some sections that it is giving way to almandite. In other sections it appears to be in equilibrium with almandite; both in and around the latter. The relation between the two is probably conditioned by the available potash. Occasionally euhedral staurolite crystals, surrounded by quartz, occur in ragged-edged cavities in the biotite. At other times contact between the two minerals is sharp. Small euhedral crystals of biotite occur in oligoclase and quartz. Where ilmenite is present the biotite seems to have used iron, which may account for the growth of anatase.

<u>Kyanite.</u>

Kyanite is a growing mineral. It does not show evidence of furnishing material for later reactions. (An exception is discussed under sillimanite.) There are apparently two generations of kyanite--the large porphyroblasts which characterize this rock, and the minute elongate blades which frequently rim the feldspars. Growth of the porphyroblasts must have occurred some time before the small crystals appeared. They are, thus, not demonstrated to have come from feldspar. It is probable that these represent earlier crystals of andalusite, since this mineral does occur rarely in the heavy concentrates. The growth of the small crystals between the feldspars appears to be the latest phase of the anamorphic cycle.

Sillimanite and andalusite.

Sillimanite was not recognized in thin-sections of the gneiss, and only a few grains were found in heavy concentrates from outcrops in section 5, T.41N, R.4E. A one-inch stringer coming from a pegmatite dike cuts through the gneiss of outcrop 13. Kyanite, staurolite, and almandite occur in this band with sillimanite. (Plate I-1,2) Kyanite and staurolite show evidence of giving rise to some of the plumes and bundles of sillimanite needles. The sillimanite is here also associated with remnants of muscovite and biotite and seems to have come, to some extent, from them. Biotite appears as relicts in muscovite, into which it was probably altered.

The andalusite of the irregular pegmatite mass in outcrop B may have had a somewhat similar origin to that of the sillimanite. It occurs intergrown with muscovite and quartz. Borders and cleavages have been greatly sericitised since its formation.

Anatase.

The development of anatase, it would seem, was one of the late processes of the metamorphism of the gneiss. It may have occurred during the late development of the biotite, or it may represent retrogressive changes. In the former case the biotite could have used the iron, and in the latter case the iron may have been carried out by the solutions which caused sericitization and chloritization.

Quartz.

Quartz is, of course, one of the earliest and yet the latest mineral to form. Its mobility is generally recognized.

Sericite and chlorite.

Retrogressive changes have affected some of the minerals of the gneiss. Most of the oligoclase shows sericitization to a minor degree, and the feldspars of the pegmatites are even more altered. (Plate II; plate V-3,4) The andalusite from outcrop B has been markedly sericitized. The kyanite rarely shows development of sericite. Chlorite has occasionally developed from biotite, and less frequently it occurs in fractures in the garnet.

PETROGENY

Zircon and its Significance.

Tyler and Marsden (1939) have found that all igneous rocks of the south shore of the Lake Superior region which are known to be of early pre-Huronian age carry a brown-purple, high-birefringent zircon which as been termed the hyacinth type. They have shows that all intrusives known to be late pre-Huronian to pre-Keweenawan in age carry a low-birefringent type known as malacon. Igneous rocks of Keweenawan age or later carry a third type of colorless, high-birefringent zircon which shows good crystal form.

Sediments which are older than Huronian contain only the hyacinth type. Huronian sediments carry some malacon in addition. Keweenawan sediments may carry all three types. The incidence of malacon in the sediments is low, which may be due to its perishable nature under conditions of sedimentation.

Only one type of zircon occurs in this gneiss and associated pegmatites --malacon. If we can accept the conclusions summarized above, and the evidence is overwhelming, we must postulate a late pre-Huronian to pre-Keweenawan age for the intrusive which metamorphosed this sediment.

In all Huronian sediments which have been examined by Tyler and Marsden the hyacinth type dominates and malacon is quite subordinate. From this fact the question arises, why is the hyacinth type absent from the kyanite-bearing gneiss?

The destruction of zircon to malacon is accompanied by breakdown of the molecule to amorphous silica and possibly crystalline ZrO_2, according to Chudoba (1937). This is probably due to the presence of radio-active elements within the crystal, according to Lietz (1938). If the crystal is of uniform composition one would expect destruction to occur throughout. Such would occur in a zircon which crystallized from one magma. Malacon from the granites is of this type. However, if the core of the crystal were a zircon of the normal type, around which malacon crystallized, one would expect such a zircon as occurs in this gneiss.

It is advanced here that the high birefringent cores represent detrital hyacinth type zircons of the original pelite from which the gneiss came. The malacon, either as entire crystals or as growths around the original zircons, came from the intrusive granite which accompanied metamorphism of the gneiss. It is believed that the larger part of the zircons which occur in the gneiss are of pneumatolytic origin.

A number of other workers have found good evidence for the pneumatolytic and contact metamorphic origin of zircon. Gillson (1925) cites an instance in the Pend Oreille District of Idaho where zircons have been introduced from a monzonite into sandstones, shales, and limestones. He includes a good bibliography of the literature on this subject. Trueman (1912) found enlargement of zircons near dikes cutting a Huronian quartzite at Rib Hill, Wisconsin.

The presence of a malacon within a crystal of monazite suggests that this mineral may be of like origin. The relatively high incidence of apatite, which forms more than 2% of one of the thin-sections, may be another indication of pneumatolytic action. The presence of a green-brown type of tourmaline, which occurs in the gneiss as well as in the pegmatites, is an additional bit of evidence. It is thus believed that this rock was permeated by the more mobile elements of the intruding magma.

The occurrence of quartz, which is free of nearly all other minerals, in lenses, stringers, and irregular elongate masses in the plane of the gneissose structure is here interpreted as due to metamorphic differentiation. It is believed that this occurred later than the influx of the zircons, since this quartz is generally quite barren, although the quartz in the groundmass of the gneiss contains a considerable quantity of malacon. Quartz of the pegmatites also contains a normal amount of malacon.

Major Mineral Assemblage.

The gneiss has been shown to correspond to an average shale with high iron content. The rock reached a stage in regional metamorphism just below the sillimanite grade. It has been shown that the system was essentially in equilibrium when the highest grade of metamorphism was consummated. Let us now examine in more detail the factors which account for the mineral assemblage.

Almandite is a characteristic mineral in rocks of this type. It apparently forms only where shearing stresses are present, except for the spessartite-bearing variety. Its formation is then conditioned by the presence of MnO_2 and it may be found in thermal aureoles. Concerning occurrence of almandite, Tilley (1926) writes, "The home of almandine in sediments is the dynamically metamorphosed pelite, and its widespread regional occurrence in these crystalline schists implies a ready synthesis under the influence of shearing stress."

Concerning the genesis of oligoclase in schists, Turner (1933) writes, "oligoclase normally appears as a product of dynamothermal metamorphism at relatively high grades such as prevail in the zones of almandine and perhaps kyanite. It is accompanied either by deeply-coloured hornblende, hornblende and biotite, or biotite and muscovite, according to the chemical composition of the rocks in which it occurs." *He thus follows Harker in accounting for the origin of oligoclase.*

Although the graphite may have come from carbonates, it is more probable that it represents reduced carbonaceous matter present in the original shale. The low content of calcium indicates that the shale was relatively free of calcite and dolomite.

From a study of progressive intensity of regional metamorphism in Dutchess County, New York, Barth (1936) has arrived at some notable conclusions. In what he introduces as the "Cyanite Schist Facies", twelve oxides are essential for mineral development, and a maximum of twelve minerals can exist in equilibrium. The oxides are divided into two groups.

Group 1: CO_2, P_2O_5, TiO_2, Fe_2O_3, SiO_2, CaO, Na_2O. This group exercises a passive role in the formation of such minerals, respectively, as, carbonates, apatite, titanium minerals and replacement of other oxides, magnetite and replacement of Al_2O_3, quartz, if silica is in excess, anorthite, and albite. The latter two form a mix crystal of composition dependent on their original ratio. (This latter concept is contrary to that of Turner and Harker.)

Group 2: Al_2O_3, FeO, MgO, K_2O, and H_2O. These oxides can give rise to any five of the following eight stable and one probably unstable minerals: Kyanite, muscovite, biotite, staurolite, garnet, chlorite, hornblende, microcline, and chloritoid (unstable?). The development of the five minerals of this group depends upon the ratio of the five oxides. Barth plots the analyses on a four component tetrahedron, disregarding water. The four components are, then: Al_2O_3 plus Fe_2O_3 (only Al_2O_3 in excess of that used by the feldspar), FeO plus MnO, MgO, and K_2O. The relation of staurolite to kyanite is conditioned by content of water, and this can be shown by plotting the above groups on another tetrahedron and combining magnesia with iron and adding H_2O. Barth shows that potash feldspar cannot exist in equilibrium with either kyanite or staurolite.

The mineral assemblage of the Iron County gneiss is compatible with the possible equilibrium assemblages outlined by Barth. These minerals are dependent, first, on original chemical composition of the sediment and, second, on the type and grade of metamorphism reached.

Pegmatites.

Most of the pegmatites which occur in the region show the typical decussate or mosaic structure of recrystallized or metamorphic rocks. These were probably intruded during the later stages in the formation of the gneiss before the stresses had entirely ceased. This was followed by still later vein material which does not show this stress effect, such as the andalusite-bearing mass in outcrop B. hether or not the sillimanite-bearing pegmatite of outcrop 13 is of the same generation cannot be known. It as least represents higher temperatures.

There is a question whether the veinlet which extends out from the large pegmatite vein of outcrop 13 is actually injected material, or whether it is merely leached gneiss along a crack which allowed passage of hot solutions containing silica. One would hardly expect kyanite and staurolite in an injected vein. The boundary with the gneiss is gradational and the biotite crystals partly project into the vein. The sillimanite needles shoot out into the quartz grains in long curved strings.

Development of sillimanite from mica has been postulated by Williams from an occurrence in New Zealand. He Says (1934), "Sillimanite was developed at the expense of mica alongside magmatic quartz veins cutting the schist. It is believed that the migration of silica in the veins provided a vehicle for the removal of the alkalies and substances of the RO group from the micas, and it is submitted that this process, more often than a paucity of silica, is responsible for the generation of the aluminium-silicate minerals." This reference is to formation of the aluminum-silicates in and along quartz veins and does not intend to account for their formation in the body of the gneiss.

Muscovite and microcline in the pegmatites are genetically related to the aluminum-silicate minerals. All these minerals, together with the small clear crystals of almandite and staurolite, identify the pegmatites as peraluminous. If these veins are not direct contributions, as such, they may represent the gneiss leached of its bases.

Retrograde Metamorphism.

Retrogressive changes are in an incipient stage. Sericitization is more pronounced than chloritization. It is probable that the solutions which caused these alterations represent the final liquids from the cooling intrusive long after the gneiss had formed and when regional stresses had subsided and temperatures had diminished. Apparently the pegmatite veins were avenues of easiest access for these solutions, indicated by more abundant sericitization .

The presence of microcline indicates inflow of potash. It is not known whether sericite in the oligoclase is an example of ex-solution of potash feldspar at lower temperatures, or whether it represents exchange of potash for soda, the soda being carried farther away. In view of the acid nature of the intrusive granite the latter seems the more probable explanation.

ECONOMIC MINERALS

Minerals of possible economic value are kyanite, almandite, and biotite. The kyanite forms 6-7% of the gneiss. It is of good quality and is relatively free of inclusions when crushed through 60 mesh. The garnet forms 5-6% of the rock. It is high in inclusions, but these are mainly quartz, which should not materially detract from the abrasive quality. It is a variety in which the almandite molecule is dominant. Most of the commercial garnets are of this type, according to Myers (1926) and Eardley-Wilmot (1937). An actual service test would have to be made to determine the toughness of the garnet. It is possible that the inclusions may cause it to crumble readily, in which case it would be valueless. Biotite forms 25-30% of the deposit. It is generally unaltered and of good quality. It may have some value as a by-product, though its market is limited.

The deposit contains no weathered rock, except that at the very surface. Successive glacial advances have scoured off all residual soil. Therefore it will be necessary to crush all the rock which is used for concentration. Although much of the kyanite occurs in large crystals--one-half to one and one-half inches in length--it is so closely associated or intergrown with other minerals that best results in concentration will come from crushing through 60 mesh screen or finer. It is possible that some combination of magnetic and electrostatic separation will be most economical and satisfactory. New methods of commercial electrostatic separation have been developed and described by Johnson (1938). This has not yet been applied to a deposit of this type, but it is believed it might be successful. Heavy liquid separations are now too costly. Flotation has not been successfully applied to this mineral assemblage. Tabling and jigging are now in use, but it is doubtful if good concentrates can be obtained from very finely crushed material.

Markets, prices, production, and consumption of kyanite are well summarized by Kerr (1937). He quotes an excellent bibliography of sixty-one references. Spence (1937) presents similar material for the micas.

SUMMARY

An occurrence of a kyanite-bearing gneiss in Iron County, Wisconsin is described. The gneiss contains the following chief minerals: Quartz, oligoclase, kyanite, almandite, and staurolite. The major mineral assemblage is one of equilibrium and is due, first, to the chemical composition of the original rock, and, second, to the stage of metamorphism which it has reached. The metamorphic stage corresponds to the kyanite schist facies as introduced by Barth. Chemical composition is characterized by high alumina and iron and low calcium content. The rock was originally a pelite which contained minor amounts of carbonaceous matter, now graphite. It closely corresponds in chemical composition to the pre-Cambrian slates of the Lake Superior region. It is probably of Huronian age and may represent one of the Huronian slates which appear along the strike to the northeast. Metamorphism was accompanied by intrusion of pre-Keweenawan acid granites.

Solutions from the intruding magma permeated the sediment and carried

and deposited the zircon which is now malacon and which is abundantly represented in the gneiss. These solutions may have brought in some of the apatite, tourmaline, and the monazite. At least two stages of pegmatite invasion are represented in the area. A localized vein effect was the possible removal of some of the bases, which caused further enrichment in alumina and the development of sillimanite and andalusite. Still later effects of a retrogressive nature were superposed on the gneiss. These are indicated by sericitization of the feldspar and slight chloritization of the biotite and garnet; possibly, also, development of anatase from ilmenite. The pegmatite veins were easiest avenues of access for the late solutions.

Minerals of possible economic value are kyanite, almandite, and biotite. By removal of quartz lenticles and pegmatites it should be possible to maintain averages of 8-10% kyanite, 6-7% almandite, and 30% biotite. Kyanite is relatively free of inclusions and is of good quality. Almandite is high in inclusions, mainly quartz, which may cause it to be too friable for commercial purposes. The biotite is of good quality. Concentration may best be accomplished by a combination of magnetic and electrostatic separation of finely crushed rock.

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[illegible] and [illegible]. Ordinary light, x10.

PLATES AND EXPLANATIONS

[illegible] as 1, showing [illegible] sillimanite [illegible]. Ordinary light, x14.

[illegible] section of large [illegible] in [illegible] 13, showing small clear garnet (G). [illegible] in quartz (Q), muscovite (M), and feldspar (F). Feldspar shows considerable sericite. Ordinary light, x12.

[illegible] section of biotite containing clear monazite inclusion. Note large [illegible]. Ordinary light, x24.

EXPLANATION OF PLATE I

1. Thin-section of one-inch pegmatite(?) in outcrop 13, showing development of sillimanite (Si) from kyanite (K). Groundmass is quartz, feldspar and muscovite. Ordinary light, x10.

2. Same as 1, showing higher magnification of sillimanite plume shown on right side of 1. Ordinary light, x34.

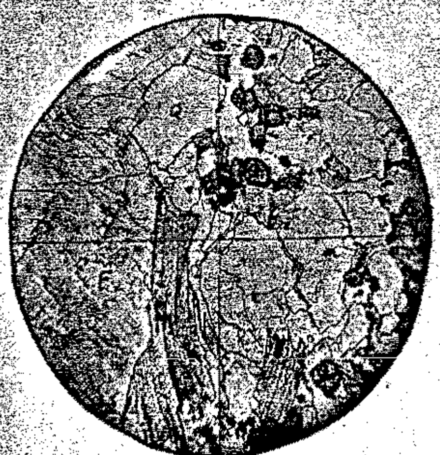
3. Thin-section of large pegmatite in outcrop 13, showing small clear garnets (G). Groundmass is quartz (Q), muscovite (M), and feldspar (F). Feldspar shows considerable sericite. Ordinary light, x19.

4. Thin-section of biotite containing clear monazite inclusion. Note large black halo. Ordinary light, x34.

PLATE I

1

2



3

4

EXPLANATION OF PLATE II

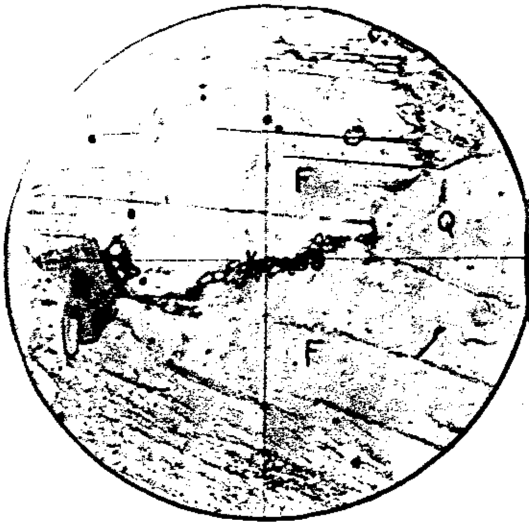
1. Thin-section of gneiss showing minute kyanite (K) blades embedded in quartz (Q) between feldspar (F) crystals. Biotite (B) and staurolite (S) are present on the left. Note sericitization of pericline lamellae in upper fledspar. Ordinary light, x34.

2. Same as 1, crossed nicols.

3. Kyanite crystals embedded in quartz between feldspars. Large feldspar near the center has thin pericline lamellae sericitized. Ordinary light, x48.

4. Thin-section showing development of small kyanite blades between feldspars. Crossed nicols, x85.

PLATE II



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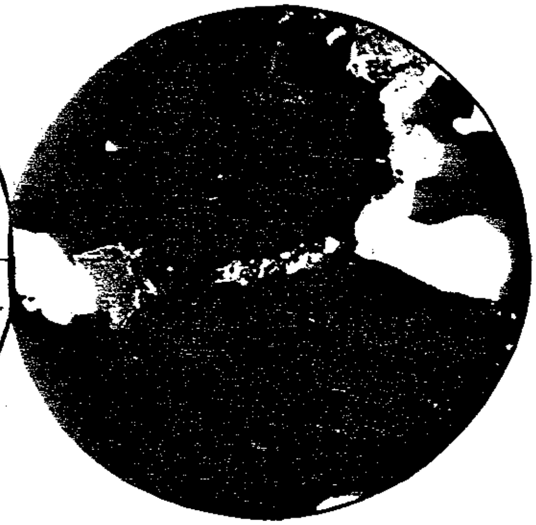

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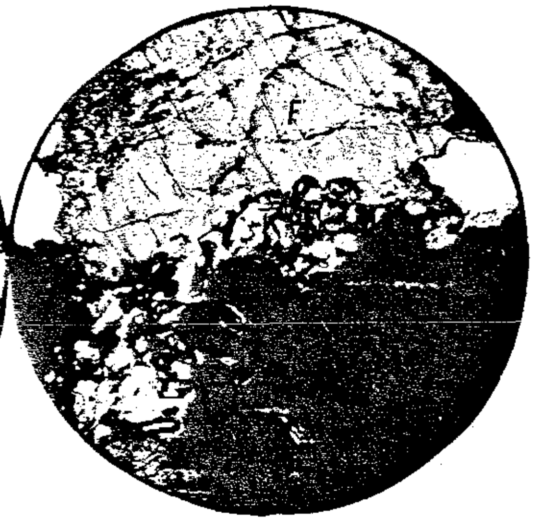


4

EXPLANATION OF PLATE III

1. Thin-section of gneiss showing halos surrounding malacon inclusions in biotite. Ordinary light, x10.

2. Thin-section of porphyroblast of kyanite, showing absence of inclusions. Ordinary light, x20.

3. Thin-section of gneiss showing euhedral staurolite. Pleochroic halos in biotite. Ordinary light, x20.

4. Thin-section showing porphyroblast of garnet. Note poikiloblastic texture and straight rows of inclusions, mainly quartz. Euhedral staurolite occurs in the lower half. Biotite has pleochroic halow. Ordinary light, x20.

PLATE III

1

2

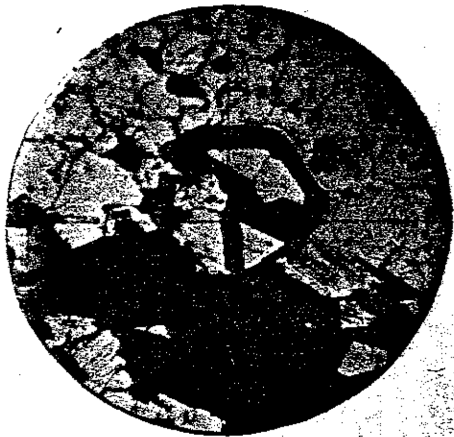
3

4

EXPLANATION OF PLATE IV

1. Thin-section of gneiss showing growth of garnet as a mere shell. Ordinary light, x19.
2. Similar to 1. Ordinary light, x19.
3. Porphyroblast of garnet. Note peculiar curved pattern of inclusions, which may be due to rotation of garnet during growth. Ordinary light, x19.
4. Similar to 3. Ordinary light, x19.

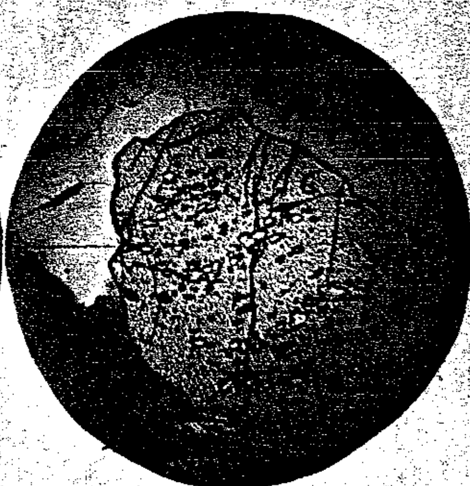
PLATE IV



1

2

3



4

EXPLANATION OF PLATE V

1. Thin-section of gneiss showing close association of kyanite, staurolite, almandite and biotite. Ordinary light, x10.

2. Thin-section through staurolite "knot". Staurolite is an optic unit. Note relict-like appearance and intermingling of garnet and kyanite. Ordinary light, x10.

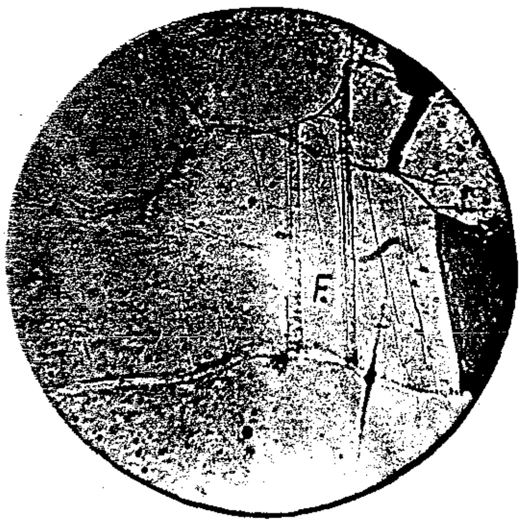
3. Thin-section of feldspar in gneiss, showing sericitization of two narrow pericline lamellae. Note relation to 001 cleavage. Ordinary light, x85.

4. Thin-section showing sericitized pericline lamellae in feldspar. Note rim of kyanite and quartz between feldspars in lower part of picture. Other minerals are biotite and apatite (A). Ordinary light, x34.

PLATE V

1

2



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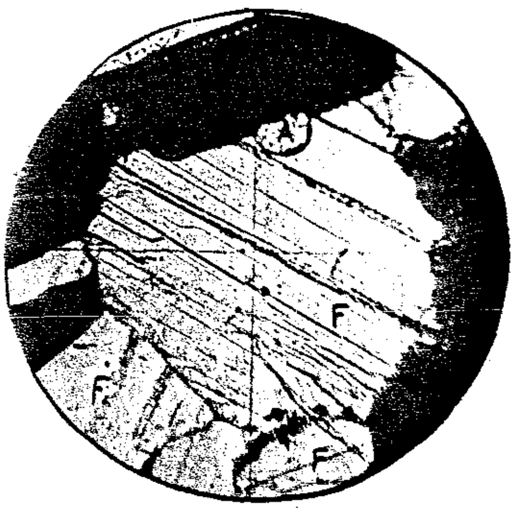


4

EXPLANATION OF PLATE VI

1, 2, and 3. Thin-sections of a large microcline crystal showing typical cross-hatch appearance and intergrowth of plagioclase of 37% An. Sections 1 and 2 are cut nearly parallel to base. Central band in 1 is plagioclase. Number 3 is cut normal to the two cleavages and shows fine ribbons of plagioclase (white) in a matrix of microcline (black). All under crossed nicols, x19.

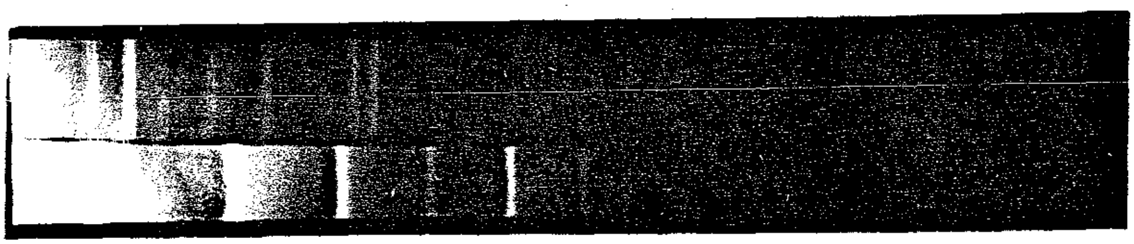
4. X-ray pattern showing lines of garnet in upper part and halite below. Spacing of lines gives length of edge of unit cube as 11.52 Å and places garnet in the non-calcium group. Low intensity of 332 line eliminates pyrope. Dominant molecule is almandite.

PLATE VI

1

2

3



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EXPLANATION OF PLATE VII

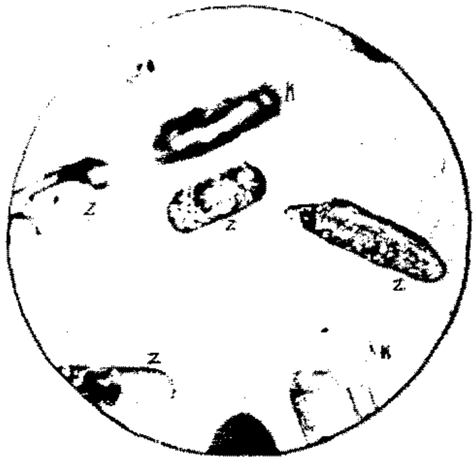
1. Photomicrograph of heavy concentrate grains mounted in Canada balsam. Note high birefringent core in zircon (Z) in center. Ordinary light, x380.

2. High birefringent core in zircon in center of field. Other minerals are kyanite (K) and anatase (An). Ordinary light, x380.

3. Core of hyacinth type zircon in malacon. Ordinary light, x380.

4. Heavy concentrate of zircon, kyanite, and anatase. Note cores and opaque inclusions in zircons. Note double zircon in lower center field. These are united along prism faces. Ordinary light, x132.

PLATE VII



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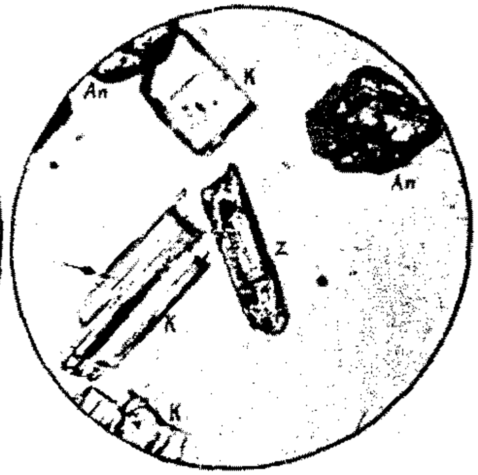

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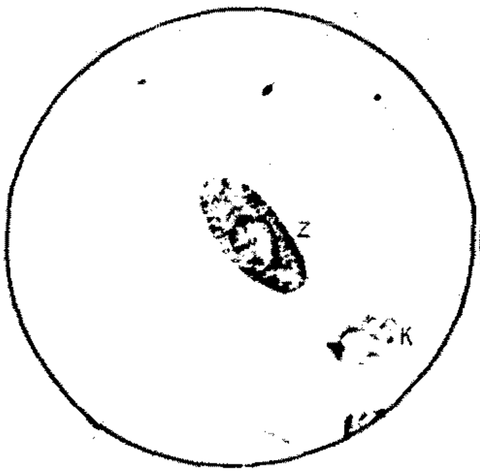

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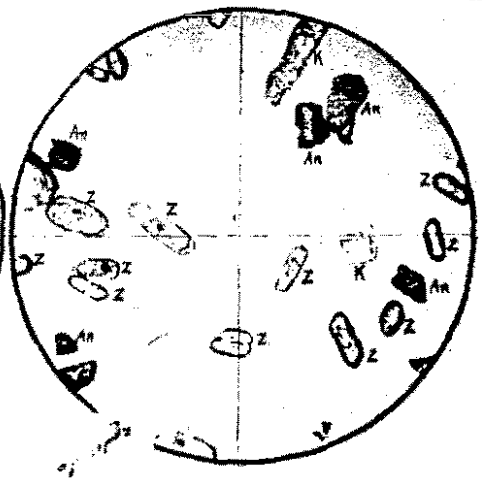

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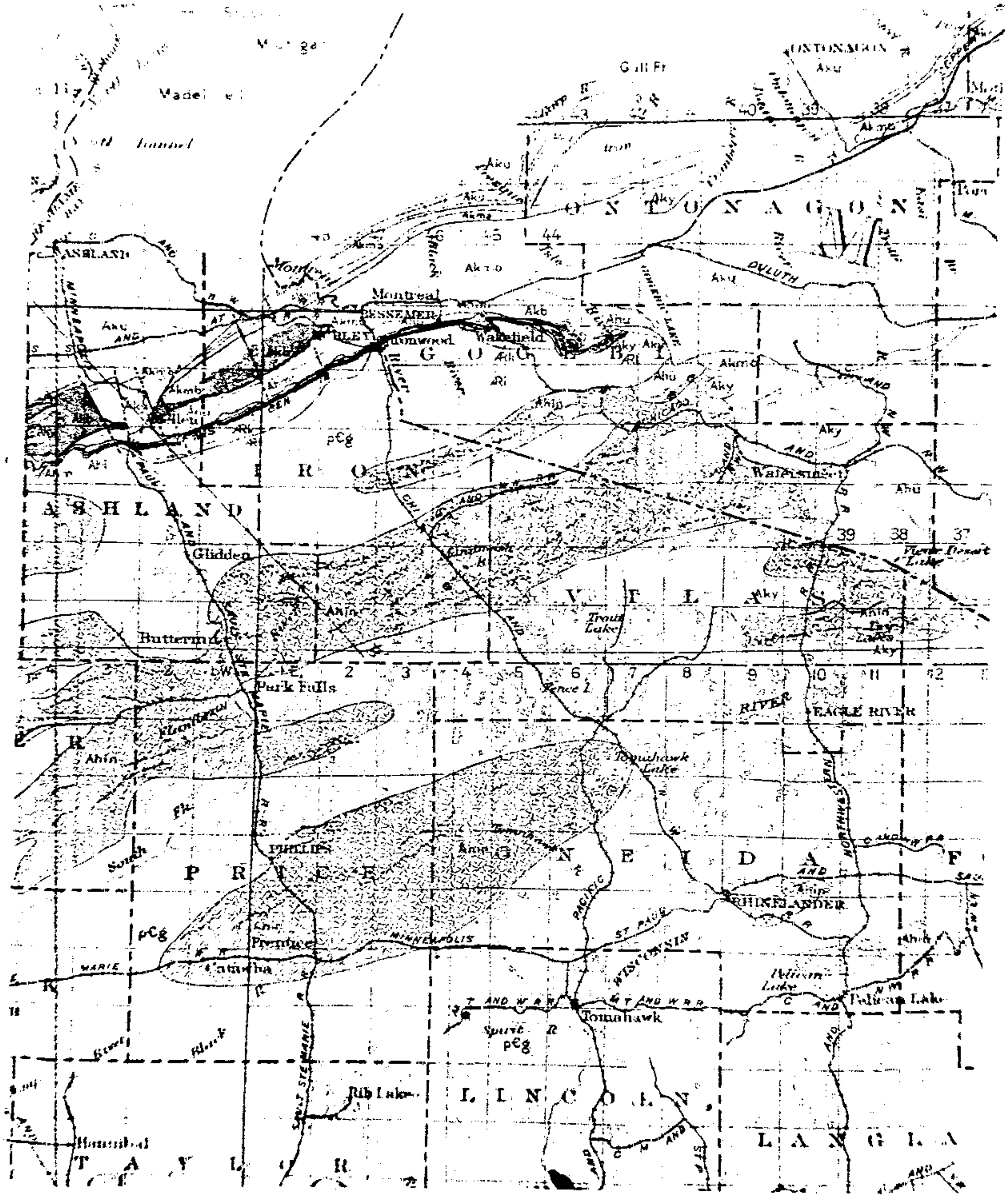
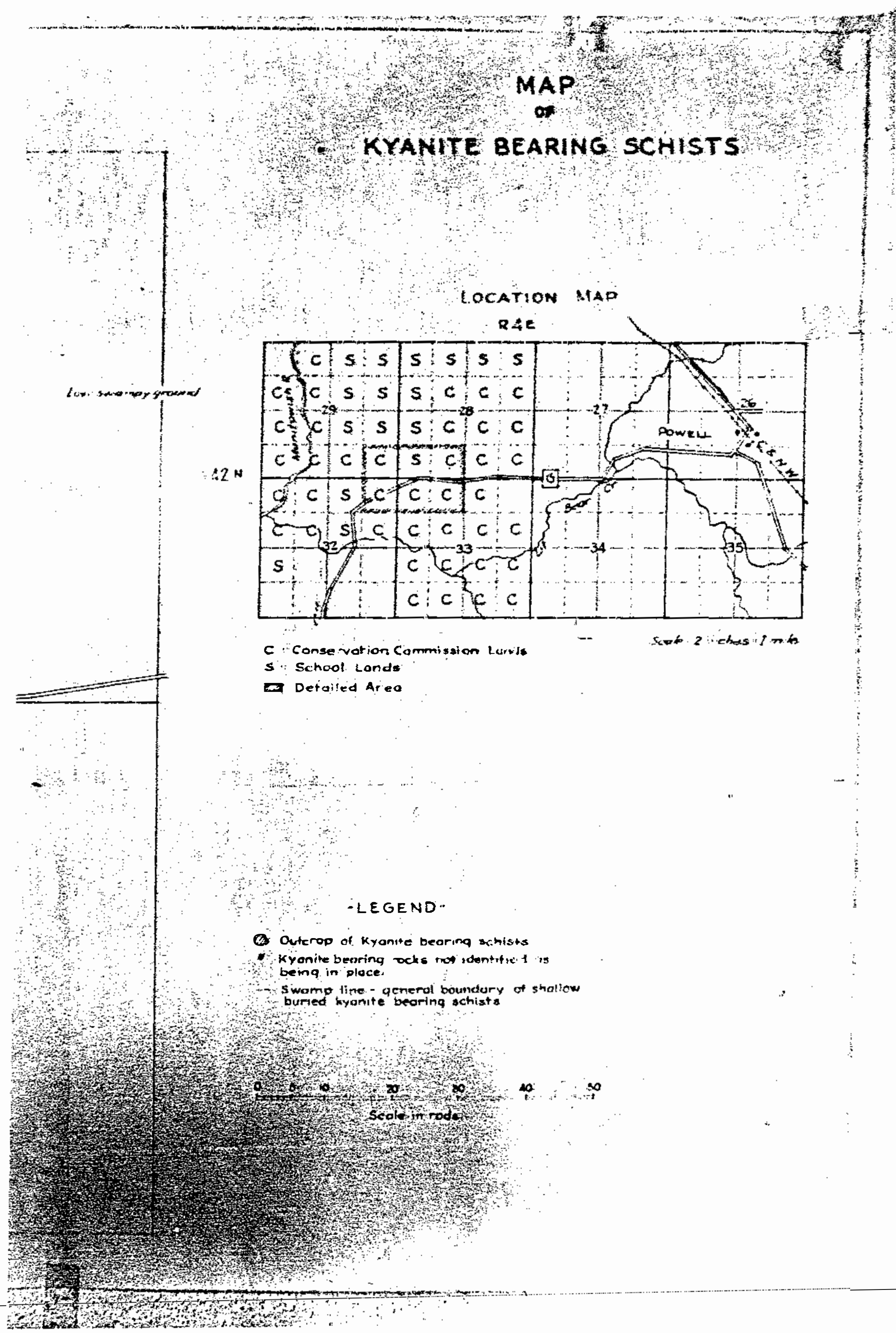
MAPS



ONTONAGON
O N T O N A G O N
DULUTH
Montreal
BESSEMER
Ironwood
Wakefield
G O G E B I C
ASHLAND
A S H L A N D
I R O N
Glidden
V I L A S
Trout Lake
Butternut
Park Falls
EAGLE RIVER
Tomahawk Lake
PHILLIPS
P R I C E
O N E I D A
RHINELANDER
Prentice
Catawba
Pelican Lake
Tomahawk
Rib Lake
L I N C O L N
L A N G L A
Hannibal
T A Y L O R
Aku
Akm
Aky
Ahn
pЄg


MAP
OF
KYANITE BEARING SCHISTS
LOCATION MAP
R4E
42 N
POWELL
C & N W
27
26
28
29
32
33
34
35
Low swampy ground
C : Conservation Commission Lands
S : School Lands
Detailed Area
-LEGEND-
Outcrop of Kyanite bearing schists
Kyanite bearing rocks not identified as being in place.
Swamp line - general boundary of shallow buried kyanite bearing schists
0 5 10 20 30 40 50
Scale in rods