Geology of the northern part of the Cherry Creek metamorphics, Madison Co., Montana
by Willard D Tompson

A THESIS Submitted to the Graduate Faculty in partial fulfillment of the requirements for the degree of Master of Science in Applied Science at Montana State College
Montana State University

Abstract:
Kyanite and sillimanite occur in the Precambrian schists, gneisses, and pegmatites of the Cherry Creek (Archean ?) metamorphics south of Ennis, Montana. The metamorphic rocks were formed as a result of the regional metamorphism of a thick sequence of sedimentary rocks—mostly limestones and shales. The stratigraphic section of metamorphic rocks is about 3,050 feet thick and consists of interlaminated dolomite-marble, dolomitic marble, kyanite-bearing schists and gneisses, amphibolites, and gneisses and schists, undivided. The rocks are tightly folded and a large isoclinal syncline, which plunges steeply to the east, repeats the section in the map area.

Three types of pegmatites occur in the area and each type displays a preference for certain host rocks: kyanite pegmatites occur in kyanite schist or gneiss; feldspar-quartz-muscovite-tourmaline pegmatites occur in marble and in kyanite schist; and feldspar-quartz pegmatites are most prominent in quartz-feldspar gneiss.

The kyanite pegmatites apparently formed by processes of metamorphic differentiation, in which aluminum ions were added to a quartz segregation and probably grew on kyanite nuclei already present in the quartz.

The inversion, sillimanite replacing kyanite, occurs repeatedly in the kyanite pegmatites and is probably due to increased temperatures subsequent to the formation of the kyanite. According to equilibrium diagrams by Miyashiro (1949) and Hietanen (1956), pegmatitic kyanite forms at low temperatures and pressures and inverts to andalusite at higher temperatures and is stable,at higher pressures. The fact that in these pegmatites, sillimanite was produced with increased temperatures, suggests that kyanite possesses no low TP stability field.

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ILLUSTRATIONS

ABSTRACT

Kyanite and sillimanite occur in the Precambrian schists, gneisses, and pegmatites of the Cherry Creek (Archean ?) metamorphics south of Ennis, Montana. The metamorphic rocks were formed as a result of the regional metamorphism of a thick sequence of sedimentary rocks--mostly limestones and shales. The stratigraphic section of metamorphic rocks is about 3,050 feet thick and consists of interlaminated dolomite-marble, dolomitic marble, kyanite-bearing schists and gneisses, amphibolites, and gneisses and schists, undivided. The rocks are tightly folded and a large isoclinal syncline, which plunges steeply to the east, repeats the section in the map area.

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INTRODUCTION AND GENERAL GEOLOGY

The aluminum silicate minerals, kyanite and sillimanite, occur in schists, gneisses and pegmatites on the northeast flank of the Gravelly Range, Montana, about 12 miles south of Ennis, Montana, and 5 miles north of and continuous with the type area of the Cherry Creek metamorphics (Peale, 1896) (See Figure 1).

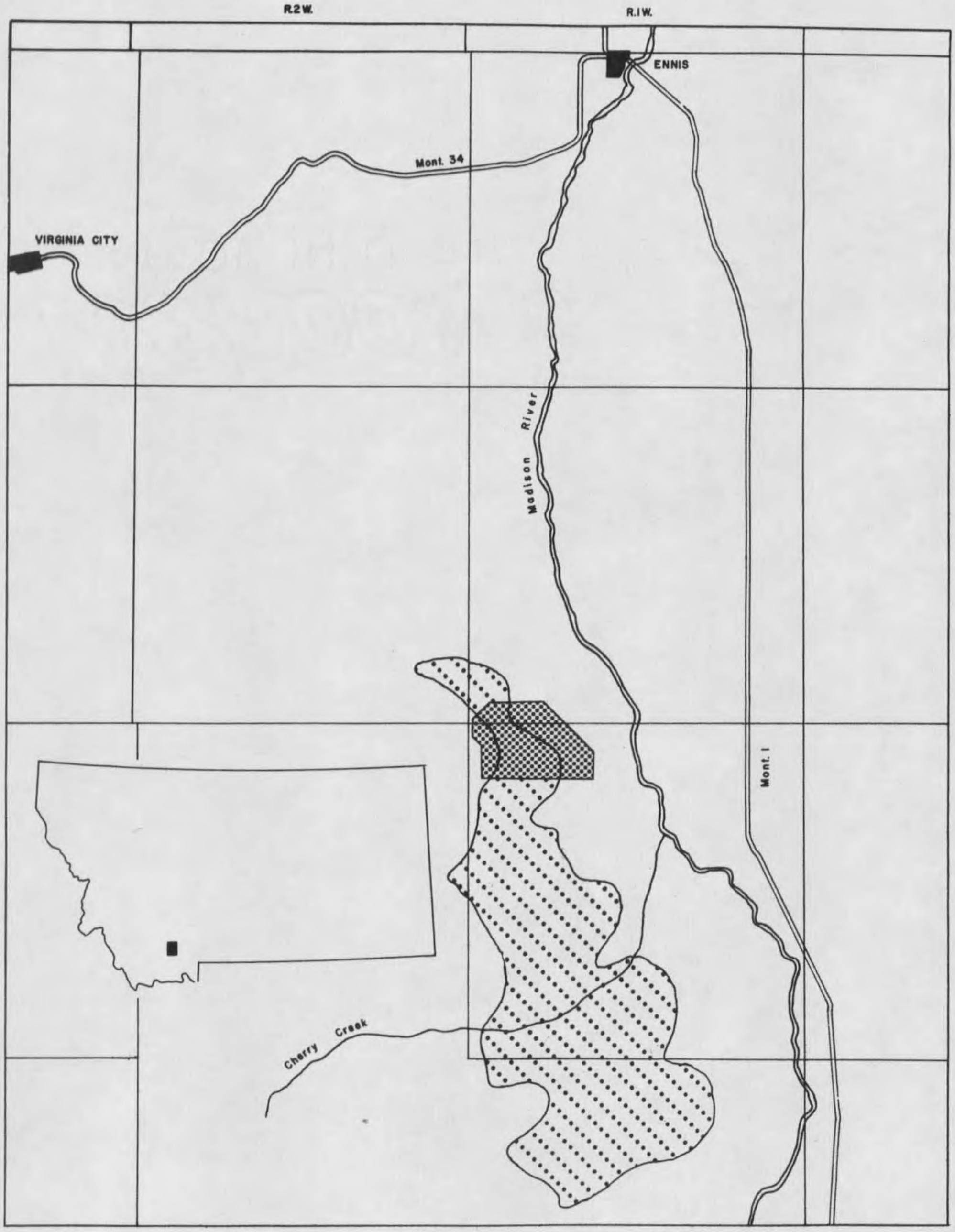
Precambrian rocks in the area include: dolomite-marble and dolomitic marble, schists, gneisses, amphibolites, and pegmatites.

Relief is moderate and outcrops of Precambrian rocks are limited; the marble layers usually form low ridges, and the schists commonly are covered by soil or alluvium.

To the west the Precambrian rocks disappear under Paleozoic rocks and display a marked nonconformity with the Middle Cambrian Flathead formation, oldest of the Paleozoic rocks in the region. To the east they are covered by large Tertiary travertine deposits and by alluvium of the Madison River. Evidence of Tertiary hot spring activity is widespread in the area and the presence of pyrolusite in the hot spring deposits has encouraged some prospecting for that mineral.

PURPOSE

The purpose of this investigation is twofold: (1) to determine in some detail the lithologic types, their extent, and the structure of a part of the Cherry Creek metamorphics, and (2) to determine the origin of the kyanite pegmatites.



After U.S.G.S.

Areal Map Showing Location of Map Area in This Report and Type Area of Cherry Creek Metamorphics.

Map Area in This Report ▩

Type Area of Cherry Creek ▨

W.D.T., 1959

FIGURE I

ACKNOWLEDGMENTS

The writer wishes to acknowledge the assistance of several individuals as well as all members of the staff of the Department of Geography and Geology, Montana State College. Dr. Robert Foster was consulted frequently during all phases of the investigation and contributed numerous valuable suggestions; Dr. William McMannis visited the area and was helpful in the interpretation of structures; Dr. Nicholas Helburn made scholarship funds available for certain phases of the investigation; Mr. Dan Andretta assisted capably in the field work; the staff of the Library of Montana State College obtained many publications which were not immediately available; Mr. Sumner Gerard provided financial support for thin sections; and Mrs. Irene Kukkola and Mrs. Nita Nickerson typed the manuscript. Field equipment was supplied by the Department of Geography and Geology, Montana State College.

FIELD WORK

Field work was carried out over a period of about three months during the summer and fall of 1958.

Mapping was done with plane table and alidade, and Brunton, directly on a topographic base map with a scale of 1 inch equals 300 feet. The base map was developed by enlarging a portion of the U. S. Geological Survey, Varney and Cameron quadrangles. Air photos were used as an aid in interpretation and in the location of significant outcrops.

SUMMARY OF PREVIOUS WORK

Most writers agree that these rocks had a sedimentary origin; however, views differ on the processes involved in their metamorphism.

Peale (1896, p.2) named the Cherry Creek rocks and assigned them to Algonkian age. They were described as consisting of

> "a series of marbles or crystalline limestones and interlaminated mica schists, quartzites, and gneisses . . . They are all highly inclined and are perfectly conformable to one another, occupying an area of 30 to 40 square miles . . . They are folded, but the folds are somewhat obscure so that it is impossible to estimate accurately the total thickness, but it is certainly not less than several thousand feet. Between Cherry Creek and Wigwam Creek, on the west side of the Madison Valley, the unchanged beds of the Cambrian rest upon the upturned edges of this group."

Runner and Thomas (1928, p. 202-203) recognized a sedimentary origin for the rocks of the Cherry Creek and attributed the alterations largely to

> "the effects of intrusive granites and silexite." "Dynamic metamorphism is regarded as having been of minor importance." "Selective metamorphism is well displayed. Highly altered sediments lie interbedded with crystalline limestones, showing little or no chemical changes."

Rabbitt (1946, p. 124) noted,

> "The thin banding, the concordancy with other rock units in the section, and the composition lead me to believe that the gneisses are metamorphosed shales and sandstones; the metamorphism being effected by the soaking of the sediments with hot solutions. It is probable that there was not much movement of material."

He later noted (p. 125),

> "The amphibolites are concordant with the gneisses, dolomites and phyllites with which they are in contact. No crosscutting has been observed . . . . The amphibolites of the area seem to have been originally sediments which have been thoroughly recrystallized without the introduction of much material.",

Reid (1957, p. 20) in proposing a sedimentary origin for the Cherry Creek metamorphics stated,

> "The complex intergradational nature of the metamorphic rocks, the wide variety of rock types present and their complex structure seem, to the

present writer, to require the proposal of a sedimentary origin for both the Pony and Cherry Creek metamorphic rocks. Earlier works, of course, have postulated that the Cherry Creek is of sedimentary origin."

In his study of the kyanite pegmatites in the Cherry Creek area, Heinrich (1948, p. 14) noted,

"The coarsest kyanite and the richest concentrations occur in the unmetamorphosed pegmatites."

He concluded,

"Most of the kyanite in the gneiss is genetically related to the intrusions of the pegmatites. The formation of kyanite does not appear to represent mere recrystallization of materials already present in the gneiss at the time of pegmatitic intrusion, but probably involves the addition of aluminum to the wall rock by pegmatitic solutions."

Thus, most workers agree on the sedimentary origin of the Cherry Creek rocks; in view of the nature of these rocks it could hardly be otherwise. However, there is no general agreement on processes involved in their metamorphism. One theory ascribes the metamorphism to a reconstitution of materials at hand while the other necessitates the introduction of new materials.

Field evidence does not support a theory for the introduction of large amounts of material and the rocks in the area could probably have been formed by the recrystallization of materials present in the sedimentary rocks with the addition of little or no new material.

DESCRIPTION OF ROCKS

Dolomite-Marble and Dolomitic Marble

Dolomite-marble and dolomitic marble are the most abundant rocks in the map area. They are very coarsely crystalline and, on the fresh surface, are white, grey, cream, pink or violet in color. The weathered outcrop is usually tan or brown.

The marble is resistant to weathering and forms the ridges of low hills. It strikes easterly and has a nearly vertical dip. It is locally siliceous and contains boudins of quartzite and wollastonite-quartz-dolomite rock.

Amphibolite pods and pegmatites occur locally in the marble. At the Rim Rock pegmatite of Stoll (1950, p. 59) (Plate 1) a large microcline-quartz-tourmaline-muscovite pegmatite is associated with a small amphibolite pod and both are conformable to the foliation of the host rock. A marble specimen taken from this locality was found to contain: 93 percent dolomite, 6 percent calcite, and 1 percent other minerals.

Kyanite Schists, Kyanite Gneiss and Associated Rocks

These rocks are largely kyanite-biotite-garnet schist and kyanite-biotite-feldspar-quartz gneiss. They contain various amounts of kyanite. Mapped with these rocks are some gneisses, amphibolites, and pegmatites which are not differentiated due to inadequate exposures or small size.

In outcrops of kyanite gneiss, kyanite blades stand out in relief and generally exhibit little, or no, lineation. Kyanite blades in the schist have a strong to weak lineation and the schist possesses moderate foliation.

Gneiss

Near the southern limit of the map area are a group of gneisses, schists, pegmatites, amphibolites, and iron formation (a thin layer, approximately 10 feet thick, Personal Communication, Dan Robertson, 1958) which are not differentiated by this writer. The foliation of these rocks is parallel to the foliation of other rocks in the area.

Lithologically, the rocks are quartz-biotite-muscovite-feldspar gneiss, quartz-biotite schists, amphibolites, and amphibole-garnet gneiss. They contain large tabular pegmatite bodies which are composed of feldspar (mostly microcline) and quartz, and are concordant with the foliation of the host rock, except for a few small pegmatites which cut the large pegmatites.

Stratigraphy of the Metamorphic Rocks

The stratigraphy of these Precambrian rocks is most conveniently expressed in terms of broad units, corresponding to the units as defined in the legend on the map (Plate I).

Structural evidence must be employed in the determination of the relative ages of the rock units since there is no general agreement among geologists as to which units are oldest or youngest, or to just how many units exist (complex folding has caused repetition of units).

The structural evidence (see Structure, p. 40 to 45) indicates that the gneisses and schists at the southern limit of the map area are the oldest of the Precambrian rocks in the area. Furthermore, there is evidence for the presence of an isoclinal fold (see Figure 5).

The calculated stratigraphy is measured along the line A'-A (see Plate I) from the southernmost contact of the kyanite-bearing rocks with the gneisses and schists, to the center of the unit in which the mica prospect (Prospect No. 2) occurs (this unit appears to be the core of the isoclinal fold, see Figure 5). The rock units are listed in order of their relative ages with the oldest rocks at the bottom of the list:

Rock Type	Thickness
Kyanite-bearing schist, schists, gneisses, and amphibolites	430 feet
Dolomite-marble and dolomitic marble with some quartzite, wollastonite rock and amphibolite. Contains many boudins	360 feet
Gneisses, schists, and marble, undivided.	210 feet
Dolomite-marble and dolomitic marble	100 feet
Kyanite-bearing schist	100 feet
Dolomite-marble and dolomitic marble	1180 feet
Kyanite-bearing schists, schists, gneisses, and amphibolites	670 feet
Total Thickness of Section	3050 feet

Local thickening and thinning is common in these rocks, so the thickness of any unit is not necessarily correlative with the thickness of the same unit in another locality.

PETROLOGY OF THE PEGMATITES

The map area is characterized by the occurrence of many pegmatites which vary widely in composition, size, and shape.

Basis for Division of Pegmatites

The pegmatites possess certain characteristics which are unique and which, when properly interpreted, may provide a clue to the pegmatite origin. These characteristics are: (1) the mineralogy of the pegmatite,

(2) the type of pegmatite host rock, (3) the contact relationship between the pegmatite and its host rock, and (4) the shape of the pegmatite body.

Although much useful information may be gained from a study of the pegmatite, the determination of the controls of pegmatite localization requires further information. Ramberg (1956, p. 188) in his study of the Greenland pegmatites noted,

> "The localization of pegmatites is (1) related to the degree of regional metamorphism in the area . . . (2) determined by the mechanical properties of the host rocks, and (3) controlled by the character of the tectonic evolution of the regions (joints and faults generally localize pegmatites). The localization of special types of pegmatites (i.e., characterized by a certain mineral composition; for example, graphite-bearing pegmatites or pegmatites with diopside) seems to have been controlled by a combination of the mineral-chemical composition of the host rocks and the temperature and pressure affecting the complex at the time of emplacement of the pegmatite."

Most pegmatites in the area can be placed into one of three groups, each group being somewhat limited in its occurrence to a particular kind of host rock. The three groups may be broadly regarded as: (1) kyanite-quartz pegmatite which commonly occur in kyanite schist and kyanite gneiss, (2) feldspar-quartz-muscovite-tourmaline pegmatites which occur in both marble and in kyanite schist and kyanite gneiss, and (3) feldspar-quartz pegmatites which are most prominent in the gneiss near the southern limit of the map area.

Kyanite Pegmatites

Kyanite pegmatites are restricted in occurrence to host rocks which contain kyanite. The pegmatite bodies are generally irregular in shape and have at least a part of the pegmatite body concordant with the foliation of the host rock (Figure 2).

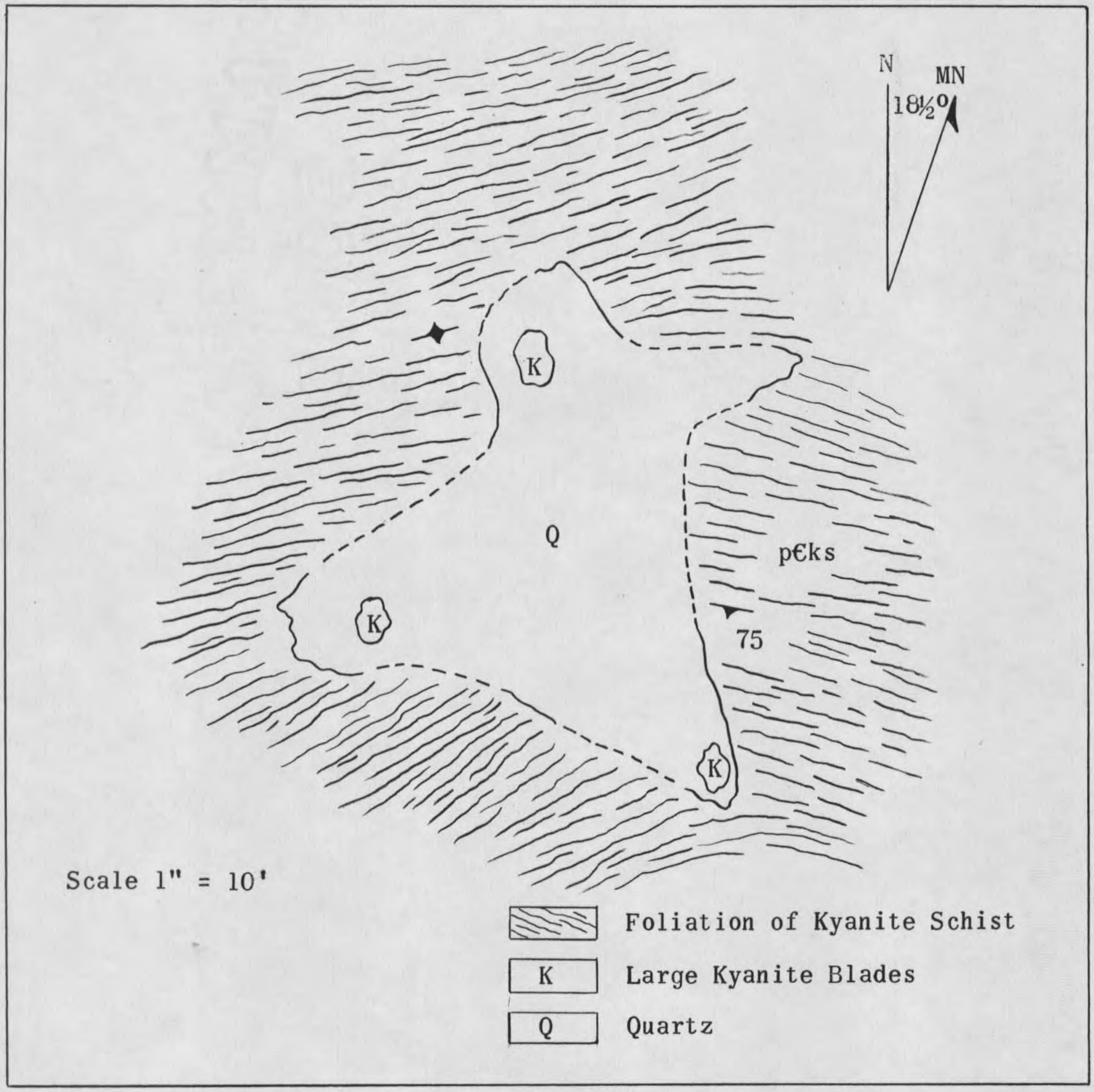


Figure 2

Kyanite bearing pegmatite in Precambrian kyanite schist, located at prospect No. 1 (See Plate 1). Pegmatite body is amoeba-like in shape and is partly concordant and partly discordant with host rock. Concentrations of large kyanite blades occur locally near the margins of the pegmatite body.

The largest concentration of the kyanite pegmatites occurs in the north central part of the map area. Local thickening of the schist in this locality and the lineation of minor fold axes suggests the presence of an "anticlinal" fold. Thus, the localization of these kyanite pegmatites may be partly related to the fold.

Heinrich (1948, p. 15) noted concentrations of kyanite "in aureoles around the quartz-rich pegmatites" and stated, "Outward from the pegmatite contacts the grade diminishes rapidly." This is inconsistent with observations made by this writer because the quantity of the kyanite in any given layer may increase, decrease, or remain constant--independent of the proximity of a pegmatite.

Kyanite blades in the schist and gneiss are generally less than one inch in length, but many are over two inches in length. The size of kyanite blades in the schist does not necessarily increase in the vicinity of a pegmatite; but certainly the largest kyanite blades occur in the pegmatites.

<u>The Sillimanite Group of Minerals</u>. - Kyanite, sillimanite, and andalusite are polymorphs of the compound Al_2SiO_5. Andalusite and sillimanite crystallize in the orthorhombic system; kyanite in the triclinic system. They all belong to the class, nesosilicates, (Winchell and Winchell, 1951, pp. 241, 250-258). The silicon-oxygen tetrahedra in nesosilicates exist as separate entities, (Mason 1958, p. 77), i.e., the oxygen atoms in the SiO_4 tetrahedra are not shared with other tetrahedra.

All three minerals dissociate to form mullite ($Al_6Si_2O_{13}$), plus liquid or glass, when heated to high temperatures. Sillimanite inverts to mullite at about 1545^{0} C. and kyanite and andalusite invert at about 1300^{0} C., (Winchell and Winchell, 1951, pp. 520, 521 and 528).

Stability Relations of the Sillimanite Group. - The stability relations of the aluminum silicate minerals are not well known because the environment in which the minerals are formed is difficult to reproduce in the laboratory. Given the proper materials with which to form the aluminum silicate minerals, three variables influence their crystallization--temperature, pressure (plus stress?), and the water vapor pressure in the system. It is the quantitative determination of these three variables which will make possible the recognition of the stability fields of the three aluminum silicate minerals.

Petrographic evidence and petrologic evidence are used to estimate the stability relations of the aluminum silicate minerals and are summarized in an equilibrium diagram (see Figure 3).

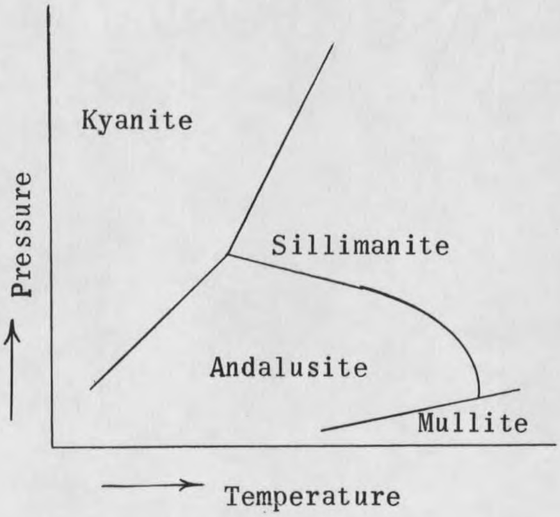


Figure 3. Diagram showing possible stability relations of the aluminum silicate minerals (after Miyashiro, 1949). Hietanen (1956) believes the triple point to be about 400^{0}.

Ramberg (1952, p. 74)(after Yoder, 1952) indicated (in equilibrium diagrams) that at 15,000 psi water vapor pressure, the triple point is about 660°, as shown in Figure 3A.

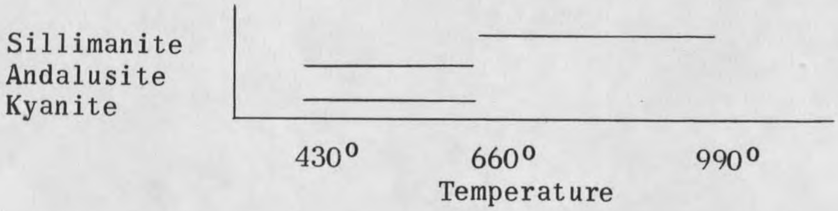


Figure 3A. Diagram showing stability relationships of kyanite, sillimanite, and andalusite under 15,000 psi water pressure.

Sillimanite is usually considered to be the highest temperature form of the Al_2SiO_5 polymorphs. Mason (1958, p. 244) has suggested that because sillimanite is the commonest of the three minerals, it may possess the largest stability field. This point is perhaps clarified by Turner and Verhoogen (1951, p. 412):

> "It is highly probable that sillimanite, usually assumed to be stable only at high temperatures, is actually the stable form of Al_2SiO_5 over a much broader range, from normal surface temperatures almost to the melting point at atmospheric pressure."

They also suggest that some high temperature reactions, e.g., the formation of sillimanite at extreme temperatures, may be irreversible:

> ". . . sillimanite, formed only at maximum metamorphic temperatures, at high pressures, or under catalytic influence of deformation or pore fluids, would remain stable and show no tendency to invert to any other form during subsequent cooling."

Andalusite apparently is stable at high temperatures and low pressures (Ramberg, 1952, p. 45) and, in particular, it does not form in rocks which are stressed (Barth, 1951, p. 256) (Mason, 1958, p. 244) (Hietanen, 1956, p. 26). Barth (1951, p. 256) notes ". . . that the lattice of andalusite is highly susceptible to, and easily destroyed by stress forces."

Writers generally agree that kyanite develops in aluminous rocks which have undergone metamorphism at high pressures and intermediate temperatures (Mason, 1958, p. 244) (Hietanen, 1956, p. 26) (Griggs and Kennedy, 1956). Some writers prefer to include stress as a contributing factor in the formation of kyanite, mostly because kyanite has a very high density (Barth, 1951, p. 256) (Hietanen, 1956, p. 26). Barth (1951, p. 257) notes that

> "although stress may favor the development of kyanite, it is not necessary; kyanite can grow in a pegmatite where no stress seems to have been present."

Miyashiro(1949a, abs.) criticizes the idea that stress is necessary for the formation of certain minerals and considers temperature, hydrostatic pressure, and concentration of the components as "the only essential factors controlling metamorphism."

Mullite is not common as a naturally-occurring mineral, but it is produced artificially.

Kennedy (1955) has found that a solid solution exists between mullite and sillimanite at temperatures of 550°-600° and 400 bars to 3000 bars (5000 psi to 43,500 psi) water pressure. Mullite is formed at the low pressures; sillimanite at the high pressures.

The significance of the stability relations of the sillimanite group and their bearing on the kyanite pegmatites in the map area is discussed below under "Origin of Kyanite Pegmatites."

Mineralogy of the Kyanite Pegmatites. - Quartz is the most abundant mineral in the kyanite-bearing pegmatites. The pegmatite at Prospect No. 1 (Plate I) in the north central part of Section 6 was mapped in some detail and concentrations of kyanite are noted on the map of the pegmatite (Figure 2). Calculations based on surface observations indicate that kyanite and sillimanite comprise about one-half percent to 1½ percent of the volume of the pegmatite. Approximately 98 percent of the pegmatite is quartz. In the areas of kyanite concentration quartz makes up about 45 percent of the total rock; kyanite and sillimanite, 35 percent; sericite, 15 percent; and the remaining 5 percent may consist of any of the following minerals: plagioclase, muscovite, garnet, tourmaline, biotite, graphite, and apatite. Other kyanite pegmatites in the area contain about the same mineral assemblage, but proportions vary in different pegmatites.

Description of Kyanite Pegmatites.- Kyanite pegmatites display many kyanite blades up to three inches in length and several are nearly eight inches. At the southwest corner of the pegmatite at Prospect No. 1 (Figure 2) are a group of large intersecting blades up to ten inches long which are the largest seen in the area. It is interesting to note that in this pegmatite all concentrations of kyanite occur near the margin of the pegmatite body, and blades of kyanite are not oriented and generally intersect other blades. The blades in the pegmatite are transparent, white or blue in color, and single blades may exhibit variations of all three colors. A brilliant blue, which is noted in some crystals, is generally restricted to the central part of the blade. Sillimanite occurs as small, white, felted masses.

At Prospect No. 5 (Plate I) massive white and brown sillimanite occurs in a small, irregular pod associated with a kyanite pegmatite. The contacts are obscure, but the pod appears to be about ten feet long and three feet wide and is exposed in a small draw at the site. A bulldozer pit has exposed a spectacular kyanite-quartz-sillimanite pegmatite at this location. Some of the quartz in this pegmatite bears deep striations where it has been in contact with kyanite blades. The striations apparently were imposed upon the quartz by kyanite.

Small garnets, species pyralspite, (a mixture of almandite and spessartite as defined by Winchell & Winchell, 1951, p. 483) occur in the schist and in the pegmatites and commonly occur as inclusions in kyanite blades. Graphite is also an abundant (up to one percent) mineral in the schist and occurs commonly in the pegmatites and as inclusions in kyanite and sillimanite.

Silvery-white sericite occurs along the cleavage planes of kyanite and appears to replace kyanite. Massive, yellow sericite occurs in some of the pegmatites and replaces kyanite, quartz, plagioclase, and biotite.

Biotite, which is a major constituent of the kyanite schist, is not common in the kyanite pegmatites.

Optical Properties of Kyanite and Petrogenesis. - A kyanite blade, which was taken from the pegmatite at Prospect No. 5, was mounted on a slide with the 100 cleavage parallel to the plane of the slide. The extinction angle, which was determined by taking the average of several measurements on this blade, was $Z \wedge c = 30.2^{\circ}$.

Under the microscope sillimanite appears in small, fibrous masses and as long, straight, or slightly curving needles projecting from the fibrous masses. Groups of needles are generally parallel to subparallel. Isolated sillimanite needles occur, but are not as common as needles which project from fibrous sillimanite. Almost without exception, the sillimanite needles appear to replace quartz or kyanite. Some needles show an inclined extinction, and these, presumably, are needles of kyanite--possibly pseudomorphs after sillimanite. Hietanen (1956, p. 17-19), in her study of the aluminum silicates in the Boehls Butte quadrangle, Idaho, noted "pseudomorphs of kyanite and andalusite after sillimanite."

Graphite is found between the mineral grains and as inclusions in some of the minerals. Kyanite commonly has graphite inclusions and sillimanite may have graphite within the fibrous masses. Graphite generally appears to have been forced into an "orientation" by the crystallization forces of the surrounding minerals.

Plagioclase is not abundant in the kyanite pegmatites and when present, it is commonly sericitized. Plagioclase from the pegmatite at Prospect No. 1 has been identified as andesine (Ab_{67}, An_{33}), as determined by measurement of extinction angles from the trace of {010} in albite twins.

Several mineral replacements occur regularly in the pegmatites and are worth noting: sillimanite $\longrightarrow$ kyanite (sillimanite replaces kyanite) (see Plate II, Figures 1 and 2, and Plate VIII, Figure 1), sillimanite quartz (see Plate V, Figure 1), sillimanite → kyanite and plagioclase (see Plate VI, Figure 1), sillimanite → tourmaline (see Plate V, Figure 1), sillimanite and kyanite → garnet (see Plate IV, Figure 1), sericite → kyanite and quartz (see Plate III, Figure 1 and 2), muscovite → kyanite (see Plate VII, Figure 2), sillimanite → biotite (in minor amounts), kyanite → biotite (in minor amounts) and calcite may replace any of the petmatite minerals (calcite is apparently a secondary mineral).

The order in which the minerals formed,may be summarized as follows: quartz and biotite, kyanite, sillimanite, sericite and calcite. In order to avoid ambiguity, it should be noted that although quartz is replaced by kyanite and sillimanite, some quartz apparently formed later than the aluminum silicate minerals and before sericite. Hence, there is probably early-formed quartz and late-formed quartz in the pegmatites.

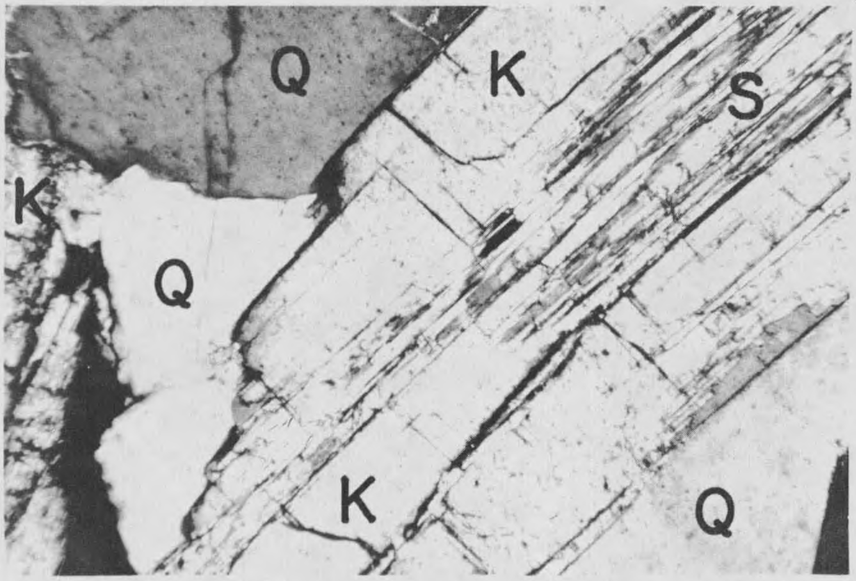


Figure 1. Large kyanite blade being replaced by sillimanite. Specimen taken from kyanite pegmatite at prospect No. 1. Crossed nicols, 67X. K = kyanite; Q = quartz; S = sillimanite.

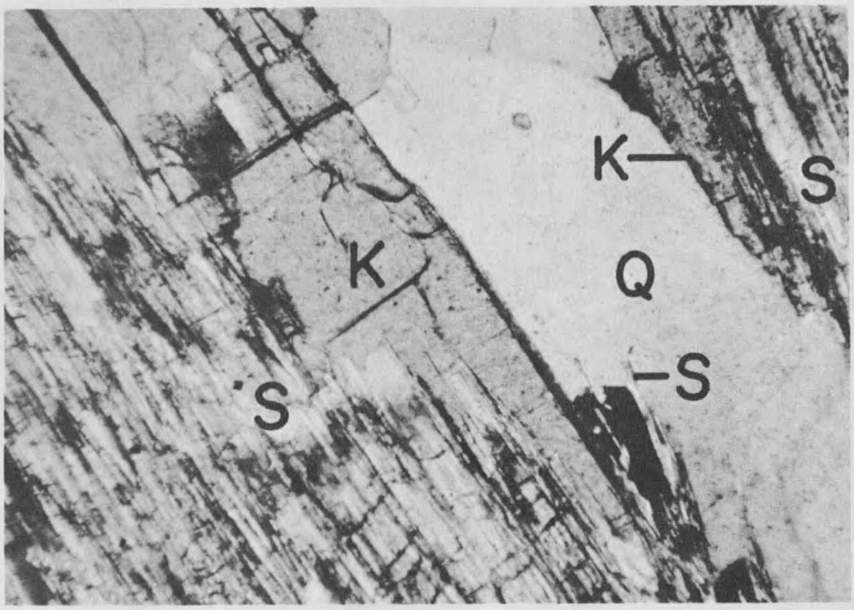


Figure 2. Sillimanite replacing kyanite and quartz. Specimen from pegmatite at prospect No. 1. Crossed nicols, 67X. K = kyanite; S = sillimanite; Q = quartz.

PHOTOMICROGRAPHS

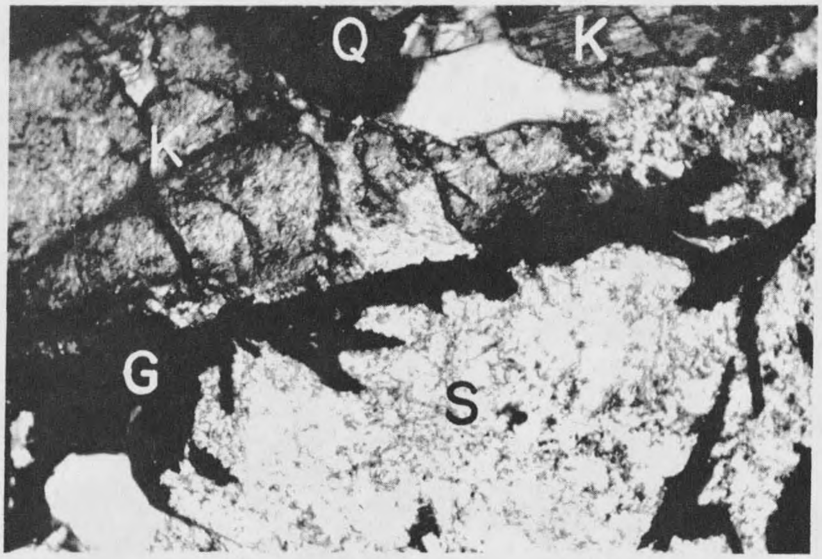


Figure 1. Sericite with graphite inclusions. Some kyanite being replaced by sericite. Crossed nicols, 67X. K = kyanite; G = graphite; Q = quartz; S = sericite. Specimen from pegmatite at prospect No. 1.

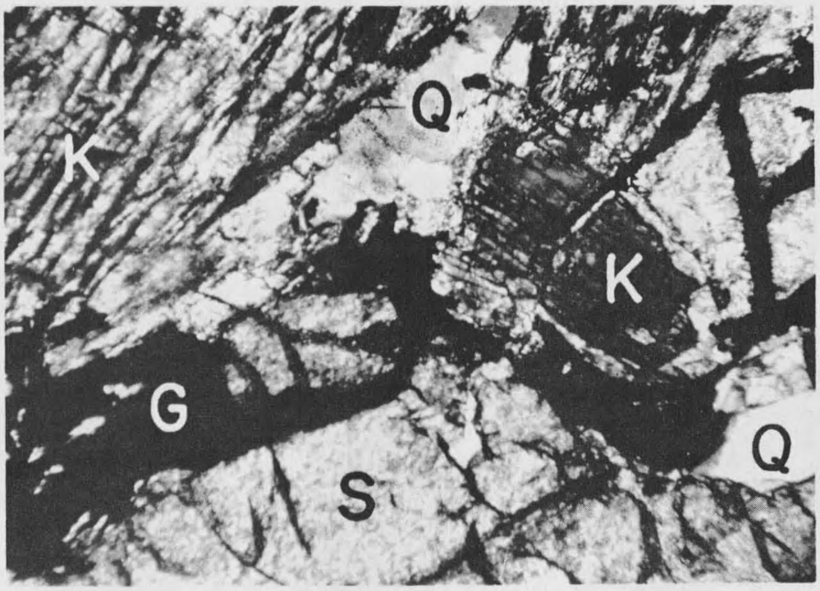


Figure 2. Kyanite and sericite with graphite inclusions. Sericite and kyanite being replaced by sericite. Crossed nicols, 67X. K = kyanite; Q = quartz; G = graphite; S = sericite. Specimen from pegmatite at Prospect No. 1

PHOTOMICROGRAPHS

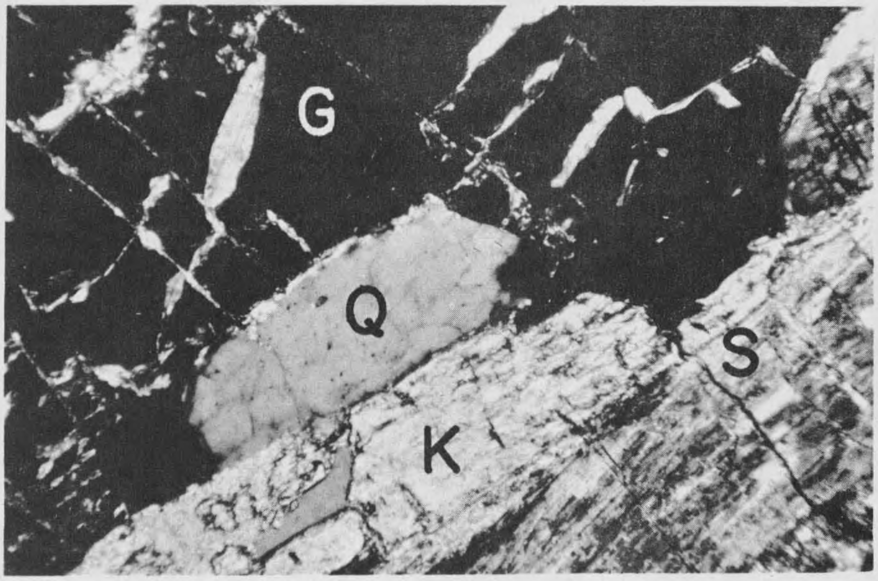


Figure 1. Sillimanite and kyanite replacing garnet. Garnet has quartz inclusions. Crossed nicols 67X. K = kyanite; S = sillimanite; G = garnet; Q = quartz. Specimen from pegmatite at prospect No. 1.

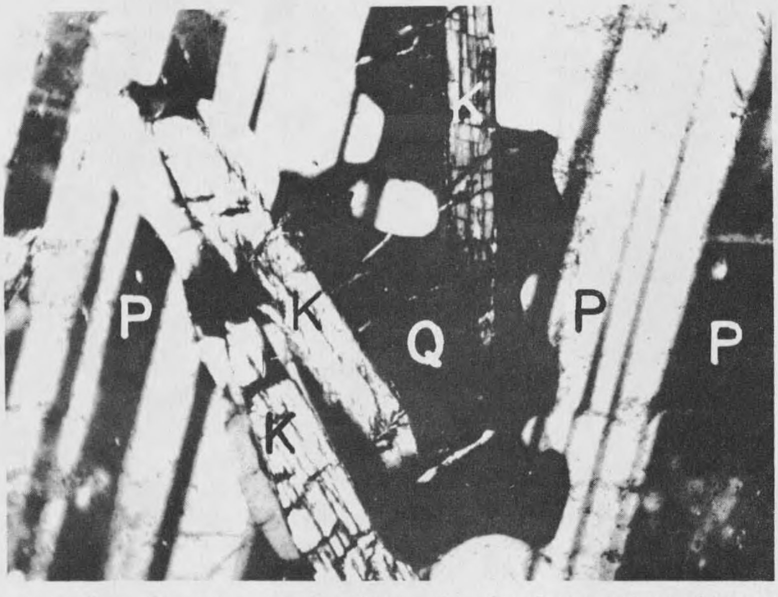


Figure 2. Quartz replacing plagioclase, kyanite replacing quartz. Crossed nicols, 67X. P = plagioclase; Q = quartz; K = kyanite. Specimen from kyanite-quartz gneiss near prospect No. 7.

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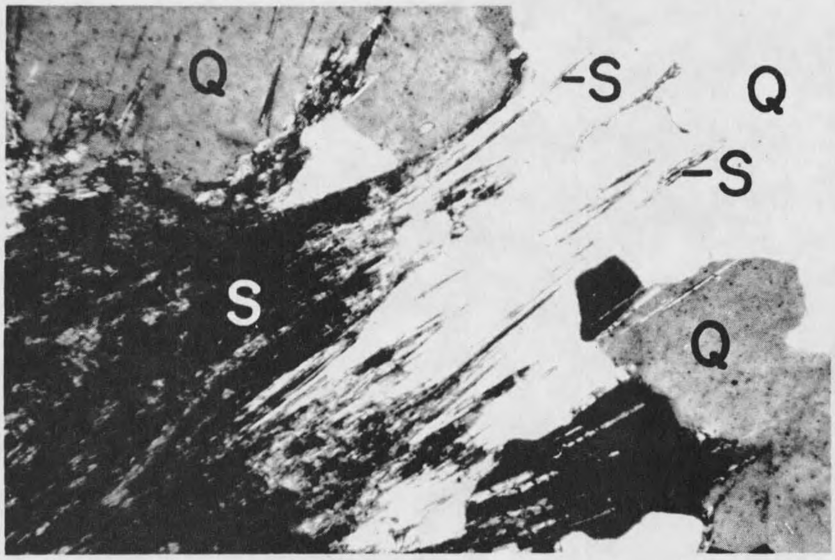

Figure 1. Sillimanite needles projecting from fibrous sillimanite and replacing quartz. Crossed nicols, 67X. S = sillimanite; Q = quartz. Specimen from pegmatite near prospect No. 1.

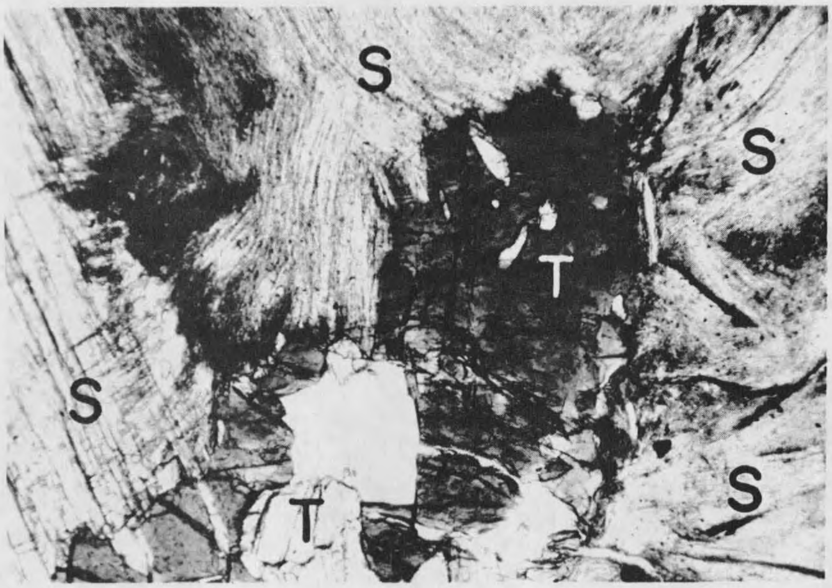

Figure 2. Sillimanite needles and fibres replacing tourmaline. Plane light, 67X. Specimen from pegmatite at prospect No. 5. S = sillimanite; T = tourmaline.

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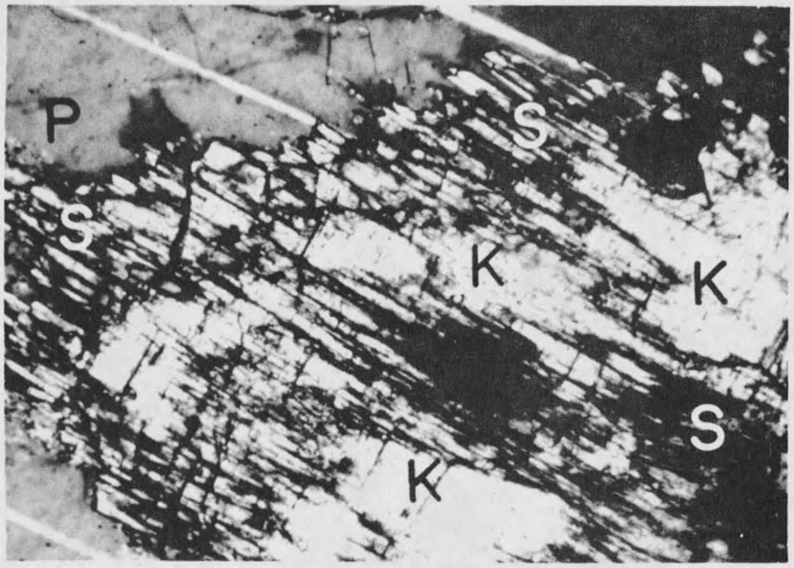

Figure 1. Sillimanite replacing kyanite and plagioclase. Specimen from prospect No. 5. Crossed nicols, 67X. P = plagioclase; K = kyanite; S = sillimanite.

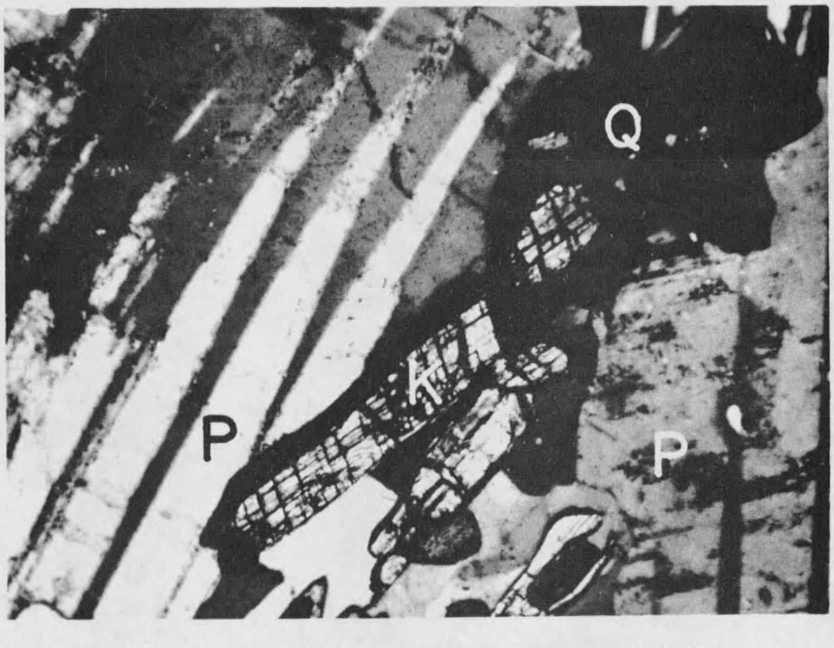

Figure 2. Quartz replacing plagioclase, kyanite replacing quartz. Specimen from quartz-kyanite gneiss near prospect No. 7. P = plagioclase; K = kyanite; Q = quartz. Crossed nicols, 67X.

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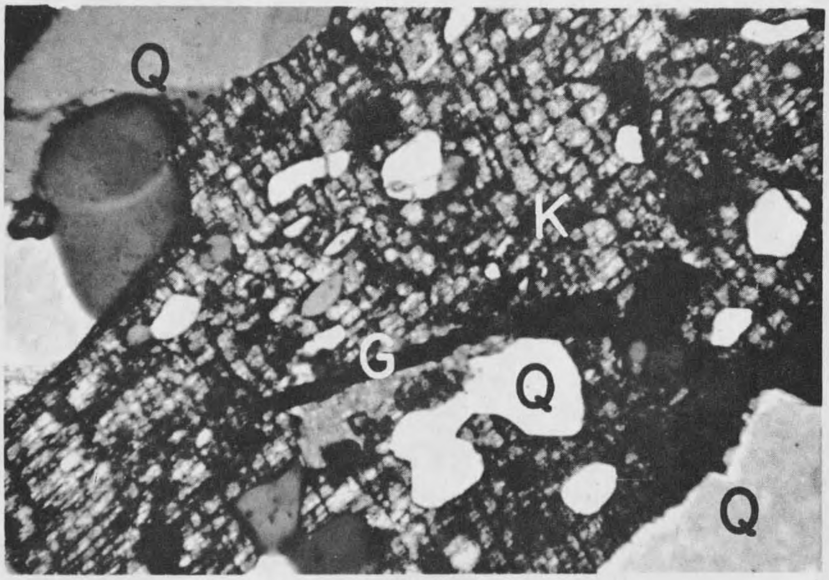


Figure 1. Large kyanite blade with quartz and graphite inclusions. Specimen from kyanite gneiss near prospect No. 4. Crossed nicols, 67X. Q = quartz; K = kyanite; G = graphite.

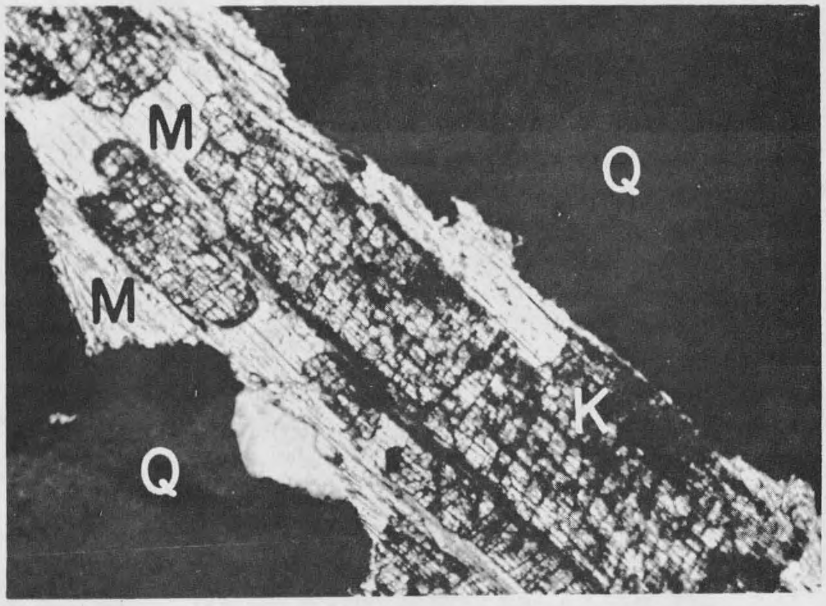


Figure 2. Kyanite blade being replaced by muscovite. Specimen from Vetter Mica prospect (prospect No. 2). Crossed nicols, 67X. Q = quartz; K = kyanite; M = muscovite.

PHOTOMICROGRAPHS

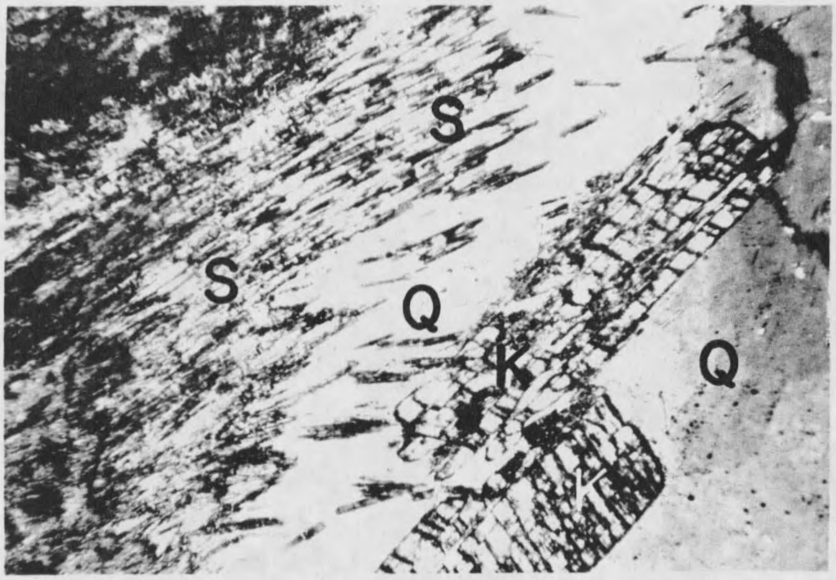


Figure 1. Sillimanite replacing quartz and kyanite (along edge of blade). Specimen from kyanite pegmatite at prospect No. 1. Crossed nicols, 67X. S = sillimanite; Q = quartz; K = kyanite.

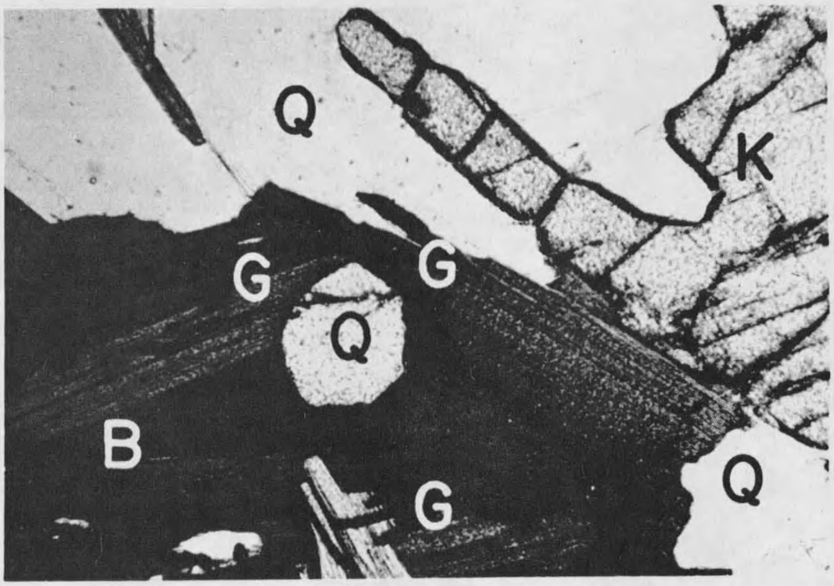


Figure 2. Typical field of kyanite-biotite schist. Specimen from prospect No. 4. Plane light, 67X. B = biotite; K = kyanite; Q = quartz; G = graphite.

PHOTOMICROGRAPHS

Inversions and Stability Relations of the Aluminum Silicate Minerals in the Kyanite Pegmatites. - Kyanite and sillimanite are the two aluminum silicate minerals which occur in the kyanite pegmatites; no andalusite was found in the pegmatites.

The most common inversion of the aluminum silicate minerals in the pegmatites is sillimanite→kyanite (sillimanite replacing kyanite), and this inversion is noted repeatedly in thin sections (see Plate II, Figures 1 and 2). The inversion, kyanite→sillimanite, may also exist because there are a few needles which look like sillimanite but have an inclined extinction, and hence, may be kyanite--possibly pseudomorphs after sillimanite.

The consistency with which the inversion, sillimanite→kyanite, occurs in the kyanite pegmatites may suggest that a change is in order for the equilibrium diagram, as shown in Figure 3. The location of the lower part of the kyanite stability field is based on the fact that kyanite may occur in a pegmatitic environment and presumably crystallizes in a manner similar to that of most minerals which are typified by pegmatitic occurrences, i.e., crystallization at low temperatures and pressures. If this were the case, i.e., if the kyanite in the pegmatites crystallized at low temperatures and pressures, then its position in the equilibrium diagram (Figure 3) should be at the lower end of the kyanite stability field. According to the diagram (Figure 3) then, an increase in pressure should not affect the kyanite since it is stable at high pressures. An increase in temperature, however, should cause the kyanite to invert to andalusite, an inversion which did not occur in the pegmatites discussed in this paper. The inversion is sillimanite⟶kyanite, as noted above. Thus, the equilibrium diagram would probably be more applicable to the kyanite-sillimanite stability relations which were observed in the kyanite pegmatites, as discussed in this paper, if the diagram were constructed as in Figure 3B.

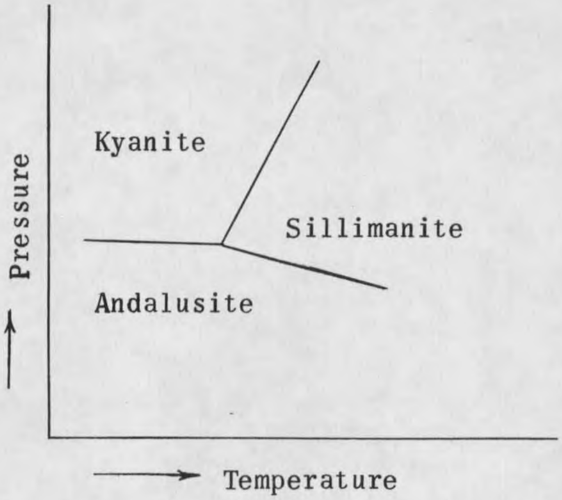


Figure 3B. Equilibrium diagram of the aluminum silicate minerals, illustrating the proposal that kyanite may have no low-pressure stability field.

The position of andalusite in this equilibrium diagram is taken from Miyashiro (1949) and since no andalusite was identified in the pegmatites, its stability field can be given no comment.

The evidence outlined above strongly suggests that the kyanite in these pegmatites did not form under low TP conditions, but formed under conditions of moderate pressures and increasing temperatures.

<u>Origin of the Kyanite Pegmatites</u>. - Occurrence of rocks composed of quartz and large kyanite blades (generally referred to as kyanite pegmatites) have been described many times in the literature, and their origin

has been attributed to various processes which range from precipitation from a hydrothermal solution to processes involving metamorphic differentiation.

The fact that kyanite does occur in pegmatites has led many writers to the conclusion that kyanite is stable at low PT conditions as well as at moderate-to-high PT conditions (see Figure 3).

Several lines of evidence lead to the conclusion that the pegmatites in the map area of this investigation formed as a result of metamorphic differentiation; possibly a combination of processes involving recrystallization and concretion (see Ramberg, 1952, p. 220-226, 237-261). The evidence may be summarized as follows: (1) kyanite-quartz pegmatites occur only in host rocks which contain kyanite and quartz; (2) kyanite (and sillimanite) are commonly shared between the pegmatite and host rock; (3) the aluminum silicate minerals commonly replace other minerals in the pegmatites; (4) there has been no great enrichment of Al_2O_3 (see Figure 2 and p. 20), but rather a relative depletion of (Fe, Mg)O and great enrichment of SiO_2 with, perhaps, slight local enrichment of Al_2O_3 (replacement of biotite by kyanite and/or sillimanite represents a relative local enrichment of about 40 percent Al_2O_3); and (5) the pegmatite bodies possess no regular shape.

Quartz is commonly replaced in the pegmatites by kyanite and sillimanite. Thus, it may be reasonable to believe that the first stage in the formation of the pegmatite occurred with the development of a quartz segregation, i.e., the formation of a quartz "vein". The formation of the quartz body could be initiated by dilation or shear, and during its growth could probably isolate some of the minerals from the host rock as inclusions.

The formation of a segregation in rocks which are in chemical equilibrium will result in chemical disequiligrium, e.g., a space which was occupied by rocks with, perhaps, 60 percent SiO_2, 20 percent Al_2O_3, and 10 percent K_2O will, after the segregation, be occupied by rocks with nearly 100 percent SiO_2.

In order to re-establish equilibrium, new mineral associations are formed in the host rocks, and certain ions (the more mobile ions) may migrate to the site of disequilibrium and establish a new assemblage of minerals--in this instance, kyanite and quartz, which are stable under the prevailing PT and chemical conditions.

The development of large crystals in a metamorphic environment is well explained by Ramberg (1952, p. 223):

> "The probability of nucleus formation at given P and T and a given degree of supersaturation is determined by the character of the pre-existing minerals [kyanite in this case] and their interfaces. The new nuclei will, therefore, preferably tend to form in or on one of the pre-existing minerals or in an interface between two particular species of old minerals. . . . If the most favorable place of nuclei formation is an interface between minerals which are rare in the host rock, then only a few nuclei will form and the growth of 'glomeroblasts' (polycrystalline monomineralic clusters) around the nuclei thus creates a certain type of metamorphic differentiation."

Thus, if the above theory is applied to the formation of the kyanite-quartz pegmatites as discussed in this paper, we may postulate that a few kyanite crystals, isolated in a quartz-rich segregation, could act as nuclei for additional aluminum and silicon ions, and when the aluminum and silicon ions became available, their growth on the nuclei could promote the development of large crystals of kyanite. The inversion, sillimanite → kyanite, which is noted repeatedly in thin sections, may be due to an increase in temperature subsequent to the formation of kyanite (see Figure 3B). Sericite replaces kyanite and sillimanite in most thin sections and appears to have formed as a result of retrogressive metamorphism, possibly accompanied by the introduction of H_2O and K_2O to the pegmatite.

It has been shown that the kyanite pegmatites do not represent areas of aluminum enrichment; and therefore, there is no need to suppose that aluminum was introduced by hydrothermal solutions or pegmatitic solutions, as proposed by Heinrich (1945, p. 14-15). Further, there is no evidence of Precambrian intrusions in the area from which solutions might emanate. Neither is there reason to believe that the pegmatites are related to the Tertiary extrusive rocks in the Gravelly Range, since none of the pegmatites intrude rocks which are younger than Precambrian in age.

Feldspar-Quartz-Muscovite-Tourmaline Pegmatites

Mineralogy. - These pegmatites occur in marble or schist and contain microcline, quartz, plagioclase (Ab_{95}, An_5), tourmaline, biotite, garnet, and muscovite. Kyanite and sillimanite may occur in minor amounts if the host rock contains kyanite or sillimanite. Microcline is generally the most abundant mineral in these pegmatites; however, some pegmatites which contain quartz, muscovite, and tourmaline contain little or no microcline.

Description. - The pegmatite bodies are lens-shaped or irregular and are conformable with the foliation of the host rock. Several of these pegmatites contain small concentrations of muscovite and some have been prospected; however, no successful mining program has developed.

Pegmatites in Marble Layers. - Several feldspar-quartz-muscovite-tourmaline pegmatites occur in marble layers in the northern one-fourth of Section 6 (Plate I), and a few are found in other parts of the map area, e.g., the pegmatite which occurs in Section 6 along the southern boundary of the southernmost marble unit. These pegmatites lie within the marble units and along the margins of schists and amphibolites, which suggests that the pegmatite-forming materials may have been derived from the schists and amphibolites.

Rim Rock Pegmatite and Vetter Prospect. - Stoll (1950, p. 59) mapped the Rim Rock pegmatite (located in northcentral Section 6, Plate I) and the Vetter mica prospect (Prospect No. 2, Plate I). He reported that the southwest end of the Rim Rock pegmatite is in fault contact with a reddish-brown, thin-bedded quartzite. No fault is evident at the location of the pegmatite, and the quartzite which is in contact with the pegmatite is talus from the Middle-Cambrian Flathead formation that crops out about 350 feet to the northwest.

Control of Localization of the Rim Rock Pegmatite. - The presence of a small amphibolite boudin adjacent to the Rim Rock pegmatite suggests that the boudin may have influenced the localization of the pegmatite. During metamorphism the boudin could act as a rigid body creating a pressure shadow to which the pegmatite-forming materials could migrate. Ramberg

(1956, p. 197) noted,

"Pegmatitic minerals will grow in pressure shadows in lee of rigid inclusions in much the same fashion that quartz grows in pressure shadows of garnet porphyroblasts."

The strike of foliation of the host rock suggests that dilation, resulting from the folding of the host rock, may also have influenced the localization of the Rim Rock pegmatite, i.e., a low pressure area produced during folding could conceivably be an area of accumulation for the pegmatite-forming materials (Figure 4).

Feldspar-Quartz Pegmatites

These pegmatites occur near the southern limit of the map area and are associated with three main host rocks: orthoclase-quartz-microcline-biotite gneiss, amphibole-quartz gneiss, and amphibolite.

The pegmatites were not examined microscopically and this discussion is based on megascopic observations.

Description of Pegmatites. - The pegmatite bodies are long and tabular and appear to be mostly concordant with the foliation of the host rock. They are the largest pegmatites in the area, but their exact size is difficult to determine due to inadequate exposures. One of these pegmatites is indicated on the map (see Plate I); however, its exact size is not shown because of its limited exposure. The pegmatite body appears to be about 100 feet thick, including some thin layers of gneiss, and may be nearly a half-mile long.

Mineralogy of Pegmatites. - The pegmatites are composed largely of microcline and microcline-perthite, and varying amounts of quartz. Tabular

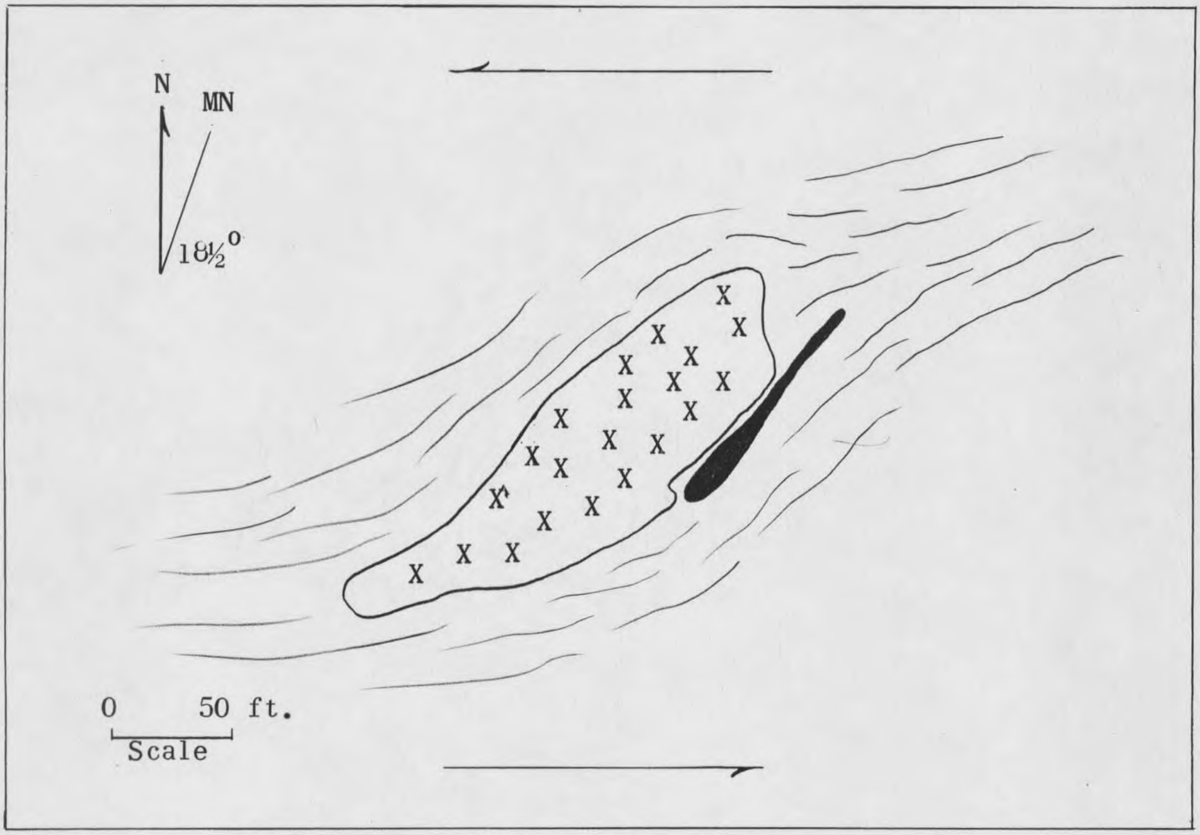


Figure 4. Map of Rim Rock Pegmatite

Map showing position of pegmatite body (X) and amphibolite (black) and their relation to foliation of marble (wavy lines). Dip of foliation is nearly vertical. Arrows indicate direction of forces that may have produced a stress couple, thus creating a dilation which could act as a sink for pegmatite-forming materials. Modified after Stoll (1950, p. 59).

quartz veins occur parallel to the feldspar pegmatites.

Pegmatite-Host Rock Contact Relationship and Origin of Pegmatites. - The contact between the pegmatites and their host rocks is diffuse, and sharing of minerals between host rocks and pegmatites is megascopically visible. Small garnets occur in the pegmatites and exhibit no particular distribution, i.e., they are not confined to the margins or the center of the pegmatites, but occur randomly throughout the pegmatites. Such a random distribution of the garnets would not be expected if the pegmatites were formed from aqueous solutions. In such case, the garnets would be present as inclusions which were picked up by the solutions from the adjacent country rock. They would be expected to concentrate, due to their higher specific gravity, and therefore, would be found in clusters rather than as isolated individuals.

A slight depletion of feldspar and quartz adjacent to "aplite" (here used to indicate small stringers of fine-grained feldspar-quartz rock of approximately the same composition as the pegmatites) stringers would seem to indicate that at least part of the feldspar and quartz may have been derived from the host rock. The chemical composition of the quartz-microcline-biotite-orthoclase gneiss, as calculated from the mode of one thin section was approximately: 70.1 percent Sio_2; 11.2 percent Al_2O_3; 3.7 percent $(al, Fe)_2O_3$; 3.1 percent (Fe, Mg)O; 11.6 percent $(Na, K)_2O$ and .3 percent H_2O. The high percentage (11.6 percent) of $(Na, K)_2O$ may indicate that some of this material was introduced during metamorphism. The diffuse contacts between the pegmatites and host rocks would seem to indicate that the $(Na, K)_2O$ was introduced by metasomatic processes. Concentration of these constituents, which resulted in the formation of pegmatites, may have occurred at the time of introduction of the material, or subsequent to introduction.

The occurrence of large amphibolite layers near the pegmatites may provide an explanation as to the source of the pegmatite-forming materials since the more volatile constituents of the amphibolites may have migrated from the amphibolites to sites favorable for precipitation, thus enriching certain rocks with feldspar and quartz and depleting other rocks of those materials. This type of metamorphic differentiation was also noted by Reid (1957, p. 20),

> ". . . the most abundantly developed ultrabasic rocks lie on the margins of the largest metamorphic pegmatite bodies."

STRUCTURE

Contact Relations Between Precambrian Rocks and Paleozoic Rocks

The contact between the Precambrian rocks and the Paleozoic rocks is clearly visible at a few places in the map area and is otherwise covered by talus from the Paleozoic sedimentary rocks.

The strike of the Paleozoic rocks is about N 10° E and the dip is about 5° W to 10° W. The foliation of the Precambrian rocks strikes generally N 80° E, but has considerable local variation. The dip varies from about 45° S to 65° N, but, in general, is nearly vertical. The foliation of the Precambrian rocks was therefore essentially vertical at the time of deposition of the Paleozoic rocks.

Folding of the Metamorphic Rocks

The repetition of distinct lithologic types suggests that the rocks may have been folded or faulted.

There is some evidence for repetition by folding, i.e., minor folds, moderate-size folds, and repetition of distinct rock types; but evidence for repetition by faulting was not observed.

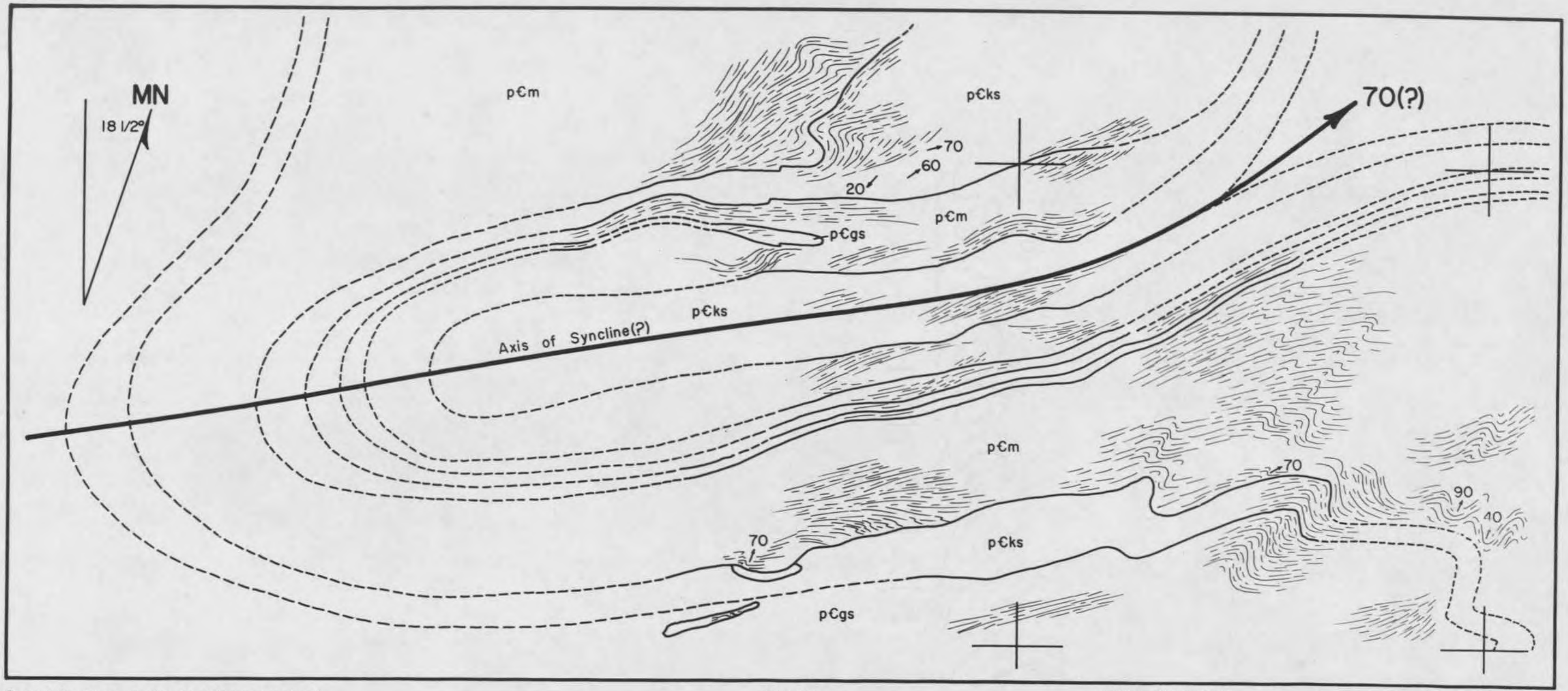
Minor folds (less than 12 inches) occur in gneissic rocks in two localities, and a few minor folds occur in marble layers. Moderate-size folds (larger than two feet) also occur in the marble, particularly in the southernmost layer (see Figures 5 and 6 and Plate I).

Structural Interpretation. - The structural interpretation is based upon the apparent repetition of certain rock layers, the lineation of fold axes, and the attitudes of foliation of the rocks.

The general structural pattern appears to be that of an isoclinal syncline (?) whose axis plunges about 60° to 70°, N 80° E (see Figure 5).

If the structure is interpreted to be an overturned anticline, i.e., an anticline in which the axis plunges 110° or 120°, N 80° E, then some cross-folding should occur. No cross-folding is observed in the map area.

If the synclinal interpretation is correct, the oldest of the Precambrian rocks in the map area are the gneisses and schists which occur at the southern limit of the area, and the youngest Precambrian rocks (not necessarily including pegmatites) occur in the core of the fold.



Geologic Map of the Northern Part of the Cherry Creek Metamorphics, Madison Co., Montana with Structural Interpretation.

W.D.T., 1959

SCALE

0 3000 Feet

EXPLANATION

p€m Dolomite-Marble and Dolomitic Marble

p€ks Kyanite Schist. Schists, Gneisses and Amphibolites

p€gs Gneisses and Schists, Undivided

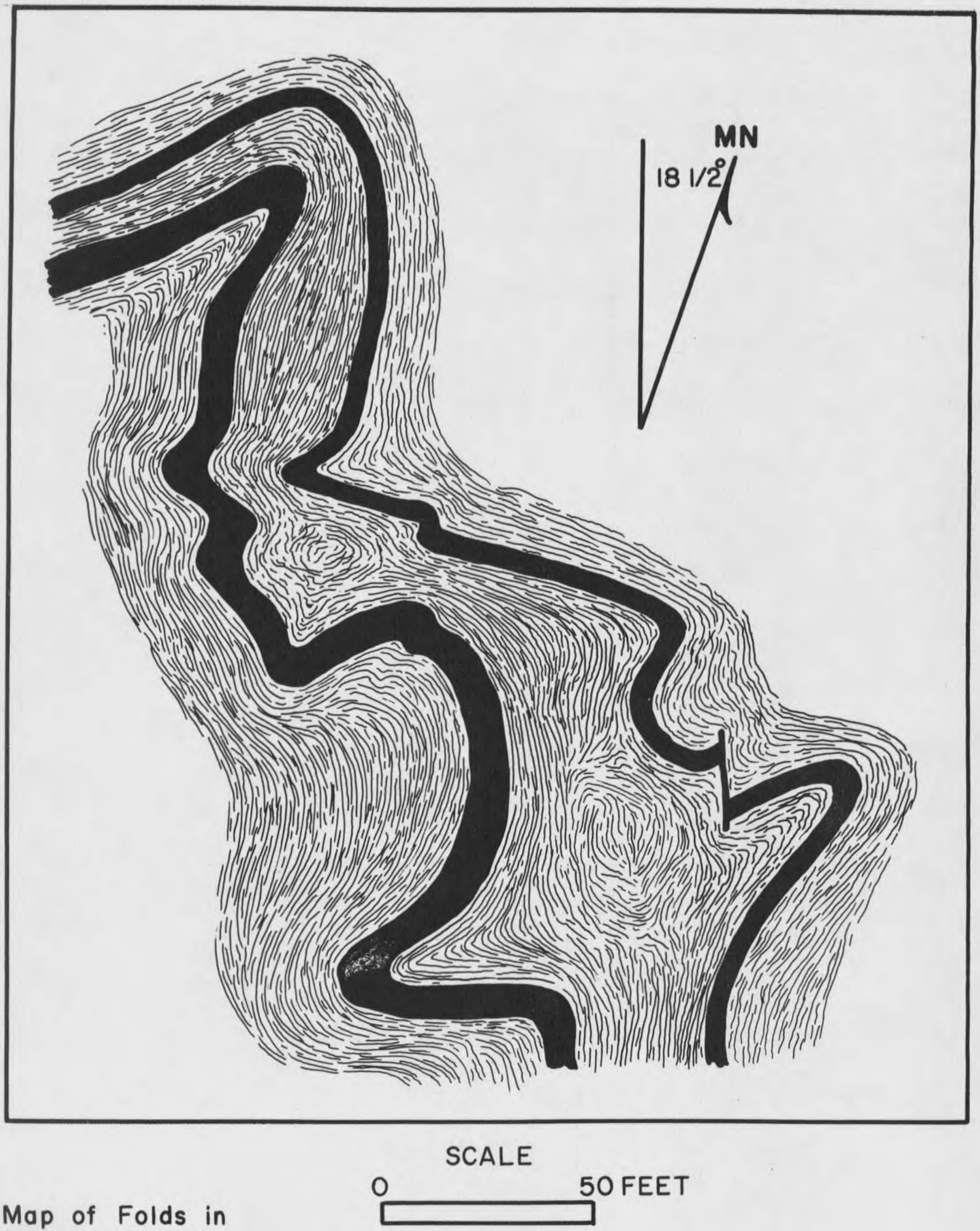
≋ Foliation of Metamorphic Rocks

— Contact as Mapped

- - - Structural Interpretation of Contact.

↗70 Plunge of Fold Axes

FIGURE 5



Map of Folds in Dolomite-Marble.
See Location "F", Plate I.
W.D.T., 1959

FIGURE 6

Boudinage Structures in Marble Layers

Boudinage structures, which occur locally in the rocks, are most fully developed in siliceous marble (see area designated "boudins", Plate I, Section 6) and commonly have their X and Y axes parallel and their Z axis perpendicular, or nearly perpendicular, to the foliation of the enclosing rock (see Ramberg, 1955, p. 522). The boudins are typically barrel-shaped (in two dimensions) and are composed of quartz, dolomite, calcite, and wollastonite (see Figure 7).

Ramberg (1955, p. 512, 513, 517) has pointed out that

"Boudins are usually oblong bodies with the shortest dimension perpendicular to the schistosity in the enclosing rocks and the longest dimension parallel to the schistosity."

As to the origin of boudinage structures, he states,

". . . the basic reason for boudinage structure is differences in competency between the boudin layer and the adjacent rocks, the latter being relatively incompetent or ductile, the former competent or brittle.

"The barrel-shape of boudins is . . . readily explained by compression perpendicular to the layering and a consequent elongation parallel to the layering . . ."

In regard to the formation of an elongate body he states (p. 517),

"Elongation of a body of matter in one or more directions can be caused by, (1) stretching under tensile stress, (2) compression in a direction perpendicular to the direction(s) of elongation, or (3) a stress couple at about a 45° angle to the elongation."

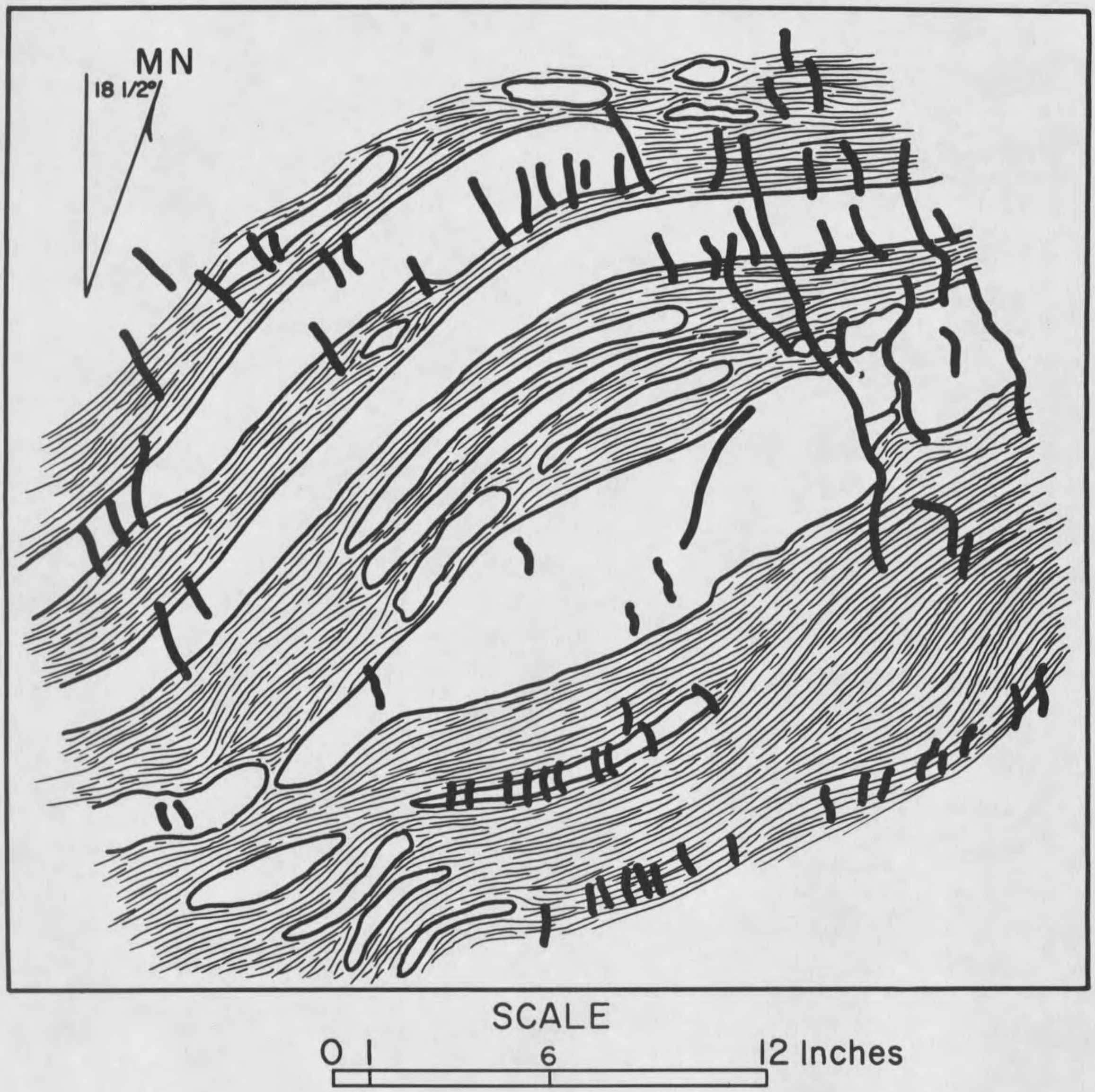
However, he concludes that most boudins are produced by compression in a direction perpendicular to boudin elongation:

". . . the structure of the incompetent rocks adjacent to boudins . . . shows that the basic reason for the elongation of the incompetent rocks, in by far the most cases, must have been a compressive stress perpendicular (or at an obtuse angle) to the boudin layer."

The quartz-dolomite-calcite-wollastonite rock is apparently more brittle than the marble, and thus it yielded to stress by rupture; whereas the marble yielded by flowage.

The lineation of the boudins is parallel to the foliation of the enclosing rocks, or about N 80° E, indicating that the compressive forces which formed the boudinage structures were perpendicular to (or at an obtuse angle to) the long axis of the boudins.

Such compressive forces could also be employed to explain the folding of the rocks, as proposed in this paper.



Boudin in dolomite-marble.
See "Boudins", Plate I.
Drawn after photograph.
W.D.T., 1959

Figure 7

PRINCIPLE OF THE METAMORPHIC FACIES APPLIED TO THE ROCKS OF THE NORTHERN PART OF THE CHERRY CREEK METAMORPHICS

The rocks in the map area appear to have been metamorphosed under conditions approximating those of the epidote-amphibolite facies or the amphibolite facies. This interpretation is based upon the observation of several critical mineral assemblages which occur in the area:

(1) Kyanite-sillimanite-muscovite-plagioclase-quartz
(2) Kyanite-sillimanite-biotite-quartz
(3) Kyanite-andalusite-pyralspite-biotite-quartz
(4) Calcite-dolomite-wollastonite-quartz
(5) Kyanite-sillimanite-biotite-pyralspite-muscovite-quartz
(6) Microcline-orthoclase-biotite-quartz
(7) Amphibole (hornblende)-plagioclase

Figure 8 represents a stable mineral assemblage of the amphibolite facies; Figure 9, a stable assemblage of the epidote-amphibolite facies. It is noted that specimens taken from widely separated points in the map area may be conveniently plotted on these diagrams.

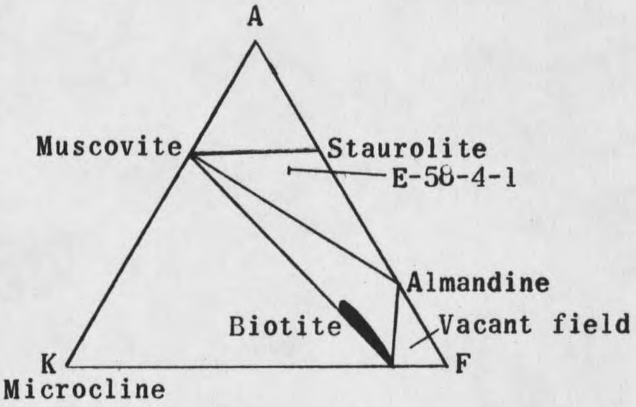


Figure 8. Amphibolite facies: AKF diagram for rocks with excess SiO_2 and Al_2O_3. Point E-58-4-1 represents position of specimen of kyanite-biotite schist taken from Prospect No. 4 (after Turner and Verhoogen, 1951, p. 453).

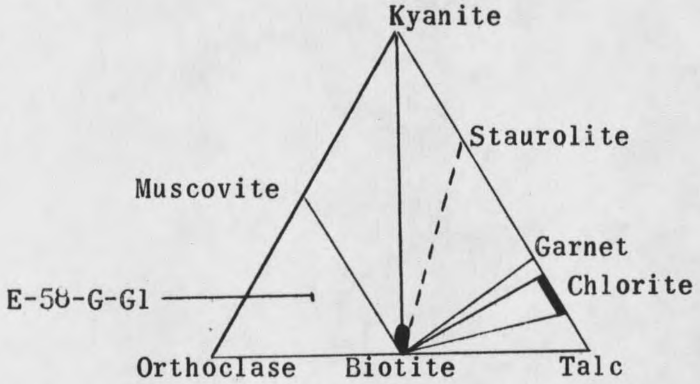


Figure 9. Epidote-amphibolite facies: Talc, kyanite-potash feldspar (AKF) diagram of the high epidote-amphibolite facies (after Ramberg, 1952, p. 149). Point E-58-G-G1 indicates position of biotite-potash feldspar-quartz gneiss. Specimen taken from gneiss near southern limit of map area.

POTENTIAL FOR ECONOMIC DEVELOPMENT OF THE ENNIS KYANITE DEPOSIT

The economic potential of this deposit of kyanite and sillimanite is dependent upon several factors: (1) the actual volume of kyanite-bearing rocks in the area and the percent of kyanite and sillimanite in the rocks, (2) the ease with which the kyanite-bearing rocks can be mined, (3) the ease with which the kyanite and sillimanite can be concentrated into a marketable product, (4) the proximity of a market for the finished product, (5) the world market situation for the refractory materials, and (6) the ability of the kyanite and sillimanite to convert to mullite.

The scope of this paper does not include a study of the above factors, with the possible exception of the first, which will be discussed briefly.

The Volume of Kyanite-Bearing Rocks in the Map Area

An accurate estimate of the volume of kyanite-bearing rock in the area and the percent of kyanite in the rock can be made only after extensive trenching and sampling. The depth to which the kyanite-bearing rocks persist can be determined by selective drilling. If the structural interpretation is correct, i.e., if the structure is a syncline (see p. 41 and Figure 6) the kyanite-bearing rocks may persist to considerable depths. There is no reason to believe that the quantity or quality (massive kyanite is considered to be high quality, and disseminated kyanite is considered to be low quality--both subject to their mullite-forming abilities) of the kyanite, in any layer of the kyanite-bearing rocks, should increase or decrease with depth.

INDUSTRIAL USES OF KYANITE

Kyanite has an industrial application in the production of mullite--mullite (plus free silica) is formed when kyanite is heated to a temperature of about 1300° C.

Mullite is used in the manufacture of highly refractory materials which possess a low coefficient of expansion, resistance to loads at high temperatures, and resistance to thermal shock and the corrosive action of reactive slags (Haw, 1954). According to Gunsallus and Tucker (1957, p.2)

> ". . . about 90 percent of all mullite refractories have been employed to line furnaces operated by the metallurgical and glass industries . . .; . . . 10 percent . . . consumed in miscellaneous applications, chiefly in the ceramics industry."

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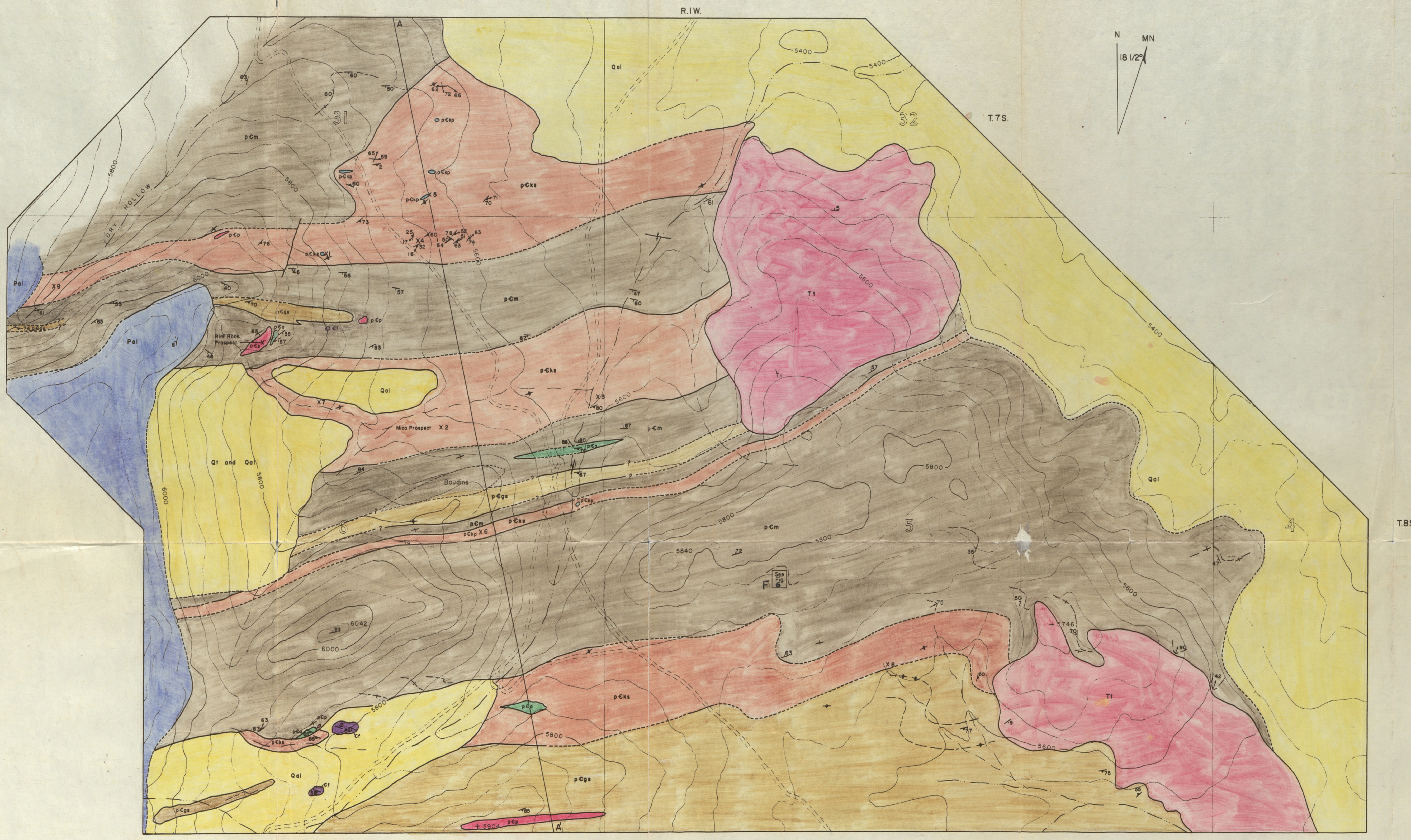
PLATE I



SCALE

0 300 1000 2000 3000 FEET

CONTOUR INTERVAL 40 FEET

EXPLANATION

Qal	Alluvium	Quaternary
Qt	Talus	
Tt	Travertine	Tertiary
Pal	Sedimentary Rocks, Undivided	Paleozoic
€f	Middle Cambrian Flathead Formation	
p€m	Dolomite Marble and Dolomitic Marble	Precambrian
p€ks	Kyanite Bearing Schist Prominent. Includes Some Gneiss and Amphibolite	
p€gs	Gneisses and Schists, Undivided	
p€a	Amphibolite	
p€kp	Kyanite Bearing Pegmatite	
p€p	Pegmatites, Undivided. Generally Contain Quartz, Feldspar, Tourmaline and (or) Muscovite	

Contact

Contact Approximately Located

10 Attitude of Bedding in Sedimentary Rocks

60 Attitude of Foliation in Crystalline Carbonates

Strike of Vertical Foliation in Crystalline Carbonates

70 Attitude of Foliation in Schists and Gneisses

Strike of Vertical Foliation in Schists and Gneisses

x Prospect in Kyanite Bearing Rock

Fault. Arrows Indicate Relative Movement

60 Strike and Dip of Joints

50 Plunge of Axes of Moderate-Size Folds

10 60 Plunge of Lineation of Minor Fold Axes

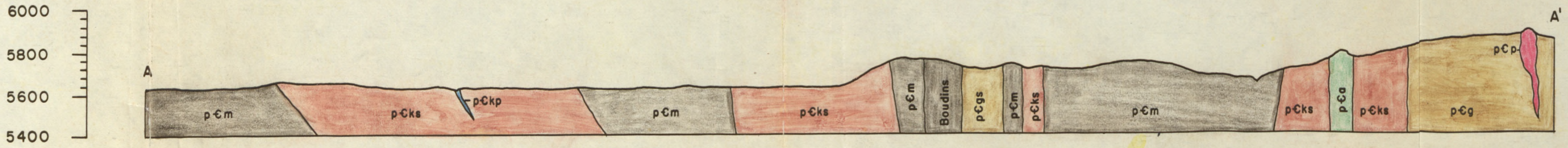
Horizontal Anticlinal Axis

Trace of Folded Foliation

A—A' Cross Section

Large Intermittent Stream

Small Draw



Cross Section

GEOLOGIC MAP AND CROSS SECTION
of
THE NORTHERN PART OF THE CHERRY CREEK METAMORPHICS
MADISON COUNTY, MONTANA

BASE MAP TOPOGRAPHY BY U.S. GEOL. SURVEY, VARNEY AND CAMERON QUADRANGLES

GEOLOGY BY
WILLARD D. TOMPSON, JR.

JANUARY, 1959

[redacted]