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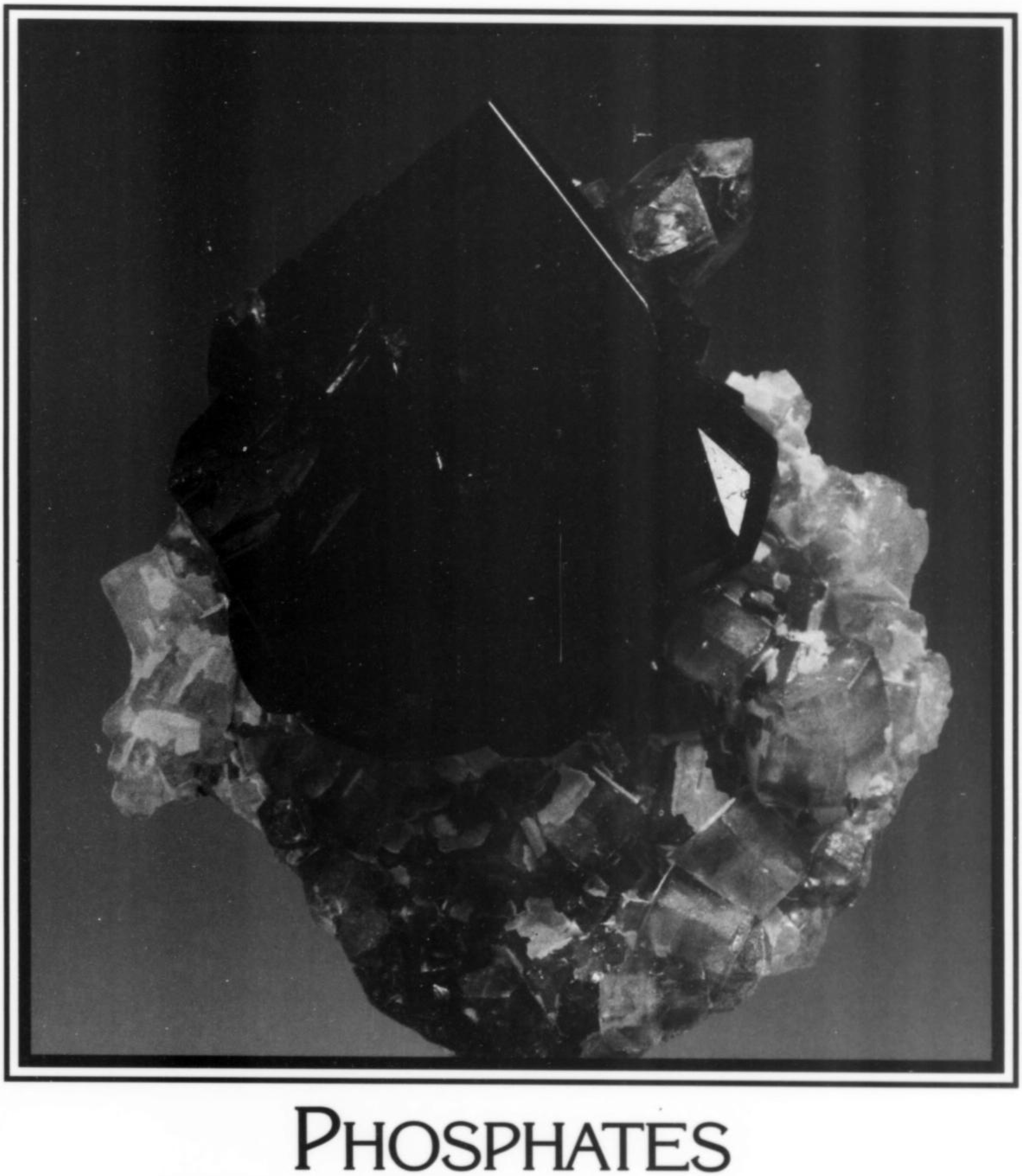

PHOSPHATES

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Mineralogy of the Rapid Creek and Big Fish River Area Yukon Territory

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COVER:
Lazulite crystal, 1.5 cm, with siderite and pale purple fluorapatite, from the Rapid Creek area, Yukon Territory. Keith Williams specimen; photo by Wendell E. Wilson.

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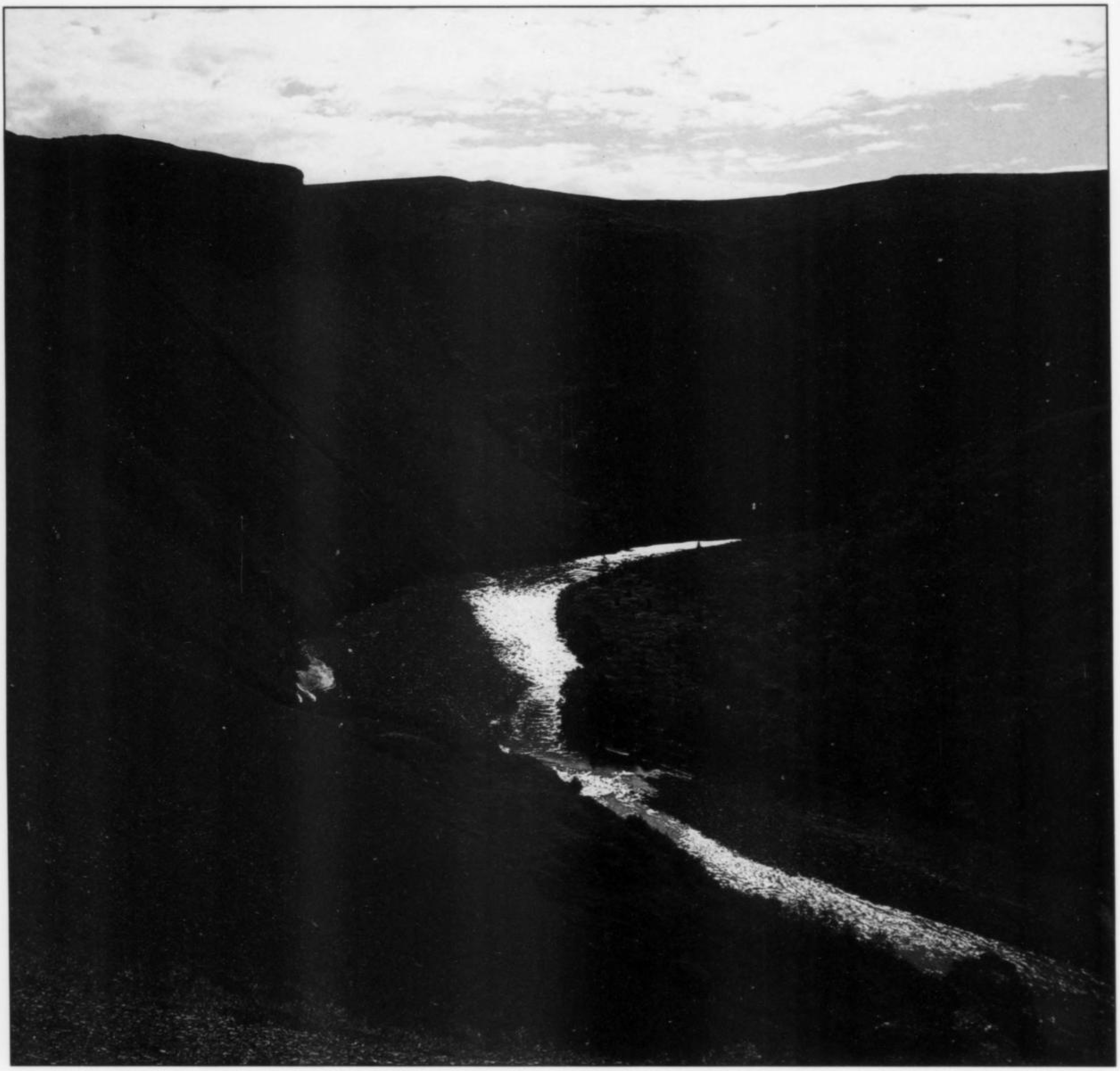


Figure 1. **The Big Fish River, northern Yukon Territory, as viewed from collecting area "C." R. A. Gault photo, 1984.**

Figure 2. **The "Stoneman" camp area on Rapid Creek, northern Yukon Territory, near collecting area "B." H. G. Ansell photo, 1984.**

INTRODUCTION

In the early 1970's a remarkable deposit of phosphate minerals was discovered in the Rapid Creek and Big Fish River areas of the northeastern Yukon Territory, Canada. The region now ranks among the most important localities for phosphate species in the world, and has been the focus of much attention among mineralogists and collectors alike. To date, a total of ten new mineral species have been described from the area, and the probability is high that this number will continue to grow. In addition to the new species found, specimens of arrojadite, augelite, collinsite, gorceixite, goyazite, kryzhanovskite, lazulite, wardite and whiteite are among the finest known, and have already been widely distributed to most major collections. Unfortunately there has also been a distribution of conflicting information concerning accessibility and locality details, and no comprehensive overview of the mineralogy, paragenesis or history of the deposit has been published. It is the purpose of this article to assemble and clarify the accumulated information.

The Rapid Creek and Big Fish River region, located north of the Arctic Circle, may be classified as a rocky desert with an average annual precipitation of approximately 15 cm. The topography is generally gently rolling tundra, with deeply incised creek systems and low profile hills. Most specimens have come from talus slopes and outcrops exposed in the creeks, where steep canyon walls average 100 to 200 meters in height. Collecting is often dangerous, and rock slides are common, especially in wet weather.

Periods of 24-hour sunlight in late June and July may raise the temperature to 30° Celsius, but an abrupt change in the winds can quickly advance a new airmass, bringing rain or snow squalls in a matter of a few hours, which may persist for several days or weeks. Consequently, a normally shallow stream may be quickly transformed into a raging torrent, flooding a camp. Caribou, moose, wolves and grizzly bears frequent the area, necessitating a special awareness and preparedness. The hordes of mosquitos must be seen to be believed.

On July 5, 1978, an Order in Council submitted in the Yukon legislature officially withdrew the area from claim staking and disposition of mineral rights. The Department of Indian Affairs and Northern Development, Canada (DIAND) stated that people entering or removing minerals from the area without official permission would face arrest and criminal prosecution. Hence, collecting is strictly prohibited unless prior authorization is granted by DIAND and the Yukon Territorial Government. At the time of this writing, such permission is not easily obtained, and individuals are discouraged from applying.

Explosives and heavy equipment are not permitted; however, they are generally not required in order to collect good specimens from this extremely sensitive environment. The potential for future specimen production is excellent, but will likely and necessarily be developed in a controlled manner. Furthermore, any expedition to this remote area quickly becomes expensive, a factor which precludes frequent collecting.

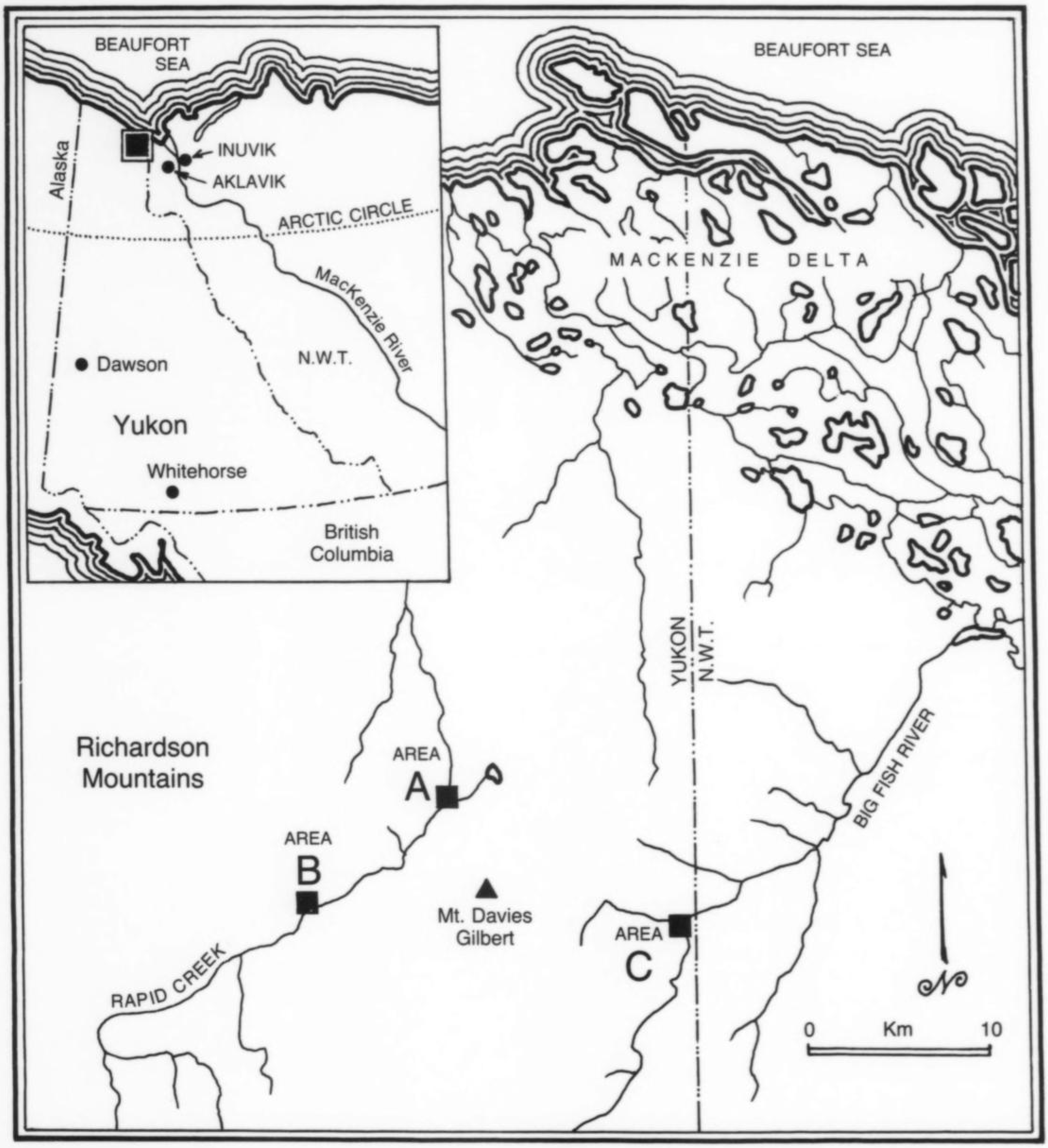


Figure 3. **Location map.**

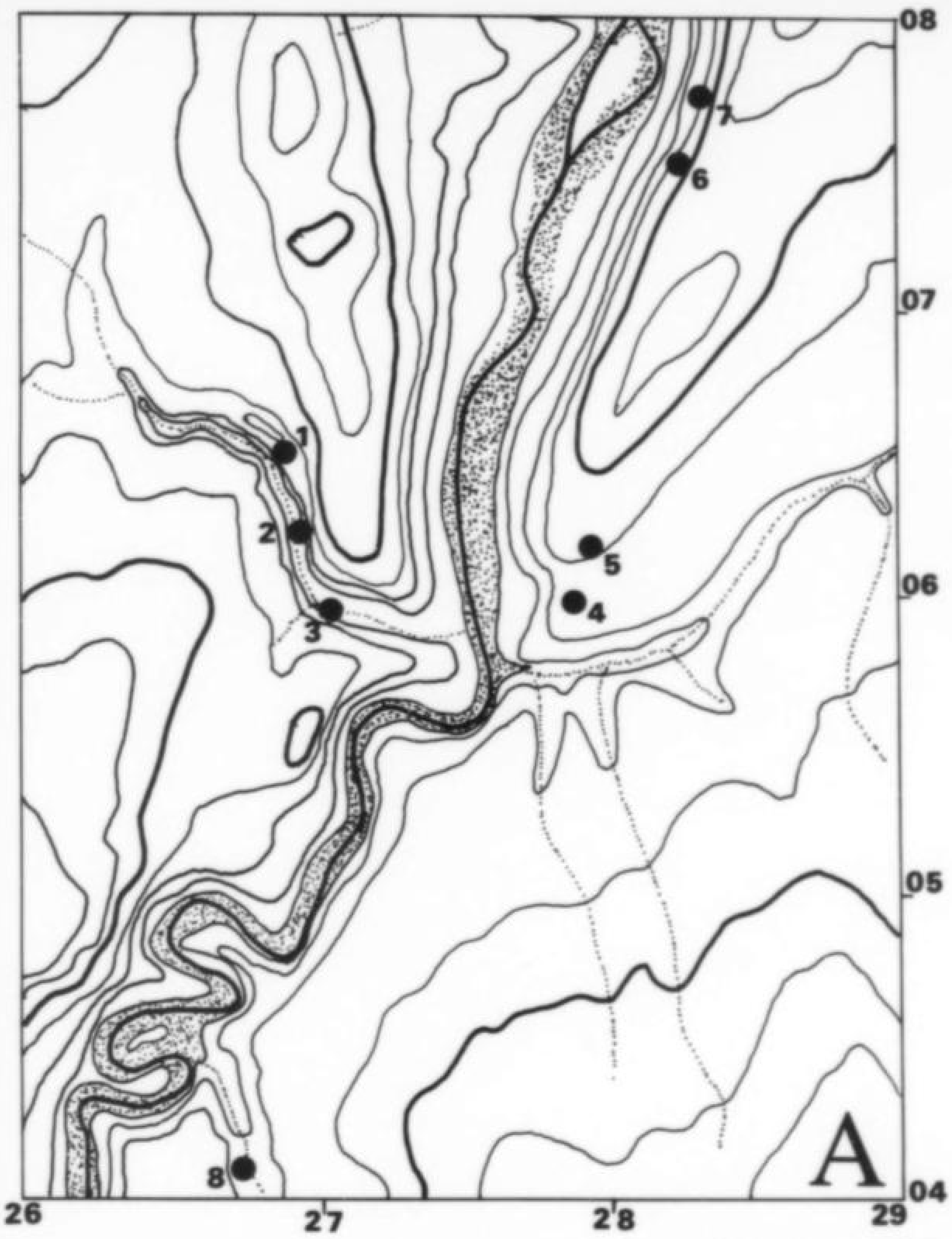


Figure 4. (above) **Collecting area "A." Adapted from Energy Mines and Resources Canada topographic map 117 A/9W (1966); grid numbers refer to U.T.M. eastings and northings.**

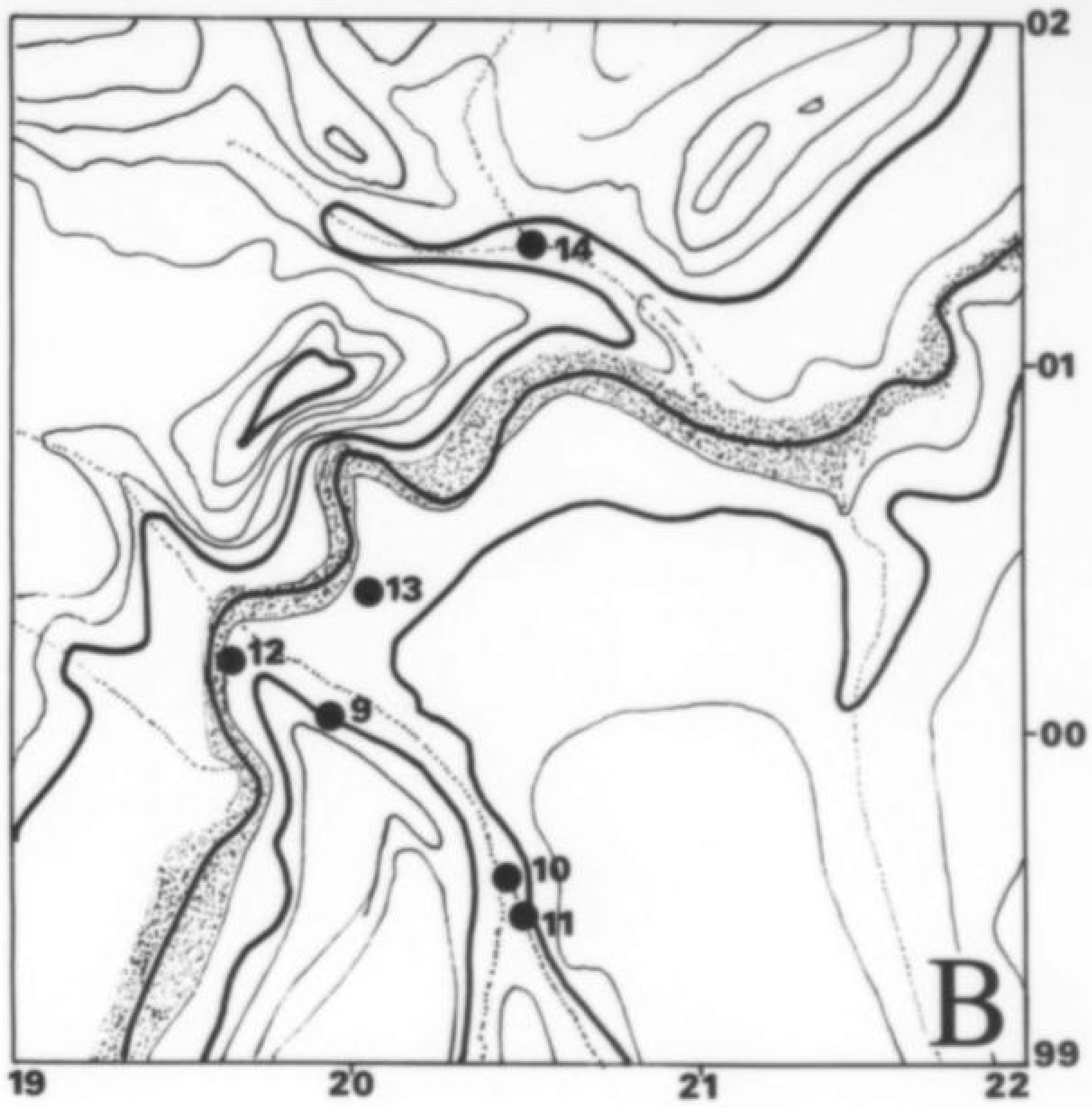


Figure 5. (top right) **Collecting area "B." Adopted from Energy Mines and Resources Canada topographic maps 117 A/9W (1966) and 117 A/8 (1973); grid numbers refer to U.T.M. eastings and northings.**

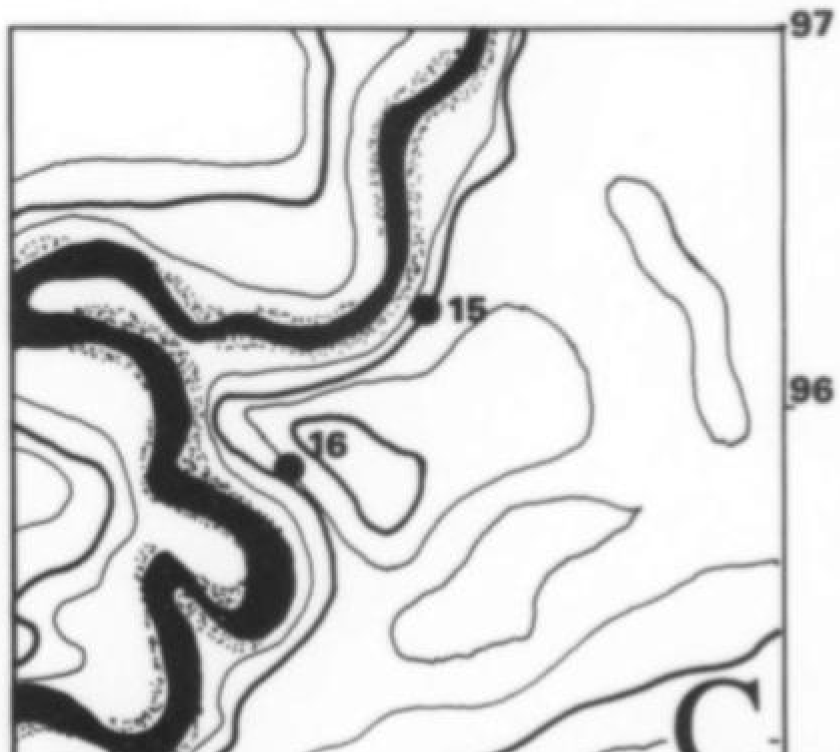


Figure 6. (right) **Collecting area "C." Adopted from Energy Mines and Resources Canada topographic map 117 A/8 (1973); grid numbers refer to U.T.M. eastings and northings.**

LOCATION

The Rapid Creek and Big Fish River area is part of the Richardson Mountains, located west of the Mackenzie River Delta in the northeastern Yukon, near the boundary separating the Yukon and Northwest Territories. The nearest native community, Aklavik, is situated approximately 70 km southeast of the area. Accessibility is best gained by helicopter (from Inuvik, 120 km to the east), which is undoubtedly the best means of transportation between the various collecting areas as well. Inuvik may be reached by the Dempster Highway, which leaves the Klondike Highway approximately 40 km east of Dawson.

It should be stated that there are few geographical features in this area with officially accepted names, a deficiency which has resulted in widespread use of unofficial names for various landmarks by individuals who are familiar with and have visited the area. While we do not wish to promote the general acceptance of these names, there exists a need to clarify the locality information that presently appears on various specimen labels. The following paragraphs explain these terms, with reference to informal names in quotes.

There are three main collecting areas referred to here simply as Areas A, B and C. Area A is located at approximately 68°39′ N latitude, 136°48′ W longitude. It is on Rapid Creek, about 35 km south of Mackenzie Bay on the Beaufort Sea, and approximately 5 km north-northwest of Mount Davies Gilbert. This area has often been referred to as "Kulan Camp." The small tributary on the west side of Rapid Creek, on which is situated localities 1, 2 and 3, is known as "Crosscut Creek," and the next tributary to the south and east is called "Lake Creek."

Area B, about 10 km upstream (southwest) from Area A, at approximately 68°31′ N latitude, 137°00′ W longitude, has been frequently referred to as "Stoneman Camp." The tributary to the southeast, leading to localities 10 and 11, has been called "Young's Creek," and the tributary about a kilometer northeast of "Stoneman Camp," at locality 14, has been referred to as "Grizzly Bear Creek."

Area C is on the Big Fish River, approximately 16 km southeast of Area A, at 68°28′ N latitude, 136°30′ W longitude, near the border of the Northwest Territories.

Figure 7. **The late Al Kulan of Ross River, Yukon Territory, among the first to recognize the specimen potential of the Rapid Creek deposits.**

HISTORY

Geological reconnaissance has revealed numerous significant mineral deposits throughout northern Canada, and the discovery of phosphates in the Rapid Creek area is no exception. While exploring for gas and oil in the summer of 1959, a Triad Oil Company geologist, Bruce Cameron, noted an unusual blue mineral occurring in a creek bed. A specimen was submitted to Dr. Finley Campbell, then at the University of Alberta in Edmonton, who identified it as lazulite, thus recording the first mention of phosphates in the northern Yukon (Campbell, 1962). After considerable investigation, however, the published locality data, given as "from along the Blow River near Mt. Fitton in the Yukon Territory . . . at 68°30′ N. Lat., 138°45′ W. Long." aroused some suspicion, and has subsequently been shown to be in error (B. Cameron, personal communication, 1985). The actual locality for the specimen has been confirmed as being on Rapid Creek, approximately 2 km southwest (upstream) from locality 12 in Figure 5.

It is assumed that no serious collectors or curators were shown the specimens that Campbell described as "clusters of well-terminated deep blue clear crystals . . . associated with . . . euhedral quartz crystals," because no one followed up on this discovery for ten years.

In the summer of 1971, Dr. F. G. Young, engaged in a regional mapping project for the Geological Survey of Canada, found lazulite and other phosphate minerals *in situ* along "Crosscut Creek," then called "Crystal Creek" (F. G. Young, personal communication, 1978). Shortly thereafter, massive lazulite was also found by Al Kulan of Ross River, Yukon, a well-known and respected prospector, and Director of Welcome North Mines. Welcome North Mines had previously been interested in the economic potential of the iron deposits in the area. The discovery of lazulite incited Kulan's curiosity, particularly after crystallized specimens were brought to his attention by a student ornithologist working in the area. Accompanied by his friend, Gunar Penikis, a geophysicist who had previously been working in Brazil, Kulan visited Young to discuss and learn more about the geology of the deposit and its interesting minerals.

In the spring of 1974, Kulan and Penikis went to the field and returned more intrigued than ever by the thought of perhaps finding gems in the area. Consequently, Kulan and his wife, Wynne, together with Penikis and Lil Dickson, formed Mackenzie Resources, Limited, and a second collecting trip was made early that summer by Kulan, Penikis and Mack Peter, an employee of the company. Once again they returned with encouraging results, and in July, Penikis brought a suite of specimens to the Royal Ontario Museum for identification.

Like many such institutions, the Royal Ontario Museum provides specimen identification services to the public, and, like most museums, typically receives a constant flow of beach pebbles, arrowheads, fossils, rocks and minerals of usually less-than-collector quality for examination. Imagine the excitement when the world's best lazulites, wardites and arrojadites were unveiled! A friendly relationship was soon established, and that fall Dr. Joseph Mandarino and one of us (BDS) visited the Kulans in Ross River to examine and identify more specimens.

After a few days in Ross River, Mandarino had to leave for an International Mineralogical Congress in Europe, but Sturman stayed on and continued north to Rapid Creek with Kulan, Penikis and Peter. With ideal weather and few mosquitos, a camp was pitched on Rapid Creek, which offered abundant grayling and spectacular views of the autumn foliage. In a mineral collector's paradise it was difficult to limit oneself to searching for geological clues to better understand the origin of the deposit, when world-class specimens were so readily available! Nevertheless, while Kulan was collecting superb lazulite and Penikis was digging out nice augelite crystals, Sturman somehow managed to pull himself away long enough to prospect for additional occurrences and record some geological observations. At that time he also collected some "curious looking, platy lazulite" that was brought back to Toronto to help complete a study of the crystal habits of that mineral. Upon investigation, however, it was soon learned that this mineral was not lazulite, but an entirely new species, which was named kulanite, in honor of Al Kulan. Further analyses of a pale blue "vivianite" collected at the same time resulted in the description of a second new species, barićite.

Over the next two years the Kulan family continued to remove many fine specimens from the area, while working closely with the Royal Ontario Museum, both in the field and in the laboratory. Satterlyite, marićite and penikisite were discovered and described, while research continued on additional unknowns. Because of recurrent attacks of malaria, Gunar Penikis sold his share of Mackenzie Resources to the Kulans in 1975, but retained a five-year contract to market specimens for the company. In February of 1976, then-Commissioner James Smith proclaimed lazulite the official gemstone of the Yukon. Although some gems have been cut, they are typically small (less than a quarter carat), due to the intense dark color and lack of larger clean areas of rough. In 1977, collecting activities were greatly diminished when Al Kulan was murdered at Ross River.

By 1978, specimens had been shown at both the Tucson and Detroit mineral shows, various talks had been given, and papers published. As an easily predictable consequence the area was once again visited

Figure 9. **Collecting at the wardite outcrop in area B, location 12. R. A. Gault photo, 1984.**

Figure 8. **Collecting in a whiteite-rich seam in area A, location 2. G. W. Robinson photo, 1983.**

by eager, new collectors from both the professional and private sectors. Armed with information from Dr. Young and the Kulans, Patrick Collins of Upper Canada Minerals and (then) private collector Jerry Van Velthuizen prospected the region around Area B, discovering many of the sites herein described, and collecting many superb specimens of wardite, gormanite and kulanite. In Area A to the north several other collecting parties were active: Darko Sturman and Robert Ramik from the Royal Ontario Museum, Gary Ansell and Scott Ercit from the Geological Survey of Canada, Ben Robertson, a graduate student from the University of Saskatchewan, his professors and assistant, not to mention several exploration geologists whose curiosity prompted a short visit to pick up a few souvenir specimens. On July 5th, the Order in Council restricting collecting in the area took effect, making it illegal for unauthorized persons to visit or collect any longer. Consequently, all subsequent collecting has been limited.

In 1979 Lil Dickson retired from Mackenzie Resources, restoring sole ownership to the Kulan family. Dr. Robert Gait and Robert Ramik from the Royal Ontario Museum, Gary Ansell and Scott Ercit from the Geological Survey and Ben Robertson returned to the field to continue their research. Excluding any unauthorized collectors who may have visited the region, the area remained relatively dormant until 1982 when it was once again visited by Gary Ansell and Dr. Ian Jonasson from the Geological Survey. In the summer of 1983 Ansell and Jonasson returned, along with Dr. Wayne Goodfellow from the Geological Survey and Dr. George Robinson and Jerry Van Velthuizen from the Canadian Museum of Nature. The Glenbow-Alberta Institute in Calgary was represented by Allan Ingelson, Gunther Kuhnlein and Ulrich Matern. The collecting was very profitable for all, and many fine and unusual specimens were recovered, including excellent whiteite, wardite, lazulite, collinsite, and the new species rapidcreekite. Robinson and Van Velthuizen, with colleagues Dr. Joel Grice and Robert Gault, returned in July, 1984, and were able to collect good specimens for the Canadian Museum of Nature and the Yukon Territorial Government, in spite of flooding and near-blizzard conditions. At the time of this writing, the last official party to visit the area consisted of Gary Ansell and Dr. Gary Yeo from Acadia University, Wolfville, Nova Scotia. Yeo and Ansell re-examined and mapped sections of the Rapid Creek formation and collected samples for petrographic and geochemical study.

Even after 20 years of intensive prospecting, the collecting potential of the area still remains relatively untouched. Hopefully, with careful collecting, it will continue to produce new, beautiful, and exciting specimens for years to come.

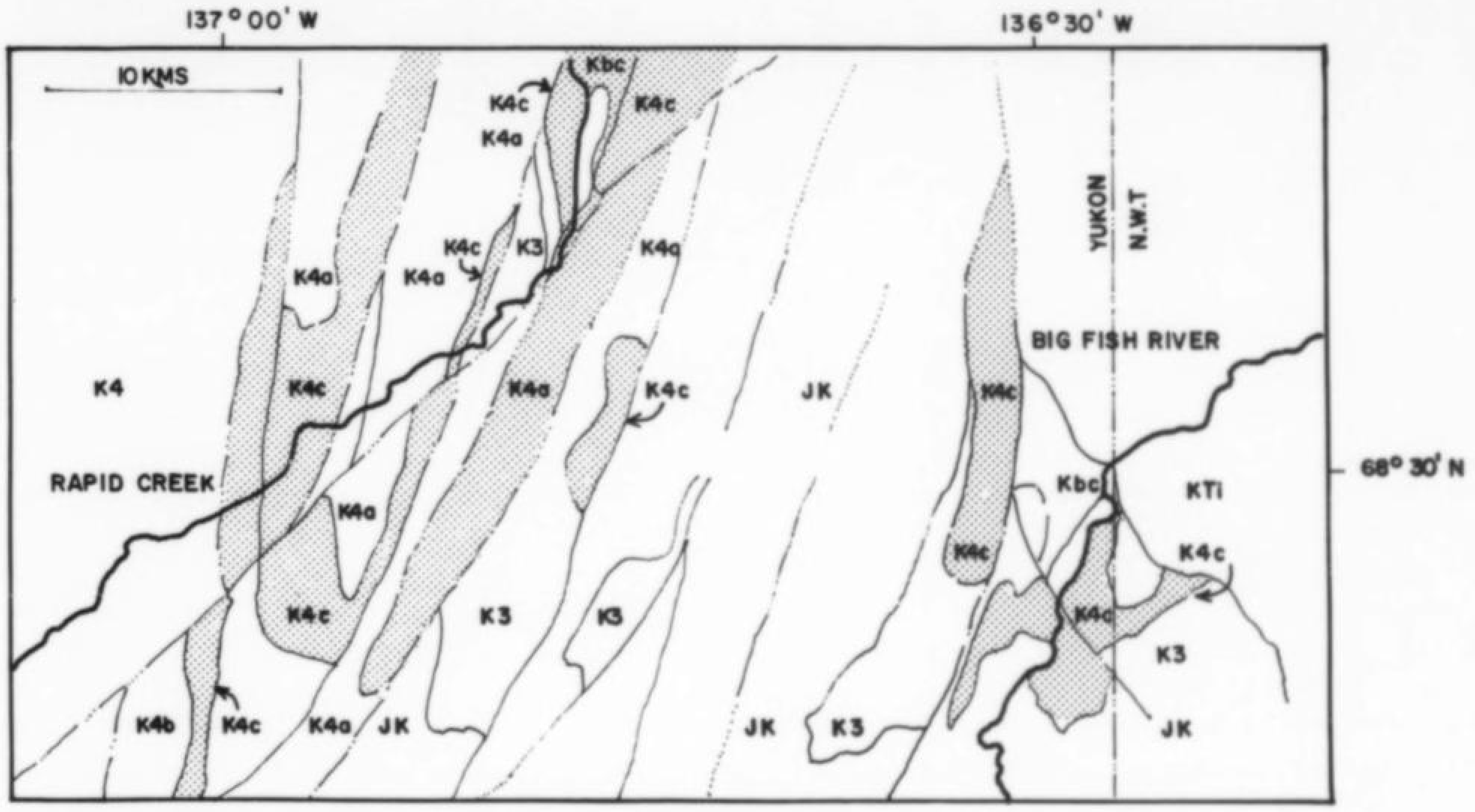


Figure 10. **Geology of the Rapid Creek and Big Fish River area.**

Upper Cretaceous	**Kbc**	**Boundary Creek Formation**
Lower Cretaceous	**K4c**	**Bedded ironstone & shale**
	K4b	**Turbite sandstone**
	K4a	**Lower shale**
	K4	**Aptian-Albian flysch (undivided)**
	K3	**Upper sandstone**
Jurassic/Lower Cretaceous	**JK**	**Sedimentary rocks older than K3**
	———	**Fault (defined, approx., assumed)**

GEOLOGY

The Rapid Creek and Big Fish River area lies within the Beaufort-Mackenzie Basin, a large (155,000 square kilometers), Mesozoic-Cenozoic structural depression created by extensional and wrench faulting near the continental margin of the southern Beaufort Sea (Young *et al.*, 1976). Sedimentation within the basin began in the Late Triassic, and has continued to the present in the active area of the Mackenzie Delta.

In early to mid-Cretaceous time, movement along a series of north-south splay faults was partially responsible for the formation of the Blow Trough, a depression 50 km wide flanked by a major area of uplift to the west and a structural high to the east. The present-day valley of lower Rapid Creek is located near the eastern margin of this trough. During Albian time (upper Lower Cretaceous) erosion of the western highland and subsidence of the Blow Trough resulted in the deposition of a thick flysch sequence of turbidite sandstones, mudstones and shales, which thins toward the eastern margin of the trough, changing facies to the interbedded ironstone and shale units comprising the Rapid Creek Formation (Young and Robertson, 1984). During the Laramide Orogeny in the Late Cretaceous to Early Tertiary, east-west compression caused local folding, faulting, uplift and subsequent erosion to expose the present-day surface.

The Rapid Creek Formation gradationally overlies the flysch sequence, and is thought to have been deposited by cold, northeast-flowing currents upwelling on the flanks of the structural high at the eastern margin of the trough (Young and Robertson, 1984). This formation is the most northerly known phosphorite, having formed at 75° north paleolatitude (Young and Robertson, 1984; Irving, 1969). It varies in thickness from a maximum of 1000 meters west of Rapid Creek to only 60 meters at Big Fish River. Due to the relative absence of well-preserved fossils and the lack of any paleomagnetic data, an accurate geological age for the Rapid Creek Formation has not been determined.

The ironstone occurs mainly as thin beds, up to about 25 cm thick, intercalated with thin layers of ferruginous shale. At Rapid Creek (Areas A and B), the ironstone beds consist mainly of compact, microcrystalline siderite-pyrite phosphate rock, and poorly sorted clastic rocks ranging from mudstone to sandstone, with breccia and conglomerate components of variable continuity and composition. In the field, however, these rocks are commonly coated by a dark patina on weathered surfaces, thus obscuring their textures and making accurate identifications difficult. The total P_2O_5 content of the rock averages about 19% (Young, 1977), with the phosphate minerals appearing as either microcrystalline inclusions, sparry replacement cements, veinlets, or as well-developed crystals lining fracture surfaces.

Curiously, many of the phosphate grains are not composed of apatite like other marine phosphorites, but rather of unusual species such as satterlyite, arrojadite and gormanite. This suggests a depositional environment relatively poor in calcium, which precipitated iron and magnesium phosphates in addition to apatite, representing a unique condition for marine phosphorites (Young and Robertson, 1984).

However, it is the fracture-filling paragenesis that has undoubtedly received the most attention, since it is that mode of occurrence which has provided the wealth of well crystallized specimens for which the area has become famous. The specific mineral assemblages observed in any given fracture filling appear, at least in part, to be related to the composition of the rocks through which the solutions migrated. While individual exceptions may exist, Robertson (1982) recognized four major assemblages characterized by the predominance of specific elements and related to a specific host rock: (1) Ca-rich assemblage with phosphatic mudstone, (2) Ba-rich with conglomeratic slump deposits, (3) Fe-Mg-rich with sideritic sandstone, and (4) Na-bearing with phosphatic sandstone. Furthermore, the length of an entire vein may easily exceed the thickness of a single bed, such that more than one rock type may have contributed to the bulk chemistry of the vein as a whole, resulting in more complex assemblages.

At Rapid Creek, uncontorted bedding strikes slightly east of due north and dips about 60° east. There is one major fracture set within the formation, striking slightly north of due east, dipping very steeply to the south, and intersecting the bedding at a high interplanal angle. These fractures maintain a consistent orientation independent of local structural features, and have thus formed during the last significant episode of tectonic activity. With minor exceptions, the quartz-siderite-phosphate vein-type mineralization occurs solely within this fracture set.

At Big Fish River (Area C), the ironstone consists mainly of microcrystalline siderite, and has a total P_2O_5 content of about 9% (Young, 1977). In many respects, the phosphate mineralization is similar to that at Rapid Creek, although somewhat less spectacular due to the relative scarcity of well developed crystal-lined fractures. One notable difference, however, is the presence of phosphate and pyrite nodules in the lower portion of the ironstone-shale sequence. These nodular segregations range in size from less than 1 cm up to 10 cm. They typically assume the form of round, flattened disks, and in some instances appear to be recrystallized replacements of ammonites or pelecypods. Many appear to be monomineralic, but upon close examination commonly contain several coexisting species. Observations of nodules *in situ* suggests the following relative order of abundance: wolfeite (most abundant), pyrite, satterlyite, marićite and wicksite (Coleman and Robertson, 1981; Sturman *et al.*, 1981).

Lastly, surface alteration and weathering have resulted in the evolution of a variety of secondary species, predominantly sulfates and carbonates, throughout the formation. These minerals occur abundantly as obvious white or yellow stains and coatings on outcrops where relatively little erosion is taking place. Additionally, many of these species may also be found in some of the fracture fillings and nodules as coatings on the eariier formed primary minerals.

MINERALOGY

Based on their modes of occurrence, all the minerals at Rapid Creek may conveniently be categorized into three separate groups: (I) fracture fillings, (II) phosphatic nodules and (III) weathering products (Table 1). The first group includes nearly all of the well crystallized minerals such as lazulite, wardite and whiteite. These, along with approximately two dozen additional species, occur with quartz and siderite in seams, fault breccias and other sites where openings permitted the invasion of mineralizing solutions.

A second, quite different suite of minerals is found in phosphatic nodules from Area C on the Big Fish River, and from along Boundary Creek, approximately 5 km to the northwest. Three new species, marićite, satterlyite and wicksite, occur in these nodules together with several other phosphates, pyrite and siderite. Most of the phosphates typically form subparallel aggregates of columnar, anhedral crystals, all of which are easily differentiated by color and cleavage.

The third group of minerals, the secondary products of weathering, occur as either microscopic, white, acicular crystals, or as powdery masses that are best identified by x-ray methods.

Finally, some species such as vivianite and siderite may be found in both the fracture fillings and nodules. Although reference is made to each mode of occurrence, the descriptions for these species appear under the genetic group which has produced the specimens of greater interest to collectors.

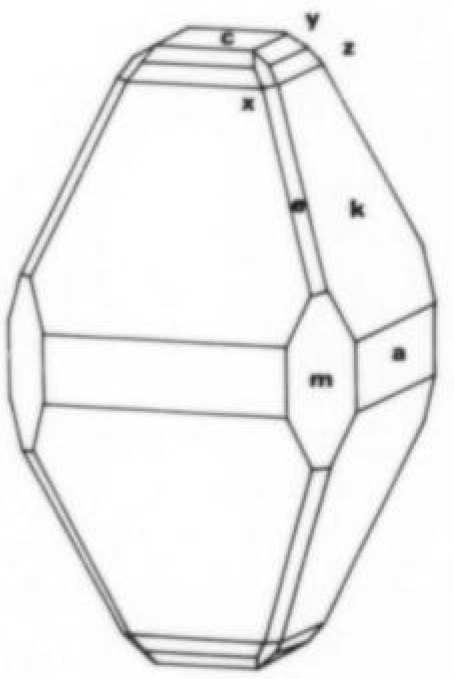


Figure 11. **Anatase crystal drawing.**

Table 1. **Minerals of the Rapid Creek and Big Fish River area.**

Fracture Fillings	***Phosphate Nodules***	***Secondary Weathering Products***
Alluaudite group	Alluaudite	Aluminite
Anatase	Arrojadite	Aragonite
Arrojadite	Ba analog (?)	Brushite
Ba analog (?)	Bobierrite	Diadochite
F analog (?)	Childrenite	Dorfmanite
Augelite	Ernstite (?)	Dypingite
Barićite	Ferroalluaudite	Epsomite
Barite	Fluorapatite	Georgiosite
Brazilianite	Hagendorfite	Goethite
Bjarebyite (?)	Fe^{+2} analog (?)	Gypsum
Celestine	Ludlamite	Halotrichite
Chalcopyrite	Maghagendorfite	Hexahydrite
Childrenite	Fe^{+2} analog (?)	Hydromagnesite
Collinsite	**Marićite**	Jarosite
Eosphorite	Metaswitzerite	Meta-aluminite
Fluorapatite	Phosphosiderite	Natrojarosite
Fluorite	Pyrite	**Nahpoite**
Garyansellite	Quartz	Nesquehonite
Gorceixite	**Satterlyite**	**Rapidcreekite**
Gordonite	Siderite	Sasaite
Gormanite	Strengite (?)	
Goyazite	Switzerite	UK-3
Kryzhanovskite	Varulite (?)	
Kulanite	Vivianite	
Lazulite	Whiteite group	***Others (see text)***
Ludlamite	**Wicksite**	Carbonate-fluorapatite
Messelite	Wolfeite	Dolomite
Metavivianite		Whitlockite
Penikisite	UK-1	
Phosphosiderite	UK-2	UK-5
Pyrite	UK-4	
Quartz	UK-6	
Siderite		
Souzalite		
Sphalerite		
Vivianite		
Wardite		
Whiteite-(CaFe^{+2}Mg)		

Species first described from the Rapid Creek and Big Fish River area are in **bold.**

Group I: Fracture-Filling Minerals

Anatase TiO_2

A very few specimens of anatase have been found associated with arrojadite, kulanite, brazilianite and apatite in a small vein in the bed of "Crosscut Creek," just below the waterfall (locality 3, Area A).

The crystals are very small (generally less than a millimeter long) and yellow-brown in color, which makes them very difficult to differentiate from the similarly colored siderite, arrojadite and iron oxide with which they occur. While their small size precludes positive identification by optical goniometry of every form present, the following have been identified: *c*{001}, *a*{010}, *m*{110}, *k*{011} and *z*{012}. In addition, one {0hl} (y) and two {hhl} (*e*,*x*) dipyramids were observed, but were too small to be accurately measured.

X-ray precession photographs of this anatase suggest that it is probably quite pure TiO_2, with cell constants of a = 3.79 Å and c = 9.51 Å.

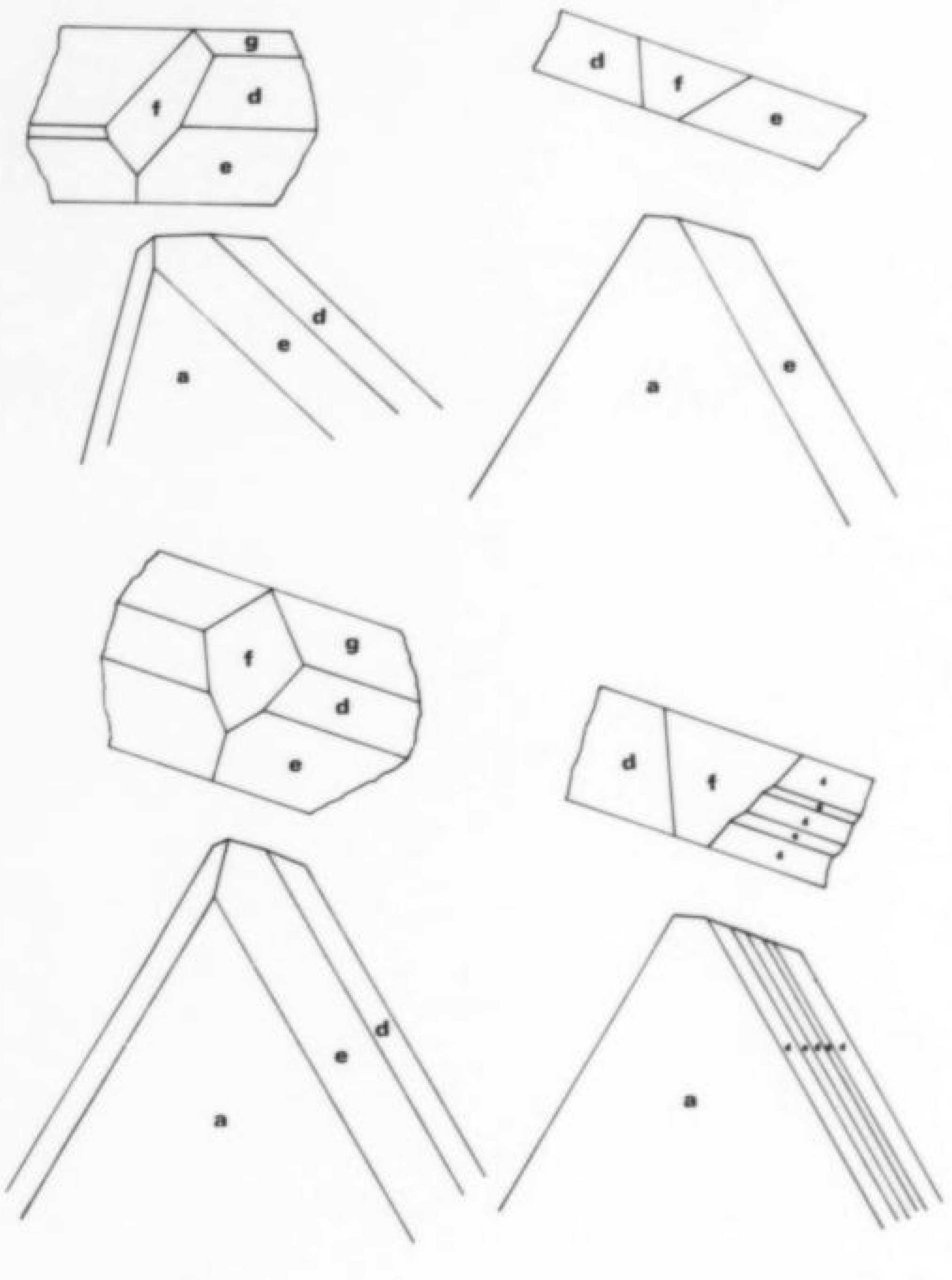


Figure 12. **Arrojadite crystal drawings.**

Arrojadite $KNa_4CaMn_4^{+2}Fe_{10}^{+2}Al(PO_4)_{12}(OH,F)_2$

Arrojadite was first described, though not named, by William Headden (1891) from the Nickel Plate mine in the Keystone district, South Dakota. Over a quarter century later the mineral was again noted from a pegmatite at Serra Branca, Picuhy, Paraiba, Brazil, and named arrojadite by Guimarães (1925). Since that time, many other occurrences have been documented, but all as cleavage masses in granite pegmatites (Lindberg, 1950; Moore *et al.*, 1981). The discovery of arrojadite in the Yukon is significant because it marks the first time this species has ever been found *outside* a granite pegmatite environment, and it represents the second known occurrence of individual, euhedral crystals. The first reported crystals of arrojadite were found at the Palermo No. 1 pegmatite in North Groton, New Hampshire in the 1950's (V. King, personal communication, 1985; Segeler *et al.*, 1981). Subsequently, well crystallized zincian arrojadite has been identified from the White Cap pegmatite in Keystone, South Dakota (W. L. Roberts, personal communication, 1985).

At Rapid Creek, arrojadite occurs in fractures cutting siderite-rich sandstone, often as the only mineral present (Robertson, 1982). Infrequently associated minerals may include quartz, kryzhanovskite, whiteite, vivianite and metavivianite. Fine specimens have been found at locality 4 and north of locality 7 in Area A, and at locality 15 in Area C. Millimeter-size gray crystals have been found inside ludlamite, wolfeite and pyrite nodules from locality 16 in Area C, but this paragenesis is less common. Normally the crystals range from 5 mm to 1.5 cm in size and are olive-green to clove-brown or yellow in color. Divergent aggregates subparallel on {100} are relatively common, but whether this is a result of twinning or parallel growth has not been resolved.

Table 2. **Angle table for arrojadite.**

	Measured		*Calculated**	
Form	**phi**	**rho**	**phi**	**rho**
{100}	90°	90°	90°	90°
{011}	9°51′ (1°)	59°03′ (15′)	9°46′	59°02′
{$\bar{1}$01}	–90°00′ (10′)	22°08′ (15′)**	–90°00′	22°23′
{111}	32°52′ (1°)	63°01′ (30′)	30°44′	62°23′
{$\bar{3}$11}	–45° (3°)	67° (3°)	–47°36′	67°41′

*Unit cell dimensions for arrojadite from Nickel Plate mine, South Dakota (Moore *et al.*, 1981): a = 24.730 Å, b = 10.057 Å, c = 16.526 Å, β = 105°47′.

**Note: on several crystals the ($\bar{1}$01) gave double signals for rho, one at ~22°, and the other at ~26°.

The morphology of arrojadite is discussed in detail below; we believe this is the first published description of such crystals. In total, nine crystals were measured by optical goniometry and their orientation confirmed by single crystal X-ray methods. The relatively high error associated with some of the measurements given in Table 2 results from multiple signals observed from those faces. The {$\bar{3}$11} faces give very poor reflections and were identified using a spindle stage. Figure 22 shows a crystal with well-developed forms *a*{100}, *d*{011}, *e*{111}, *f*{$\bar{1}$01} and *g*{$\bar{3}$11}. The {100} faces are normally the largest ones on the crystal, and the {$\bar{3}$11} faces are typically frosted. Once these and the {$\bar{1}$01} faces are located, it is relatively simple to orient well-developed crystals. However, multiple crystals, distorted crystals and crystals with fewer faces developed are more difficult to orient because their monoclinic symmetry may not be readily apparent.

Arrojadite forms a solid-solution series with dickinsonite, its manganese analog. Moore *et al.* (1981) state that "arrojadite-dickinsonite is probably the most complicated of all mineral structures, even when studied by modern crystal structure techniques. . . . The arrojadite end-member would ideally be $KNa_4CaFe_{14}^{+2}Al(F,OH)_2(PO_4)_{12}$, but in such a complex structure with a limited but variegated range of vacancies . . . no precise formula can be expressed." There exist no less than 15 different sites among which K, Na, Ca, Sr, Ba, Pb, Mn, Fe^{+2}, Fe^{+3}, Mg, Zn and Li must be distributed, following a scheme of complex disorder and coupled relationships with partially occupied sites and multiple site vacancies (Moore and Ito, 1979; Moore *et al.*, 1981). Thus, without crystal structure data it is virtually impossible to write a sensible formula, given even the best possible chemical analyses. Furthermore, as is the case with the Rapid Creek arrojadites, the problem may be compounded by chemical zoning within a single crystal.

Figure 14 is a backscattered-electron image of an arrojadite specimen from the Big Fish River area. This mode of SEM imaging is particularly useful for demonstrating compositional variation in a sample. The brighter areas in the photograph correspond to regions enriched in elements having overall higher atomic numbers relative to the darker areas, which have overall lower average atomic numbers. The dark background is childrenite-eosphorite with an average atomic number of 8.9. The individual arrojadite crystals enclosed in this childrenite-eosphorite matrix are dramatically zoned. The major portion of each crystal that appears gray in the backscattered electron

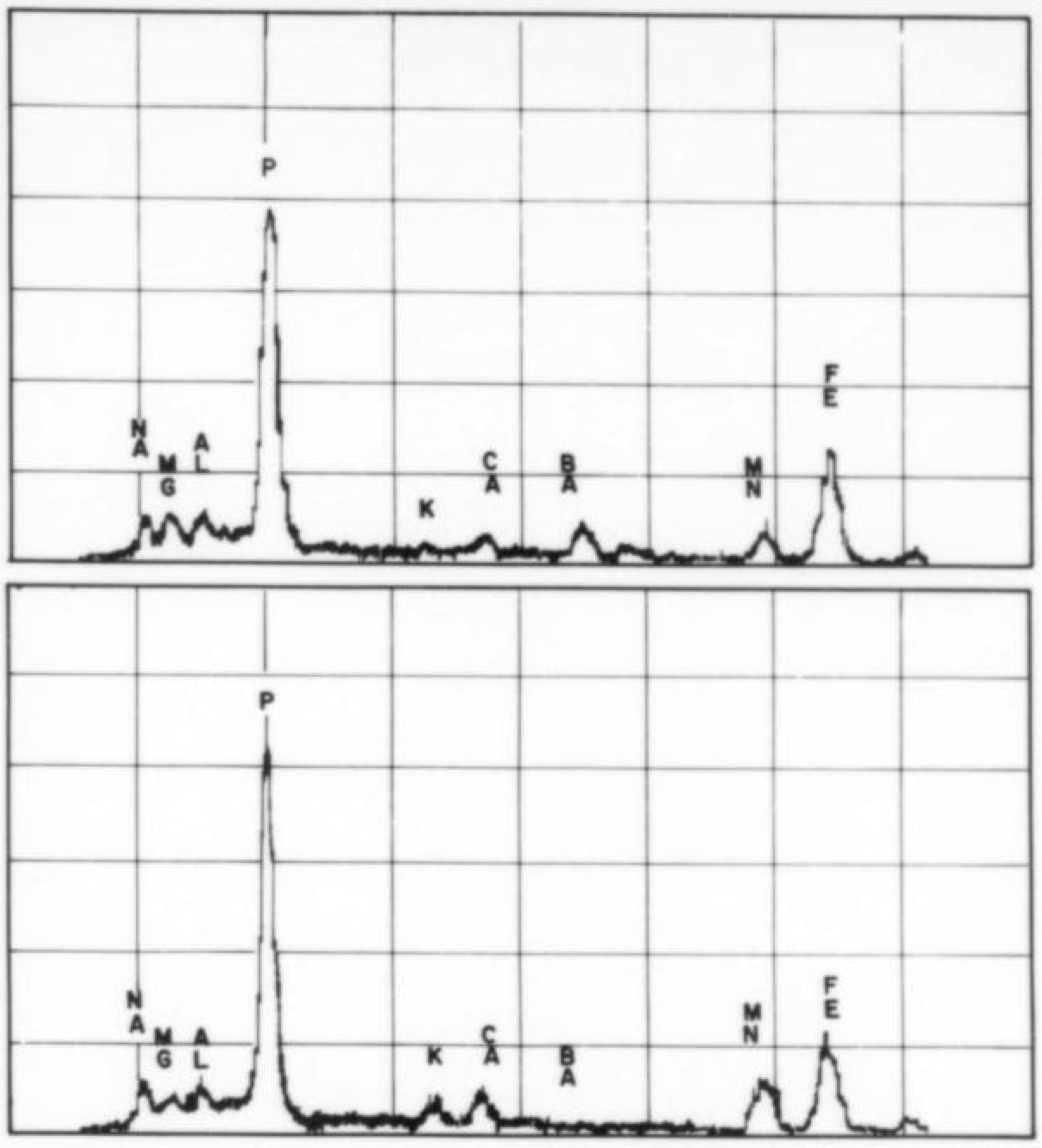


Figure 13. **Energy-dispersive X-ray spectra showing elements indicated in arrojadite. Note the replacement of barium for potassium in the upper spectrum, possibly indicating a new species, the barium analog of arrojadite.**

image has an average atomic number of about 11.8, while the white rims are approximately 12.2. This is due to the presence of barium (atomic number 56) replacing potassium (atomic number 19) in the rims of these crystals, as shown by comparing their respective energy dispersion X-ray spectra (which are given in Figure 13).

We believe these barium-enriched zones probably represent a new species, but so far no crystals large enough to permit a crystal structure analysis required to properly characterize such a species have been found, though we are still investigating the matter. Without assigning the "excess" sodium to any particular *X* or *M* site, preliminary microprobe analyses of these crystals yield the following formulas, based on 12 phosphorus atoms and assuming the unique Al site to be full, with Al^{+3} + Fe^{+3} = 1.00 (H_2O calculated by stoichiometry):
$(Ba_{0.95}K_{0.04})Ca_{0.74}Na_{4.11}Al_{1.06}(Fe_{8.23}Mg_{2.33}Mn_{2.17})(OH_{1.36}F_{0.64})(PO_4)_{12}$
for the Ba-rich rims and
$K_{0.67}Ca_{0.90}Na_{5.56}(Al_{0.96}Fe_{0.04})(Fe_{6.70}Mn_{4.30}Mg_{1.54})(OH_{1.21}F_{0.79})(PO_4)_{12}$
for the cores. A plot of K^+ vs. (Ba^{+2} + Sr^{+2}), based on 31 arrojadite analyses from Rapid Creek, shows an inverse relationship suggesting that barium does indeed substitute for potassium, probably in the *X5* site.

A microprobe survey of other arrojadites from Rapid Creek resulted in a wide range of compositions being found. Some of these are given in Table 3. In general, Rapid Creek arrojadites often contain more than five Na atoms per formula unit, have from 1.6 to 2.6 Mg^{+2} substituting for Fe^{+2} and show some F^- substituting for $(OH)^-$. Mn^{+2} never seems to be greater than Fe^{+2}, so no dickinsonites are known. A few analyses (e.g., no. 6) even show $F^- > (OH)^-$, which may also represent a new species. Analysis 3 is an arrojadite inclusion in a satterleyite-wolfeite-alluaudite group nodule from locality 16, Area C. The low Al^{+3}, relatively high total Fe and relatively low analytical sum all suggest that perhaps some iron is present as Fe^{+3} substituting for the bulk of the Al^{+3}, making this yet another potentially new member of the group.

Figure 14. **Back-scattered electron image of arrojadeite (gray) and the barium analog of arrojadite (white).**

Table 3. **Arrojadite analyses.**

	1	2	3	4	5	6
MgO	4.49	3.04	3.11	5.21	4.61	3.23
FeO*	28.35	23.68	33.06	29.98	32.39	25.02
MnO	7.36	14.94	5.99	6.03	3.66	12.84
K_2O	0.08	1.54	0.76	1.63	1.77	1.48
Na_2O	6.10	8.43	6.41	7.93	7.70	8.10
CaO	1.99	2.47	2.78	2.17	2.43	2.47
BaO	7.00	0.00	4.69	0.00	0.00	0.00
SrO	0.00	0.21	0.23	0.00	0.00	0.35
Al_2O_3	2.58	2.40	0.50	2.56	2.44	2.30
P_2O_5	40.74	41.67	39.77	41.76	41.17	41.50
SiO_2	0.06	0.00	0.05	0.06	0.00	0.00
F	0.58	0.73	0.67	0.79	0.73	0.97
H_2O**	0.59	0.54	0.52	0.51	0.52	0.42
O=F	–0.24	–0.31	–0.28	–0.33	–0.31	–0.41
sum	99.68	99.34	98.26	98.30	97.11	98.27
Mg^{+2}	2.33	1.54	1.65	2.63	2.37	1.65
Fe^{+2}	8.23	6.74	9.84	8.50	9.33	7.15
Mn^{+2}	2.17	4.30	1.81	1.73	1.07	3.71
K^+	0.04	0.67	0.35	0.71	0.78	0.65
Na^+	4.11	5.56	4.42	5.21	5.14	5.36
Ca^{+2}	0.74	0.90	1.06	0.79	0.90	0.90
Ba^{+2}	0.95	0.00	0.65	0.00	0.00	0.00
Sr^{+2}	0.00	0.04	0.05	0.00	0.00	0.07
Al^{+3}	1.06	0.96	0.21	1.02	0.99	0.93
P^{+5}	11.98	12.00	11.98	11.98	12.00	12.00
Si^{+4}	0.02	0.00	0.02	0.02	0.00	0.00
F^-	0.64	0.79	0.75	0.85	0.80	1.05
H^+	1.36	1.21	1.25	1.15	1.20	0.95
O^{-2}	48.43	48.30	47.99	48.28	48.30	47.82

*Total Fe reported as FeO
**Calculated stoichiometrically

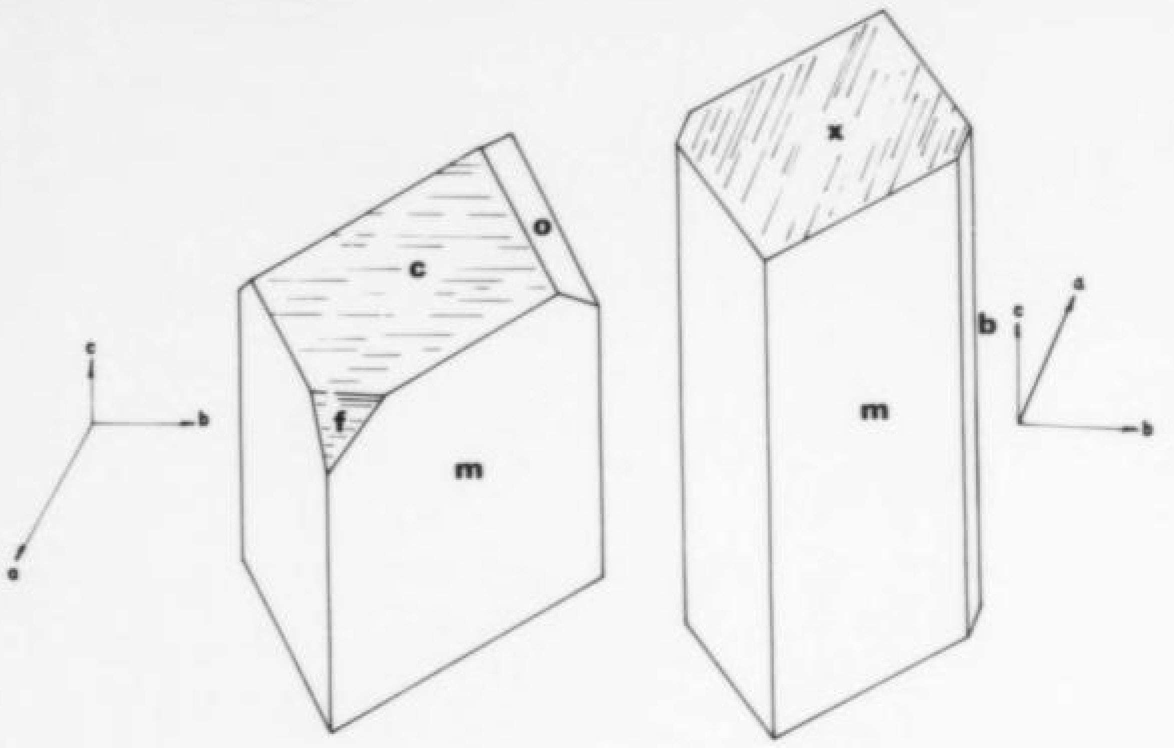


Figure 15. **Crystal drawing of augelite (left) and brazilianite compared.**

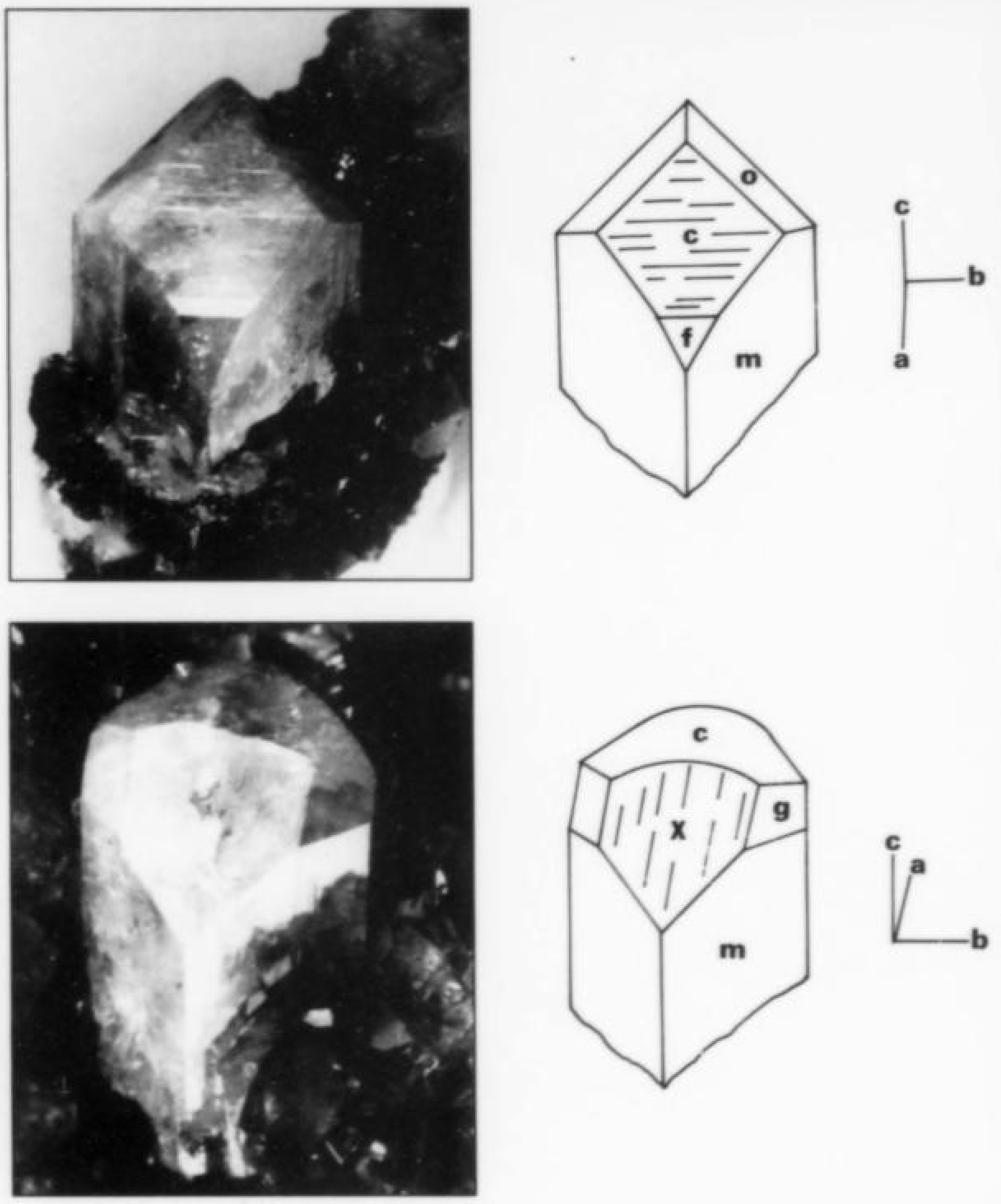


Figure 17. **Crystals of a 2-cm, Rapid Creek augelite (top) and a 6-mm brazilianite (bottom) compared, 180° apart in rotation about [001]. Note difference in direction of striations on augelite** ***c*****{001} and brazilianite** ***x*****{$\bar{1}$01}. CMN specimens 52125 and MOC3454; G. Robinson photos.**

Augelite $Al_2(PO_4)(OH)_3$

Most of the major augelite occurrences at Rapid Creek are located in fault veins and their associated breccias. Robertson (1982) notes that crystals generally decrease in size with increasing distance from the fault zones, indicating their genetic relationship with these structures. Curiously, the more common aluminum phosphate minerals, variscite and wavellite, have thus far not been identified from these deposits.

Good augelite crystals are known from relatively few places worldwide (Palache, Berman and Frondel, 1951; Wise, 1977), and those from the Rapid Creek area rank among the best. The most productive collecting sites found thus far are in the vicinity of locality 1, Area A, where yellow-green crystals up to 2 cm have been found associated with quartz and siderite. Additional good specimens have also been collected at locality 6, Area A, and in Area B at locality 10. Most of these crystals show dominant *m*{110} prisms and *c*{001} pinacoids, with smaller *o*{$\bar{1}$11} and *f*{201} faces often developed. Less frequent forms include *a*{100}, *x*{$\bar{2}$01} and *y*{$\bar{4}$01} (?). Occasionally contact twins, twinned by reflection on (100), are found.

Microprobe analyses indicate this augelite is essentially pure $Al_2(PO_4)(OH)_3$, with only occasional traces of iron, which may account for its pale yellow-green color.

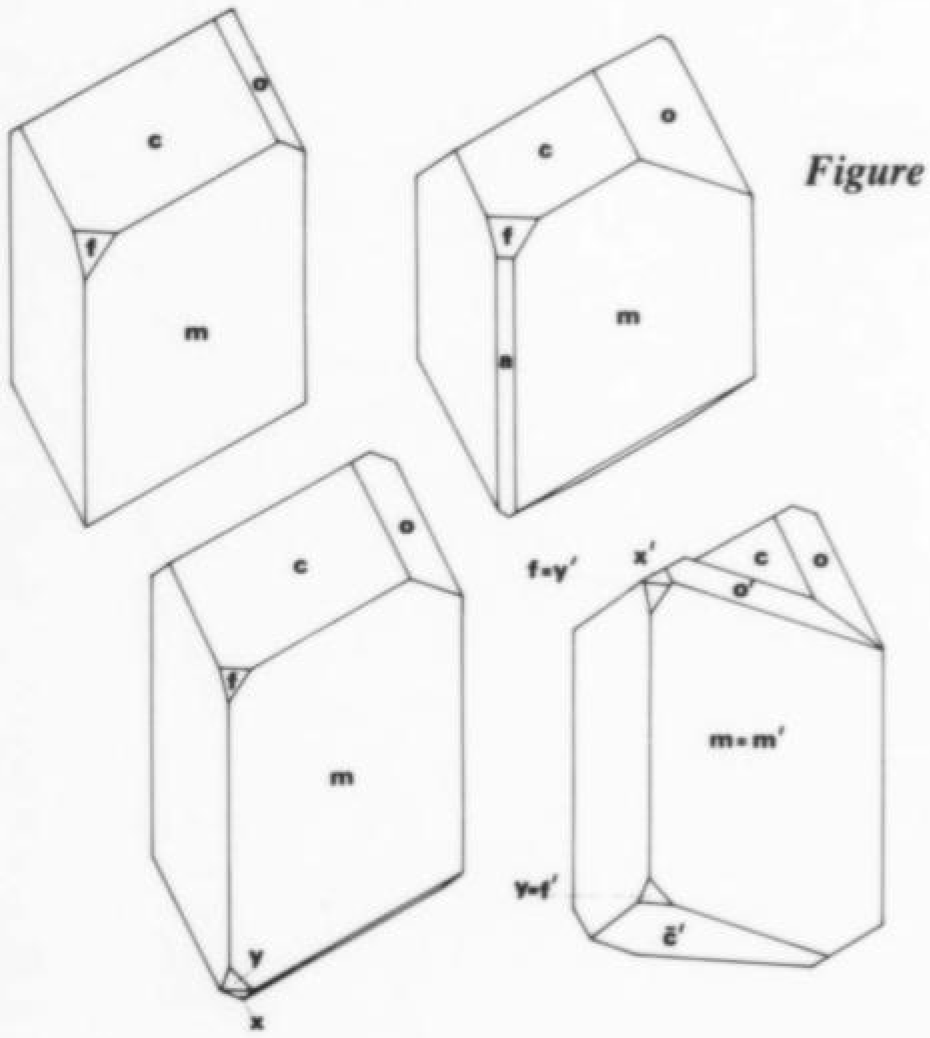
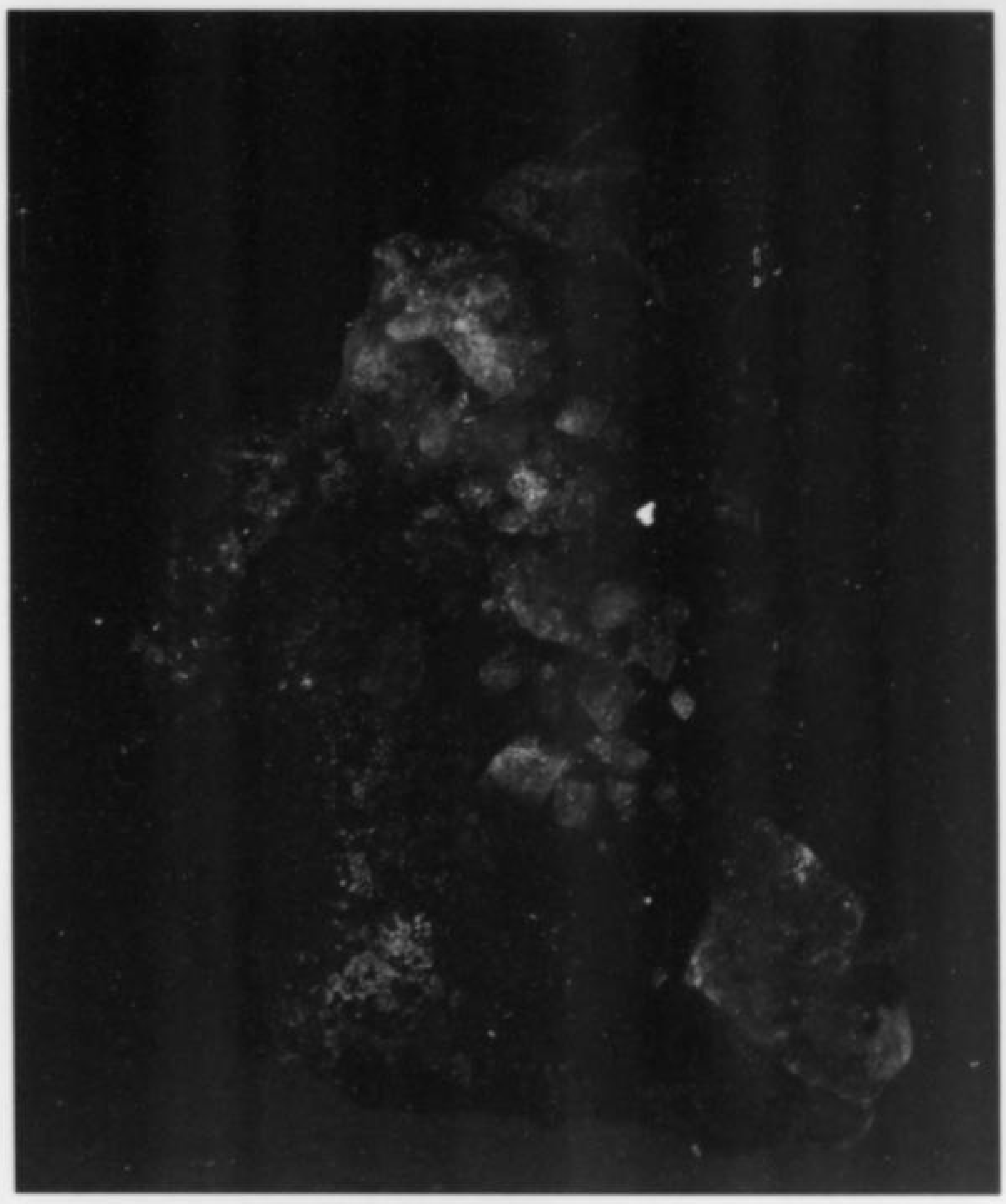
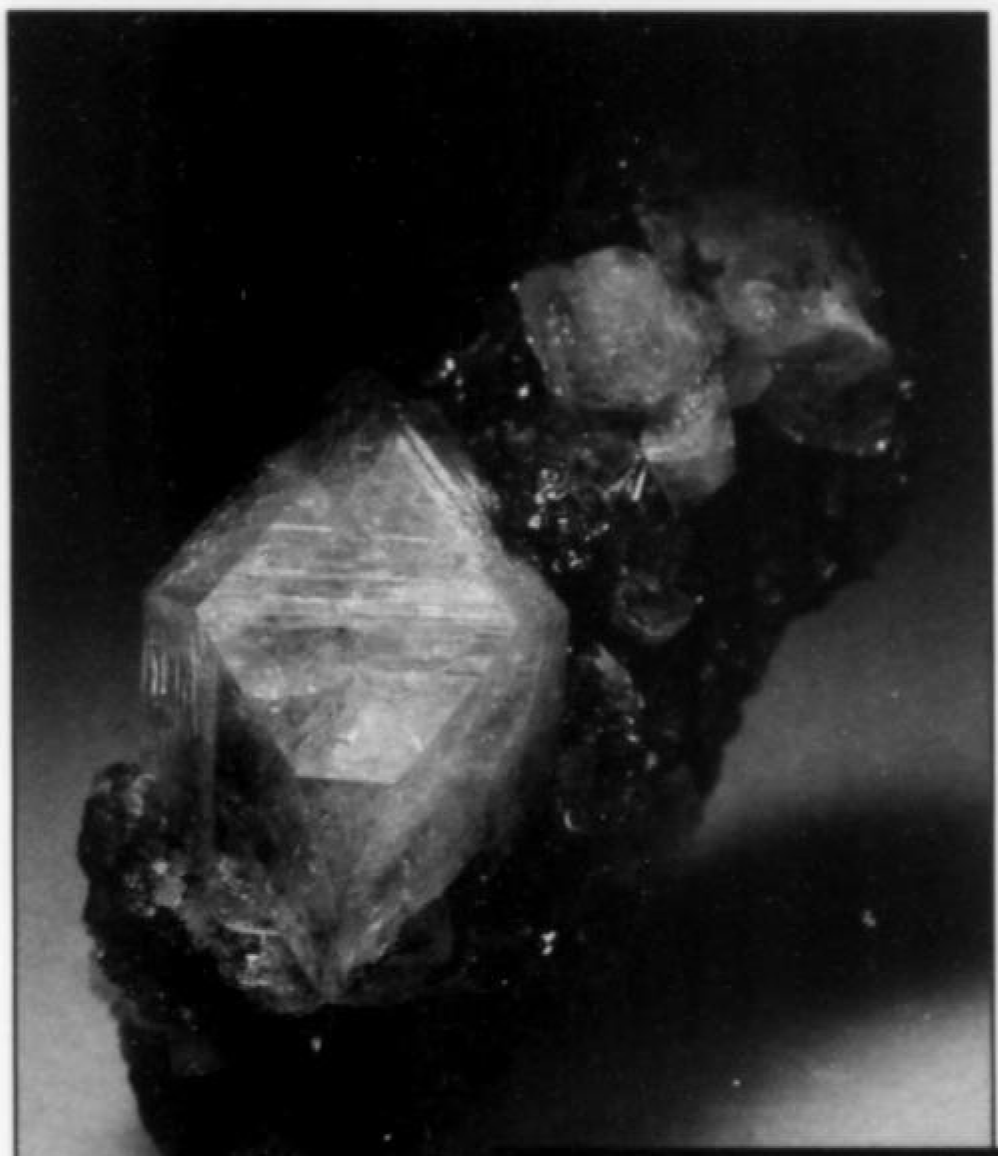


Figure 16. **Crystal drawings of augelite.**

Figure 18. **Augelite, a yellow-green, 1-cm crystal, twinned on (100), probably from Area A, Location 6. CMN specimen 39947; G. Robinson photo.**





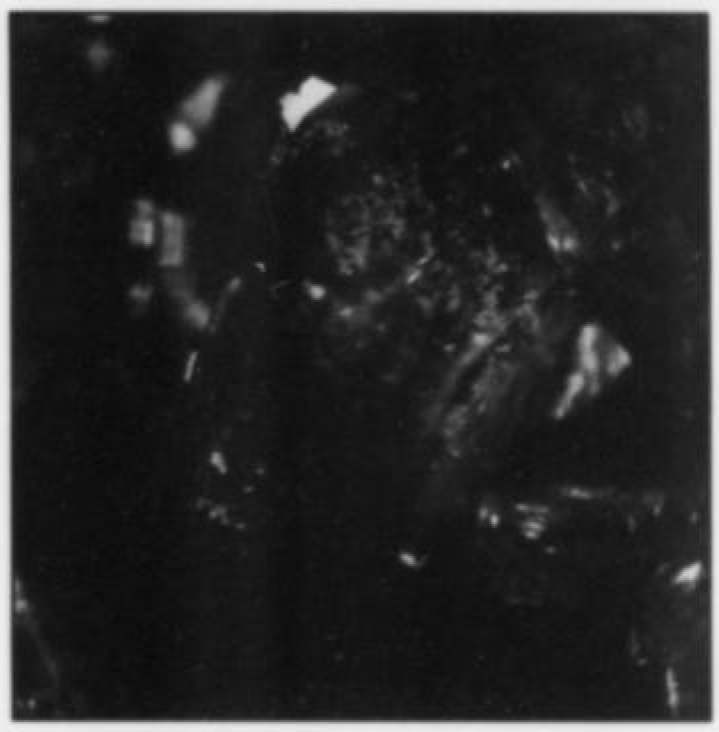


Figure 21. (above) **Augelite (green) and lazulite crystal group, 8.4 cm, from the Rapid Creek area. William Moller collection; R. Currier photo.**

Figure 22. (left) **Arrojadite crystals to 3 mm. CMN specimen 50836; S. Chamberlain photo.**

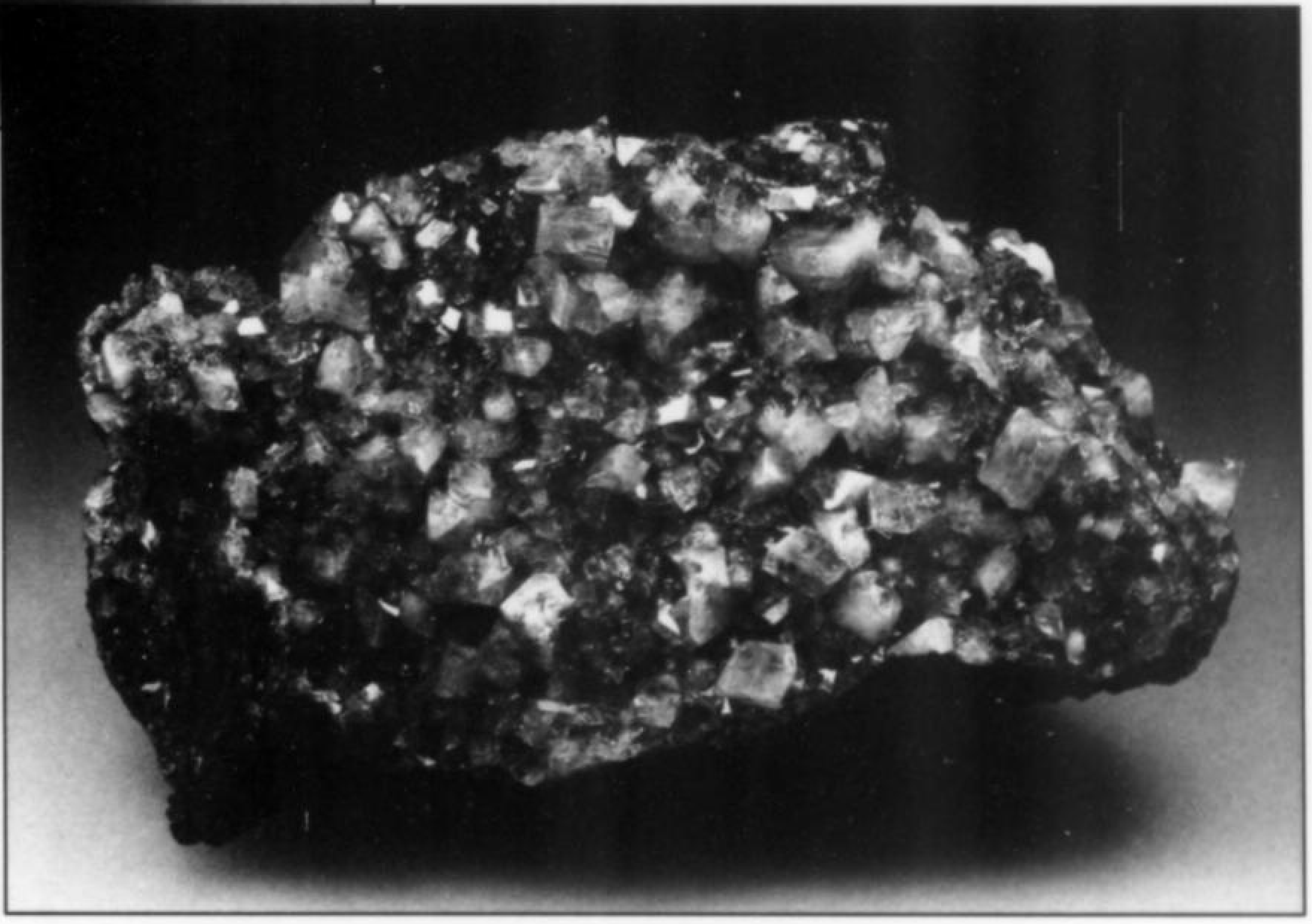


Figure 19. (top) **Arrojadite crystal group, 4 cm, from the Big Fish River area. P. Collins collection; G. Robinson photo.**

Figure 20. (above) **Augelite crystals to 1.8 cm, from the Rapid Creek area. CMN specimen 52125; G. Robinson photo.**

Figure 23. **Augelite crystals on matrix, 11 cm. CMN specimen 31873; W. E. Wilson photo.**

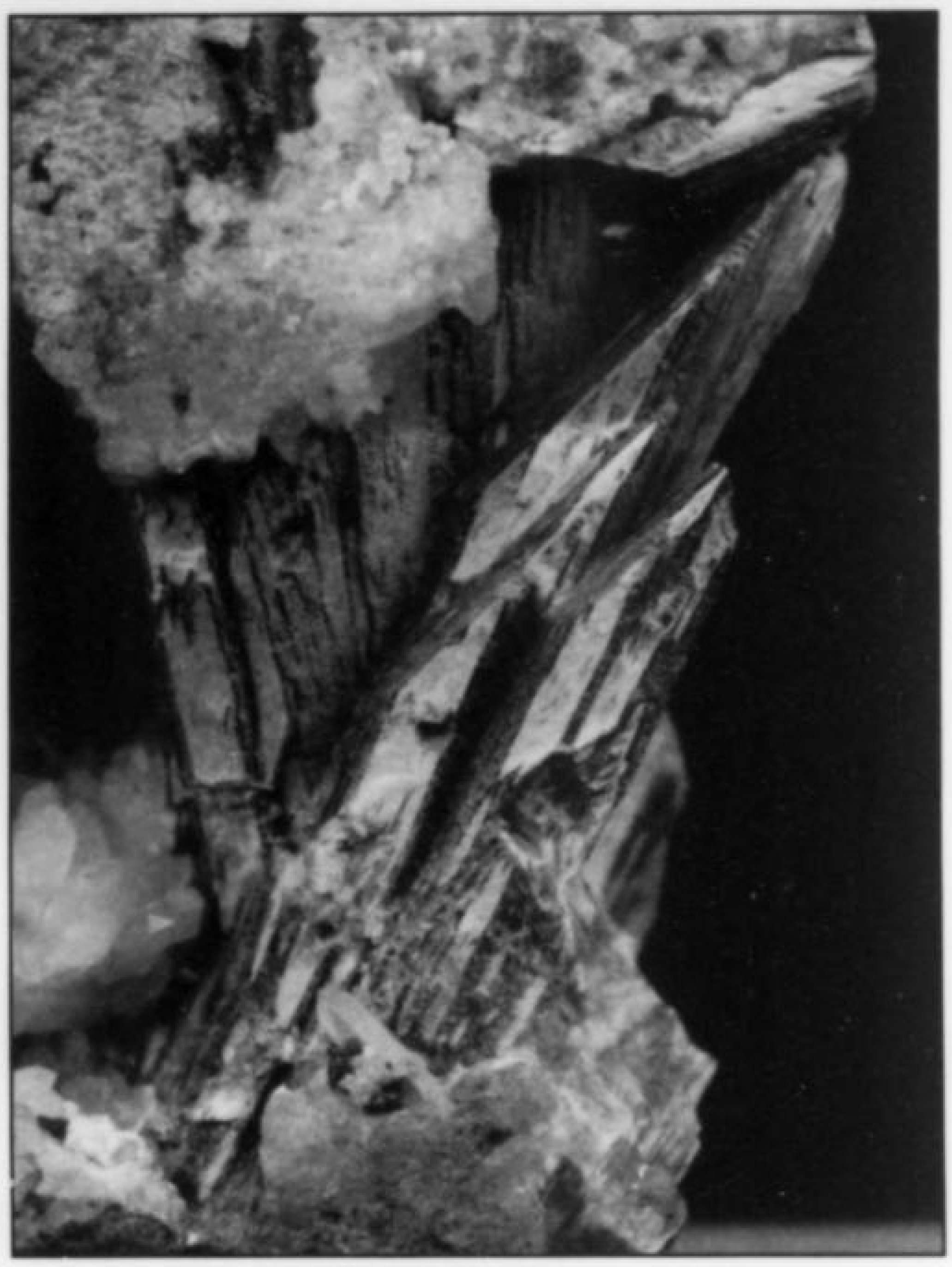


Figure 24. **Baričite crystal, pale blue-gray, 5 cm, from Area A, locality 2. CMN specimen 53124; G. Robinson photo.**

Baričite $(Mg,Fe^{+2})_3(PO_4)_2\cdot 8H_2O$

Baričite is the magnesium analog of vivianite, and was first described from near locality 2 in Area A, where it occurs as pale, gray-blue cleavage plates over 10 cm across associated with quartz, siderite, vivianite and lazulite (Sturman and Mandarino, 1976). Crystals are uncommon and generally resemble vivianite.

Baričite is not easily differentiated from vivianite. Even the type baričite contains approximately 45 mole % vivianite, and most vivianite (q.v.) from the area contains some magnesium. X-ray methods are of little use in distinguishing these two minerals because of their similar cell parameters. Optically, however, baričite has overall lower refractive indices and a smaller $2V_z$ than vivianite, with $n_\alpha = 1.554$, $n_\beta = 1.564$, $n_\gamma = 1.595$ and $2V_z = 59°$ (Sturman and Mandarino, 1976). Also, baričite has a much lower density (2.42 g/cm³ as compared to 2.68 g/cm³ for pure vivianite). Nevertheless, chemistry is still the deciding factor, and Mg must be greater than the other divalent cations in order to have baričite.

Barite $BaSO_4$

Barite has been found locally in Area A at locality 1, and near the mouth of "Crosscut Creek," where it occurs as colorless, tabular crystals up to 7 mm in length, associated with siderite, fluorapatite and quartz in cavities in a brecciated matrix. Barite has also been observed as 0.1-mm crystals in vugs in altered wolfeite nodules from Area C.

Brazilianite $NaAl_3(PO_4)_2(OH)_4$

While perhaps not as large or as gemmy as the more famous Brazilian specimens (Cassedanne, 1983), sharp, lustrous, yellow-green crystals of brazilianite over a centimeter in size have been found at Rapid Creek. These crystals occur in a variety of habits. The most common forms are *c*{001}, *x*{$\bar{1}01$}, *m*{110} and *g*{$\bar{1}11$}, with *b*{010}, *n*{011} and *s*{211} (?) observed less frequently.

Brazilianite occurs sporadically throughout the region. The best collecting sites have probably been localities 9 and 14 in Area B,

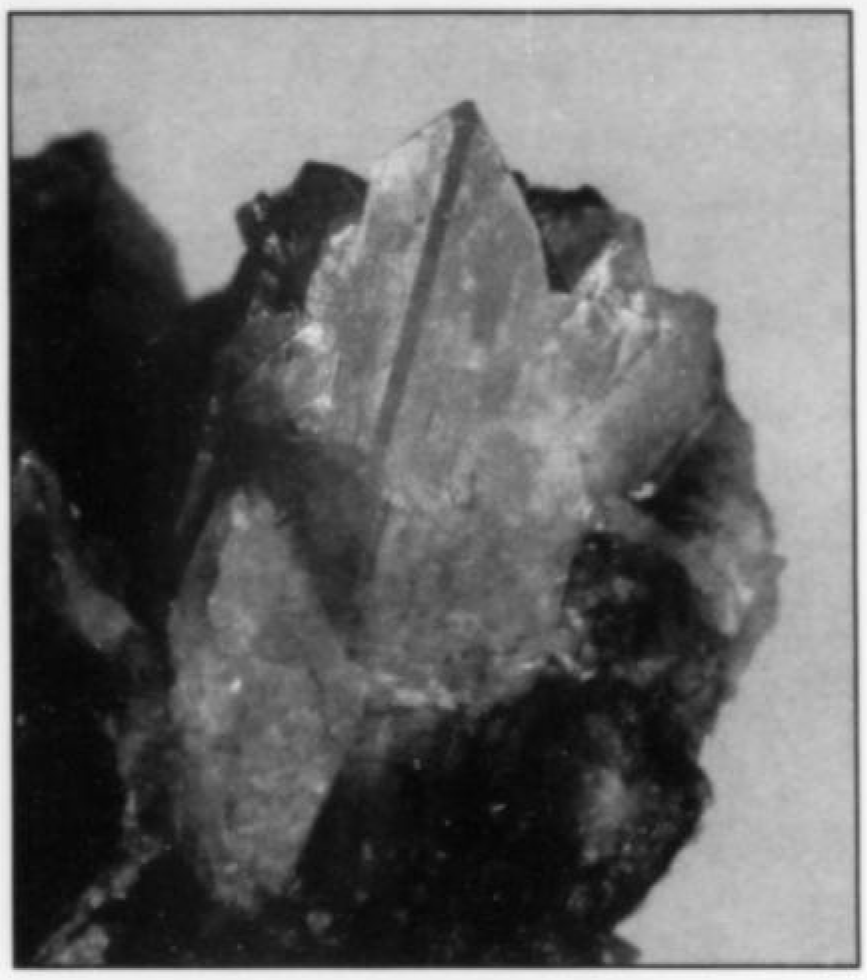


Figure 25. **Brazilianite crystal, pale yellow, 1.3 cm, from ≈500 meters southwest of Area A, locality 4. CMN specimen 53787; G. Robinson photo.**

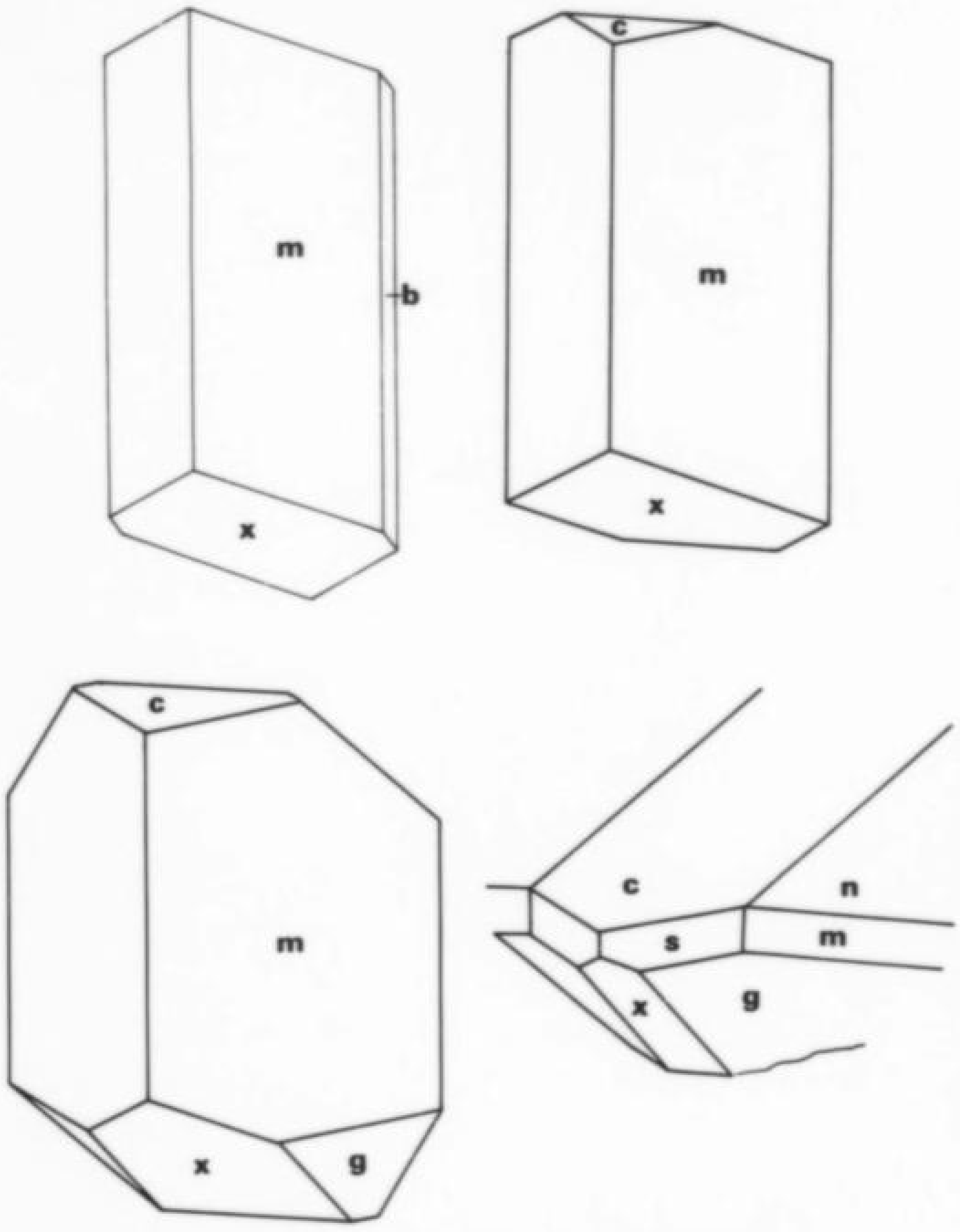


Figure 26. **Brazilianite crystal drawings.**

although other good specimens have been found at locality 3 on "Crosscut Creek," and elsewhere in Area A.

Crystals of brazilianite and augelite look very much alike, and the two are often confused. Careful observations, however, may reveal subtle differences in morphology. A second, confirming identification may also be made by comparing densities: augelite (2.69) will float in bromoform, whereas brazilianite (2.98–3.01) sinks.

Some of the brazilianite crystals from Area B show twinning and optically anomalous zones with slight differences in refractive indices and optic axial angles. Subsequent microprobe analyses showed these zones to be slightly enriched in iron and calcium, which appear to substitute for aluminum, though Ca^{+2}–Al^{+3} diadochy seems unlikely from a crystallochemical viewpoint. The formula of these zones is approximately $Na_{1.00}(Al_{2.83}Fe^{+3}_{0.07}Ca_{0.06})(PO_4)_{2.04} \cdot 4H_2O$, based on six cations.

Celestine $SrSO_4$

Celestine has been identified by qualitative energy dispersive microprobe analysis as a single grain associated with whitlockite (q.v.), phosphosiderite and vivianite in a satterlyite specimen collected from talus near locality 8 in Area A.

Chalcopyrite $CuFeS_2$

To date, chalcopyrite has been found at only one site: locality 10, area B, where it occurs as microscopic brassy crystals sparsely scattered on the surfaces of some of the pink goyazite crystals. Only a few specimens are known, but others likely exist, since the tiny crystals are easily overlooked.

Childrenite $Fe^{+2}Al(PO_4)(OH)_2 \cdot H_2O$ and
Eosphorite $Mn^{+2}Al(PO_4)(OH)_2 \cdot H_2O$

Childrenite-eosphorite occurs as flattened, radiating sprays up to 4 cm across on fracture surfaces, and as smaller free-standing crystals in some of the quartz veins. Like apatite, childrenite-eosphorite is widespread, but good specimens are not especially abundant. Its color ranges from gray-white to clove-brown, and microprobe analyses show considerable variation in composition, with both iron-dominant and manganese-dominant zones occurring in a single crystal. Observed compositions range from near $Chl_{80}Eos_{20}$ to $Eos_{55}Chl_{45}$, making it virtually impossible to differentiate the two visually. Of those specimens analyzed, the more manganese-rich members are from near locality 9, Area B, which has produced some of the best specimens collected, and the drusy, microscopic, brown crystals associated with the wardite from locality 12 nearby are eosphorite with an average composition of approximately $Eos_{55}Chl_{45}$. The larger, more bladed, gray crystals from locality 15, Area C, are mostly childrenite.

Figure 27. **Collinsite crystal group, gray-white, 8 cm, from Area B, locality 11. CMN specimen 49000; G. Robinson photo.**

Figure 28. **Collinsite crystal aggregates, gray-white, to 2.5 cm, from Area B, locality 11. CMN specimen 49305; G. Robinson photo.**

Collinsite $Ca(Mg,Fe^{+2})(PO_4)_2 \cdot H_2O$

Well-formed crystals of collinsite are not common, and until now, only two localities, the Tiptop mine in South Dakota, and Reaphook Hill in South Australia, have produced most of the better specimens known (Nriagu and Moore, 1984; Johnston and Hill, 1978; W. Roberts, personal communication, 1985). In July, 1983, what are probably the finest collinsite specimens ever found were collected by two of us (GWR and JVV) while being harassed by a grizzly bear at locality 11 in Area B. These consist of stellate aggregates of cream-white crystals up to 2 cm with quartz and lesser amounts of siderite, apatite, metavivianite and gorceixite. Microprobe analyses indicate these crystals have variable Mg:Fe:Mn contents, ranging from $Mg_{0.76}Fe_{0.23}Mn_{0.01}$ to $Mg_{0.67}Fe_{0.32}Mn_{0.01}$ per formula unit, and contain an average of about $0.17\ F^-$.

A few noteworthy specimens have also been found between localities 15 and 16 in Area C, at locality 14, in Area B and north of locality 7 in Area A, but none of these are as spectacular as those from locality 11.

This is the second reported occurrence of collinsite in Canada, the type locality being Francois Lake, British Columbia (Poitevin, 1927). Collinsite was named after William Henry Collins (1878–1937), a former Director of the Geological Survey of Canada (Drolet, 1982).

Dolomite $CaMg(CO_3)_2$

While not a major constituent of the phosphate-bearing veins, crystals of dolomite have been collected from Rapid Creek between localities 5 and 6 in Area A. They occur as beige to tan, botryoidal aggregates of discoidal, rhombohedral crystals up to 5 mm lining fracture surfaces in large, septarian-like nodules. No other species have been noted in association with these crystals, but not many specimens have been collected.

Rapid Creek dolomite was previously thought to be ankerite, but microprobe analyses have shown that the major phase present is actually dolomite, with a formula near $Ca(Mg_{0.93}Fe_{0.06}Mn_{0.01})(CO_3)_2$. The crystals are rhythmically zoned, but even the most iron-rich portions are still 82 mole % dolomite. We have not found ankerite at Rapid Creek.

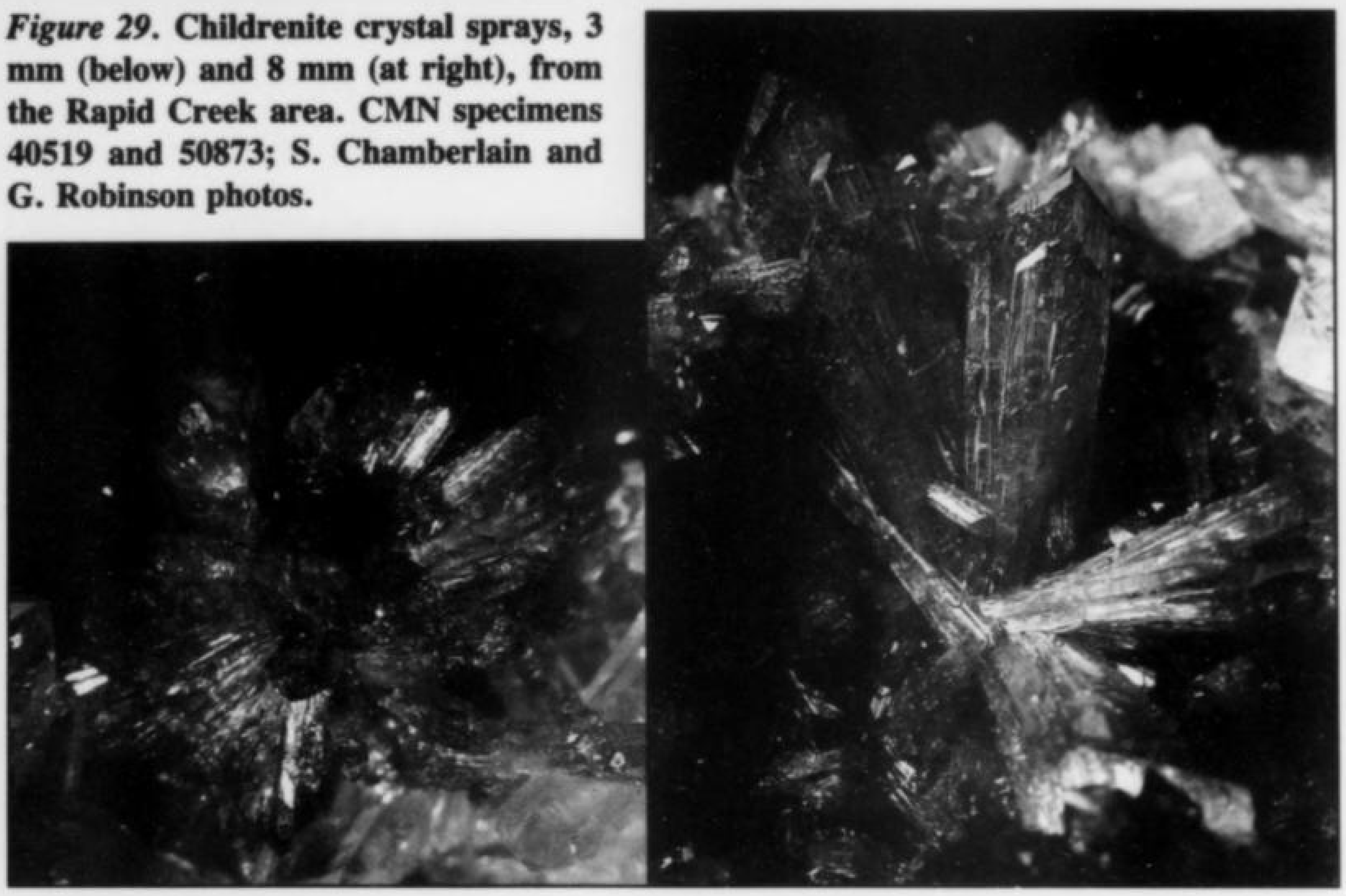


***Figure 29*. Childrenite crystal sprays, 3 mm (below) and 8 mm (at right), from the Rapid Creek area. CMN specimens 40519 and 50873; S. Chamberlain and G. Robinson photos.**

***Figure 30*. Collinsite crystal group, 1.5 cm, from Area B, locality 11. CMN specimen 50015; G. Robinson photo.**

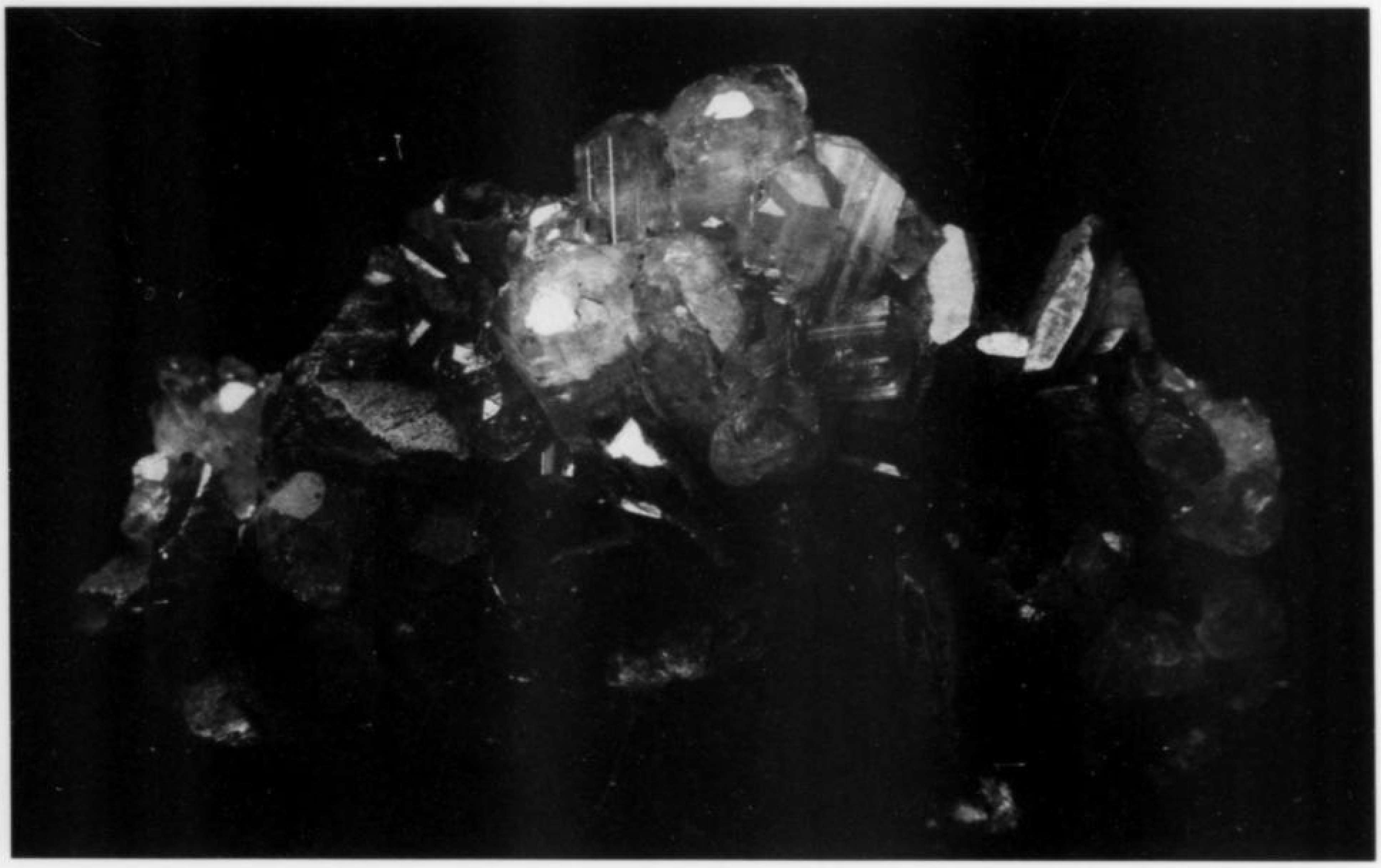


***Figure 31*. Fluorapatite crystal group (pale purple) with siderite, 2 cm across, from Area A, locality 8. CMN specimen 42481; G. Robinson photo.**

Eosphorite: See under Childrenite

Fluorapatite $Ca_5(PO_4,CO_3)_3F$

Both fluorapatite and carbonate-fluorapatite are found in the Rapid Creek Formation, but from the collector's viewpoint only fluorapatite occurs in well-crystallized, desirable specimens. This species is seldom found in great amounts, despite its widespread occurrence. Fluorapatite is most commonly associated with lazulite, quartz and siderite, but may occur with other species, too. Good specimens have been collected from localities 1 and 8 in Area A, and from numerous other sites throughout the formation.

Fluorapatite ranges in color from colorless to white or purple, and in crystal size from microscopic to nearly 2 cm across. A few color-zoned, white to pale lavender crystals somewhat reminiscent of those from the King Lithia mine in South Dakota (Wilson *et al.*, 1984) have been found, but are not common. Other crystals sometimes show fibrous bands at their terminations that probably resulted from a hiatus in crystallization.

Though the crystal habit, color and associated species may vary

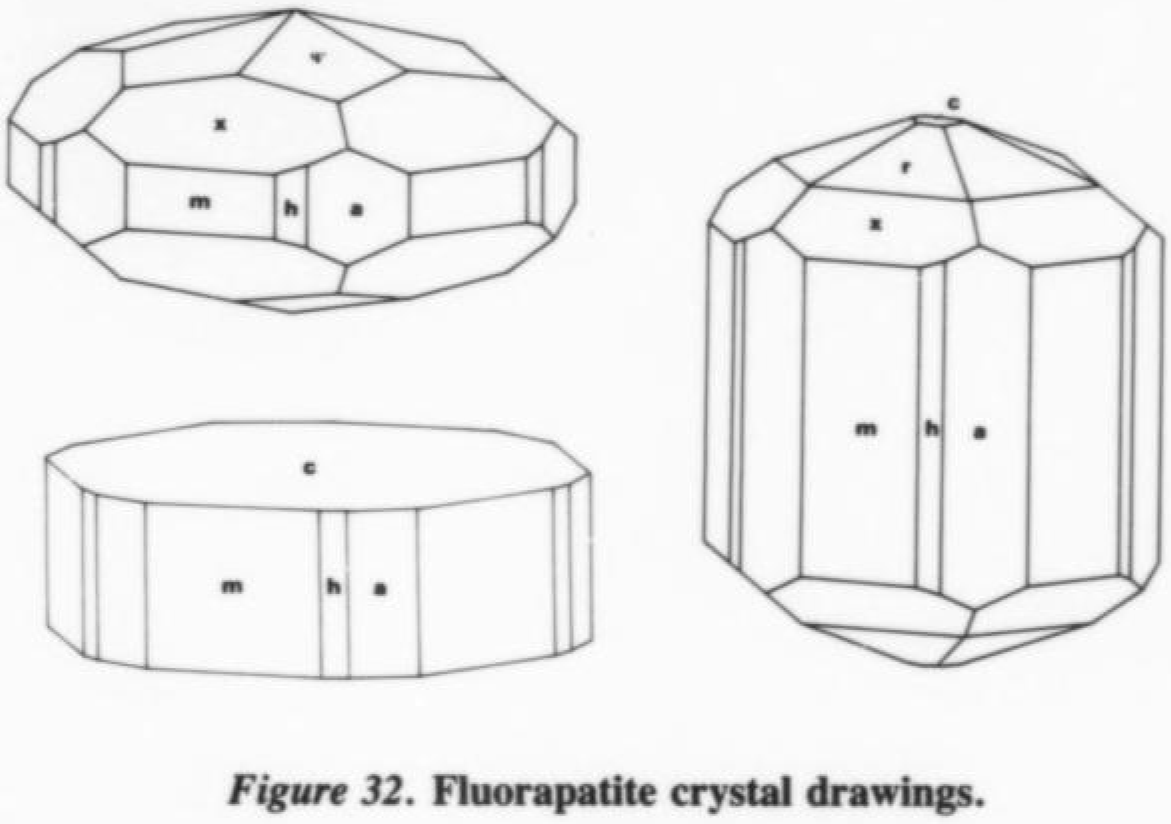


***Figure 32*. Fluorapatite crystal drawings.**

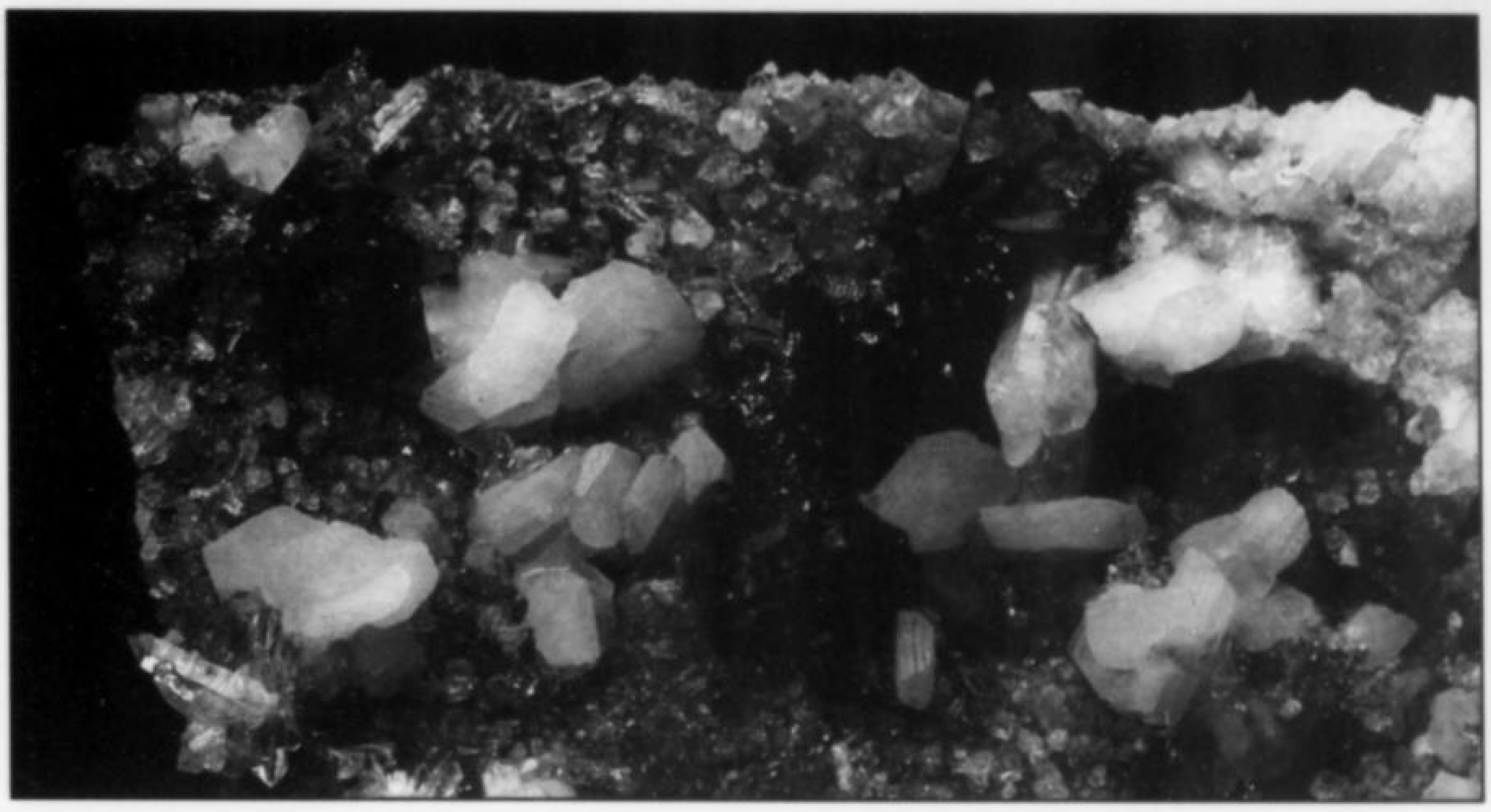


***Figure 33*. Gorceixite crystals (cream colored) with lazulite (blue) on matrix, 3 cm. Barry Kulan specimen and photo.**

considerably, the predominant forms tend to be the same, and most often appear in various combinations of prisms $m\{10\bar{1}0\}$, $h\{21\bar{3}0\}$ and $a\{11\bar{2}0\}$, and dipyramids $x\{10\bar{1}1\}$ and $\psi\{11\bar{2}4\}$ (?), with or without basal pinacoids $c\{0001\}$. These crystals form individuals either tabular or elongate along [0001], and frequently show oscillatory growth patterns and hillocks on their terminations.

The purple crystals with siderite from locality 8, Area A, show a slightly different morphology, with dipyramids $x\{10\bar{1}1\}$ and $r\{10\bar{1}2\}$ forming the terminations. Upon close examination, the purple color in these crystals is seen to be confined to a zone about their outer margin and parallel to [0001]. Microprobe analyses show these zones contain up to about 0.2 weight % MnO, which may account for the color (Vasilieva, 1958).

Carbonate-fluorapatite is less common and occurs as botryoidal crusts lining cavities in breccia, and as tiny nodules in the mudstone (Robertson, 1982).

Fluorite CaF_2

A single occurrence of fluorite has been noted in the vicinity of locality 1, Area A, where it occurs as small mauve colored crystals with barite (I. Jonasson, personal communication, 1988).

Garyansellite: See under Kryzhanovskite

Gorceixite $BaAl_3(PO_4)_2(OH)_5 \cdot H_2O$

Euhedral crystals of gorceixite were first reported from the Lengenbach quarry in Switzerland in 1975 (Graeser and Stalder, 1976), and from Rapid Creek shortly thereafter. Prior to these discoveries, the species was known only in the form of grains and pebbles from diamond-bearing gravels in Africa and Brazil (Palache, Berman and Frondel, 1951). Gorceixite crystals have also been found at the Moculta quarry near Angaston, South Australia (Noble *et al.*, 1983; Henderson and Peisley, 1985), Indian Mountain, Alabama (Gordon and Hollabaugh, 1989), and at a roadcut near Ayer's Cliff, Quebec; but clearly, the largest and best crystals have come from the Yukon.

Gorceixite is not a particularly common species at Rapid Creek. Along with other barium-rich phosphates, it seems to be restricted to brecciated fault zones and conglomeratic slump deposits (Robertson, 1982). Only a few occurrences have been documented. Undoubtedly the best specimens are the tabular, white crystals associated with

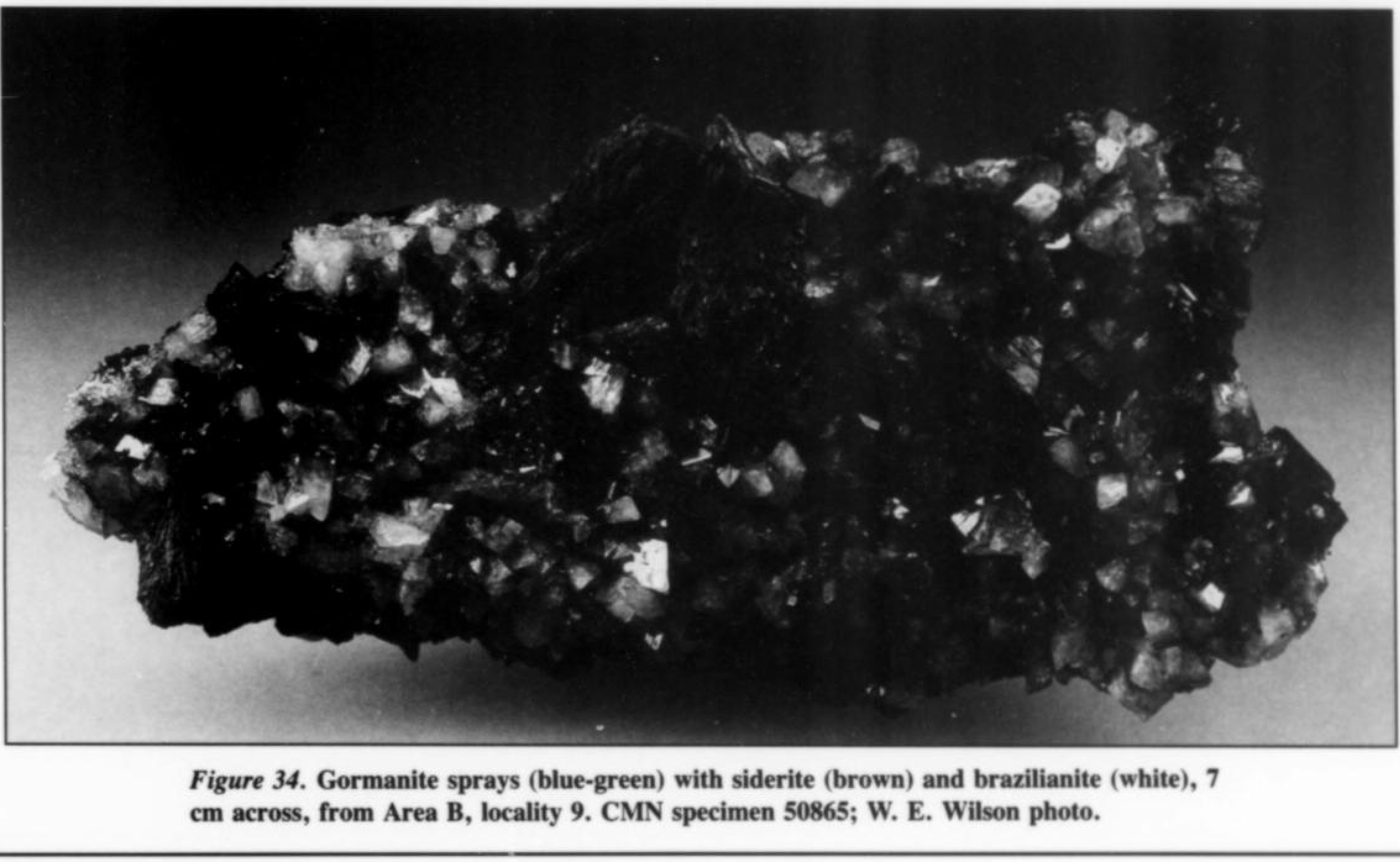


***Figure 34*. Gormanite sprays (blue-green) with siderite (brown) and brazilianite (white), 7 cm across, from Area B, locality 9. CMN specimen 50865; W. E. Wilson photo.**

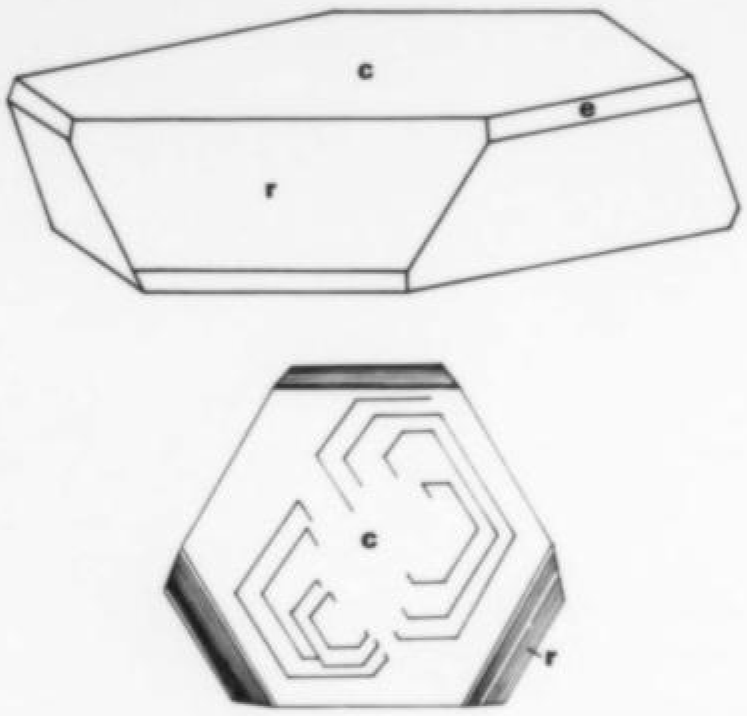


Figure 35. **Gorceixite crystal drawings, idealized (top) and actual (bottom).**

quartz, siderite and lazulite which were found just downstream from locality 1, in Area A. Unfortunately, this was a very localized occurrence sandwiched between a kulanite-bearing and a lazulite-bearing layer, and was depleted soon after its discovery. Repeated searches for similar sites in the surrounding area have been unsuccessful.

Crystals of gorceixite from this occurrence may approach 5 mm across, although individuals of 1 to 2 mm are by far more common. Morphologically the crystals are relatively simple, and are composed of many thin plates parallel to *c*{0001}, which gives rise to a step-like appearance on the *r*{$10\bar{1}1$} rhombohedron faces. Smaller *e*{$01\bar{1}1$} faces are also occasionally developed. In Area B, smaller but similar crystals have been found at locality 13; and at locality 11 gorceixite has been observed as microscopic white flakes associated with quartz and collinsite.

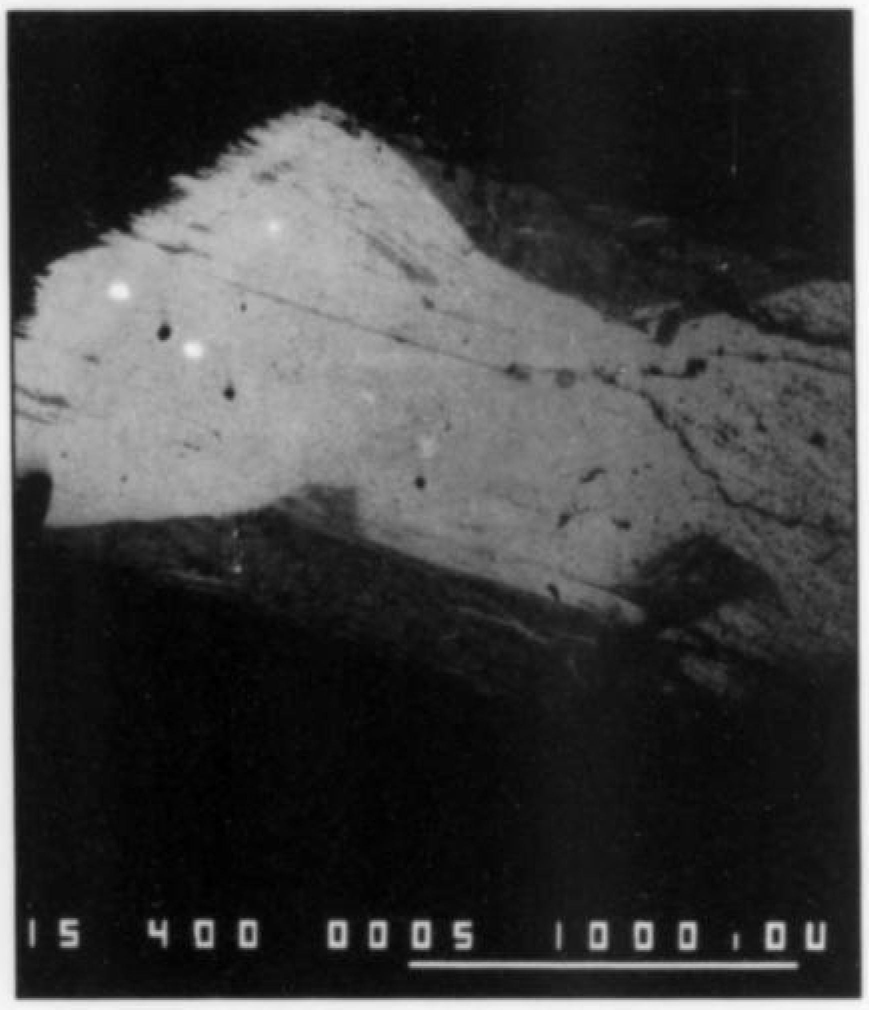


Figure 36. **Gorceixite, back-scattered electron image showing darker calcium/strontium-rich zones.**

Figure 36 is a backscattered-electron image of a single gorceixite crystal from the occurrence near locality 1, Area A. While microprobe analyses of all the various zones in this crystal yield compositions that are well within the gorceixite field, the zones corresponding to the darker regions in the photograph show that up to 30 atomic % of the barium may be replaced by calcium and strontium in various proportions, but generally close to Ca:Sr = 2:1. Whether this is merely the result of compositional changes in the original fluid from which the crystal grew or due to more complex chemical processes, remains uncertain.

Figure 37. **Gorceixite crystal, gray-white, 3 mm, from Area A, locality 1. CMN specimen 51268; G. Robinson photo.**

Gordonite $MgAl_2(PO_4)_2(OH)_2\cdot 8H_2O$

Gordonite is a relatively uncommon mineral at Rapid Creek. It has been found at locality 7, Area A, where it occurs sparingly as yellow to white stilbite-like sheaves up to 2 mm in size encrusting wardite. A number of the Yukon wardite specimens now in collections probably contained associated gordonite before they were cleaned. Microprobe analyses of this gordonite show that it is relatively pure, with an average of only about 15 atomic % of the magnesium replaced by iron.

A few tiny, clear, prismatic crystals found embedded in messelite from locality 2, Area A, also give an X-ray pattern that quite closely matches that of gordonite, but they have not been chemically analyzed.

Gormanite $Fe_3^{+2}Al_4(PO_4)_4(OH)_6\cdot 2H_2O$ and
Souzalite $Mg_3^{+2}Al_4(PO_4)_4(OH)_6\cdot 2H_2O$

Gormanite is the ferrous iron analog of souzalite, and was named for Professor Donald Gorman of the University of Toronto by Sturman *et al.* in 1981. These authors discuss the intimate association between the two species and demonstrate the difficulties inherent in labeling unanalyzed specimens. Even individual crystals show variable Fe/Mg ratios, and yield compositions which prove both species to be present. Since there are no discernible differences in color, habit or appearance in general, it is recommended that unanalyzed specimens be labeled gormanite-souzalite, since there is a high probability that both species are in fact present.

Gormanite-souzalite occurs throughout the exposed formation as flattened, blue, radial sprays on fracture surfaces, as inclusions in quartz, and as radial aggregates of elongate blue-green crystals. The most commonly associated species tend to be quartz, siderite and brazilianite, although several others have been noted. The best specimens have undoubtedly come from locality 9 in Area B, but excellent material also occurs at locality 15 in Area C.

Goyazite $SrAl_3(PO_4)_2(OH)_5\cdot H_2O$

Very fine crystals of goyazite have been found at locality 10 in Area B; these represent the only major strontium-bearing species known from the formation. The crystals form white to pink rhombohedrons up to a centimeter across and are commonly associated

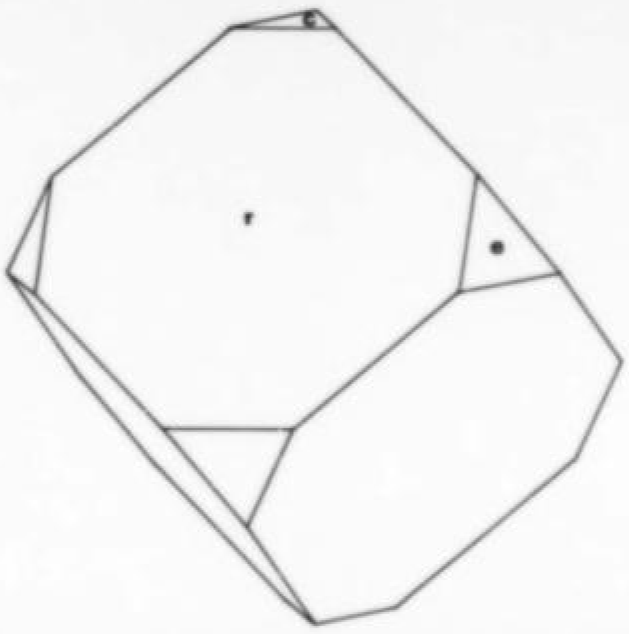


Figure 38. **Goyazite crystal drawing.**

Figure 39. **Goyazite crystals, white, to 6 mm, showing the forms *r*{10$\bar{1}$2} and *e*{01$\bar{1}$1}, from Area B, locality 10. CMN specimen 50822; G. Robinson photo.**

with siderite, kulanite and quartz. The most frequently observed forms are *r*{10$\bar{1}$2}, *e*{01$\bar{1}$1} and *c*{0001}. Striations parallel to {0001} provide a convenient means to orient these crystals.

Interestingly, the association of kulanite with these specimens indicates that both barium and strontium were present during crystallization, although gorceixite (the Ba analog of goyazite) is not present. In fact, microprobe data show this goyazite to be relatively pure, with only a minor amount of barium concentrated near the cores of the crystals. Wavelength dispersive scans for iron and manganese were conducted on both the white and pink crystals, but neither element was detected. Traces of cerium were found in both samples, but whether that element is responsible for the pink color is uncertain.

The unit cell dimensions, refined from X-ray powder data, are also quite close to those of pure goyazite, with a = 7.014(1) Å and c = 16.59(1) Å.

Kryzhanovskite $MnFe^{+3}_2(PO_4)_2(OH)_2\cdot H_2O$ and
Garyansellite $(Mg,Fe^{+3})_3(PO_4)_2(OH,O)\cdot 1.5H_2O$

Kryzhanovskite and garyansellite, along with reddingite (**Mn_3**$(PO_4)_2\cdot 3H_2O$), phosphoferrite (**Fe^{+2}_3**$(PO_4)_2\cdot 3H_2O$) and landesite (**Mn_2Fe^{+3}**$(PO_4)_2(OH)\cdot 2H_2O$), form a crystallochemically complex series of minerals characterized by extensive ordering between cations of variable size and valence (Moore *et al.*, 1980; Sturman and Dunn, 1984). The chemical formula for type kryzhanovskite approximates that given above (Ginzburg, 1950; Moore, 1971a) only because its composition is in fact intermediate, and not end-member kryzhanovskite. Crystal structure analyses by Moore (1971a) and Moore *et al.* (1980) have proven the existence of two metal sites that exhibit rigorous ordering of both divalent and trivalent cations, due primarily to differences in size. Ideal, end-member kryzhanovskite is defined as $Fe^{+3}_3(PO_4)_2(OH)_3$, with ferric iron the dominant cation in each of the metal sites. Garyansellite is the magnesium-dominant member, named for H. Gary Ansell "in recognition of his pioneering work in the mineralogy of Rapid Creek" (Sturman and Dunn, 1984).

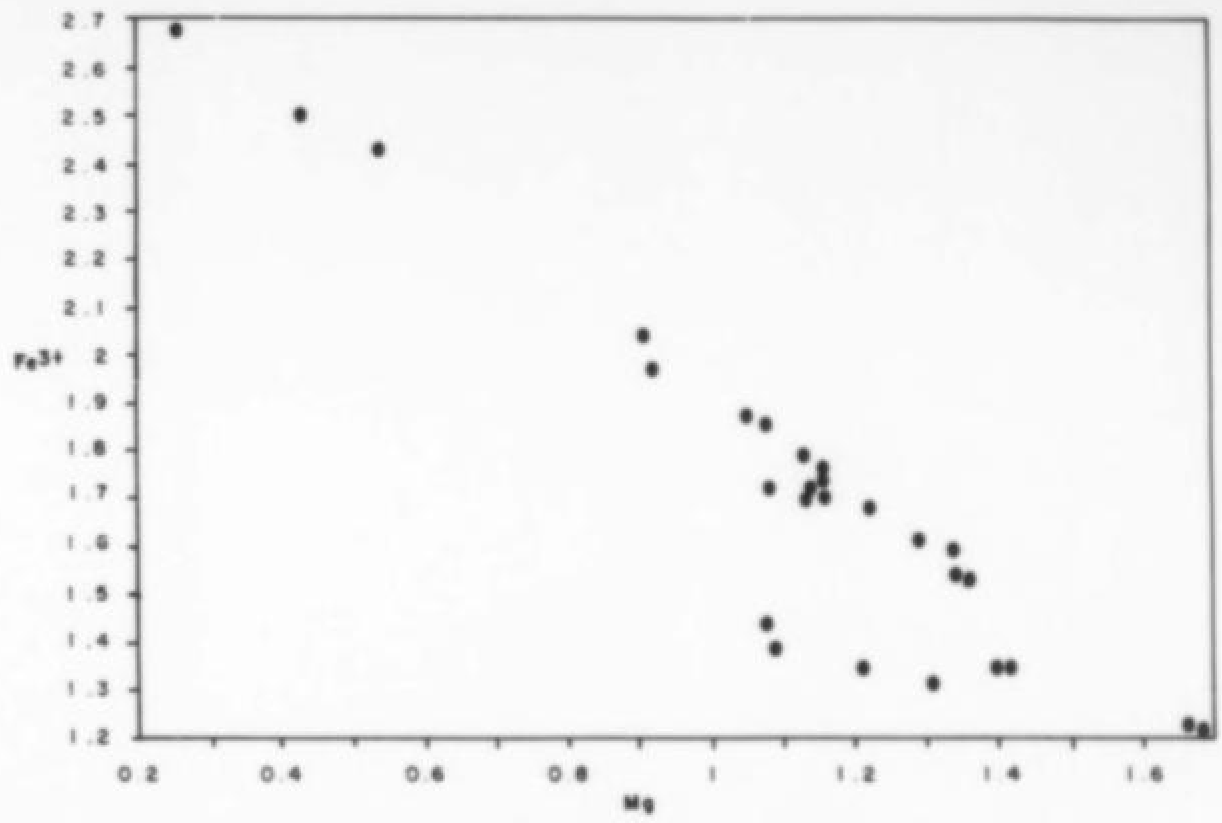


Figure 40. **Variations observed in the Fe^{+3} and Mg content of Rapid Creek kryzhanovskite.**

It has also been suggested by some of the above investigators that kryzhanovskite may form from the oxidation of phosphoferrite, $Fe^{+2}_3(PO_4)_2\cdot 3H_2O$, with charge balance being maintained by (OH) substitution for H_2O. A similar mechanism has been proposed for the formation of metavivianite from vivianite (Dormann and Poullen, 1980), and it is interesting to note the coexistence of these two species at both Rapid Creek and the type locality for metavivianite, the Big Chief pegmatite near Glendale, South Dakota (Ritz *et al.*, 1974).

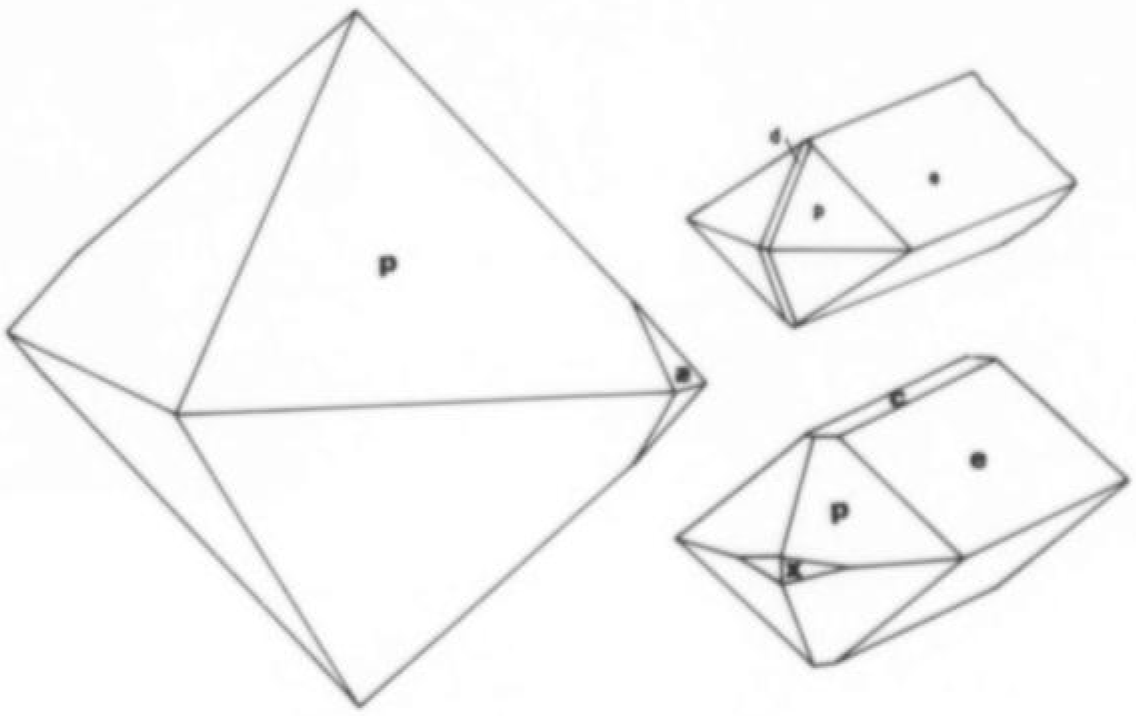


Figure 41. **Garyansellite crystal drawing (top right; type specimen) and kryzhanovskite/garyansellite (left and bottom) from Area A, localities 7 and 5 respectively.**

Since phosphoferrite and kryzhanovskite have measurably different b and c cell dimensions (Moore and Araki, 1976), the interfacial angles between corresponding adjacent forms in the [100] zone should also be measurably different. Furthermore, it would seem that the crystals from Rapid Creek should be ideally suited for such a comparison, due to the predominance of their {011} faces. In theory, measuring the angle between the (011) and (01$\bar{1}$) faces might help

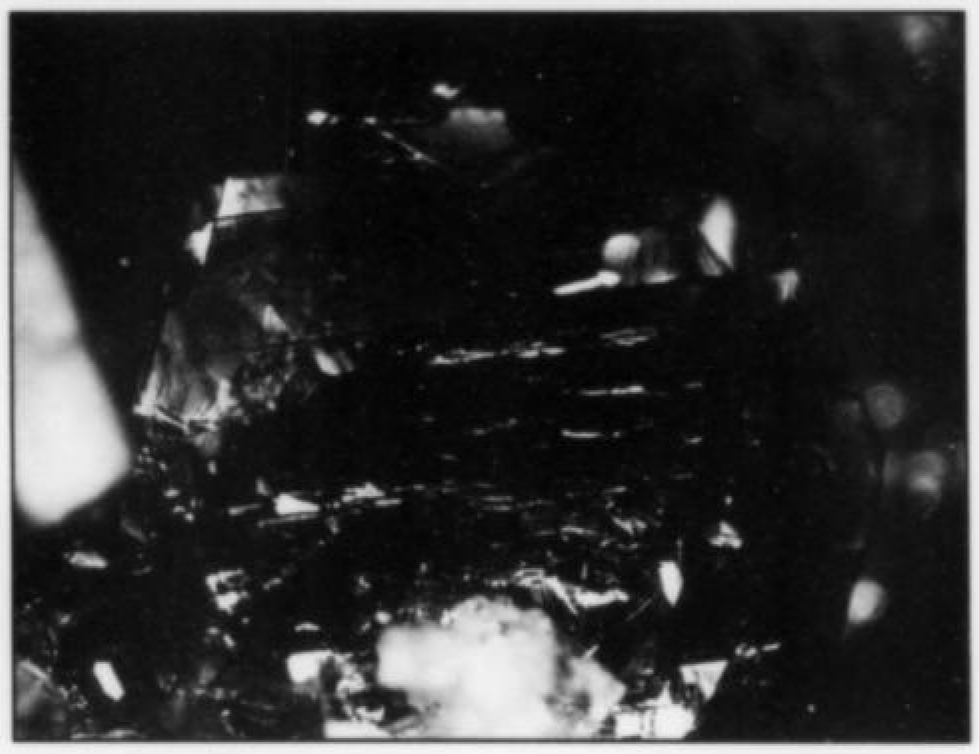


Figure 43. **Kulanite crystal, 1.4 mm, from Area A, locality 3. CMN specimen MOC 3470; S. Chamberlain photo.**

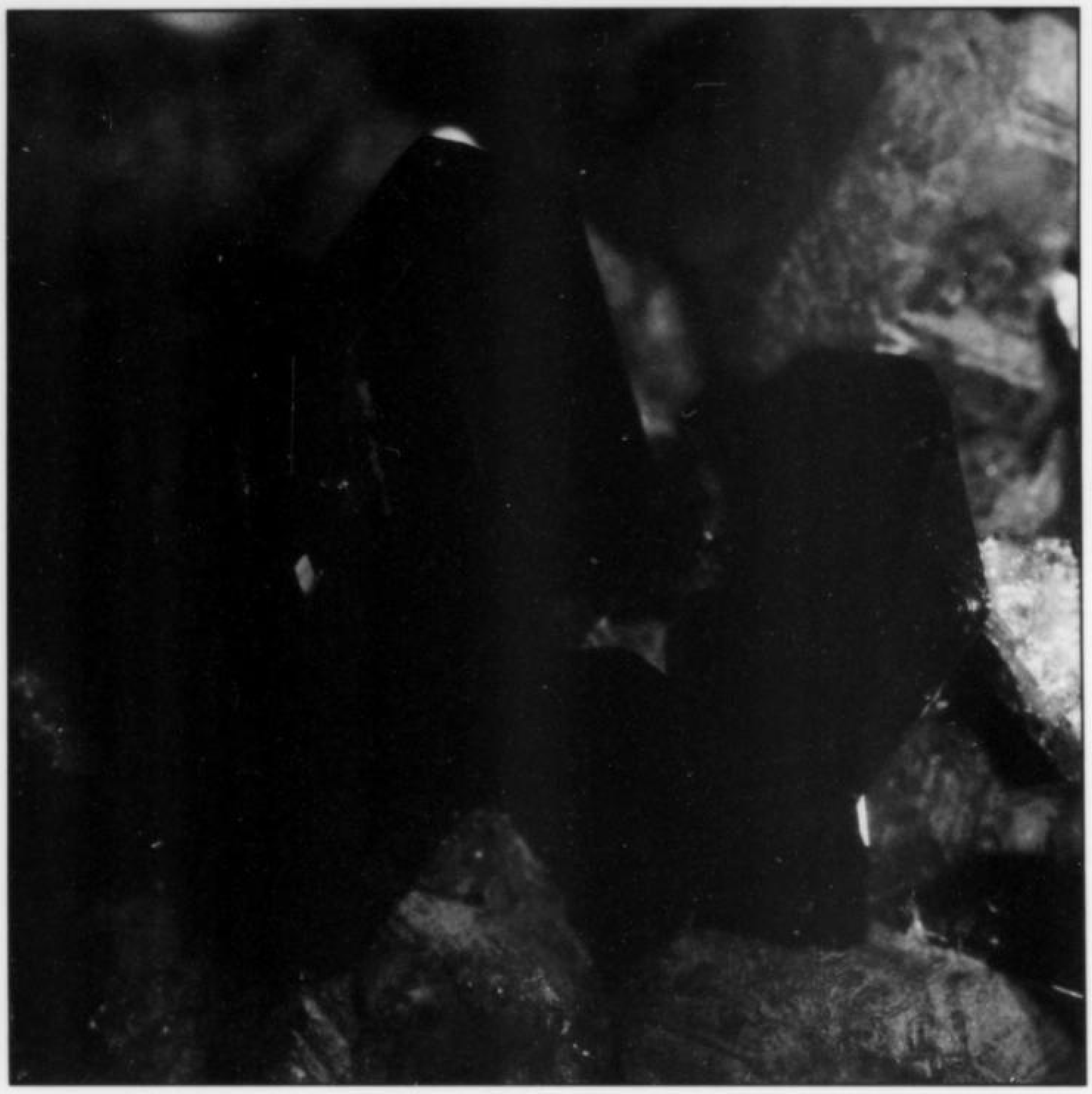


Figure 42. **Kulanite crystals to 6 mm, on siderite, from Area B, locality 10. CMN specimen 55503 (Pinch collection); G. Robinson photo.**

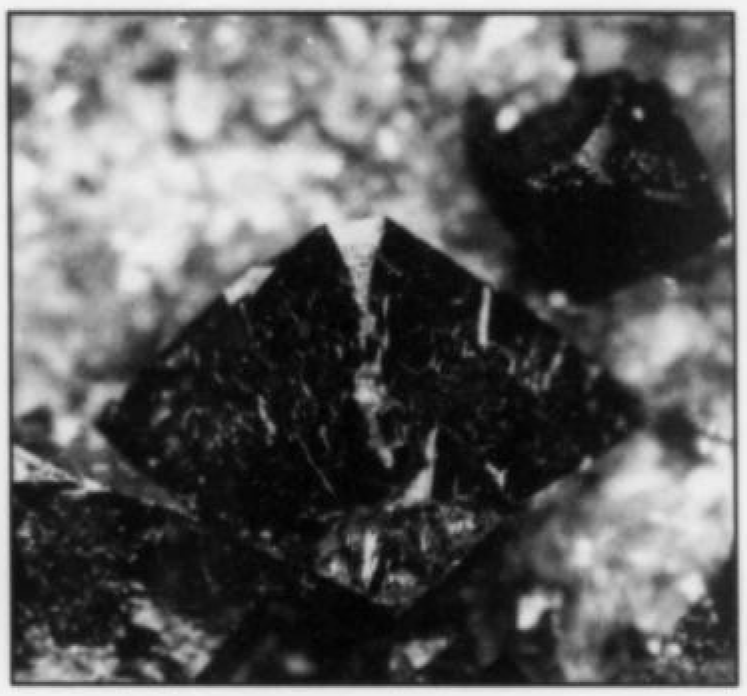


Figure 44. **Kryzhanovskite crystals, dark brown, to 5 mm, from Area A, locality 7. CMN specimen 52211; G. Robinson photo.**

Figure 45. **Kulanite crystal group, 3 cm across, from the Rapid Creek area. P. Collins specimen; G. Robinson photo.**

resolve the dilemma of whether the crystals were once phosphosiderite and were subsequently oxidized to kryzhanovskite, or are primary kryzhanovskite. A preliminary examination of several crystals, however, indicated the situation is not that simple. Unfortunately, when mounted for examination on the reflecting goniometer, it was readily seen that what appear as perfect, flat crystal faces when viewed with the binocular microscope are, in fact, rounded, multiple faces that are unsuitable for accurate measurement. The problem is further complicated by the fact that the Rapid Creek material is typically not of end-member composition, and thus has intermediate cell dimensions, which narrows the tolerance for error even more. Nevertheless, additional research along these lines, and accurate determination of the Fe^{+2}/Fe^{+3} contents of the various phases present may ultimately help resolve the problem.

A chemical survey of Rapid Creek kryzhanovskites shows that nearly all are zoned and relatively enriched in magnesium, with a nearly continuous range of $Mg:Fe^{+3}$ ratios from 0.10 to 1.39, as shown in Figure 40. Manganese contents range from 0.01 to 0.47 atoms per formula unit, which probably accounts for the scatter of points in the lower right of the figure. Without confirming crystal structure data, it is extremely difficult, if not impossible, to positively characterize these minerals. For the Rapid Creek specimens, the problem is further exacerbated by complex chemical zoning within the individual crystals themselves. Virtually all the crystals we have examined are so zoned. All contain kryzhanovskite, and some probably contain zones of garyansellite, though the only confirmed garyansellite specimen is the holotype.

Kryzhanovskite-bearing veins tend to be quite narrow, and normally contain few additional species, save for occasional quartz, arrojadite or metavivianite. Crystals occur as chocolate-brown to reddish brown individuals that approach 2 cm, but most are less than a tenth that size.

The most prolific collecting sites yet discovered are along Rapid Creek in Area A, at locality 5 and north of locality 7. Crystals from locality 5 are typically small and elongated on [010] with prominent *e*{011} prisms, whereas those from north of locality 7 tend to be larger with prominent *p*{111} dipyramids. Their perfect {001} cleavage makes these crystals relatively easy to orient. Less commonly observed forms include *c*{001}, *d*{101}, *z*{032} (?) and *x*{430} (?). Some of the crystals from this occurrence may be twinned, and will require additional research for the proper completion of their description.

Kryzhanovskite-garyansellite has also been noted as small platelets associated with vivianite-baricite in an altered wolfeite nodule and on fracture surfaces in a satterlyite nodule from locality 16, Area C.

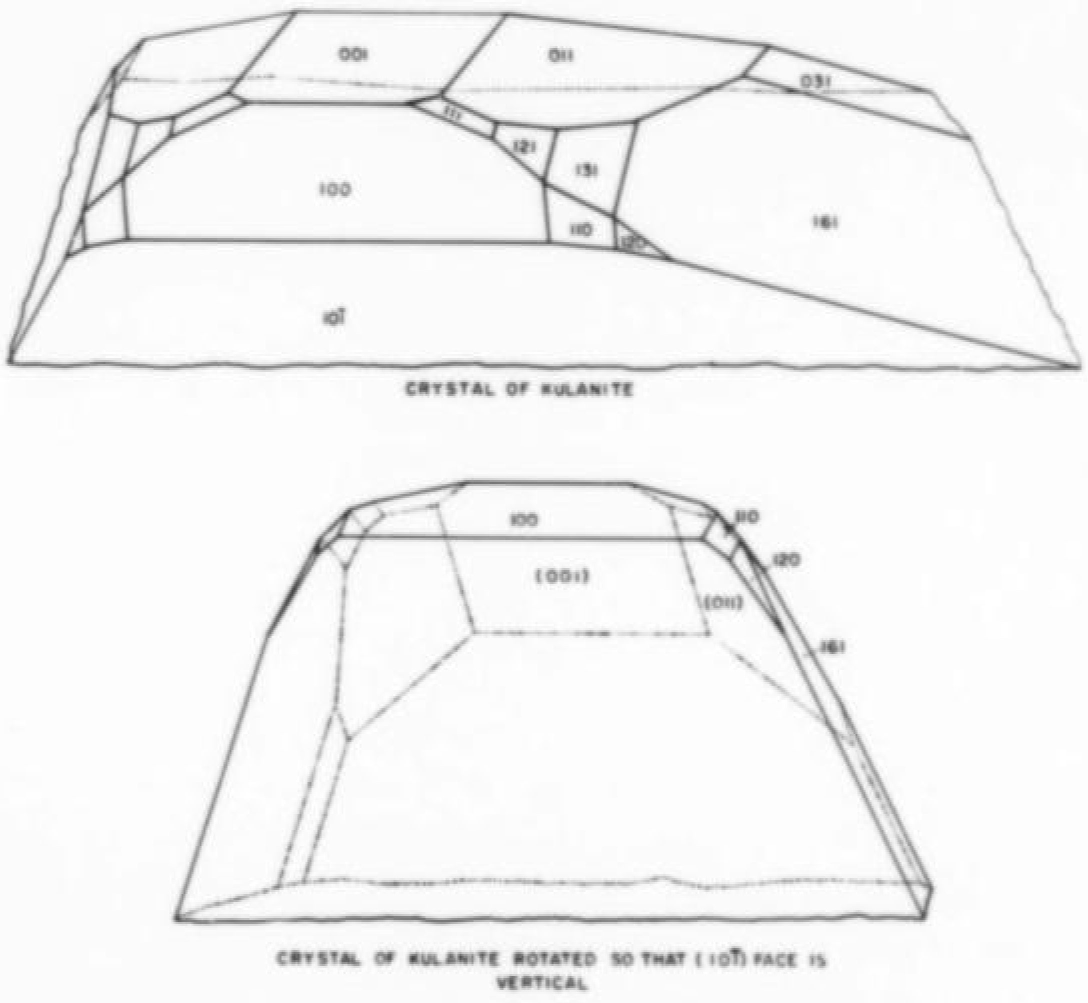


Figure 46. **Kulanite crystal drawings (from Mandarino and Sturman, 1976).**

Kulanite Ba(Fe^{+2},Mn,Mg)$_2$Al$_2$(PO$_4$)$_3$(OH)$_3$ and
Penikisite Ba(Mg,Fe^{+2})$_2$Al$_2$(PO$_4$)$_3$(OH)$_3$

Kulanite and penikisite are both members of the bjarebyite group of minerals, which also includes the **Mn**-Al and Mn-**Fe**$^{+3}$ analogs, bjarebyite and perloffite. Kulanite, first described as a new species from Rapid Creek by Mandarino and Sturman (1976), was named for the late Alan Kulan, the successful and well-known Yukon prospector who was first intrigued by the specimen potential of the Rapid Creek area. Penikisite, which occurs as magnesium-dominant zones in kulanite, was named for the late Gunar Penikis, Kulan's partner (Mandarino *et al.*, 1977).

Microprobe studies show the chemical composition of kulanite may vary significantly from locality to locality in the Rapid Creek area. For example, kulanites from locality 1 in Area A contain little Mn, whereas those from locality 8 have higher Mn contents, with one analysis suggesting the presence of bjarebyite. Interestingly, in their description of bjarebyite from the Palermo mine in New Hampshire, Moore *et al.* (1973) predicted that "a ferrous predominant bjarebyite also exists" based on some of their analyses. Kulanite from locality 10 in Area B contains very little Mg, and is the closest in composition to end-member kulanite yet found. Compositions within the penikisite field are seldom encountered, and it appears that this mineral is an extremely rare species at Rapid Creek.

Although penikisite has also been found in the Hess River area in the central Yukon, its occurrence there is geologically unrelated to the Rapid Creek Formation, and the two occurrences should not be confused.

While probably not infallible, the color variation in kulanite, which ranges from deep sea-green to various shades of blue, may give some indication of its chemistry. Crystals with relatively low Mg and high Mn contents are noticeably less green in color. Similarly, Mandarino *et al.* (1977) have noted that in zoned kulanite-penikisite crystals, pale blue zones have more Mg than dark blue zones.

Figure 47. **Kulanite crystals, dark green to black, 5 mm, from Area B, locality 10. CMN specimen 53926; G. Robinson photo.**

Figure 48. **Kulanite crystal, dark blue, 9 mm, from Area A, near locality 1. CMN specimen 31883; G. Robinson photo.**

Kulanite crystals occur in a variety of habits, from relatively simple thin plates, tabular on $\{\bar{1}01\}$, to rosette-like aggregates and thick, tabular, complex individuals with up to 12 crystal forms present (Mandarino and Sturman, 1976). In general, crystals rarely exceed 5 mm in any dimension, although a few individuals over 1.5 cm in length are known. At its type locality just below the waterfall on "Crosscut Creek" (locality 3, Area A), kulanite occurs as rosettes of small, platy blue-green crystals associated with quartz, siderite, brazilianite, arrojadite, fluorapatite and anatase. Just downstream from locality 1, at the type locality for penikisite, larger, strongly zoned crystals occur with siderite, quartz and lazulite. This locality has produced most of the largest and best specimens found to date. Lastly, very fine specimens of kulanite with crystals up to 1.5 cm have also been found with goyazite and siderite at locality 10 in Area B.

Lazulite MgAl$_2$(PO$_4$)$_2$(OH)$_2$

Of all the species found in the Rapid Creek area, certainly the one

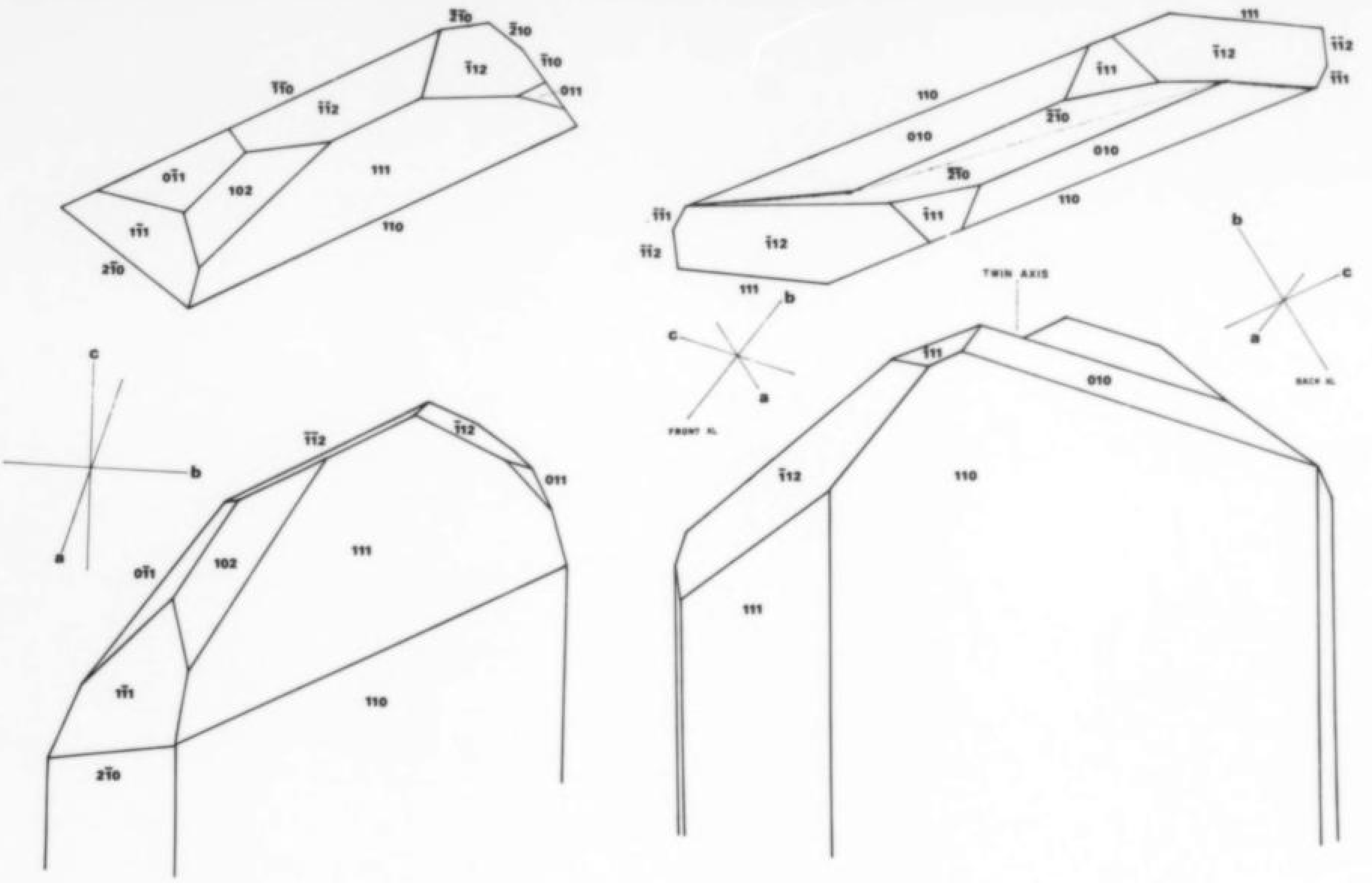


Figure 49. **Lazulite crystal drawings.**

that has received the most attention is lazulite (Mossman and Robertson, 1978; Mossman and Van Velthuizen, 1979). No other locality in the world has produced specimens of comparable quality and quantity. Lustrous crystals up to a centimeter are quite common, and crystals nearly 2.5 cm are known. It is one of the most abundant phosphate minerals in the fracture fillings throughout the entire deposit. Thus, lazulite may appear with a wide variety of other species, though its most common association is lazulite + quartz + siderite ± apatite.

Crystals of lazulite from this locality are morphologically complex, and twinned crystals are common. Since lazulite crystals from other localities have been measured on the optical goniometer for over a hundred years, we expected that the identification of forms on the Yukon crystals would be a simple and enjoyable study. It turned out to be just the opposite! After several months of very frustrating efforts, we have to report incomplete results.

Lazulite crystals described from other localities appear to have different axial ratios than those from Rapid Creek. We have so far been unable to correlate those different unit cells with the one chosen for this study, and consequently cannot compare the forms observed on lazulite crystals from different localities. Normally an easy task, it took us several days just to identify the proper unit cell, because the single-crystal X-ray photographs offered several possible choices for *a* and *c*. Furthermore, the relative lengths of *a* and *c* vary between members of the lazulite-scorzalite series; sometimes $a > c$ and others $c > a$. As a result there are three nearly identical axes inclined approximately 120° to each other so that each could be chosen as *a* or *c*. Eventually the proper unit cell was found by comparing the intensities of the spots along each axis to those of indexed lines in the powder diffraction pattern for lazulite (J.C.P.D.S. No. 25-1179). After identifying the correct axes on the films it became relatively easy to orient crystals for measurement on the optical goniometer. Table 4 and the accompanying crystal drawings show the forms developed on lazulite crystals from this locality, based on the unit cell $a = 7.15$, $b = 7.28$, $c = 7.23$ Å; $\beta = 120°30'$. These forms were determined by optical goniometer on the same crystals previously studied and oriented with single crystal X-ray diffraction methods.

Most lazulite crystals from Rapid Creek are twinned, and the twin law is different from the one reported for lazulite from other localities. Palache *et al.* (1951) give twinning on {100} as the most common twin law for lazulite. Twins on this law have their *b* axes parallel to each other, and we have confirmed this type of twinning on lazulite crystals from Graves Mountain, Georgia, using a petrographic microscope with a universal stage. It was readily apparent that the Rapid Creek crystals were twinned by a different law, since their *b* axes were inclined about 90° to each other. Our study of these twins by optical goniometric, universal stage and single crystal X-ray methods shows that both the small and large crystals are twinned by reflection on $\{\bar{2}21\}$, but joined on the composition plane {331}. Alternatively, this twin law may be expressed by rotation of 180° on the normal to $\{\bar{2}21\}$.

At first, a normal to a plane with such complex indices as $\{\bar{2}21\}$ seemed a very unlikely twin axis. However, a brief look at Figure 49

Table 4. **Angle table for lazulite.**

Form	***Measured*** **phi**	***Measured*** **rho**	***Calculated**** **phi**	***Calculated**** **rho**
(100)	90°09′	90°00′	90°00′	90°00′
(110)	49°57′	90°02′	49°44′	90°00′
(430)	57°04′	90°23′	57°14′	90°00′
(210)	66°20′	90°10′	67°04′	90°00′
(011)	30°33′	49°29′	30°40′	49°06′
(102)	90°07′	49°52′	90°00′	49°37′
(111)	60°42′	63°53′	60°36′	63°42′
($\bar{1}$11)	–30°43′	49°25′	–30°29′	49°03′
($\bar{1}$12)	0°26′	26°35′	0°15′	26°25′
($\bar{2}$12)	49°08′	37°02′	–49°16′	37°39′

Twin Elements

	phi	rho
Twin Plane $\{\bar{2}21\}$	–41°07′	69°14′
Composition plane {331}	53°41′	78°55′

*Based on unit cell dimensions $a = 7.15$ Å, $b = 7.28$ Å, $c = 7.23$ Å, $\beta = 120°30'$. a:b:c = 0.982:1:0.993.

shows that this is a very prominent direction in these crystals, and is nearly parallel to several large faces. It can be shown by stereographic projection that other forms also share nearly parallel faces between the twinned individuals.

The identification of forms on these crystals is very difficult, particularly when they are intergrown and randomly oriented on matrix. Fortunately, the twinned crystals typically show distinct composition planes which help to orient them. The single crystals may actually present a greater challenge, because their monoclinic symmetry is not readily apparent. Corresponding faces of the same form such as (111) and $(1\bar{1}1)$ frequently have very different sizes. Similarly, only three of the possible four {110} faces are usually developed, and they are not of uniform size. On most crystals (110), (111) and $(\bar{1}12)$ are the largest faces, and faces of the form {210} are often curved. The crystal drawings shown here reflect the actual sizes of the faces observed on the crystals that were measured on the optical goniometer.

The color of lazulite from Rapid Creek ranges from yellow-green to blue-green and pale blue to a dark, Prussian blue that appears almost black in hand specimens. Some of the crystals have greenish rims and dark blue cores, although this phenomenon is difficult to observe unless viewed in thin section. Microprobe analyses of these different color zones show remarkably little variation in composition, differing on the average by only about 0.03 more iron atoms per formula unit in the darker blue regions. A corresponding minor decrease in the aluminum content observed in these zones suggests some of this iron may exist as Fe^{+3}, since the Mg^{+2} content remains nearly constant at approximately 0.91 magnesium atoms per unit formula across all the zones. The ferrous-ferric intervalence charge transfer is a well-known mechanism that produces blue colors in various minerals (Nassau, 1983). Amthauer and Rossman (1984) have shown this mechanism to be operative in lazulite from Graves Mountain, Georgia, and it appears also to be the cause of color in the lazulites from Rapid Creek.

Because of its widespread occurrence, it is virtually impossible to document all the specific sites where good lazulite specimens have been found, for that possibility potentially exists in almost every seam. However, the most prolific site yet discovered has been the general area about locality 1 in Area A, which has produced the majority of specimens that have reached the mineral market in recent years.

Ludlamite $(Fe^{+2},Mg,Mn)_3(PO_4)_2\cdot 4H_2O$

Ludlamite is relatively uncommon at Rapid Creek, though in places it may appear locally abundant as pale green cleavages or weathered granular masses filling some of the quartz-phosphate seams. Cleavages up to 2 cm have been observed *in situ*. Unfortunately, ludlamite appears to be adversely affected by the permafrost, and most specimens decrepitate upon extraction. Hence, good specimens are scarce. Probably the best specimens found to date are from locality 15, Area C. Here pale green crystals up to a centimeter across are found associated with vivianite and quartz. These crystals commonly display large *c*{001} faces that are often striated parallel to [100]. Once these striations and the *d*$(\bar{1}01)$ face have been recognized, the crystals become relatively easy to orient. Additional forms commonly encountered include *a*{100}, *s*$\{51\bar{1}\}$, *p*{111}, *m*{110} and *q*$\{11\bar{1}\}$.

A chemical survey of several ludlamites from Rapid Creek showed variable (and generally sympathetic) contents of both magnesium and manganese substituting for iron. Specimens from locality 9, Area B, have compositions near $(Fe^{+2}_{2.66}Mn_{0.26}Mg_{0.08})(PO_4)_2\cdot 4H_2O$, whereas those from near locality 4, Area A, and locality 15, Area C, are richer in magnesium, with compositions closer to $(Fe^{+2}_{2.55}Mg_{0.40}Mn_{0.05})(PO_4)_2\cdot 4H_2O$ and $(Fe^{+2}_{2.51}Mg_{0.39}Mn_{0.10})(PO_4)_2\cdot 4H_2O$, respectively.

Some of the nodules from Area C consist of an unusual light brown ludlamite interlayered with vivianite-barićite, the whole of which shows no green or blue color whatsoever. In spite of its highly unusual color, microprobe analyses of this ludlamite suggest it is very much like other, more normal, green specimens from the area, with a composition near $(Fe^{+2}_{2.77}Mg_{0.12}Mn_{0.11})(PO_4)_2\cdot 4H_2O$.

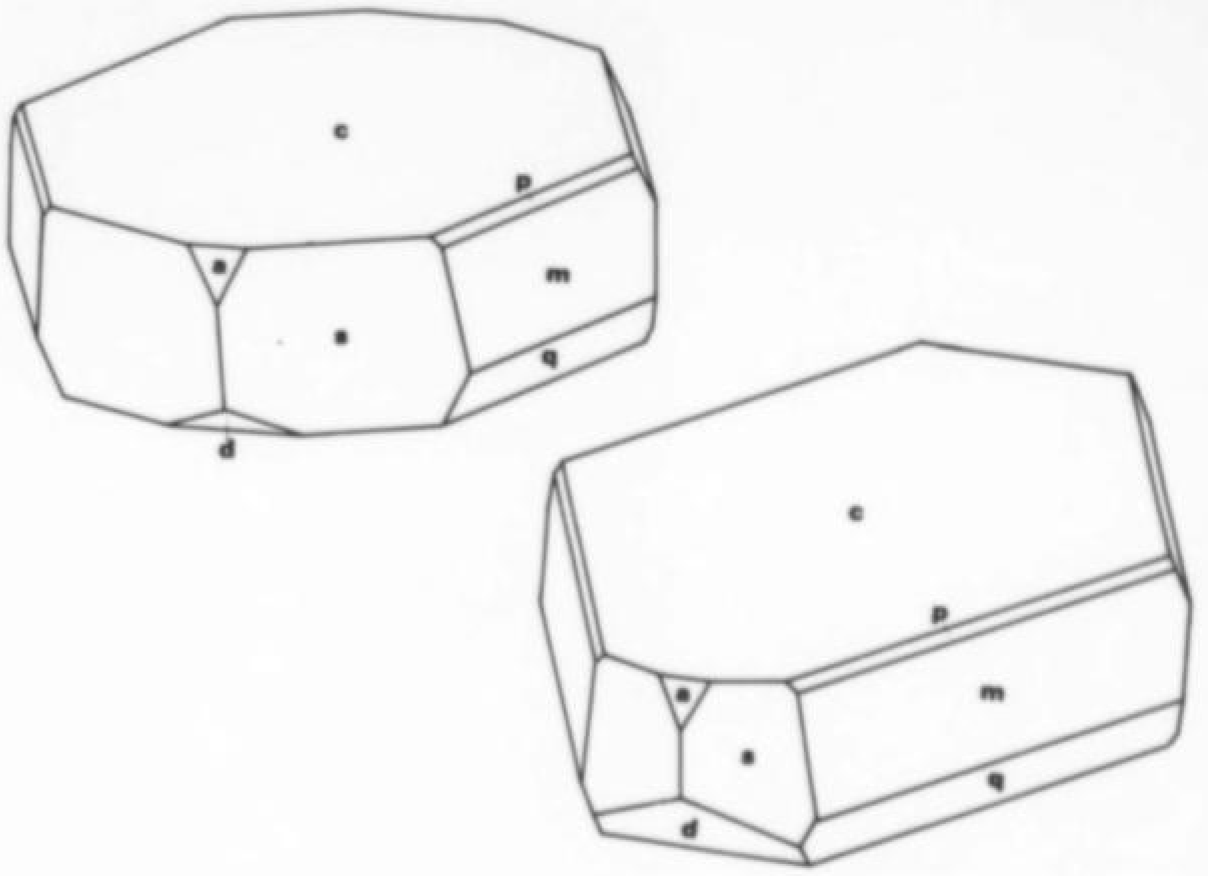


Figure 50. **Ludlamite crystal drawings.**

Robertson (1980) mentions an unusual asbestiform ludlamite from the area, but regrettably none was available for the present study.

Messelite $Ca_2(Fe^{+2},Mn)(PO_4)_2\cdot 2H_2O$

Messelite occurs in Area A near locality 2, as radial, globular, tan to white spherical aggregates up to 2 cm in diameter. It is associated with quartz, siderite, lazulite, whiteite and gordonite, and appears to be one of the last minerals to have formed. Some messelite has also been found in Area C and at locality 9 in Area B, but the best specimens are from the Area A locality.

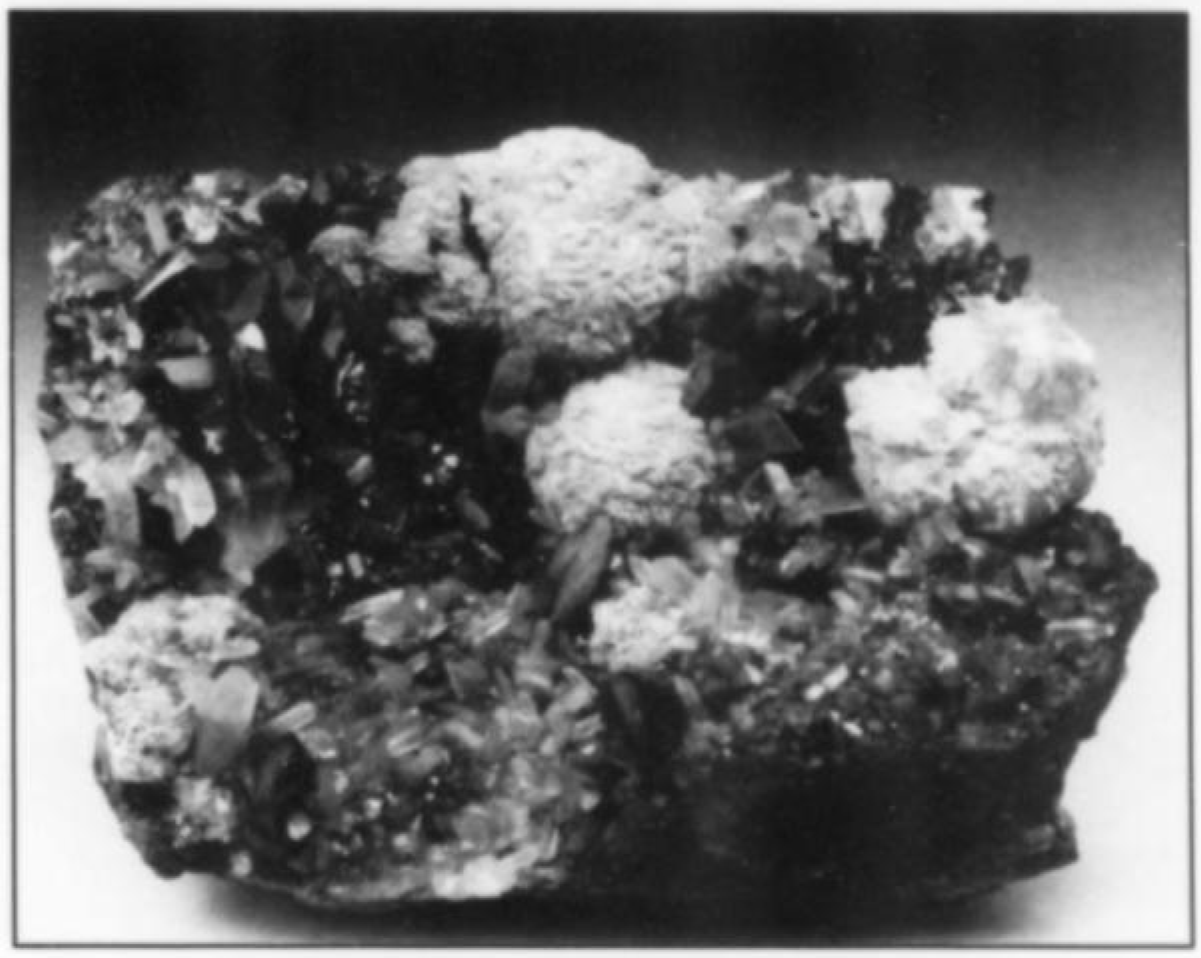


Figure 51. **Messelite hemispheres, pale tan, to 1.3 cm, with lazulite and minor whiteite on quartz, from Area A, locality 2. Geological Survey of Canada specimen 18328; G. Robinson photo.**

Microprobe examination of the messelite from locality 2 shows minor Mg/Mn zoning, and an average of about 0.16 F^-. The Fe^{+2} content of each zone is about the same, at approximately 0.6 atoms per formula unit, clearly establishing the identity of the species as messelite. The Mg^{+2} and Mn^{+2} contents, however, vary between different zones, from 0.23 to 0.34 and 0.04 to 0.11 atoms per formula unit, respectively.

***Figure 52*. Lazulite crystals on matrix, 10.3 cm. CMN specimen 39167; W. E. Wilson photo.**

***Figure 53*. Lazulite crystal group, 7 cm, from the Rapid Creek area. M. Brunet collection; G. Robinson photo.**

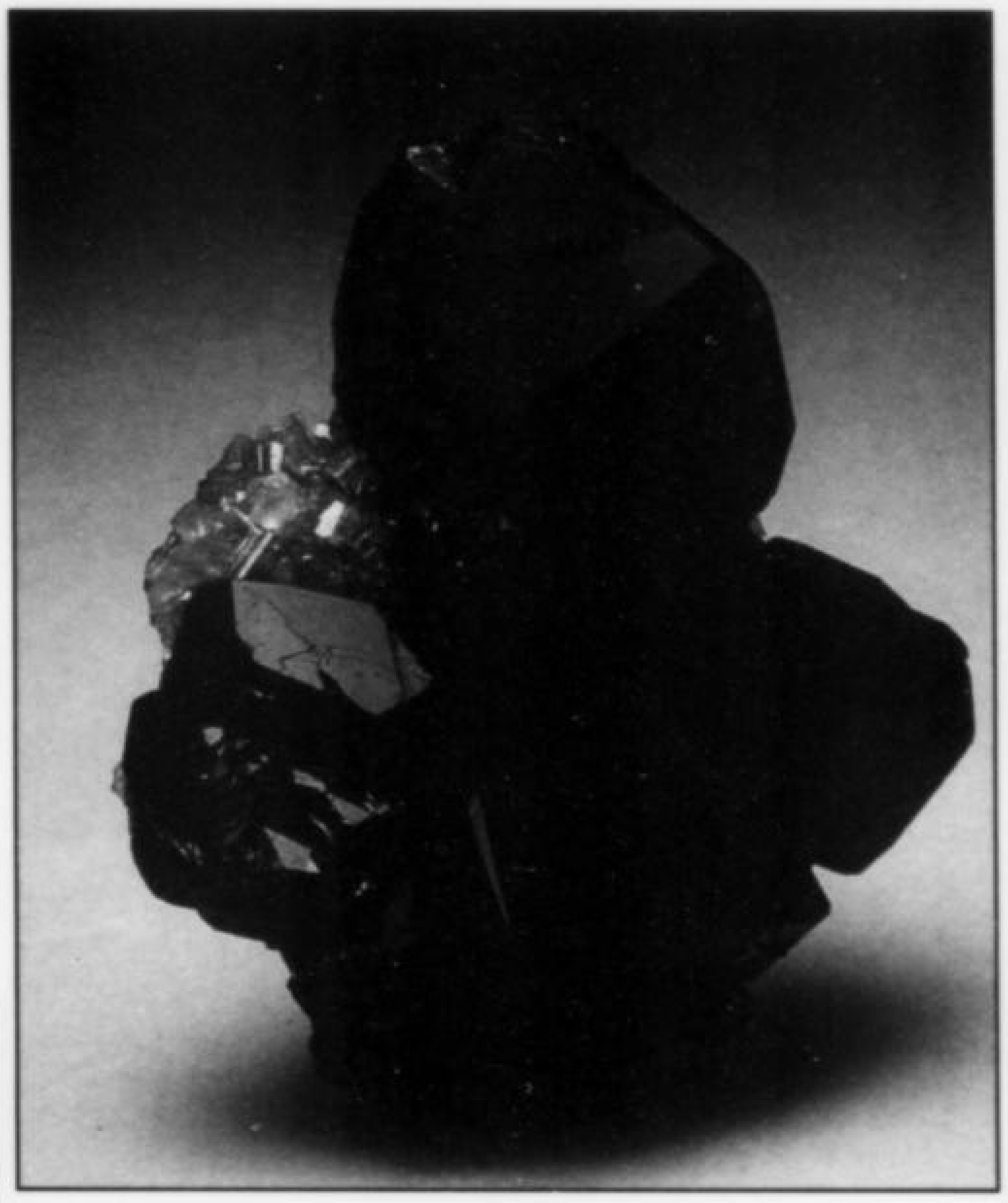


***Figure 54*. Lazulite crystal group, 3 cm, from the Rapid Creek area. M. Brunet collection; G. Robinson photo.**

***Figure 55*. Ludlamite crystal group, 5.5 cm, with minor vivianite (blue), from the Big Fish River area. M. Brunet collection; G. Robinson photo.**

Figure 56. **Lazulite crystal group, 5 cm across. G. Kuhnlein collection; D. Leighton photo.**

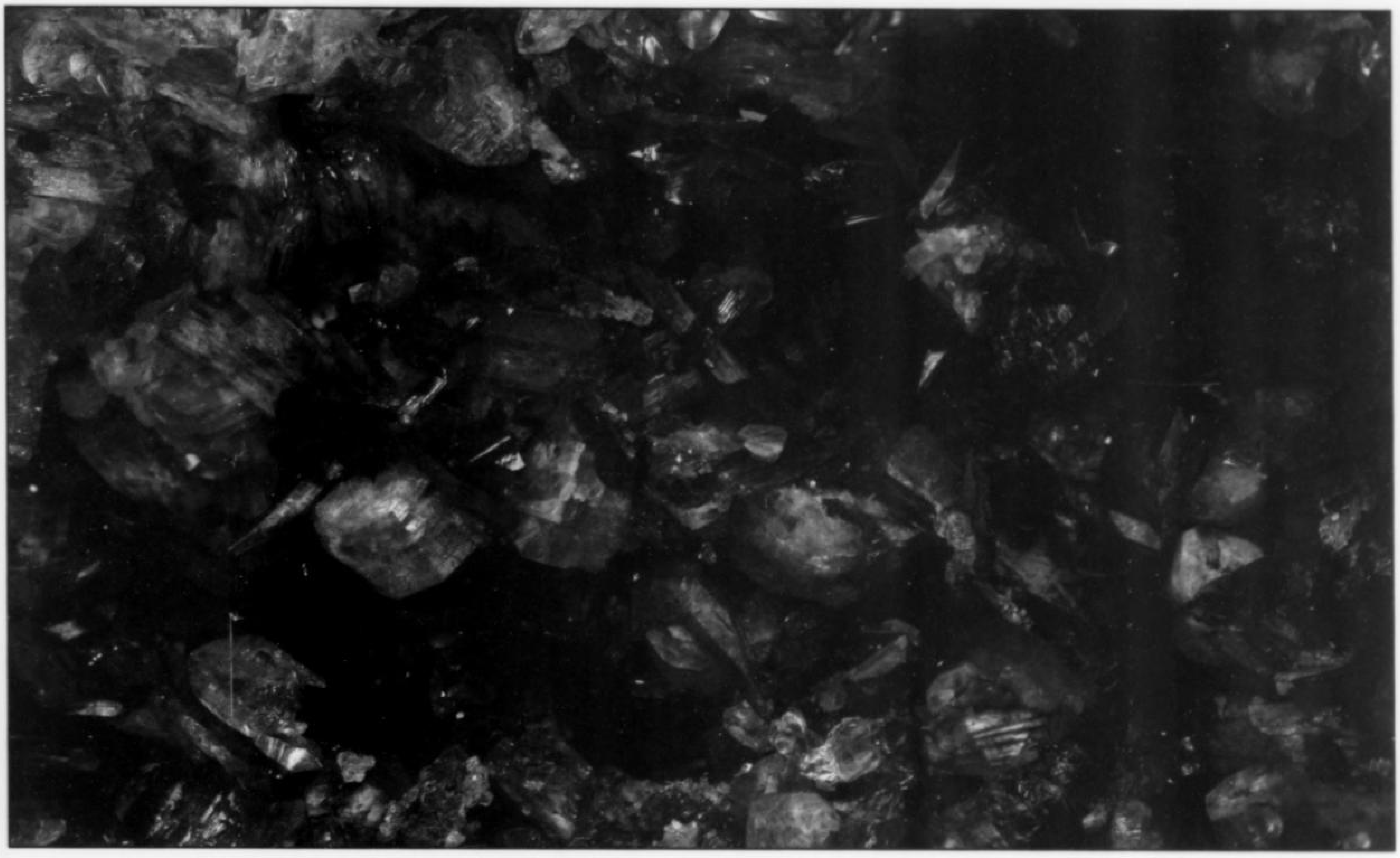


Figure 57. **Ludlamite (green) and vivianite (blue), 6.5 cm across, from Area C, locality 15. CMN specimen 46170; G. Robinson photo.**

Metavivianite $Fe^{+2}_{(3-x)}Fe^{+3}_{x}(PO_4)_2(OH)_x\cdot(8-x)H_2O$

Metavivianite is encountered throughout the Rapid Creek area as a late-stage, fracture-filling mineral. Where space permits growth, cleavages to 10 cm may completely fill voids. Metavivianite is typically drab olive-green to gray or gray-brown in hand specimens, and exhibits somewhat of an oily luster, especially when freshly collected. It has been suggested that metavivianite may form through the oxidation of vivianite, and thus be pseudomorphous after that mineral (Dormann and Poullen, 1980; Sameshima *et al.*, 1985). Most specimens from Rapid Creek are very friable, and thus difficult to both collect and preserve intact. Reasonably good specimens, however, have been recovered from locality 4 and between localities 5 and 6 in Area A, and at locality 9 in Area B.

Penikisite: See under Kulanite

Phosphosiderite $Fe^{+3}PO_4 \cdot 2H_2O$

Phosphosiderite occurs sparingly in some of the quartz veins at Rapid Creek. Relatively few specimens are known; the best of these were collected from an area of irregular fractures containing siderite, gormanite-souzalite and brazilianite at locality 9 in Area B, where the phosphosiderite forms rust-coated, randomly oriented, buff-to-white, platy crystals completely replacing an unknown hexagonal (or pseudohexagonal) mineral. The original mineral occurred as elongated, prismatic crystals to 1 cm in size.

Phosphosiderite has also been found as pink to white powdery masses associated with whitlockite (q.v.), vivianite-barićite and other minerals on a single specimen of satterlyite collected from talus near locality 8, Area A. Lastly, phosphosiderite has been observed as pink to white, waxy veinlets and masses on the exteriors of ludlamite, wolfeite, marićite and pyrite nodules from Area C.

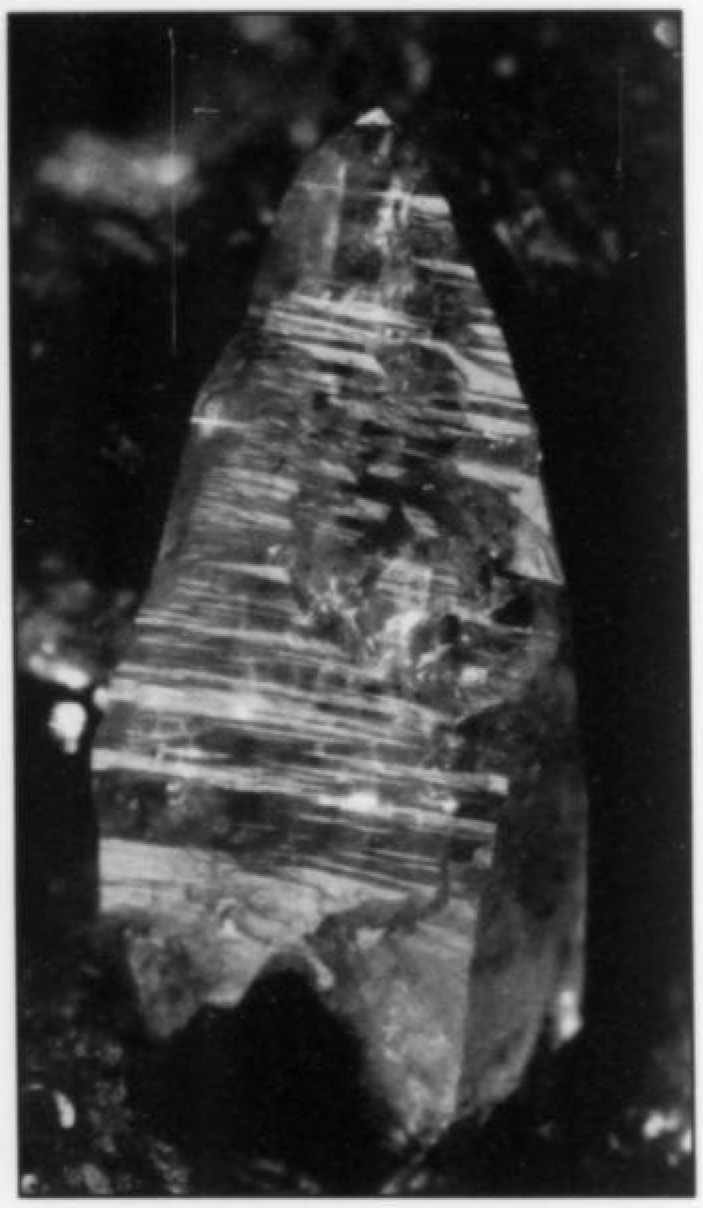


Figure 58. **Quartz crystal, 1.4 cm, from Area C, locality 15. GSC specimen 19341; G. Robinson photo.**

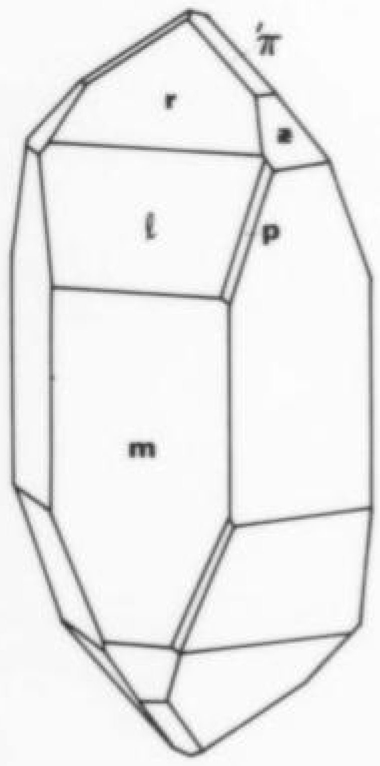


Figure 59. **Quartz crystal drawing.**

Quartz SiO_2

Quartz is ubiquitous as a fracture-filling mineral throughout the formation. In general it tends to form slender, colorless prismatic crystals with rhombohedral terminations, providing a particularly aesthetic contrast when associated with some of the darker colored phosphates. The commonest forms are $m\{10\bar{1}0\}$, $r\{10\bar{1}1\}$, $z\{01\bar{1}1\}$ and $p\{21\bar{3}1\}$. Larger crystals of a more equant habit have been found up to 10 or more centimeters in size, but are most often milky, and of rather poor quality.

The pale smoky crystals associated with vivianite, arrojadite and ludlamite from locality 15, Area C, exhibit more unusual morphology, forming tapered, trigonal crystals showing development of the more infrequently encountered rhombohedrons $\{20\bar{2}1\}$ and $\{01\bar{1}2\}$.

Siderite $FeCO_3$

Siderite is an important constituent of both the fracture-fillings and the phosphatic nodules, although only the former offers good specimens. Like quartz, siderite is omnipresent throughout the formation, and literally thousands of collecting sites exist. In fact, were it not so greatly overshadowed by the abundance of particularly fine phosphates, Rapid Creek might have achieved considerable recognition as a locality for siderite. The crystals occur in a variety of habits and colors, and make very fine specimens on their own. While the large negative rhombohedron $f\{02\bar{2}1\}$ appears to be the most commonly observed form, others include various combinations of $m\{10\bar{1}0\}$, $a\{11\bar{2}0\}$ and $c\{0001\}$. The positive rhombohedron $\{10\bar{1}1\}$ and trigonal scalenohedron $\{21\bar{3}1\}$ (?) occur infrequently.

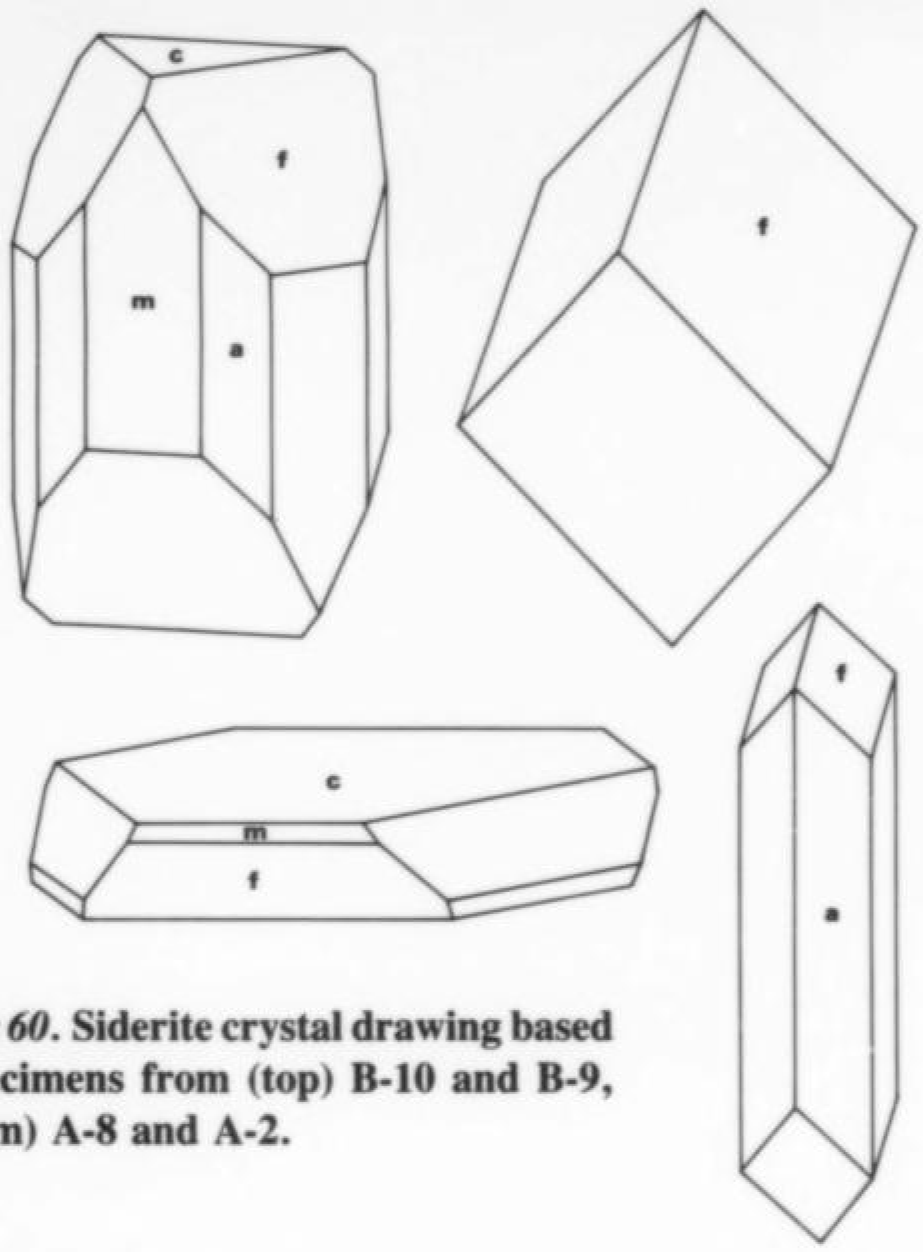


Figure 60. **Siderite crystal drawing based on specimens from (top) B-10 and B-9, (bottom) A-8 and A-2.**

Figure 61. **Siderite crystals, (left) dark brown, 2 cm, from Area B, locality 10, and showing forms *m, a, f* and *c,* and (right) pale brown, 5 mm, from Area A, locality 2, showing forms *a* and *f*. CMN specimens 50823 and MOC3462; G. Robinson photos.**

Souzalite: See under Gormanite

Sphalerite ZnS

Sphalerite has been found only at locality 10 in Area B, where it occurs as rounded, resinous, red-brown crystals up to a centimeter in association with siderite, kulanite, lazulite and goyazite. It is the only zinc-bearing mineral thus far reported from the area, and very few specimens have been found.

Figure 62. **Siderite crystal group, dark brown, 3 cm, from Area A, locality 8, showing forms *c*, *f* and *m*. CMN specimen MOC3463; G. Robinson photo.**

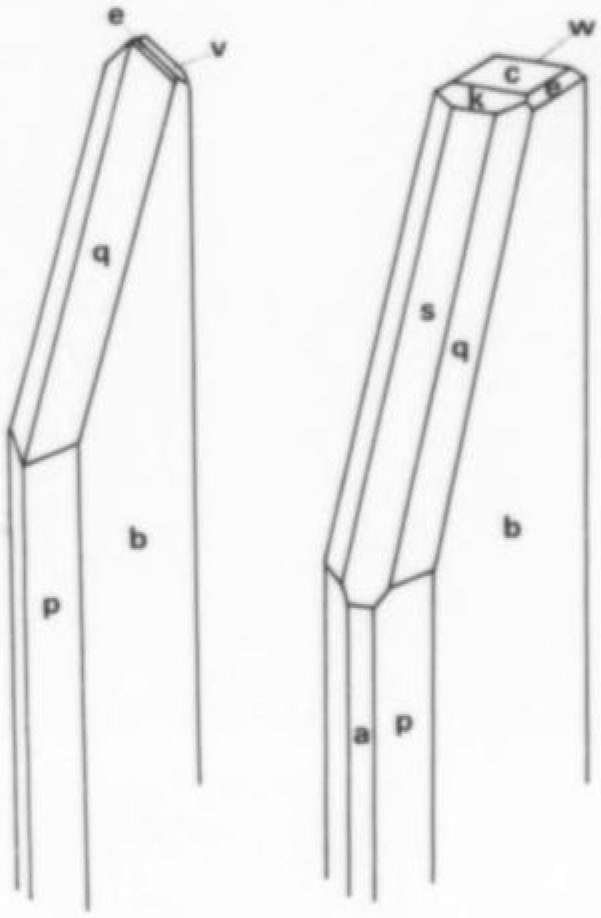


Figure 63. **Vivianite crystal drawings.**

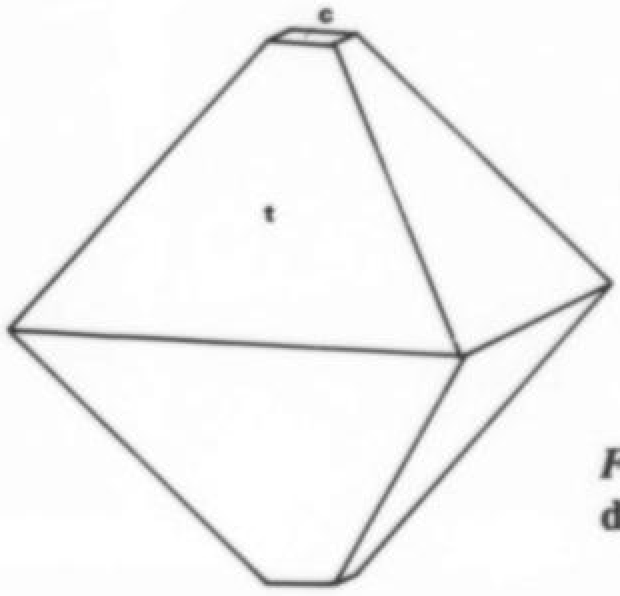


Figure 64. **Wardite crystal drawing.**

Vivianite $Fe_3^{+2}(PO_4)_2 \cdot 8H_2O$

Vivianite has been observed throughout the Rapid Creek area, where it ranges in form from pulverulent blue coatings on shale to fine, blue-green crystals in some of the quartz veins. Without a doubt, the best specimens found thus far are from locality 15, Area C, where prismatic crystals to 5 cm occur with quartz, ludlamite, arrojadite, fluorapatite and messelite. These crystals form prismatic individuals, elongated parallel to [001], with dominant *b*{010} pinacoids and prisms (probably *p*{540} and *q*{531}) resulting in a somewhat diamond-shaped habit. Frequently they form divergent, sub-parallel growths on {010}, widening outward toward their terminations. Smaller forms that appear with fair regularity include *e*{021}, *v*{$\bar{2}$21}, *c*{001}, *w*{$\bar{2}$01}, *k*{101}, *a*{100} and *s*{501}.

In general, all vivianites from the Rapid Creek area that we have examined show some replacement of iron by magnesium and/or manganese. Even the perfectly formed transparent blue crystals from the Big Fish River show complex chemical zoning. Actual analyses of these vivianites yield formulas ranging from $(Fe_{2.86}Mn_{0.08}Mg_{0.06})(PO_4)_2 \cdot 8H_2O$ to $(Fe_{1.77}Mg_{1.03}Mn_{0.20})(PO_4)_2 \cdot 8H_2O$.

Wardite $NaAl_3(PO_4)_2(OH)_4 \cdot 2H_2O$

After lazulite, probably the next species from Rapid Creek most familiar to collectors is wardite, for no other locality has produced such an abundance of fine specimens. Like wardite crystals from Brazil, New Hampshire and other worldwide localities, those from Rapid Creek show a pronounced pseudo-octahedral habit, due to the strong predominance of the nearly equant dipyramid *t*{012}, which is virtually always striated parallel to the *a* axes. Tiny *a*{100} prisms and *c*{001} pinacoids are less commonly seen. Though a few crystals approaching 3 cm have been found, the majority are less than a third that size.

Colors range from colorless to white, pale yellow to brown, or pale yellow-green to blue-green. Microprobe analyses of these wardites show them to be essentially pure, with an average of 0.15 F atoms replacing (OH) groups. One pale blue-green specimen was found to contain approximately 0.02 Fe atoms per formula unit, which may explain its color. It is likely that other similarly colored wardites have resulted from finely dispersed inclusions of lazulite or gormanite-souzalite.

Despite its widespread occurrence, the majority of the wardite specimens currently in collections have come principally from only two sites: locality 7 in Area A, and locality 12 in Area B. Specimens from each occurrence can usually be differentiated by the date they were acquired, their color, and the presence or absence of associated eosphorite. Crystals from locality 12 tend to be white to pale blue-green, are frequently encrusted on one side with microscopic, drusy, brown eosphorite, and were generally not available to collectors until after 1978. Those from locality 7 appear more yellow-brown in color, most often lack the brown eosphorite association and have been available since 1974. It must be emphasized, however, that there always exists an unavoidable risk of error with such locality attributions. While it is perhaps correct for the majority of the cases, it may not apply in every instance.

Whiteite-(CaFeMg) $Ca(Fe^{+2},Mn^{+2})Mg_2Al_2(PO_4)_4(OH)_2 \cdot 8H_2O$

Whiteite was described by Moore and Ito (1978) as the aluminum analog of jahnsite. The name honors John S. White Jr., former curator of minerals at the Smithsonian Institution and founder of the *Mineralogical Record*. Though their essential work had already been completed on specimens from Taquaral, Minas Gerais, Brazil, Moore and Ito also examined some similar material from Rapid Creek, and confirmed its identity as whiteite.

Whiteite ranges in color from white to tan, and in habit from blocky, twinned crystals to fan-like growths of sub-parallel individuals somewhat resembling stilbite. The crystals are universally twinned by reflection on {001}, the repetition of which produces the curved edges

Figure 65. Siderite crystal group, 3 cm, with gormanite (blue), from Area B, locality 9. CMN specimen 50871; G. Robinson photo.

Figure 66. Vivianite crystal, 9 mm, on ludlamite, from Area C, locality 15. CMN specimen 53780; G. Robinson photo.

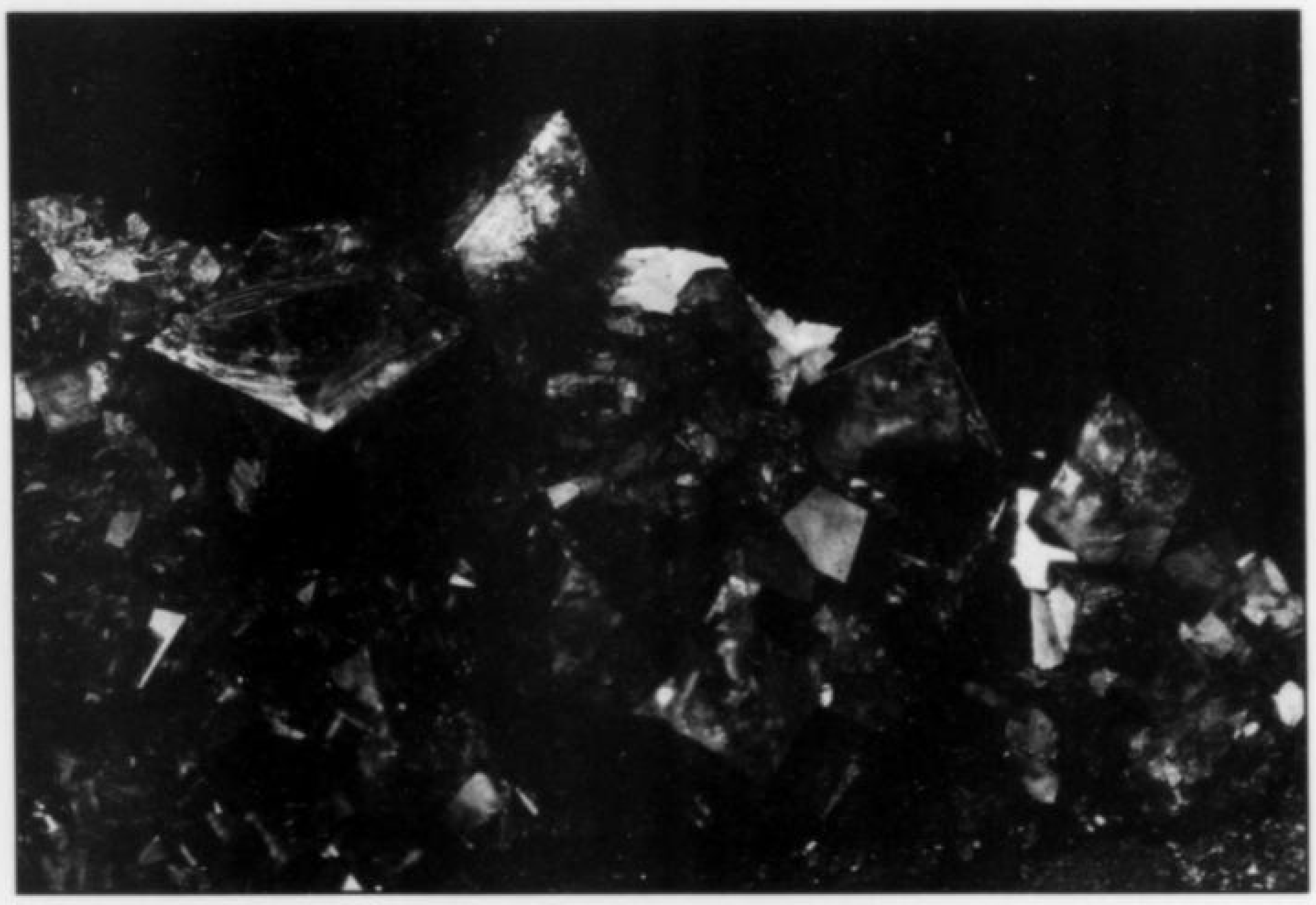


Figure 67. Siderite crystal group, 4 cm across, from Area B, locality 9. CMN specimen 50866; G. Robinson photo.

Figure 68. Vivianite crystals on quartz, 3 cm across, from Area C, locality 15. CMN specimen 50841; G. Robinson photo.

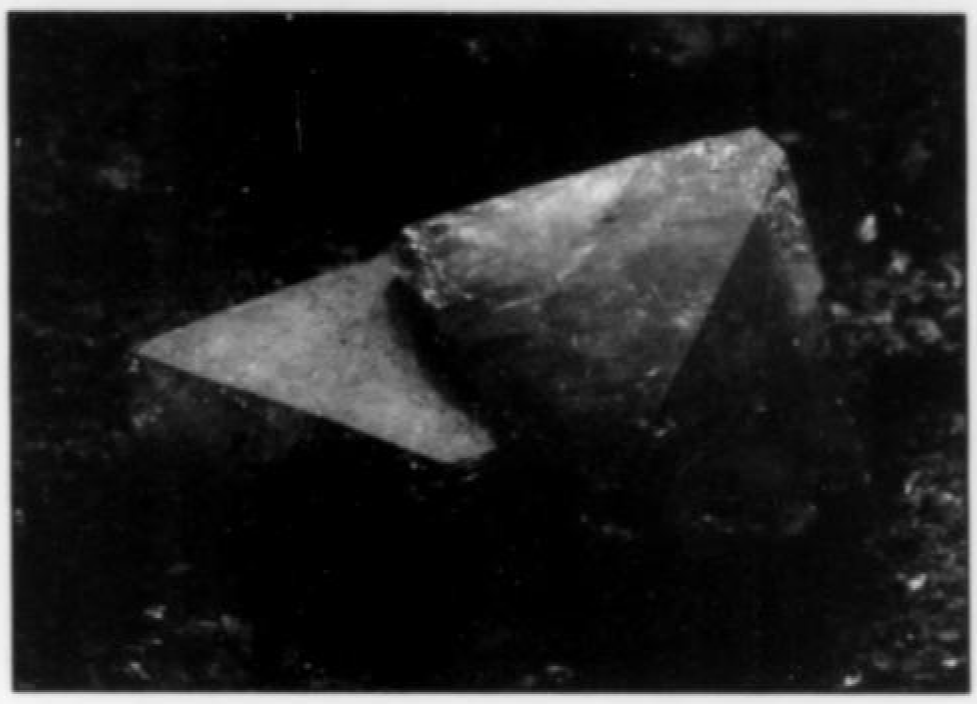


Figure 69. Wardite crystals to 1 cm, from the Rapid Creek area. Barry Kulan specimen and photo.

Figure 70. Wardite crystal group, 4.5 cm, from Area B, locality 12. CMN specimen 50847; G. Robinson photo.

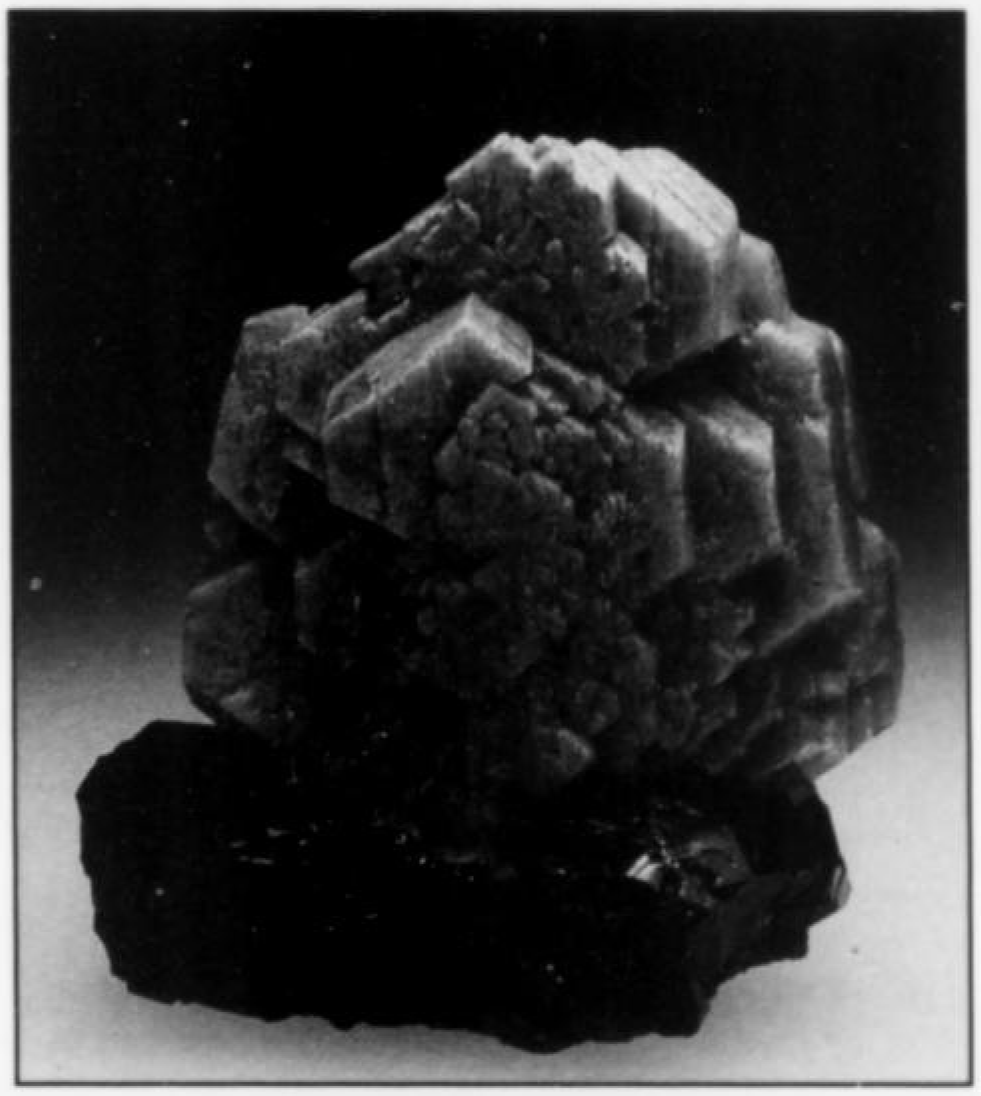


Figure 71. Whiteite crystal, 2.3 cm, on lazulite. Barry Kulan specimen and photo.

Figure 72. Whiteite crystal group, 4 cm. G. Kuhnlein collection; D. Leighton photo.

Figure 73. Whiteite crystals to 2.3 cm from Area A, locality 2. CMN specimens 49009 and 49304; W. E. Wilson photo.

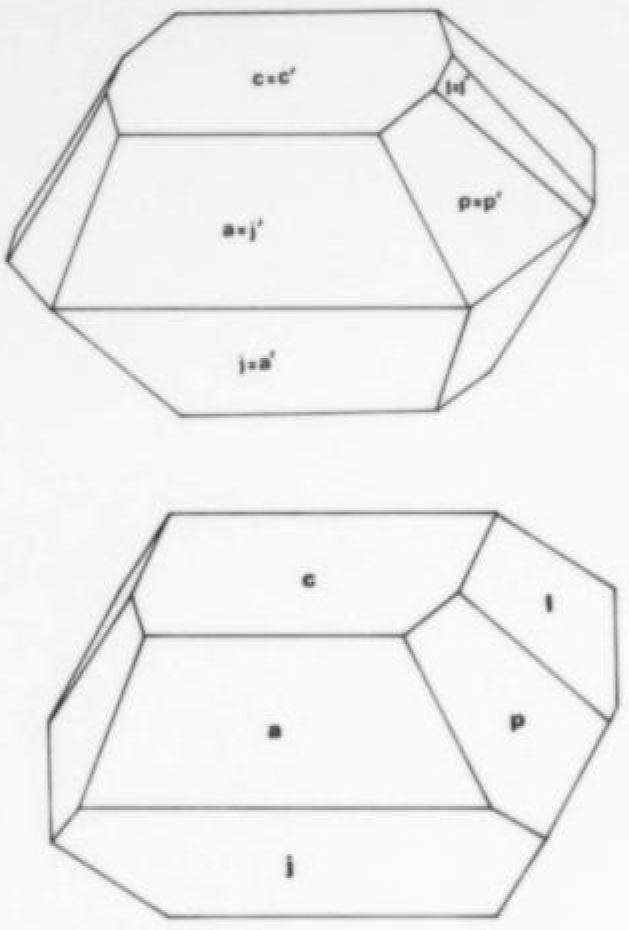


Figure 74. **Whiteite crystal drawings, (top) twinned on (001), from Area A, locality 2, and (bottom) untwinned.**

observed on most specimens. The most common forms are *c*{001}, *j*{$\bar{2}$01}, *a*{100}, *l*{011} and *p*{332} (?), with smaller {$\bar{1}$01}, {201}, {$\bar{3}$04}, {221} and {111} (?) faces less commonly developed. Repeated twinning accentuates the curvature due to the slight mismatch between the shared planes in the individual crystals.

Certainly the most prolific occurrence to date has been locality 2, Area A, where several closely-spaced, vertical quartz veins have been excavated for several meters, yielding virtually all the familiar blocky crystals that have been offered for sale in recent years. The most prevalent associated species are quartz, lazulite and siderite; bright yellow, microscopic crystals of arrojadite have also occasionally been noted. Fine specimens of whiteite have also been recovered from locality 1 in Area A and locality 9 in Area B, but in smaller quantities.

For this study, two whiteites (one from locality 2, area A, and one from locality 9, area B) were chosen for microprobe analysis. Like so many of the other phosphate minerals previously discussed, whiteite, too, is a very complex species, with multiple sites, among which several cations can be distributed (Moore and Ito, 1978). Without a complete crystal structure analysis and knowledge of their valences, one can never be certain if the method chosen to distribute these cations was the correct one. For our analyses we have assumed that in the general formula, $AB^{+2}C_2X_2(PO_4)_4(OH)_2 \cdot 8H_2O$, Mg would first be alloted to **C**, Ca and Mn to **A**, Fe^{+2} to **B**, Al to **X**, with any excess Mg and Fe^{+2} then filling **A**, since there was insufficient (Ca + Mn) to fill that position. Assuming there are four PO_4 groups, eight H_2O molecules and two (OH + F) per formula unit, calculations based on six Ca + Mn + Fe + Mg + Al atoms yield the following formulas for whiteite from locality 2 $(Ca_{0.75}Mg_{0.16}Fe_{0.04}Mn_{0.02})Fe_{1.00}Mg_{2.00}Al_{2.03}(PO_4)_4(OH_{1.71}F_{0.29}) \cdot 8H_2O$ and locality 9B $(Ca_{0.52}Fe_{0.25}Mn_{0.23})Fe_{1.00}Mg_{1.99}Al_{2.01}(PO_4)_4(OH_{1.61}F_{0.39}) \cdot 8H_2O$. The formula given here for the locality-2 specimen agrees reasonably well with that presented by Moore and Ito (1978) for their Rapid Creek material, with the exception of approximately 0.3 more Al atoms and 0.2 less Mg atoms, suggesting that some Mg may be present in the Al site in their specimen. Regardless of how the various cations are apportioned, however, it appears that there is always more than enough calcium, iron, magnesium and aluminum present to confirm the identity of the Yukon material as whiteite-(CaFeMg), following the nomenclature currently in use (Moore and Ito, 1978).

Whitlockite $Ca_9(Mg,Fe^{+2})H(PO_4)_7$

Whitlockite has been identified on a single specimen of satterlyite collected from the talus near locality 8, Area A. It occurs as white, translucent, subhedral masses to 2 mm associated with phosphosiderite, vivianite-baricite, gormanite-souzalite and a number of other minerals. Because this specimen was not collected *in situ*, its inclusion here with the fracture-filling minerals is purely arbitrary, and cannot be confirmed. A possible alternate provenance might be a satterlyite-rich layer within the ironstone formation (see satterlyite).

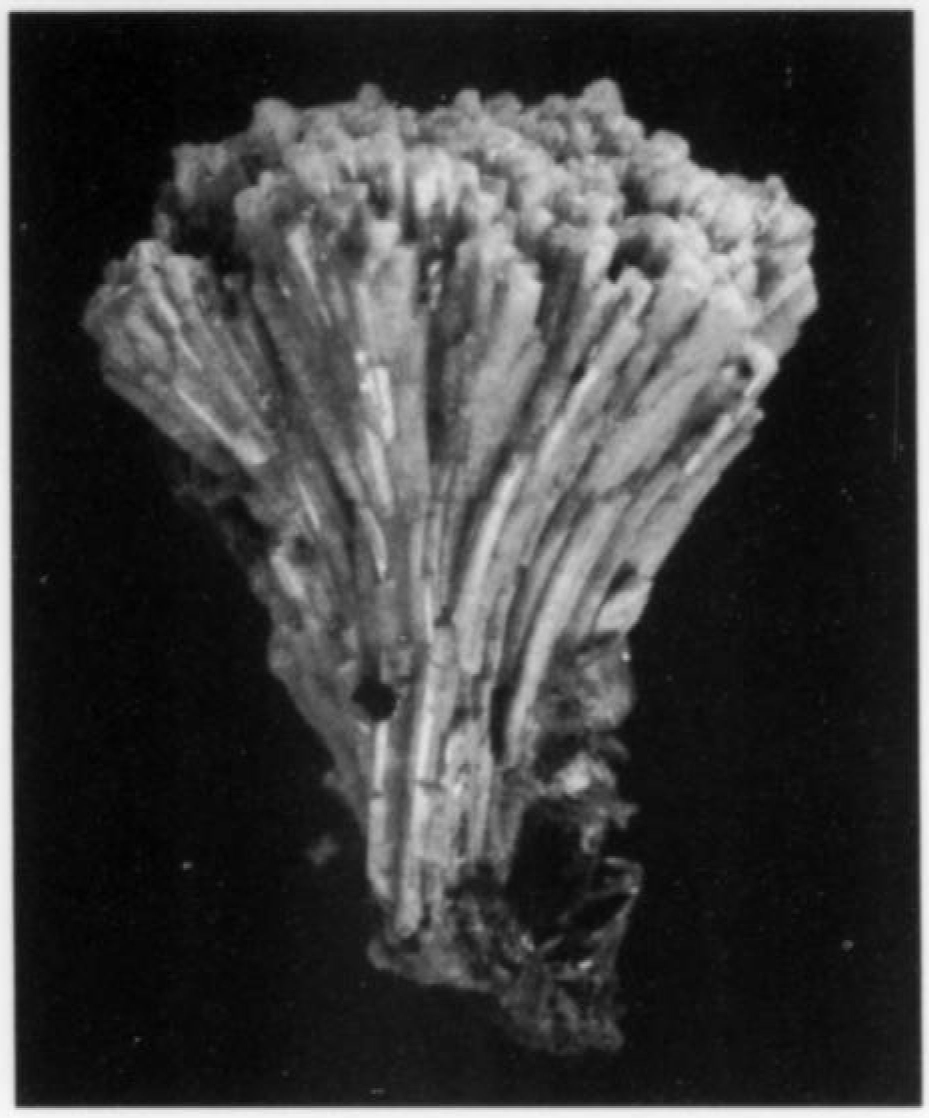


Figure 75. **Whiteite, in a tan-colored diverging spray 2.3 cm tall, from Area B, locality 9. CMN specimen 50882; G. Robinson photo.**

Group II: Minerals of the Phosphate Nodules

Alluaudite group $X1X2M1M2_2(PO_4)_3$

The alluaudite group is yet another group of phosphate minerals exhibiting crystallochemical complexities, with cation ordering, multiple site occupancies by the same cation, site vacancies and variable oxidation states of iron (Moore and Ito, 1979; Ercit *et al.*, 1986a,b). Without accurate chemical analyses and crystal structure data, positive identification of these minerals is virtually impossible. Nevertheless, if chemical data are available, and cations are assigned site occupancies based on the results of crystal structure analyses for known members of the group, at least a reasonable guess as to the identity of a given sample can be made.

Following such a scheme, we have tentatively identified six different alluaudite group minerals from Rapid Creek, having examined only five specimens! Two of these may be new species (the ferrous iron analogs of hagendorfite and maghagendorfite), and are currently under investigation. Table 5 gives preliminary microprobe analyses of these minerals. Formula contents, including ferrous and ferric iron, were calculated by normalizing to six (P^{+5} + Si^{+4}) and 24 total anions (O^{-2} + F^-). Assigning these cations to the X1, X2, M1, and M2 sites by analogy to known similar structure types (Moore, 1971b; Moore and Molin-Case, 1974; Moore and Ito, 1979; Ercit *et al.*, 1986b), results in the various distributions reported in Table 5. The nomenclature presently in use defines members of the alluaudite group according to the occupancies of the M1 and M2 sites, as shown on Table 6. Although the calculated Fe^{+2}/Fe^{+3} contents require verification, these analyses suggest that at least six different alluaudite group minerals exist at Rapid Creek: alluaudite (analysis 1), ferroalluaudite (analysis 2), hagendorfite (analysis 3), maghagendorfite (analysis 4), ferrous iron analog (?) of hagendorfite (analysis 6) and ferrous iron

Table 5. **Alluaudite analyses.**

	1	2	3	4	5	6	7
MgO	3.55	3.49	2.95	6.88	6.21	2.30	4.39
FeO*	9.40	21.44	14.75	22.12	21.70	21.82	21.40
Fe_2O_3*	14.13	14.54	10.40	6.77	9.97	12.08	7.33
MnO	13.42	3.96	13.74	7.46	3.12	5.64	5.45
Na_2O	8.57	10.32	9.94	7.44	9.36	10.62	3.05
CaO	2.07	2.21	3.12	2.38	5.08	3.95	10.92
Al_2O_3	2.94	0.00	0.58	0.07	0.00	0.00	0.75
P_2O_5	45.15	44.38	43.37	42.14	44.95	43.73	42.81
SiO_2	0.00	0.00	0.05	0.00	0.00	0.00	0.00
F	0.72	0.69	0.67	0.57	0.80	0.58	0.65
F=O	–0.30	–0.29	–0.28	–0.24	–0.34	–0.24	–0.27
sum	99.65	100.74	99.29	95.59	100.85	100.48	96.48
Mg^{+2}	.83	.83	.72	1.73	1.46	.56	1.08
Fe^{+2}	1.23	2.86	2.01	3.11	2.86	2.96	2.96
Fe^{+3}	1.67	1.75	1.28	.86	1.18	1.47	.91
Mn^{+2}	1.78	.54	1.90	1.06	.42	.77	.76
Na^+	2.61	3.20	3.15	2.43	2.86	3.34	.98
Ca^{+2}	.35	.38	.55	.43	.86	.69	1.94
Al^{+3}	.54	.00	.11	.01	.00	.00	.15
P^{+5}	6.00	6.00	5.99	6.00	6.00	6.00	6.00
Si^{+4}	.00	.00	.01	.00	.00	.00	.00
F^-	.36	.35	.35	.30	.40	.30	.34
O^{-2}	23.64	23.65	23.65	23.70	23.60	23.70	23.66
Proposed Site Occupancies							
X1							
Na^+	1.60	1.62	1.43	.80	1.14	1.31	0.06
Ca^{+2}	.35	.38	.55	.43	.86	.69	1.94
Fe^{+2}	.05	.00	.02	.77	.00	.00	.00
X2							
Na^+	1.01	1.58	1.72	1.63	1.72	2.07	.92
	.99	.42	.28	.37	.28	.00	1.08
M1							
Mn^{+2}	1.78	.54	1.90	1.06	.42	.77	.76
Fe^{+2}	.22	1.46	.10	.94	1.58	1.23	1.24
M2							
Fe^{+2}	.96	1.40	1.89	1.40	1.28	1.73	1.72
Fe^{+3}	1.67	1.75	1.28	.86	1.18	1.47	.91
Mg^{+2}	.83	.83	.72	1.73	1.46	.56	1.08
Al^{+3}	.54	.00	.11	.01	.00	.00	.15

*Calculated stoichiometrically

analog (?) of maghagendorfite (analysis 5). Analysis 7 is similar to analysis 6, but with more Ca^{+2}, some of which may actually occupy the M1 site. Although we have not been able to confirm the presence of varulite reported by Robertson (1982), a more detailed study may do so, considering the wide range of iron and manganese contents that has been demonstrated by our own brief survey of these minerals.

Many of these species may coexist in a single specimen, and probably would have gone unnoticed without employing backscattered-electron imagery as part of the routine microprobe investigation. Figure 77 shows a typical intergrowth of maghagendorfite laths in hagendorfite together with their corresponding energy dispersion spectra. Although the maghagendorfite appears darker in the photograph due to its overall slightly lower average atomic number, the pair are indistinguishable in hand specimen. The same holds for the other members of the group we have observed, and it is therefore advisable to label unanalyzed specimens as "alluaudite group."

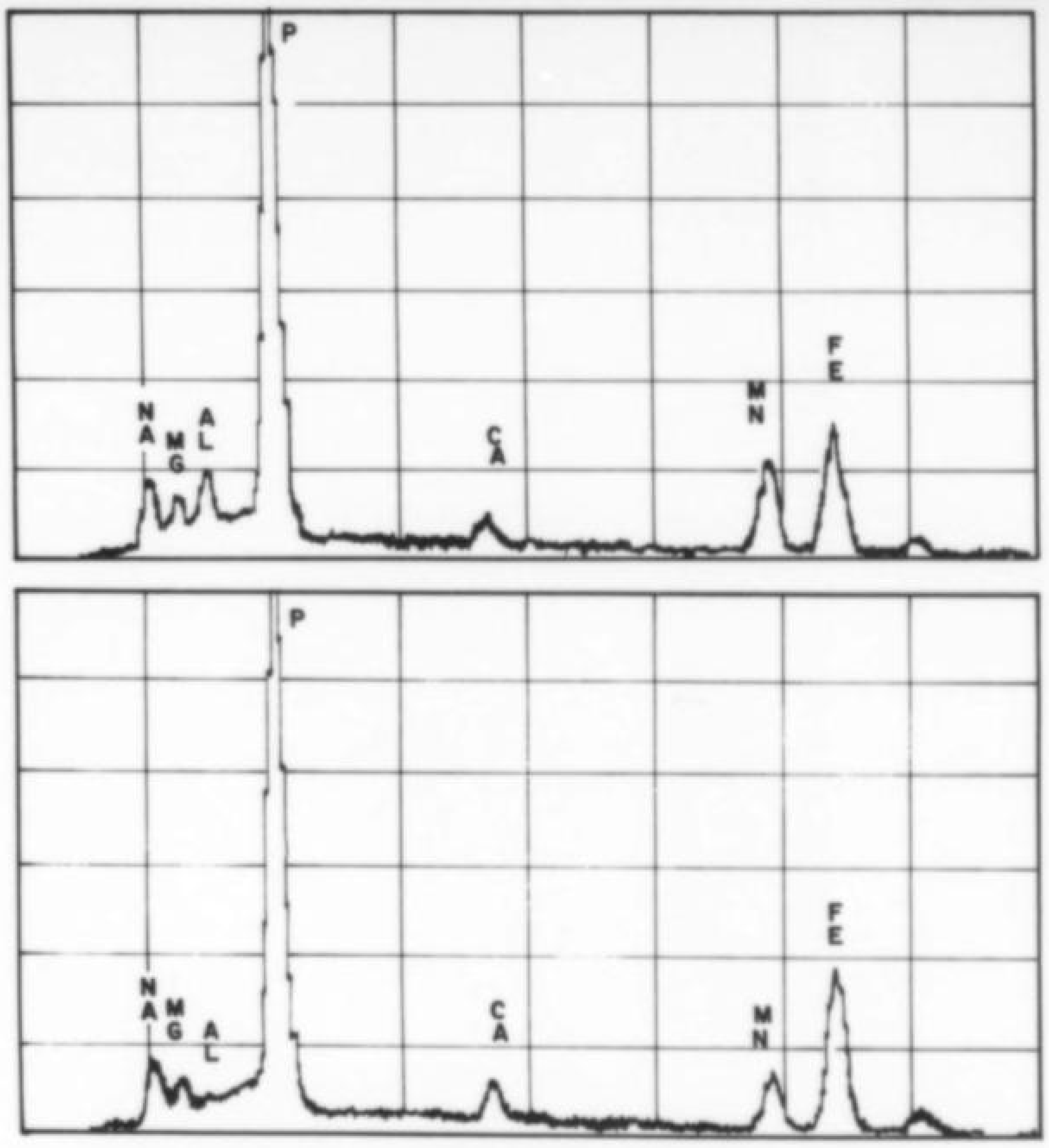


Figure 76. **Energy-dispersive X-ray spectra of maghagendorfite (top) and hagendorfite (bottom).**

Figure 77. **Back-scattered electron image showing maghagendorfite (dark) and hagendorfite (light).**

Table 6. **Classification of alluaudite-group minerals.***
$X1X2M1M2_2(PO_4)_3$

M1 Site	M2 Site	Species
Mn^{+2}	Fe^{+2}	Hagendorfite
Fe^{+2}	Fe^{+2}	Undescribed
Mn^{+2}	Mg^{+2}	Maghagendorfite
Fe^{+2}	Mg^{+2}	Undescribed
Mn^{+2}	Mn^{+2}	Varulite
Fe^{+2}	Mn^{+2}	Predicted unstable
Mn^{+2}	Fe^{+3}	Alluaudite
Fe^{+2}	Fe^{+3}	Ferroalluaudite

*Modified after Moore and Ito (1979) and Ercit *et al*. (1986a)

Figure 78. **Nodules of satterleyite (left), marićite (center) and wolfeite (right, 6 cm). P. Collins collection; G. Robinson photo.**

These minerals occur predominately in the phosphatic nodules from both locality 16, Area C, and Boundary Creek, 5 km to the northwest, but occasionally also in some of the quartz veins, particularly near locality 4 in Area A. They typically appear as dark blue-green, fibrous to platy, radial aggregates up to several millimeters in length, associated with satterlyite, wicksite, wolfeite and pyrite.

Bobierrite $Mg_3(PO_4)_2 \cdot 8H_2O$

This rare species has been identified on a single specimen of altered marićite from locality 16, Area C. The mineral occurs as thin, lamellar, translucent white clusters of crystals up to 0.2 mm coating fracture surfaces in the marićite. Vivianite, metavivianite and switzerite/metaswitzerite are the associated species. The X-ray powder diffraction pattern agrees well with that of synthetic bobierrite (J.C.P.D.S. No. 16-330), and qualitative energy-dispersive microprobe analysis confirms its composition as a magnesium phosphate.

Ernstite $(Mn^{+2}_{1-x}Fe^{+3}_{x})Al(PO_4)(OH)_{2-x}O_x$

An ernstite-like mineral has been found as golden to dark yellow-brown veinlets and radial sprays in a single nodule of pyrite from locality 16, Area C. The strongest lines in its X-ray powder pattern are (d in Å, I/I_o) 6.69 (20), 5.20 (30), 4.35 (30), 2.81 (100), 2.42 (40) and 2.38 (30). Qualitative energy-dispersive microprobe analysis shows Fe, Mn, Al and P as the major elements present.

Marićite $NaFePO_4$

Marićite was first described as a new mineral from the Big Fish River by Sturman *et al.* (1977). Gray to colorless with pale blue or green hue, marićite occurs as coarse, radial to subparallel aggregates of crude crystals elongated parallel to [100]. Marićite-bearing nodules may be monomineralic, but more commonly contain satterlyite, wolfeite, pyrite, alluaudite group, ludlamite, vivianite, quartz, apatite and/or siderite. Marićite has been found only at locality 16, Area C.

Metaswitzerite $(Mn^{+2},Fe^{+2})_3(PO_4)_2 \cdot 4H_2O$ and
Switzerite $(Mn^{+2},Fe^{+2})_3(PO_4)_2 \cdot 7H_2O$

Switzerite and metaswitzerite form bright white to pink, silky, flattened radial sprays of crystals up to half a millimeter across both on and in marićite nodules from locality 16, Area C. Associated species include wolfeite, ludlamite, quartz, pyrite, vivianite, wicksite, alluaudite group minerals, and unknowns 1 and 2 described below. Most of the X-ray powder diffraction patterns match well with that of metaswitzerite, although a few show a strong reflection at 11.10 Å, indicating the presence of switzerite as well (White *et al.*, 1986).

Microprobe analysis of these minerals show that part of the Mn is replaced by Ca, Fe and other cations. An average of two analyses yielded the following formula contents, based on 8 anions, with 4 or 7 H_2O assumed: $(Mn_{2.56},Ca_{0.28},Mg_{0.09},Fe_{0.06},Al_{0.03})_{3.02}(P_{0.99}O_4)_2 \cdot nH_2O$.

To the authors' knowledge this represents the second known world occurrence for each of these species.

Pyrite FeS_2

Pyrite is very common throughout the area, occurring as fine-grained disseminations and small, euhedral cubic crystals in some of the units of the iron formation. Many of the nodules from locality 16 in Area C contain pyrite, either as coarsely crystalline, anhedral aggregates to several centimeters or, less commonly, as striated cubes or pyritohedra up to 2 cm in diameter. A few small octahedral crystals have also been noted in association with eosphorite, coating the wardite from locality 12 in Area B.

Satterlyite $(Fe^{+2},Mg,Fe^{+3},H,Na,Mn)_2(PO_4)(OH)$

Mandarino *et al.* (1978) first described satterlyite as a new hexagonal polymorph of wolfeite, occurring in the phosphatic nodules from locality 16, Area C. It forms radiating to divergent, columnar aggregates of yellow, glassy, crude crystals, rarely with pyramidal terminations. Marićite, wolfeite, wicksite, alluaudite group minerals, pyrite and ludlamite have been identified as associated species.

Satterlyite has also been found in at least one site near locality A-4, where it occurs as greasy to dull, yellow, divergent columnar aggregates, associated with gray, glassy arrojadite and massive, red-brown siderite. At this locality satterlyite appears as a rock-forming mineral, and constitutes a discrete, albeit narrow, unit of the iron formation. The name honors Dr. Jack Satterly, a renowned geologist with the Ontario Ministry of Natural Resources, Division of Mines, and Research Associate with the Royal Ontario Museum.

Strengite $Fe^{+3}PO_4 \cdot 2H_2O$

A strengite-like mineral was found as a white powder intimately mixed with gypsum in a vug in a single nodule of pyrite from locality 16, Area C. Associated species include quartz, fluorapatite, arrojadite and unknown No. 6. Qualitative energy dispersive microprobe analysis detected iron and phosphorus as the only elements present. The X-ray powder pattern for this mineral matches well for a mixture of strengite and gypsum.

Switzerite: See under Metaswitzerite

Wicksite $NaCa_2(Fe^{+2},Mn)_4MgFe^{+3}(PO_4)_6 \cdot 2H_2O$

Named for Dr. Fred Wicks of the Royal Ontario Museum, wicksite was first described by Sturman *et al.* (1981) as a new mineral occurring with satterlyite from locality C-16. Wicksite usually appears as dark green to black, platy cleavage aggregates with a nearly submetallic luster. It forms inclusions up to 1 cm in wolfeite-bearing nodules. Other species less frequently observed with wicksite include pyrite, alluaudite group minerals and vivianite.

Wolfeite $(Fe,Mn)_2(PO_4)(OH)$

Wolfeite is a common constituent of the phosphatic nodules. Like marićite and satterlyite, wolfeite forms divergent, columnar aggregates of crude, glassy crystals up to several centimeters in length. Wolfeite is typically transparent, light brown to clove-brown, and may be associated with satterlyite, marićite, wicksite, alluaudite group minerals, pyrite, vivianite, ludlamite and siderite.

Microprobe analyses of this wolfeite yield an average formula close to $(Fe_{1.65}Mg_{0.20}Mn_{0.15})PO_4(OH_{0.95}F_{0.05})$.

Group III: Secondary Minerals

Aluminite $Al_2(SO_4)(OH)_4 \cdot 7H_2O$ and
Meta-aluminite $Al_2(SO_4)(OH)_4 \cdot 5H_2O$

Both aluminite and meta-aluminite have been identified on a single specimen collected from talus between localities 5 and 6 in Area A. The aluminite occurs as silky white fibers in and on iron-stained earthy masses of meta-aluminite associated with siderite, quartz and iron oxide filling voids in what appears to be a brecciated, weathered ironstone.

Aragonite $CaCO_3$

Aragonite, although widespread throughout the area, is easily overlooked. It occurs as tiny, colorless to white, spheroidal aggregates of acicular crystals up to a millimeter, commonly coating siderite and quartz.

Brushite $CaHPO_4 \cdot 2H_2O$

A widespread mineral normally found in guano and phosphorite deposits, brushite is known on but one specimen from Rapid Creek. This specimen consists of a nodule of wolfeite, quartz and vivianite from locality 16, Area C. The brushite occurs as colorless, transparent to translucent, prismatic sprays of crystals up to about 0.1 mm long.

Diadochite $Fe_2^{+3}(PO_4)(SO_4)(OH) \cdot 5H_2O$

Earthy, crudely botryoidal masses of light yellow-brown diadochite have been found loose in talus in the vicinity of locality 6 in Area A. Elsewhere it has been observed as translucent, red-brown to nearly black, waxy masses or gel-like crusts occupying voids between crystals of the primary phosphates.

Dypingite $Mg_5(CO_3)_4(OH)_2 \cdot 5H_2O$

Bright white with a distinctive pearly luster, dypingite is locally common as crusts or thick coatings on shale throughout the area. Upon closer examination, these coatings are seen to consist of felted aggregates of minute, acicular crystals, and masses of spheroidal, radial crystal aggregates.

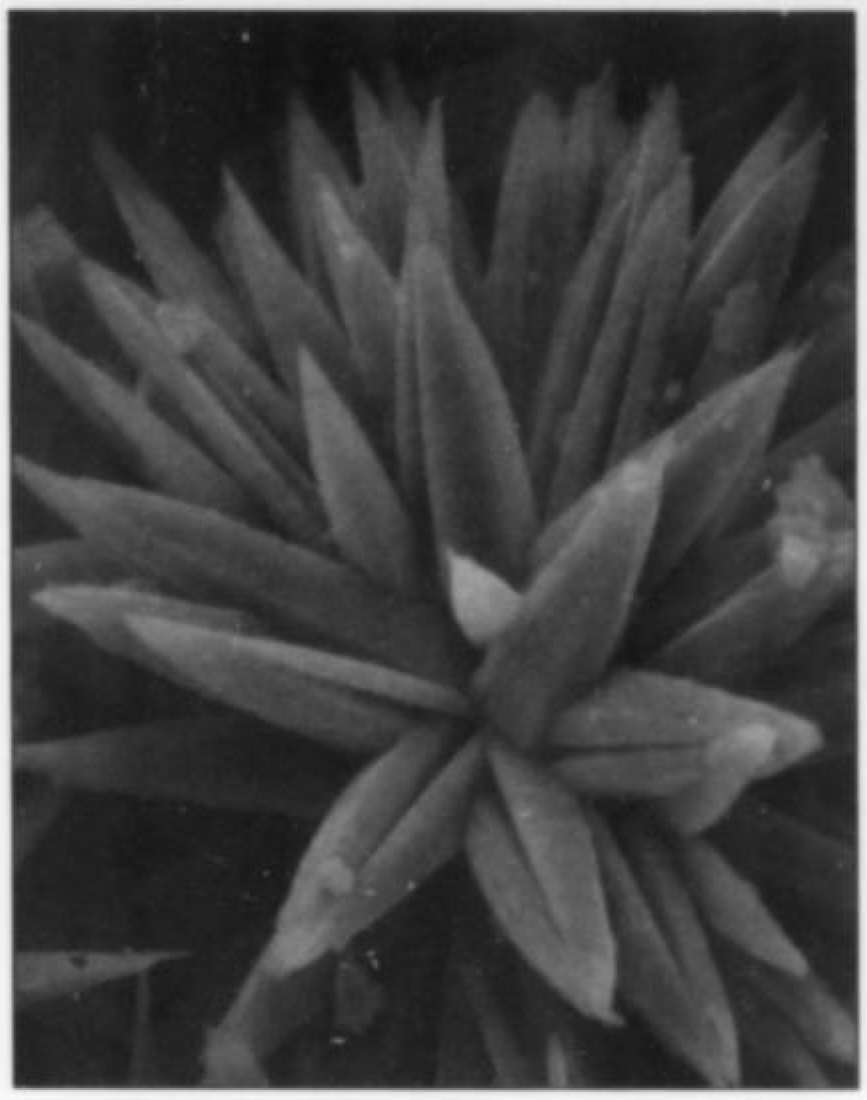


***Figure 79*. Aragonite crystal spray, 70µ, from Area B, locality 11. CMN specimen MOC3457; G. Robinson photo.**

Epsomite $MgSO_4 \cdot 7H_2O$

Epsomite has been found at locality 16 in Area C as white efflorescences and rounded aggregates on surfaces and cavities in rock.

Giorgiosite $Mg_5(CO_3)_4(OH)_2 \cdot 5H_2O$ (?)

Giorgiosite has been identified on a single specimen of kulanite from locality 10, Area B, in the collection of Patrick Collins of Kingston, Ontario (catalog no. Y-166). The mineral occurs as a 1-cm, silky, bright white, powdery mass surrounded by aragonite. The strongest reflections in its X-ray powder diffraction pattern are (d in Å, I/I_o) 11.88 (100), 3.29 (60), 3.40 (50), 5.35 (30), 3.97 (30), 6.78 (20), 4.44 (20), 3.51 (20), 3.37 (20) and 4.20 (10), which are in reasonably close agreement with the published data for the species (Raade, 1970; Friedel, 1975). Qualitative energy dispersion microprobe analyses show Mg as the only element detected. To the authors' knowledge, this represents the second world occurrence of giorgiosite (Lacroix, 1905; Raade, 1970).

Goethite $FeO(OH)$

Goethite and undifferentiated hydrous iron oxides ("limonite") appear ubiquitously as earthy, yellow to orange-brown coatings, and dark red-brown, botryoidal crusts. Siderite is a common associate, and in some instances is the likely parent from which the goethite formed. Goethite has also been observed as curved, pseudomorphous (?) flakes up to 6 mm coating a 2-meter rock face near locality 14, Area B.

Gypsum $CaSO_4 \cdot 2H_2O$

Gypsum is probably the most common constituent of the white deposits that are frequently observed coating the outcrops and cliff faces in the region. Together with other secondary minerals such as hexahydrite, halotrichite, rapidcreekite and jarosite, gypsum occurs as radiating sprays of colorless, platy, prismatic crystals and as fibrous to pulverulent coatings.

Halotrichite $FeAl_2(SO_4)_4 \cdot 22H_2O$

Halotrichite has been identified with hexahydrite and gypsum at one occurrence only, south of locality 4 in Area A, where it forms yellowish white, botryoidal aggregates of rather poorly developed crystals, efflorescing from an ironstone matrix.

Hexahydrite $MgSO_4 \cdot 6H_2O$

Hexahydrite occurs with gypsum and halotrichite south of locality 4 in Area A. It appears as platy to fibrous, white crystals up to 2 mm in length, randomly oriented in efflorescent growths on rock, and may easily be mistaken for gypsum. Hexahydrite is water-soluble, and the only known specimens were found where the snow cover had recently sublimated away, thus sheltering the site from water.

The presence of both epsomite and hexahydrite leads one to suspect the existence of some of the less hydrated magnesium sulfates such as pentahydrite, starkeyite, sanderite or kieserite, since these minerals occupy stability fields within the temperature and relative humidity ranges common to the area (Waller, 1989).

Hydromagnesite $Mg_5(CO_3)_4(OH)_2 \cdot 4H_2O$

Small, silky, white, botryoidal masses of hydromagnesite have been identified on specimens collected from the talus north of locality 7 in Area A, and from locality 10 in Area B.

Jarosite $KFe_3^{+3}(SO_4)_2(OH)_6$

Jarosite has been found as earthy, deep yellow-brown masses filling voids in highly ferruginous rocks along the northwest side of Rapid Creek, 5 km northwest of Mount Davies Gilbert. Gypsum and second-generation siderite are the associated minerals. Jarosite has also been noted as 0.2-mm orange-brown "octahedra" (possibly pseudomorphs after pyrite) on quartz with messelite and metavivianite from near the mouth of "Crosscut Creek" in Area A (P. Collins, personal communication, 1988).

Nahpoite Na_2HPO_4

The anhydrous acid phosphate, nahpoite, was originally described as a white, fine grained, powdery substance in marićite nodules from locality 16 in Area C (Coleman and Robertson, 1981). It appears to have formed as a direct alteration product of marićite, which is the only other species present.

Nahpoite is extremely water-soluble, which may help explain its scarcity, due to its inherently ephemeral existence in nature. It readily hydrates to dorfmanite ($Na_2HPO_4 \cdot 2H_2O$) at 25° C and 28% relative humidity, suggesting that specimens probably exist as nahpoite in the winter and dorfmanite in the summer (Waller, 1989). Do not wash your nahpoite!

Natrojarosite $NaFe_3^{+3}(SO_4)_2(OH)_6$

Natrojarosite has been collected from the talus on the east side of Rapid Creek, 5.2 km north-northwest of Mount Davies Gilbert. It occurs with goethite and siderite as earthy, yellow-orange masses and as translucent, orange-brown, subhedral crystals up to a millimeter across filling voids in ferruginous rocks.

Nesquehonite $Mg(HCO_3)(OH) \cdot 2H_2O$

Nesquehonite has been found with aragonite and dypingite in cavities in brecciated ironstone at locality 9 in Area B, where colorless, fibrous, prismatic crystals to 8 mm in length form radial aggregates and flattened coatings on siderite.

Rapidcreekite $Ca_2(SO_4)(CO_3) \cdot 4H_2O$

Rapidcreekite is a new mineral first found in 1983, just south of locality 1 in Area A (Roberts *et al.*, 1986). It occurs as coatings and divergent tufts of colorless, acicular crystals up to 2 mm in length. The associated species are aragonite and gypsum, both of which may at first be easily confused with rapidcreekite, but the latter has a distinct silky appearance that usually permits a visual identification. Rapidcreekite was named for the general locality despite its actual occurrence on "Crosscut Creek."

Sasaite $(Al,Fe^{+3})_{14}(PO_4)_{11}(SO_4)(OH)_7 \cdot 83H_2O$ (?)

A white, silky botryoidal mineral on a single specimen collected from near locality 8, Area A, gave an X-ray powder diffraction pattern similar to that of partially dehydrated sasaite (Martini, 1978). The strongest reflections are (d_{ave} in Å, I/I_o) 9.32 (100), 7.37 (40), 2.87 (30), 4.13 (20), 6.46 (10), 5.35 (5) and 3.47 (5). Qualitative energy-dispersive microprobe analyses indicate Al, Fe, P and S are the major elements present. The associated species are satterlyite, gormanite-souzalite, vivianite, phosphosiderite, quartz and siderite. To the authors' knowledge this is the third world occurrence of sasaite, and the first outside a cave environment (Martini, 1978; Coulsell, 1987).

Like many heavily hydrated minerals, sasaite readily loses water at ambient temperature and low relative humidity (Martini, 1978). In

***Figure 80*. Nesquehonite crystals, colorless and transparent, to 2 mm, with aragonite spherules from Area B, locality 10. Geological Survey of Canada specimen 61243; G. Robinson photo.**

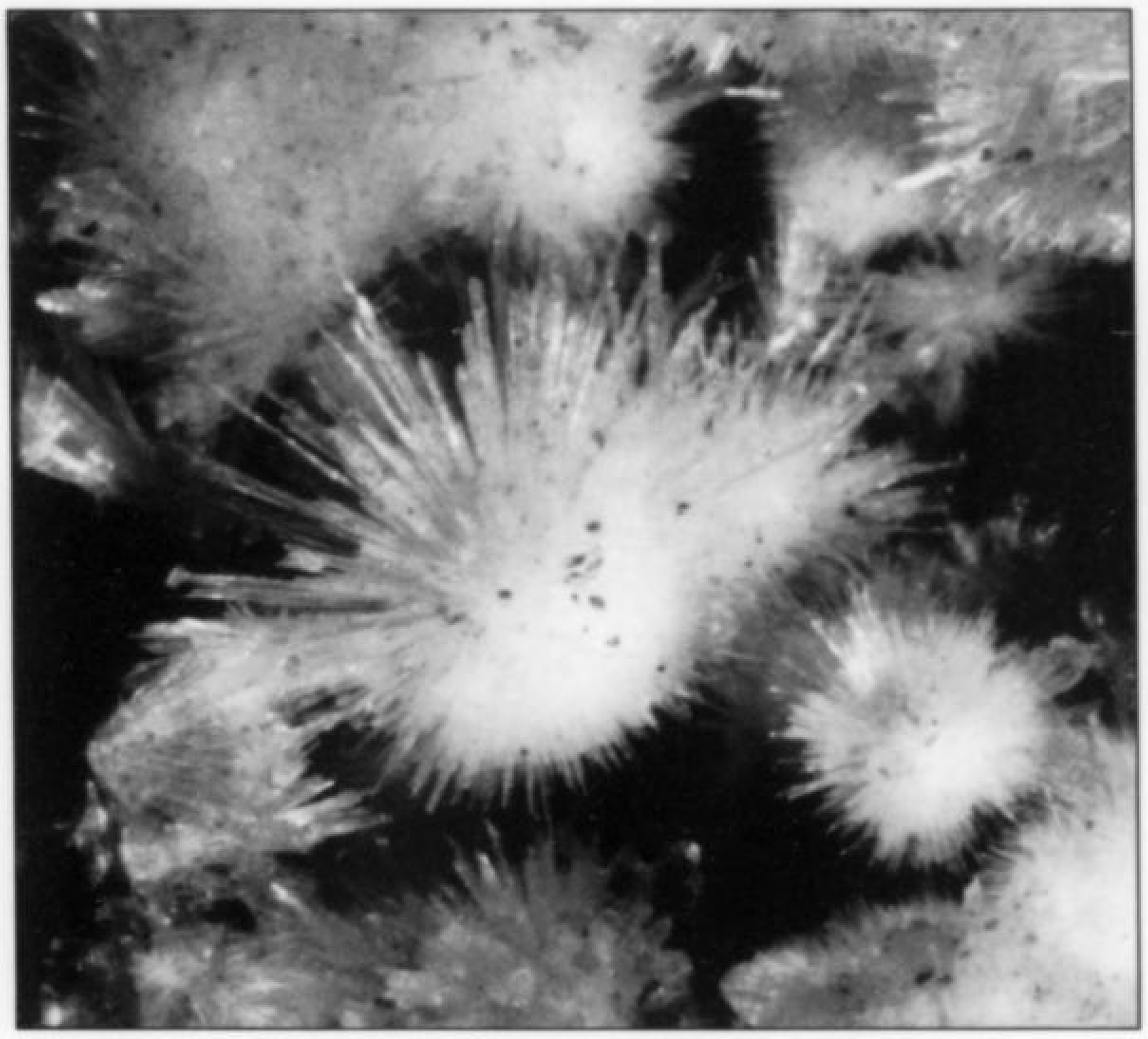


***Figure 81*. Rapidcreekite crystal spray, white, 3 mm, from ≈100 meters downstream from locality 1, Area A. CMN specimen 50825; G. Robinson photo.**

the case of sasaite, the process is reversible. Thus, both sasaite and partially dehydrated sasaite probably exist at Rapid Creek, depending on which phase is more stable for the prevailing conditions of temperature and relative humidity.

Unknown Minerals

Several unknowns have been found in the course of this study. Most occur on a very few marićite nodules from locality 16, Area C, as either coatings on the surfaces of the nodules or along fracture planes within them. We are uncertain whether these minerals have formed solely as weathering products of the earlier-formed minerals that constitute the nodules or if they formed as late-stage phases near the end of the original mineralizing event. Very little of each mineral has been found, especially in a relatively pure form, unmixed with associated species. Therefore, the information presented here is only preliminary; more and better crystallized material will surely be required before any of these minerals can be properly characterized.

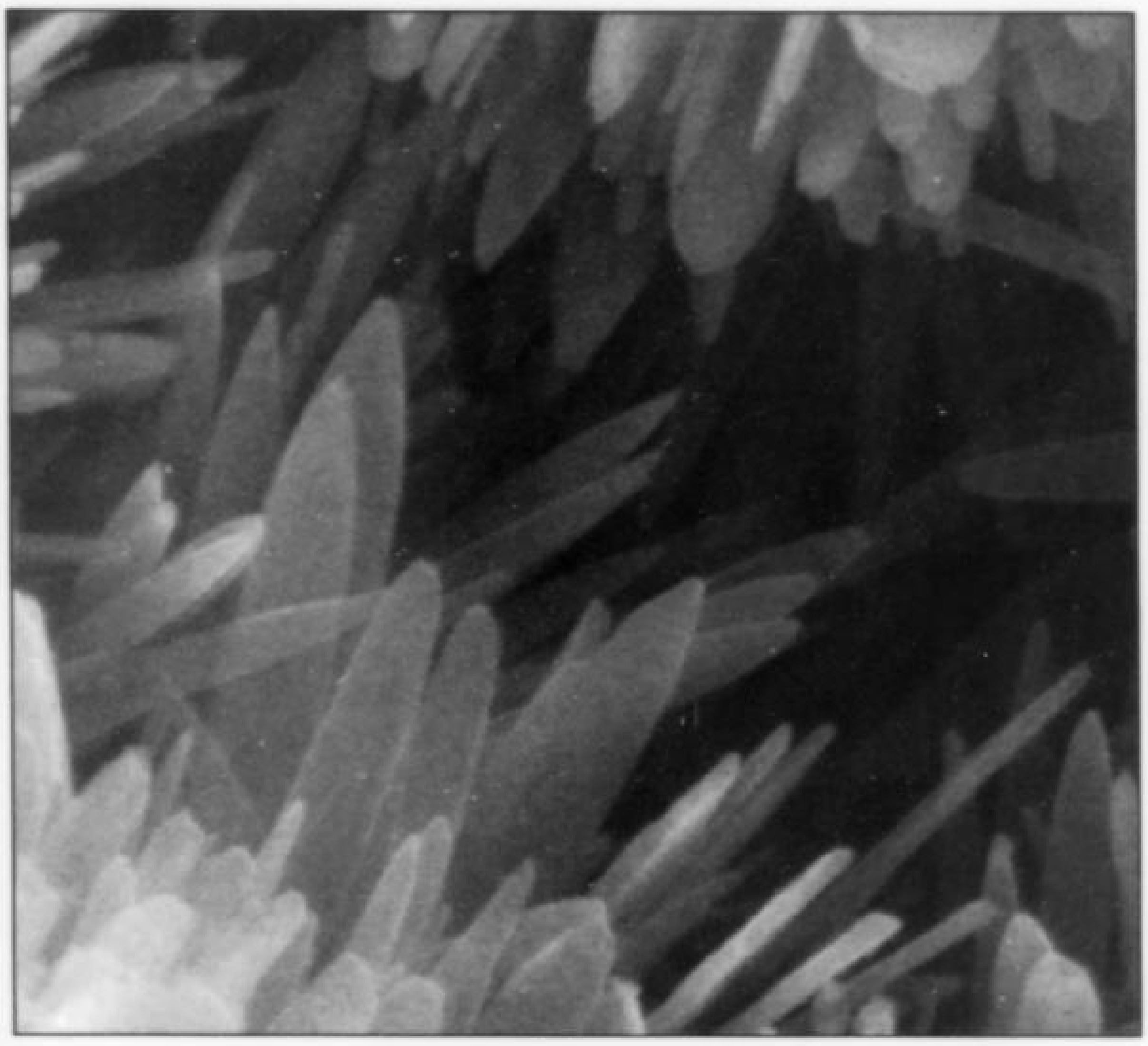


Figure 82. **Unknown no. 1, from Area C, locality 16, magnified 6600X. CMN specimen MOC3458; G. Robinson SEM.**

Unknown No. 1

This mineral appears as an interstitial, gray-to-white, scaly coating between marićite crystals, and as dull, yellowish felted mats coating fracture planes in the marićite. These yellow crusts are actually composed of radiating sprays of acicular crystals that visually resemble cacoxenite or goethite. Electron microprobe analyses indicate it is probably a hydrated sodium iron phosphate, with a Na:Fe:P ratio of 1:1:1. One analysis gave K_2O 0.08, Na_2O 14.17, CaO 0.43, FeO 33.24, MnO 0.22, MgO 0.45, Al_2O_3 0.49, P_2O_5 34.24, SiO_2 0.08, H_2O(calc) 17.26, sum 100.66 weight %. Based on this analysis, assuming all iron is Fe^{+2} and no undetected elements other than H are present, the simplest formula for the mineral, based on 3 total cations, would be $NaFePO_4 \cdot 2H_2O$.

The strongest reflections in its X-ray powder diffraction pattern are (d in Å, I/I_o) 11.3 (100, 3.71 (20), 3.28 (20), 3.07 (20), and 2.52 (30). Although parts of the pattern bear some similarities to those of various known minerals or inorganic compounds, none matches it completely, and none is a sodium iron phosphate.

Unknown No. 2

During the microprobe examination of metaswitzerite, the presence of a second mineral was noted. This mineral occurs as microscopic, silky white crystals radiating from a central core. Both the radiating crystals and central mass appear to be hydrated Fe-Mn-Ca phosphates, and the preliminary analyses suggest an inverse relationship between Ca and Mn. Typical analyses of the inner mass and outer crystals gave, respectively, K_2O 0.36, Na_2O 0.30, CaO 6.16, FeO 25.24, MnO 8.51, MgO 0.96, Al_2O_3 0.73, P_2O_5 38.10, SO_3 0.56, sum 80.92; and K_2O 0.30, Na_2O 0.27, CaO 1.48, FeO 18.79, MnO 12.77, MgO 0.53, Al_2O_3 0.66, P_2O_5 27.10, SO_3 1.06, sum 62.96.

Obtaining an X-ray powder diffraction pattern for this material is difficult, for not only is it intimately associated with switzerite and metaswitzerite, which it physically resembles, but it may itself be a mixture. The strongest reflections in the pattern that cannot be attributed to either switzerite or metaswitzerite are (d in Å, I/I_o) 10.93 (100), 5.83 (20), 3.21 (20) and 2.19 (10).

There is regrettably little of this material available, and it is clear that more research will be necessary to properly characterize it.

Unknown No. 3

This unknown consists of small, pearly white crusts coating one surface of a single marićite-vivianite nodule. Minor pyrite and yellowish iron oxides are the associated minerals. The sample does not diffract X-rays well, and thus only a few weak, diffuse reflections are apparent in its powder diffraction pattern (d in Å, I/I_o): 4.12 (100), 3.73 (10), 3.33 (20), 3.22 (10), 2.98 (5), 2.56 (5), 2.22 (5), 2.08 (5) and 2.02 (5). Qualitative energy-dispersive microprobe analyses show iron, aluminum and phosphorus as the only elements present. The surface of this mineral consists of a desiccated, botryoidal crust.

Unknown No. 4

This mineral occurs as waxy orange spheres up to 0.1 mm associated with unknown No. 1, vivianite-barićite and brushite coating fracture surfaces in marićite. A preliminary microprobe analysis of one of the spheres gave K_2O 0.10, Na_2O 3.76, CaO 0.44, FeO 31.82, MnO 2.71, MgO 1.58, Al_2O_3 1.28, P_2O_5 38.51, SiO_2 0.06, sum 80.26 weight %. The strongest lines in its X-ray powder diffraction pattern are (d in Å, I/I_o) 12.84 (100), 11.36 (30), 9.22 (20), 7.45 (20) and 2.62 (20).

Unknown No. 5

Unlike the previously described unknowns, this mineral was found with satterlyite and gormanite-souzalite on a single specimen collected from the talus near locality 8 in Area A. The major accessory minerals are ludlamite, whitlockite and siderite. The unknown forms fibrous green prisms up to 3 mm in length. Electron microprobe analyses show the mineral is zoned with respect to Fe and Mg, and if both occupy the same site, there may actually be two different species present, one Fe-dominant, the other Mg-dominant. Analyses for the Fe-rich and Mg-rich zones, respectively are Na_2O 0.75, CaO 1.38, FeO 42.29, MnO 0.54, MgO 9.89, Al_2O_3 0.00, P_2O_5 38.32, SiO_2 0.13, sum 93.30; and Na_2O 0.78, CaO 1.74, FeO 31.60, MnO 0.31, MgO 18.47, Al_2O_3 0.04, P_2O_5 40.41, SiO_2 0.08, sum 93.43 weight %.

The strongest reflections in the X-ray powder diffraction pattern for these zoned crystals are (d in Å, I/I_o) 3.20 (100), 2.41 (50), 6.32 (40), 3.71 (40), 2.74 (40), 2.25 (40), 1.58 (40), 4.58 (30), 1.85 (30), 1.83 (30) and 10.97 (20).

Unknown No. 6

This mineral occurs as fibrous, pale green spherical aggregates to 0.2 mm associated with quartz, fluorapatite, arrojadite, gypsum and strengite in microscopic vugs in a single nodule of pyrite from locality 16, in Area C. Iron, manganese and phosphorus are the major elements detected by qualitative energy dispersive microprobe analysis. The strongest X-ray powder diffraction lines are (d in Å, I/I_o) 7.78 (100), 6.73 (20), 4.35 (20), 3.29 (50), 3.11 (20), 3.00 (30), 2.57 (40) and 2.51 (30).

PARAGENESIS

In spite of the fact that phosphates constitute an incredibly widespread and diverse suite of minerals of great interest to some scientists and most mineral collectors, relatively little research has been done that explains their various modes of occurrence and specific origins. This is undoubtedly due to the unfortunate fact that they are, for the most part, not an economically important group of minerals nor do they form an important suite of rock-forming minerals of general interest to petrologists. Most of our understanding of the genesis of phosphate minerals is based on the work of a few dedicated individuals who have studied various phosphate assemblages in granitic pegmatites (Jahns, 1955; Moore, 1973; Shigley, 1982; and Campbell and Roberts, 1986).

In order to better establish the chemical and physical conditions present and the sequence of changes that occurred during the formation of the quartz-phosphate veins at Rapid Creek, a paragenetic study was undertaken by one of us (GWR). Because our present knowledge of phosphate mineral paragenesis results largely from work done on pegmatite phosphates, it is, to a certain extent, necessary to compare what we know about the origin of the Rapid Creek deposit to what has been learned from these studies. *It must be remembered, however, that the quartz-phosphate veins at Rapid Creek are definitely not granitic pegmatites, and that the validity of such a comparison has its limits.* Though both may host similar suites of phosphate species, there exist many important differences between the two types of occurrences. For example, at Rapid Creek the host rock is a sedimentary iron formation, affording an inexhaustible supply of iron, manganese and magnesium to the phosphate-rich fluid throughout the entire period of crystallization. In pegmatites these elements never enjoy such widespread abundance, and are normally depleted from the phosphate-bearing pegmatitic fluids because of the early crystallization of such primary phosphates as triphylite-lithiophillite (Moore, 1973).

Similarly, alkali components such as lithium, sodium and potassium that are relatively abundant in granitic pegmatites and play an important role in the genesis of pegmatite phosphates are virtually absent from the majority of the veins at Rapid Creek. The ubiquitous occurrence of large amounts of siderite at Rapid Creek suggests that a significantly higher carbon dioxide fugacity was present for a longer duration than in most pegmatites. Most granitic pegmatites host iron-bearing oxides rather than carbonates. Finally, the total phosphate concentration itself was probably different. In pegmatites the total concentration of phosphate relative to other components in the fluid phase seldom exceeds a few percent (Shigley, 1982), whereas at Rapid Creek it was likely much higher due to the relative absence of alkalis and silica (after the initial crystallization of quartz) and the reservoir of phosphorus contained in the host rocks.

The continual availability of these essential components (i.e., iron, phosphorus and probably aluminum) to the fluid phase resulted in yet another significant departure from the way phosphates are formed in pegmatites. In pegmatites two or more generations of phosphates are common, the latter of which form at the expense of those which crystallized earlier via metasomatic and hydrothermal alteration. Because pegmatites behave as closed geochemical systems, and because their primary phosphates deplete the pegmatitic fluid of transition-metal cations, the cations required to form the later generations of phosphates can only be remobilized through chemical attack of the primary phosphates by residual fluids concentrated later in the sequence (Moore, 1973). Hence, many of the large, primary crystals of triphylite-lithiophilite found in phosphate-bearing pegmatites exhibit zones of alteration and replacement by later-formed, secondary phosphate minerals. At Rapid Creek, there is almost no evidence of such a chemical attack on early-formed minerals. Species of both early and later-formed phosphates containing the same general elements coexist as fresh, unaltered crystals with lustrous faces. This would certainly not be the case if the later-formed species were dependent on the earlier-formed ones as their source of essential constituents. Instead, both the geological and mineralogical observations suggest that the host sediments were capable of providing a continual supply of both the major and minor elements required to produce the observed suite of minerals.

Figures 83–100 are paragenesis diagrams showing the sequential crystallization of mineral species for each of the more significant locations described in the preceding pages. The information contained in these diagrams was deduced from a microscopic examination of approximately 300 hand specimens. In general, the first species to form appears at the top of the list, with each additional one in its observed relative succession downward to the last-formed species

Figure 83. **Area A, locality 1, kulanite assemblage.**

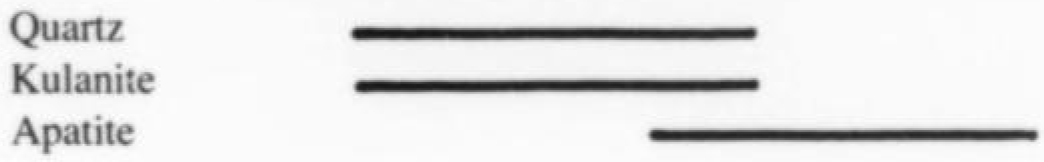


Figure 84. **Area A, locality 1, augelite assemblage.**

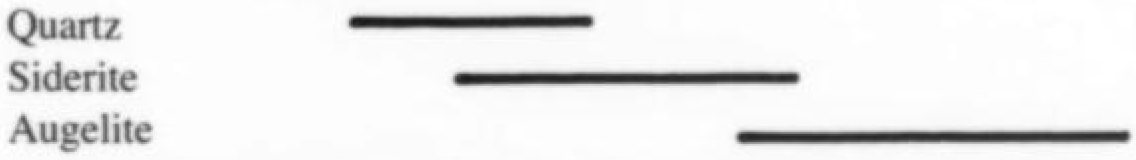


Figure 85. **Area A, locality 1, gorceixite assemblage.**

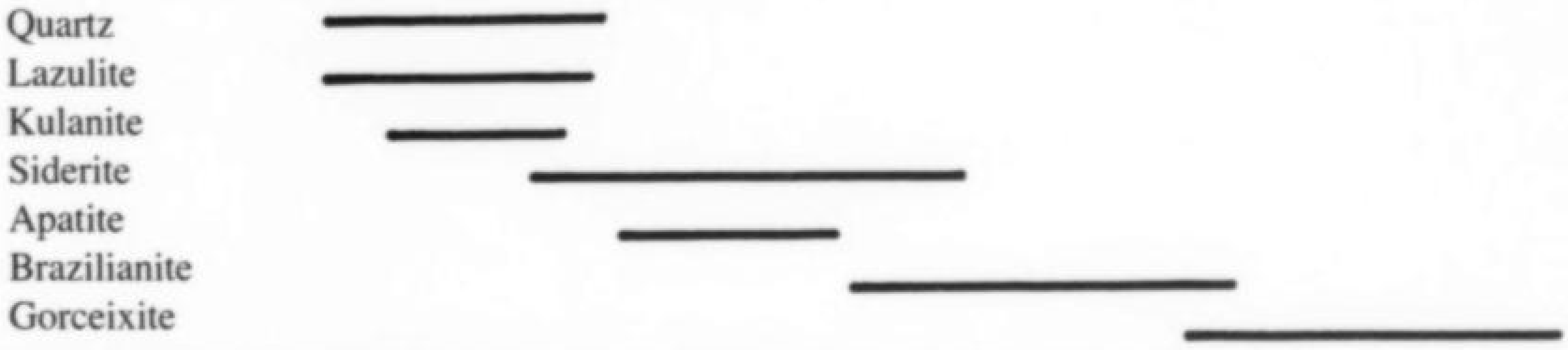


Figure 86. **Area A, locality 1, lazulite assemblage.**

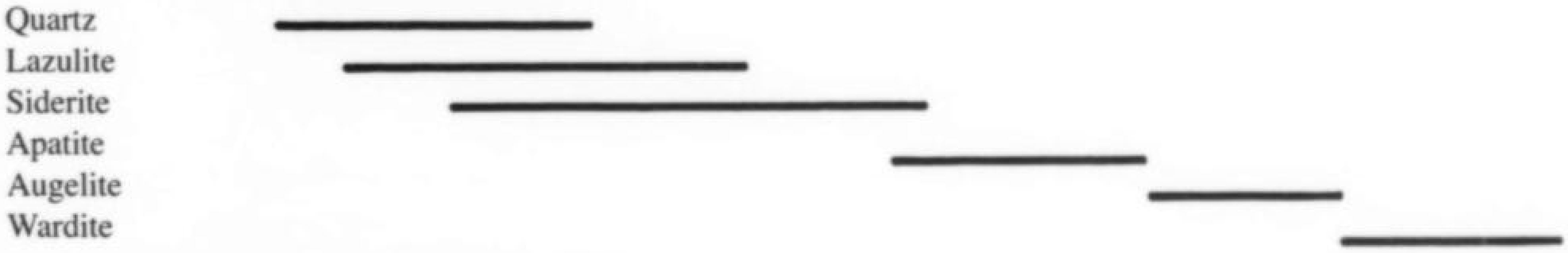


Figure 87. **Area A, locality 2, whiteite assemblage.**

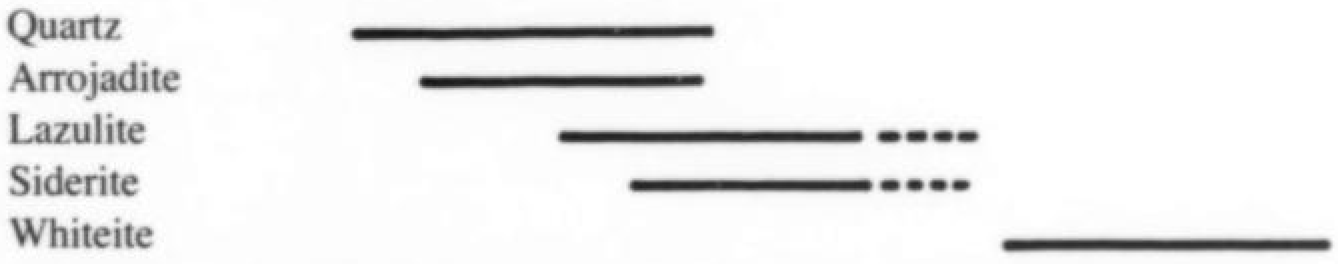


Figure 88. **Area A, locality 3, kulanite assemblage.**

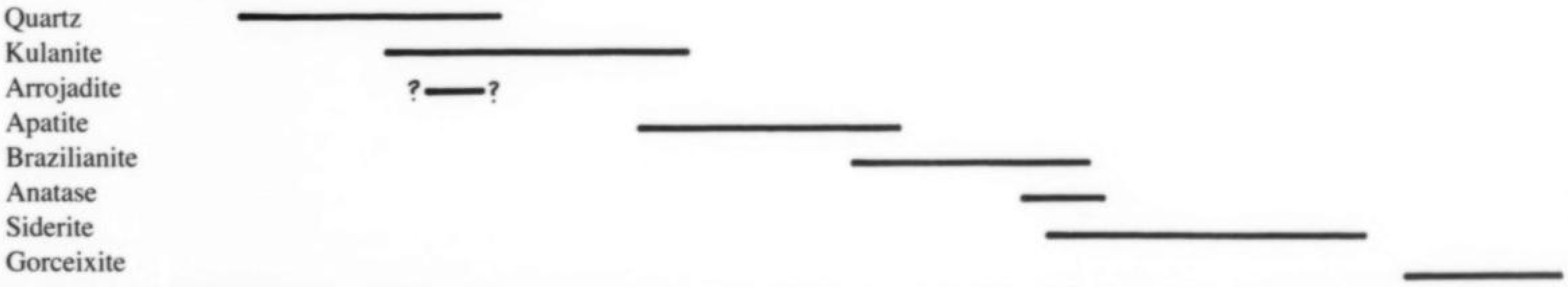


Figure 89. **Area A, locality 5, kryzhanovskite assemblage.**

Figure 90. **Area A, locality 7, wardite assemblage.**

Figure 91. **Area A, locality 7, kryzhanovskite/arrojadite assemblage.**

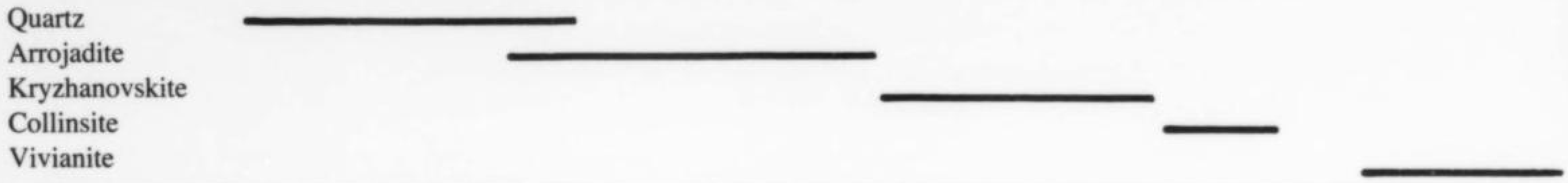


Figure 92. **Area A, locality 7, messelite assemblage.**

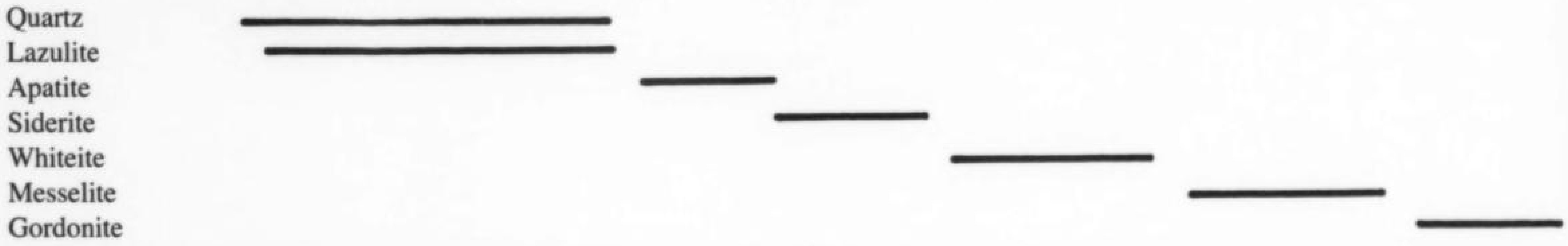


Figure 93. **Area A, locality 8, purple apatite assemblage.**

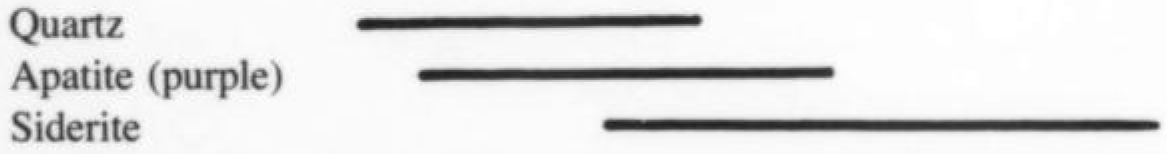


Figure 94. **Area A, locality 13, gorceixite assemblage.**

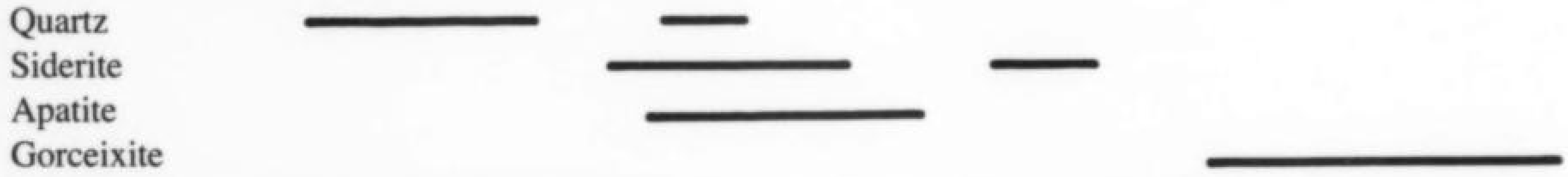


Figure 95. **Area B, locality 9, gormanite assemblage.**

Figure 96. **Area B, locality 10, kulanite/gormanite assemblage.**

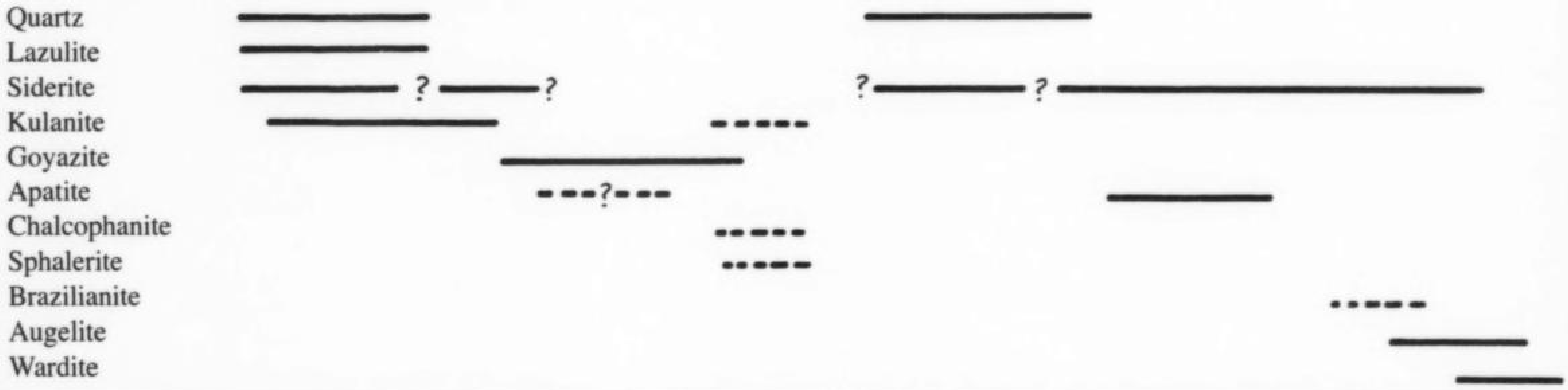


Figure 97. **Area B, locality 11, collinsite assemblage.**

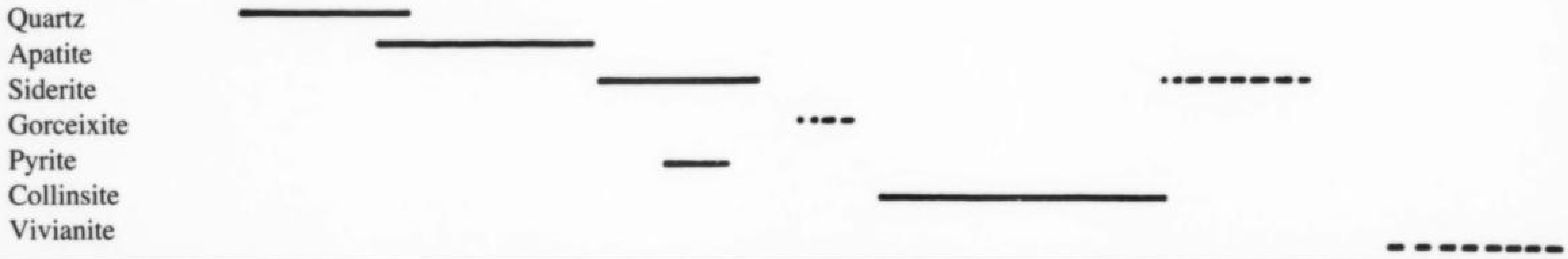


Figure 98. **Area B, locality 12, wardite assemblage.**

Figure 99. **Area B, locality 14, brazilianite assemblage.**

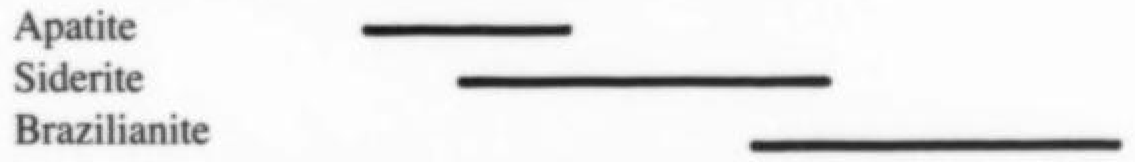
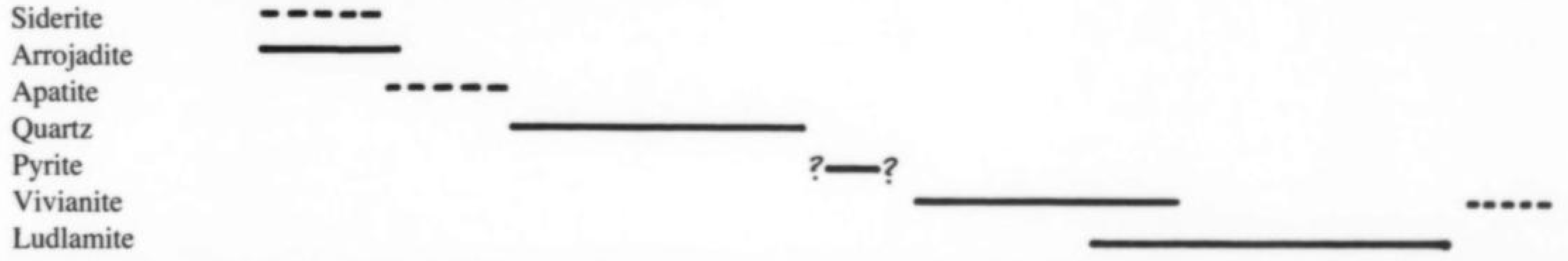


Figure 100. **Area C, locality 15, vivianite/ludlamite assemblage.**



appearing at the bottom. The horizontal bars indicate the relative importance and duration of crystallization for each species by their relative size and positions. Dashed lines have been used to indicate when a given species is not an abundant constituent of a particular assemblage, and question marks indicate uncertainty as to its placement in the crystallization sequence. Usually such species were observed on only one or two specimens, precluding more certain placement within the overall sequence. For the sake of brevity, many solid-solution series minerals, such as gormanite-souzalite, childrenite-eosphorite, vivianite-barićite, etc., have been entered simply as gormanite, childrenite or vivianite, respectively, but it should be understood that the series is implied. Similarly, species such as metavivianite and kryzhanovskite that may have initially crystallized as vivianite and phosphoferrite, respectively, and were later oxidized to their present state, have been referred to simply as vivianite or kryzhanovskite in the paragenesis diagrams. Exactly when the oxidation required to form these minerals occurred is not known, but it likely took place at the same time, and therefore after the crystallization of vivianite.

Most of the diagrams are self-explanatory, and indicate a single episode of mineralization with little to no recurrence of species within a given sequence. One notable exception, however, is the diagram for locality 10 in area B. The apparent recurrence of quartz, siderite, kulanite and apatite along with the anomalous presence of sphalerite and chalcopyrite may be indicative of two phases of mineralization. Also worthy of mention is the apparent lack of quartz and lazulite at both of the major wardite localities (7-A and 12-B). Whether this is merely a consequence of a localized relative absence of available silica, iron and magnesium at the time of crystallization, or due to a lower initial temperature at the start of crystallization, or both, remains uncertain. Much of what little lazulite there is at locality 7-A appears to be etched, especially when directly associated with the wardite. Whether or not this is due to hydrothermal attack by a fluid enriched in sodium at the time of wardite crystallization, and thus analogous to the pegmatitic sequence previously described, is unclear.

Figure 101 groups the predominant fracture-filling minerals into various categories based on their probable relative temperatures of crystallization as implied by compiling all the individual paragenetic diagrams. Such a categorization is admittedly arbitrary, and some minerals such as quartz, apatite, siderite and perhaps many of the individual phosphate species themselves have stability fields with enough overlap to arguably justify their placement in adjacent categories as well. Nevertheless, if we bear in mind the validity of the *relative* sequence that is established through paragenetic studies, much can be learned about specific events, even if their specific causes cannot be established. By simply looking at what elements are present in the individual minerals within each group we can infer what cations and anions were present throughout the sequence of crystallization, relative changes in their concentrations and possible changes in pH and oxidation potential, pressure and temperature.

Ferrous iron is present in the minerals of every stage throughout the entire paragenetic sequence. This indicates that relatively nonoxidizing conditions were prevalent for the duration of mineralization in the quartz-phosphate veins. Although very sparsely distributed, the occasional presence of pyrite further suggests a reducing environment in which both the oxygen fugacity and chemical potential or quantity of sulfur were very low. The removal of siderite fairly early in the sequence is also significant, for it suggests that carbonate anion species present in the mineralizing solution were also removed early in the sequence, since no other carbonates (except weathering products) appear in the veins. Some of the dissolved carbonate may also have been released as CO_2 due to a drop in pressure, or it may simply have all been consumed by the precipitating siderite, which may also have buffered the solution to a neutral or slightly basic pH (Garrels and Christ, 1965).

The crystallization of quartz early in the sequence effectively removed all the available silica from the system, as no later-formed low-temperature silicates such as clays or chlorites are found in the quartz-phosphate veins despite the persistence of ample iron, magnesium and aluminum throughout the entire episode of mineralization. Whether there were two immiscible liquids present early in the paragenesis, one silica-rich, the other phosphate-rich is not known, but seems unlikely, as no fluid inclusions have been observed in either the quartz or lazulite with the other species present as daughter crystals or with significantly different freezing point depressions or liquid-vapor ratios. More likely, there existed only one original fluid that simply became saturated with respect to silica due to decreasing temperature.

The crystallization of quartz and siderite from the solution removed two major anions, SiO_4^{-4} and CO_3^{-2}, from the system, which caused a relative increase in the activity of both H_3O^+ and $(OH)^-$, making them a more important part of the processes which were to follow. A quick scan of Figure 101 from left to right shows groups of minerals with increasing amounts of water. This is not surprising, as ligand water becomes increasingly stable with decreasing temperature. Moore (1973) shows a similar trend for pegmatitic phosphates (Fig. 102), and estimates the temperature above which water molecules would

HIGH		INTERMEDIATE		LOW
QUARTZ	SIDERITE	BRAZILIANITE	KRYZHANOVSKITE	COLLINSITE
LAZULITE	APATITE	GORMANITE	WARDITE	GORCEIXITE
ARROJADITE	GOYAZITE	WHITEITE	CHILDRENITE	MESSELITE
KULANITE		AUGELITE		LUDLAMITE
				VIVIANITE

***Figure 101.* Relative temperatures of crystallization for the principal minerals in the Yukon assemblages.**

not be stably bound as ligands to transition-metal cations to be in the vicinity of 200° C.

Other cations such as Na^{+}, Ca^{+2}, Mg^{+2}, Mn^{+2}, Ba^{+2} and Sr^{+2} were present in lesser amounts, and appear fairly evenly distributed between the various accessory minerals throughout the entire duration of crystallization. This is probably a result of local abundances of these elements being supplied to the mineralizing solutions from the host rocks through which they passed. Robertson (1980) has shown the lateral variation in composition of a given bed is greater than any measurable change induced by preferential leaching of elements that may have occurred during the formation of phosphate-bearing veins cutting that bed.

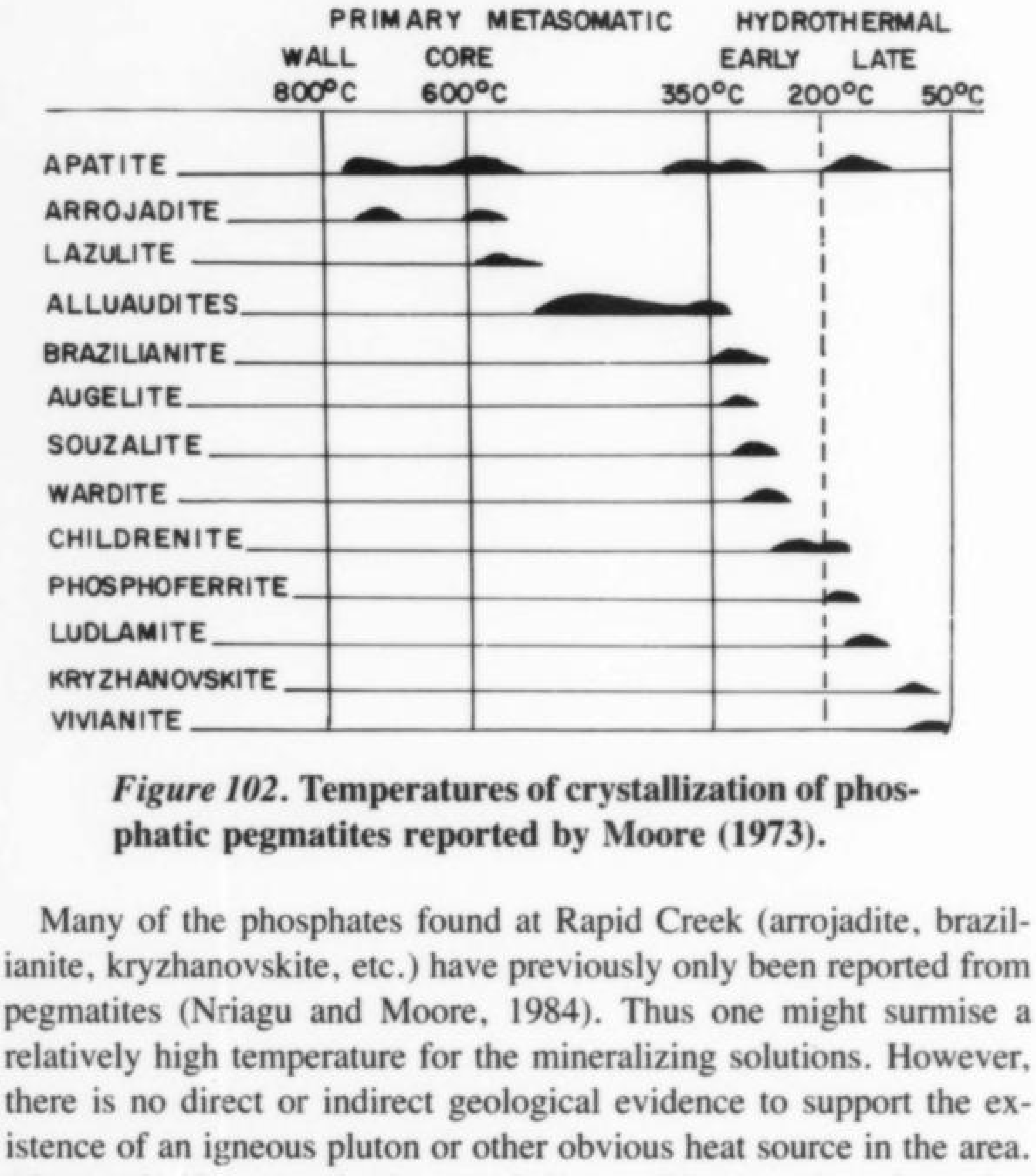


***Figure 102.* Temperatures of crystallization of phosphatic pegmatites reported by Moore (1973).**

Many of the phosphates found at Rapid Creek (arrojadite, brazilianite, kryzhanovskite, etc.) have previously only been reported from pegmatites (Nriagu and Moore, 1984). Thus one might surmise a relatively high temperature for the mineralizing solutions. However, there is no direct or indirect geological evidence to support the existence of an igneous pluton or other obvious heat source in the area. Alternately, because the host rock is a sedimentary iron formation with marine phosphorites and shales, it is equally easy to surmise a very low-temperature origin for the veins.

In order to help resolve this dilemma, a fluid inclusion study of the fracture-filling minerals has been started by one of us (GWR), and some of the preliminary findings are reported here. Since it has been demonstrated that quartz and lazulite were the first minerals to crystallize, it follows that their inclusions should yield homogenization temperatures indicative of the peak temperature of formation for the quartz-phosphate veins. Thus far only about a dozen samples have been examined for fluid inclusions, and these are mostly quartz-lazulite specimens from locality 1, Area A. Consequently it is unknown at this time whether the information presented here is truly representative of the entire deposit or peculiar to the veins sampled at locality 1-A. More samples including additional species from a large number of different veins throughout the formation will have to be studied before more definite conclusions can be drawn.

The lazulite and quartz from locality 1, Area A. contain both primary and secondary fluid inclusions. Obvious secondary inclusions confined to fracture planes were not studied, since, by definition, they were introduced after the crystal had formed, and would therefore not likely contain the original fluid from which the crystal grew. Only primary inclusions are trapped during crystal growth, and thus contain fluids indicative of the mineralizing solutions. In practice, however, it is often difficult, if not impossible, to differentiate primary from secondary inclusions. For the preliminary data reported here, only larger, more isolated inclusions that were not on fracture planes, had not shown evidence of necking, had consistent liquid-to-vapor ratios, and could (in the ideal instance) be related to a growth feature in the crystal were considered as primary and used for the heating-freezing runs.

Before commencing the heating-freezing runs, several of the sections were examined in ultraviolet light to determine the presence of any aromatic hydrocarbons, which commonly fluoresce in ultraviolet light. None was found to be present. The inclusions were then frozen to approximately −196° C and slowly warmed until all solid phases had melted. No carbon dioxide, hydrogen sulfide, sulfur dioxide or methane was detected. In this way it was determined that the fluid consists of water with a measured freezing point depression of −1.3 to −1.4° C, which corresponds to an NaCl equivalent salinity of approximately 2.3 weight %. This indicates the mineralizing solutions were neither basinal brines nor pegmatitic fluids, because both these kinds of solutions are characterized by much higher salinities. The inclusion was then heated until it homogenized. The observed homogenization temperatures ranged from 180° to 200° C.

The homogenization temperature is generally not the same as the temperature of entrapment (i.e., the temperature at the time the crystal formed), and must be corrected for the effects of pressure. The homogenization temperature does, however, establish the *minimum* temperature at which the crystal could have formed. In order to correct for pressure, we must have an independent means of determining the pressure at the time of crystallization. This is normally derived from known P-T conditions for equilibrium assemblages of indicator minerals, from thermodynamic data based on various mineral geobarometers, or from estimates of thickness of overlying strata. The maximum thickness of the Upper Cretaceous and Tertiary sediments overlying the Rapid Creek formation have been estimated at approximately 2,300 meters (Young, 1975). However, the absolute age of the quartz-phosphate veins is not known and it is therefore uncertain if a pressure correction based solely on overlying strata is valid. Except for minor amounts of illite and chlorite reported in some of the shales (Robertson, 1980; A. Ingelson, personal communication, 1988), there are no common metamorphic indicator minerals such as lawsonite, laumontite or pyrophyllite present. A study of the crystallinity of the illite (Winkler, 1979) might provide additional information, but has not been undertaken. Thus, we can only assume that the P-T conditions in effect at the time the veins were formed probably lie within the range of that uncertain boundary that separates diagenesis from very-low-grade metamorphism.

In the absence of more definite information, any pressure correction applied to the observed homogenization temperature would be merely a guess, and therefore we can only conclude the *minimum* temperature of formation for the veins must have been in the range of 180° to 200° C. This is significantly higher than the 50° to 96° C temperature range reported by Robertson (1982). Those values were derived from preliminary oxygen isotope investigations and an estimated geothermal gradient based on 2,300 meters of overlying sediments, respectively.

The paragenesis of the phosphate nodules is perhaps less well understood, as comparatively less work has been done in that regard. Sturman *et al.* (1981) conclude that satterlyite, wolfeite, maricite and wicksite formed contemporaneously, although the wicksite usually occurs interstitial to the other species. The presence of associated quartz and pyrite was also noted, and ludlamite and vivianite were observed coating all the other minerals. Mandarino *et al.* (1978) note that satterlyite is in direct contact with pyrite, quartz, wolfeite and maricite, but make no mention of the paragenetic sequence. Similarly, Sturman *et al.* 1977) observed that in thin sections, maricite is in direct contact with quartz, ludlamite, vivianite, pyrite, wolfeite, apatite and an alluaudite group mineral, and that ludlamite, quartz and vivianite also occur along fractures and as inclusions in the maricite.

Based on a petrographic study, Robertson (1980, 1982) concludes that the paragenesis of the nodules is complex and suggests the following general sequence: satterlyite, wolfeite, maricite, alluaudite group, arrojadite, ludlamite, vivianite-baricite, metavivianite and goethite. The position of apatite could not be determined. He also notes that some of the phosphates appear to be replaced by pyrite, quartz or siderite, and that the pyrite nodules near the base of the Rapid Creek Formation in Area C, may actually be replaced phosphate nodules.

A detailed paragenetic study of the phosphate nodules has not been attempted by the authors; and while we cannot confirm the *specific* sequence suggested by Robertson, the *overall relative* positions seem to be accurate. Similarly, the paragenesis of the species derived by weathering has not been studied by the authors.

SUMMARY

In little more than a decade, the Rapid Creek and Big Fish River area has achieved world prominence as an important locality for phosphate minerals. A unique geological environment has produced a unique suite of minerals, several of which were previously unknown to science. Much of the area remains relatively untouched by collectors, and should continue to produce fine collector-quality specimens and perhaps even more new species if prospected in a careful, diligent manner in the future.

The sequence of crystallization of the phosphate species in the quartz-phosphate veins is similar to that reported for granite pegmatites, although the geological occurrence is grossly different. Contrary to earlier reports, the temperature of formation of these veins must have been at least 180–200° C, based on direct evidence from fluid inclusions. All the essential constituents required to form the minerals observed in the veins are present in the host rocks, and were probably derived from them. The fracture-filling minerals most likely formed during or after the Laramide Orogeny, which tilted and fractured the host rock, creating open spaces for a fluid phase to enter and precipitate the observed mineral assemblages. The pressure and temperature conditions prevalent during this event were probably in the uppermost range of diagenesis to the lowermost range of regional metamorphism. In fact, species such as satterlyite, gormanite-souzalite, and arrojadite which are found as rock-forming minerals in some of the units described by Robertson (1980) may themselves be metamorphic indicator minerals that are a natural consequence of very-low-grade regional metamorphism of a phosphatic ironstone. Our present-day knowledge concerning the stability fields of such minerals is severely limited, as almost no thermodynamic data or bases for comparison to similar deposits exist.

Detailed mapping of local structures and vein systems along with petrologic studies and whole-rock geochemical studies are in progress. However, the exact P-T-X constraints operative at the time of mineralization and the paragenetic relationship between the nodules and fracture-fillings remains unclear. More research combining petrologic, fluid inclusion and paragenetic studies of both the fracture-filling and nodule minerals will undoubtedly need to be done before we can hope to understand the processes that led to the formation of these unique and beautiful minerals.

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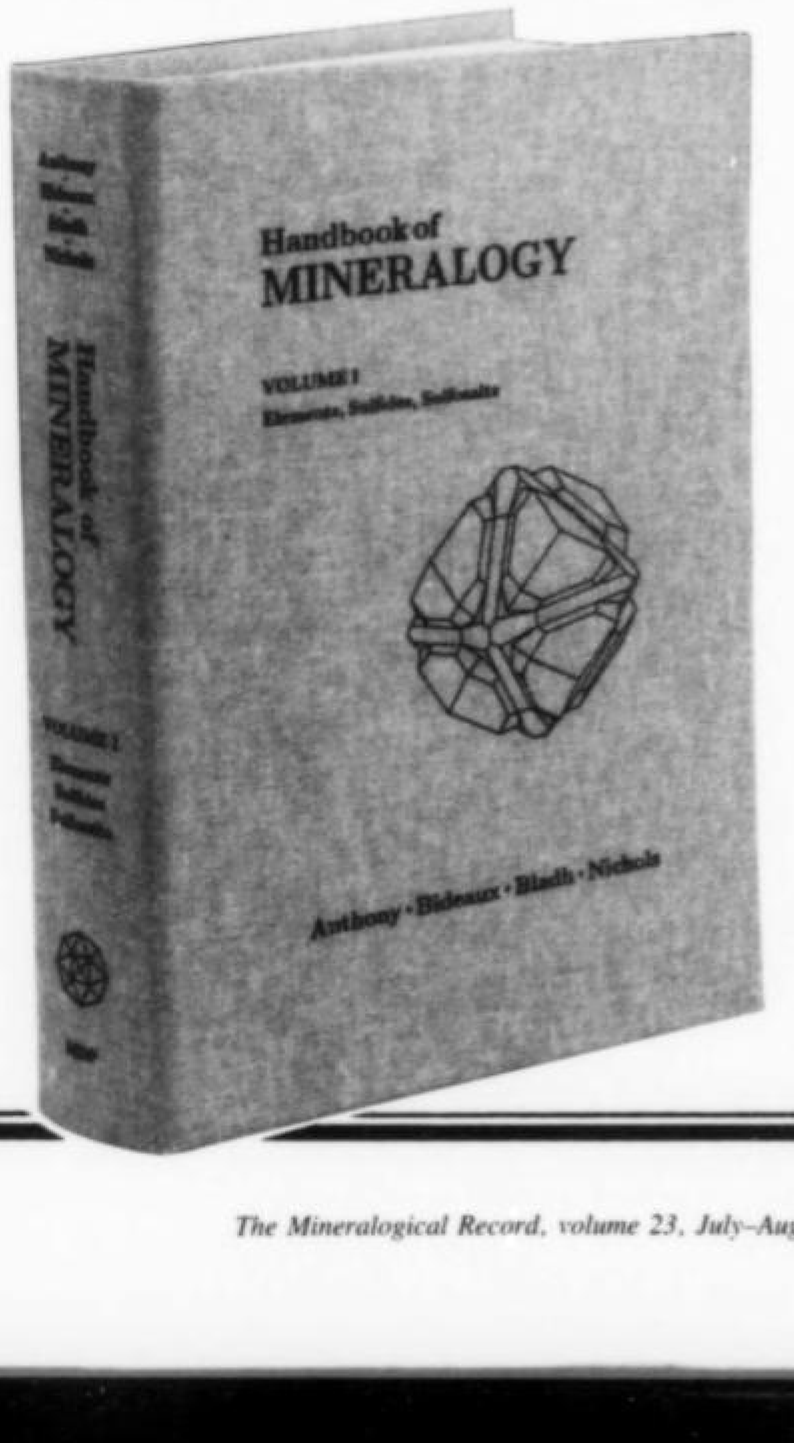
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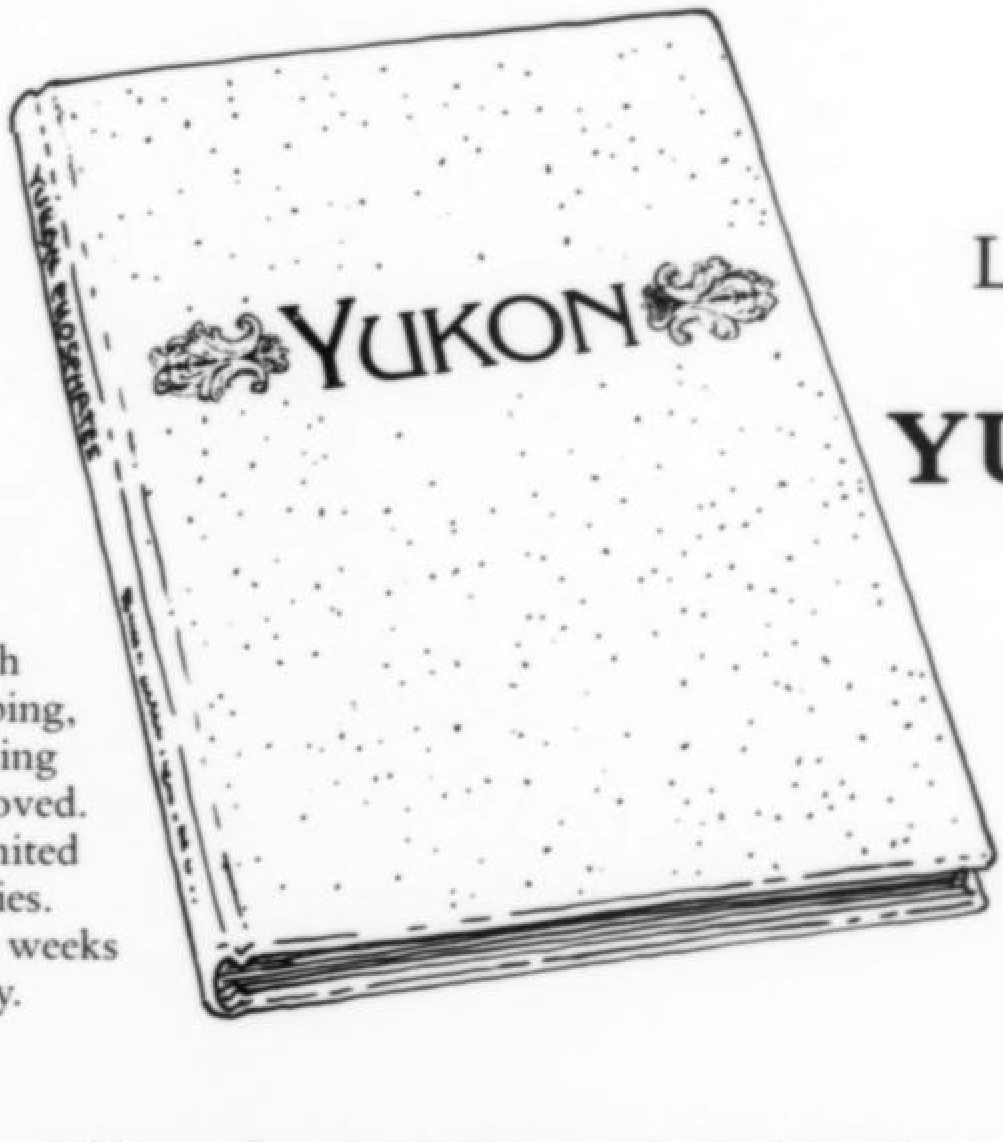

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Tel: (406) 496-4414
c/o Montana Tech
Butte, MT 59701-9981
Hours: 8–5 daily June–Labor Day;
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Specialties: Montana &
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Curator (mineralogy):
Michael S. Evick
Tel: (403) 264-8300
Glenbow Alberta Institute
130 Ninth Avenue S.E.
Calgary, Alberta
Canada T2G 0P3
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Specialties: W. Canadian and
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Harvard Mineralogical Museum

Curators:
Dr. Carl A. Francis
William Metropolis
Tel: (617) 495-4758
24 Oxford Street
Cambridge, Mass. 02138
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Specialties: Systematic
Mineral Collection

William Weinman Mineral Museum

Curator:
Kim B. Cochran
Tel: (404) 386-0576
P.O. Box 1255
Cartersville, GA 30120
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Curator:
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Tel: (418) 656-2193
Geology Dept., 4th floor
Adrien-Pouliot Building
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Curators:
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Specialty: New Mexico minerals

M.Y. Williams Geological Museum
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Specialty: Midwest minerals

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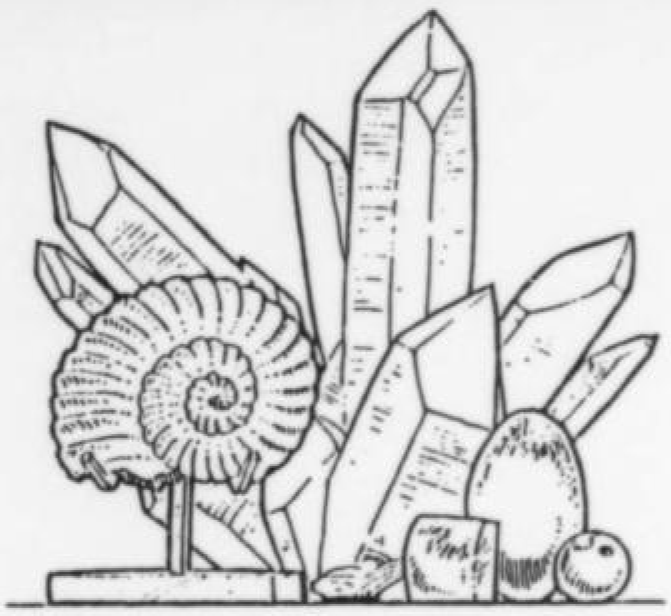

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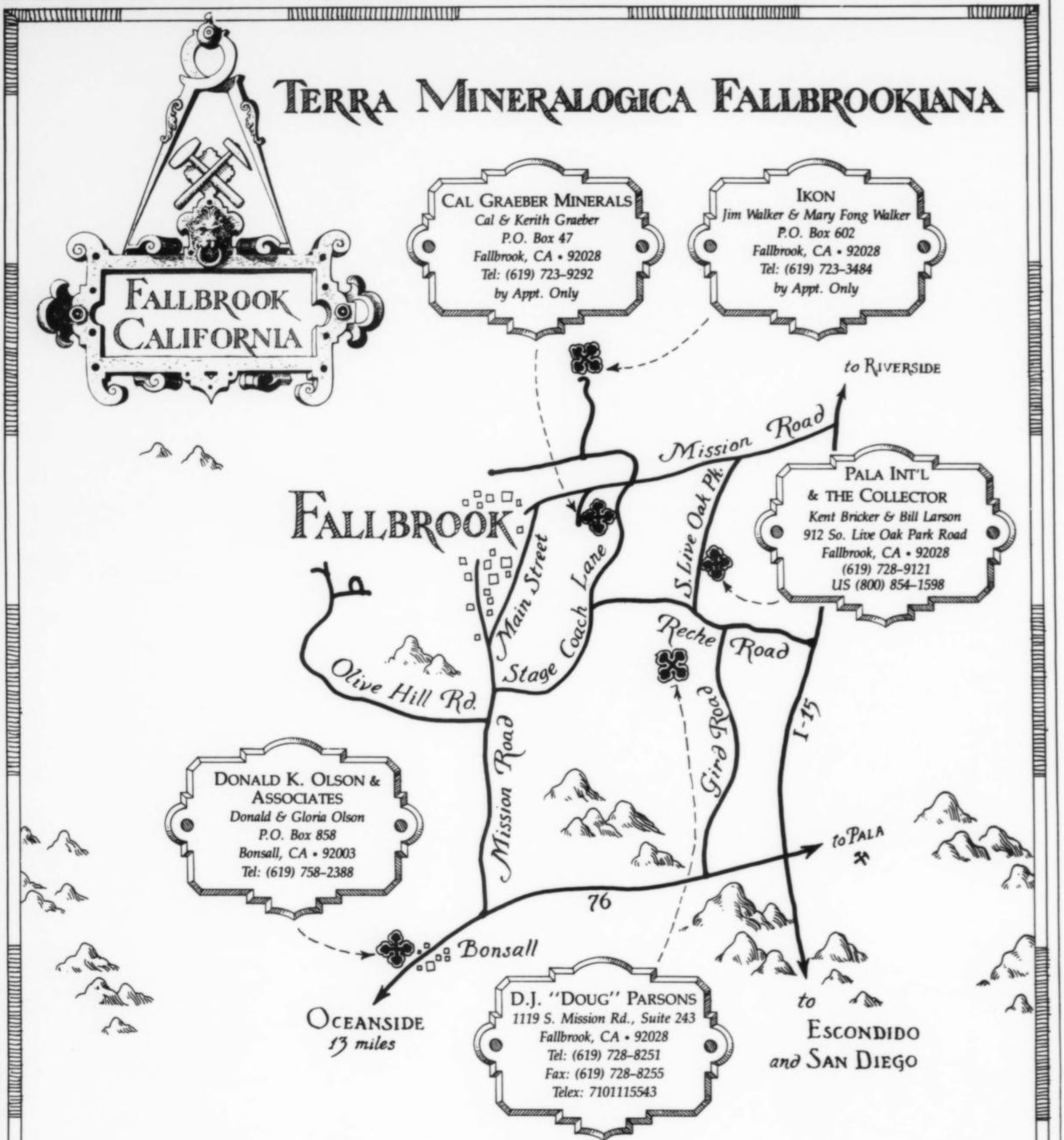
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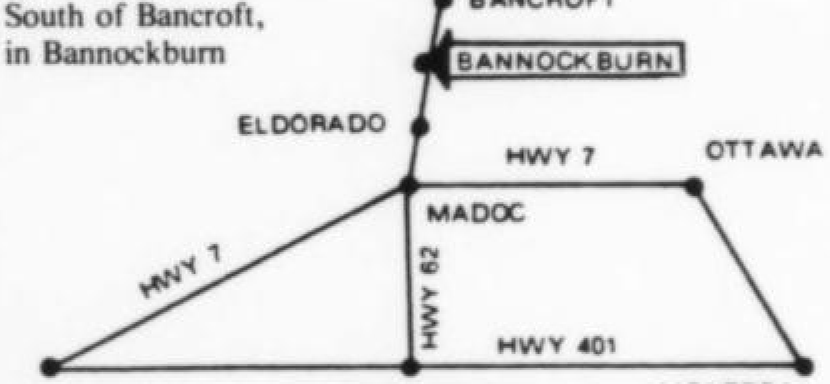
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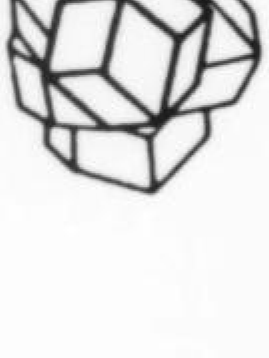

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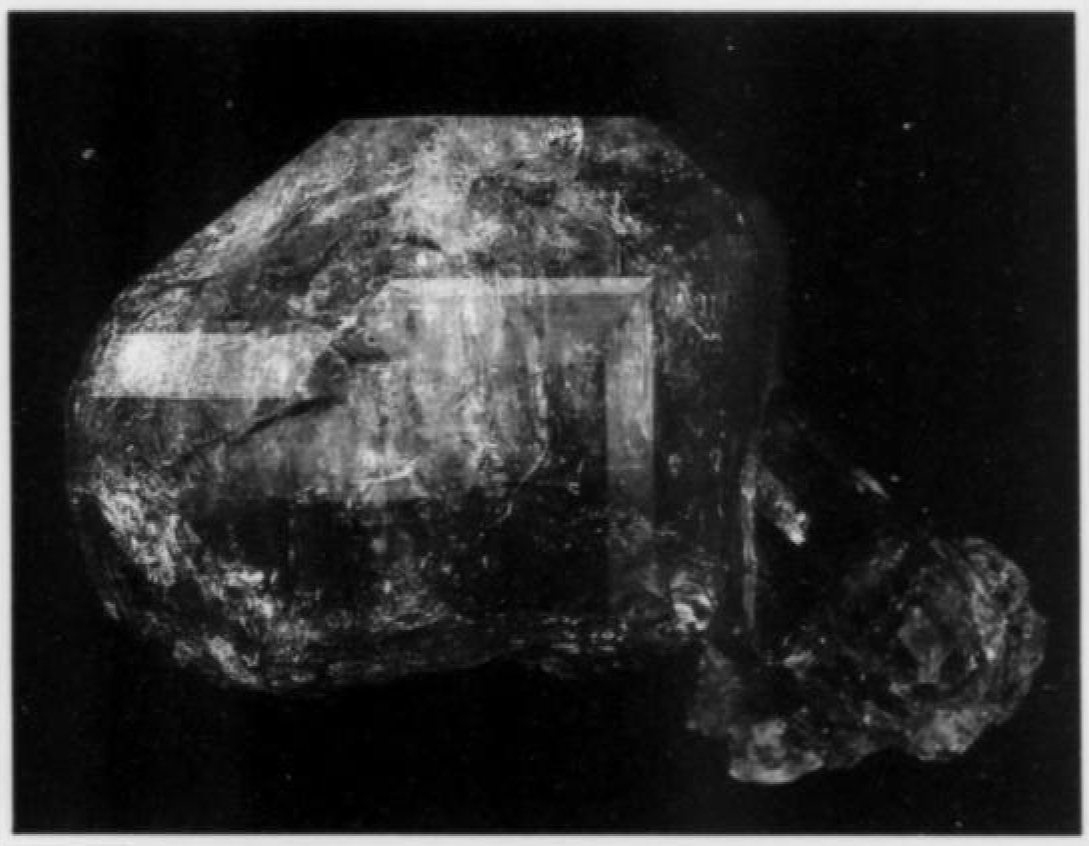

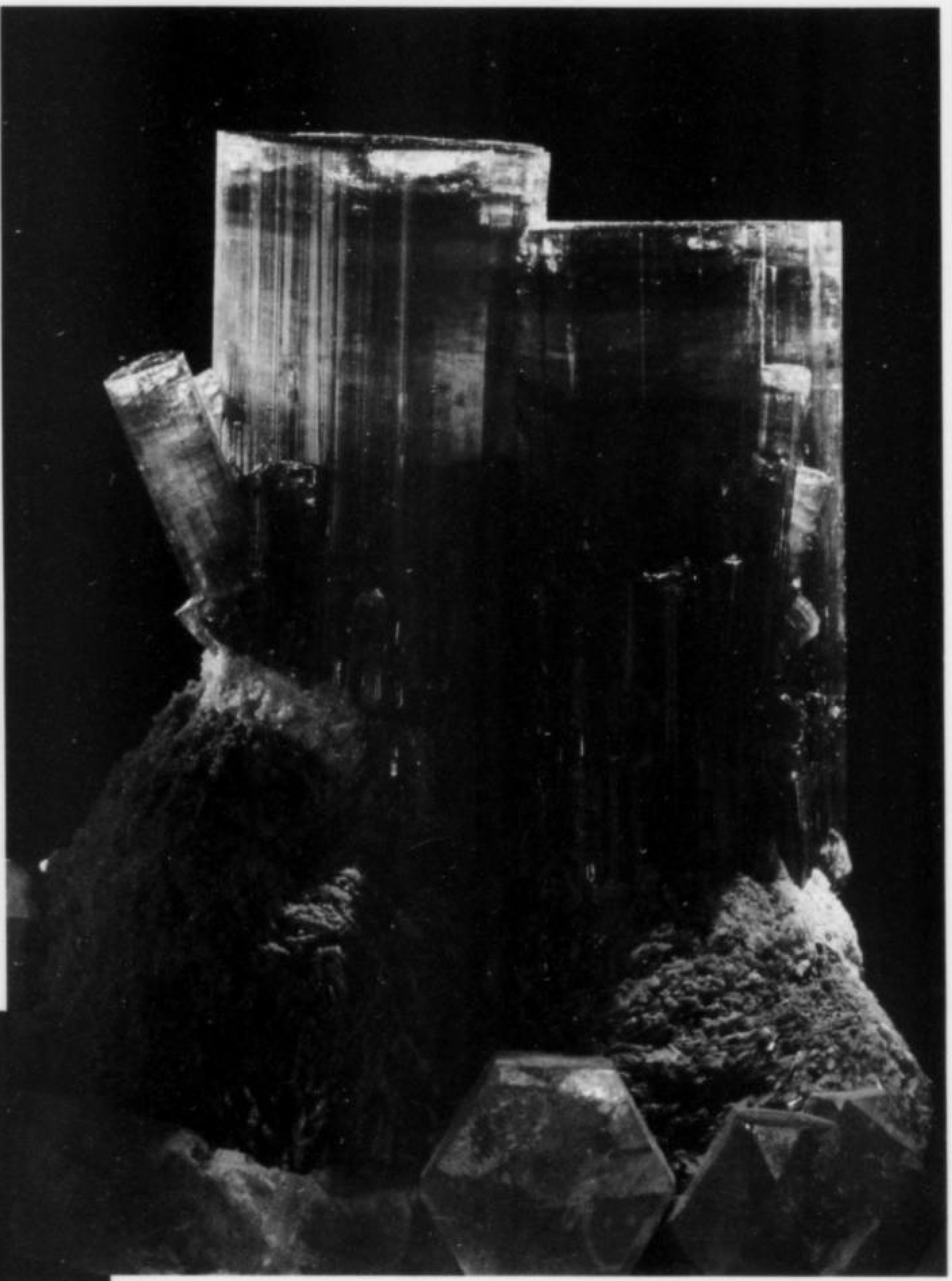

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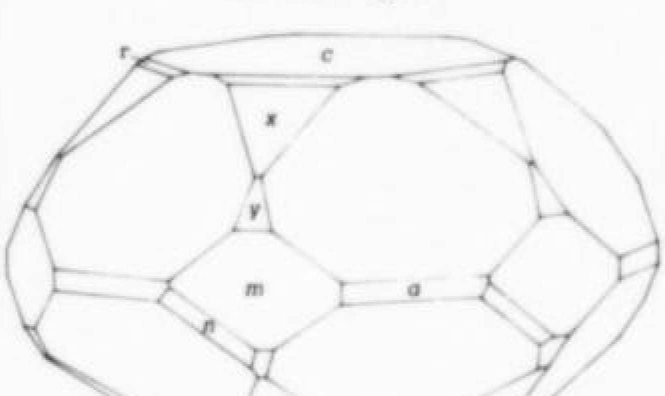

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If you wish to present a paper, please write or call **(immediately)** Dr. Karen Wenrich, Chairperson (USGS, Mail Stop 939, Federal Center, Denver, CO 80225; 303-236-1563) with your topic, a few sentences describing the paper, and your address and phone number. Presentations will be 15 or 20 minutes in length followed by a period for questions. Upon acceptance of topics all authors will be required to submit a 200–300 word abstract by September 30, 1992 **(firm date)**. Those abstracts deemed to be scientifically sound and substantive by the editor of the *Mineralogical Record* will be published in the January–February issue, which will be available for sale at the 39th Tucson Gem and Mineral Show.

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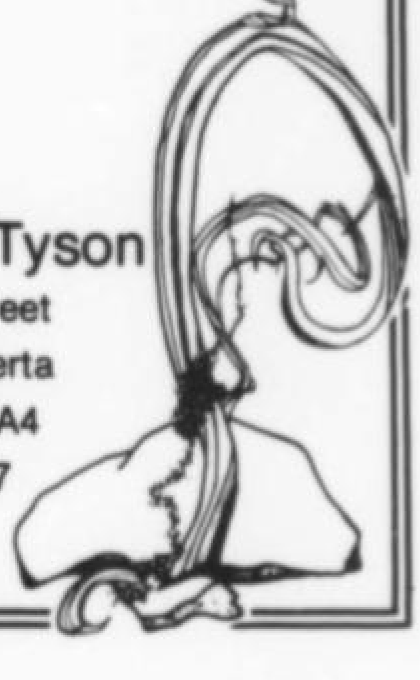

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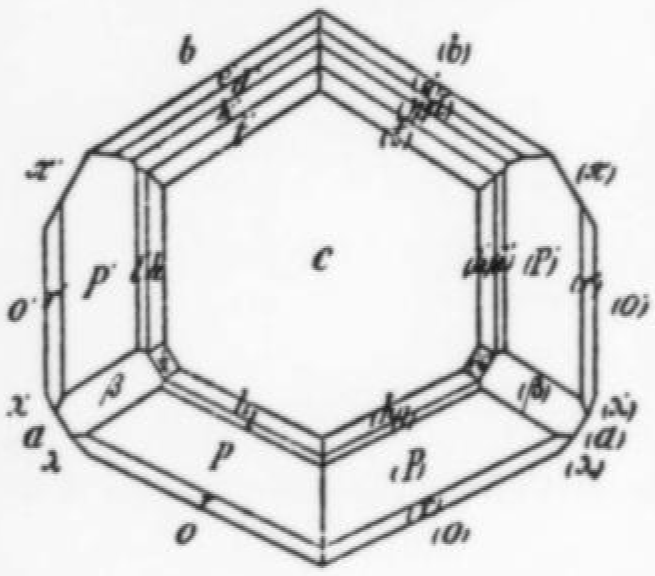

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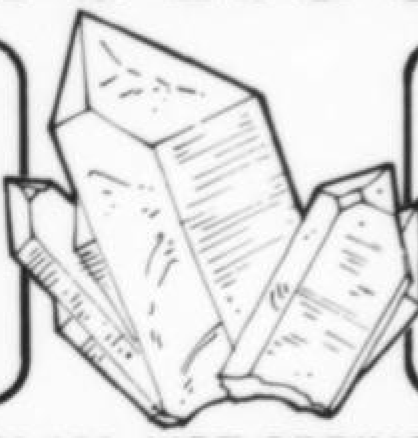

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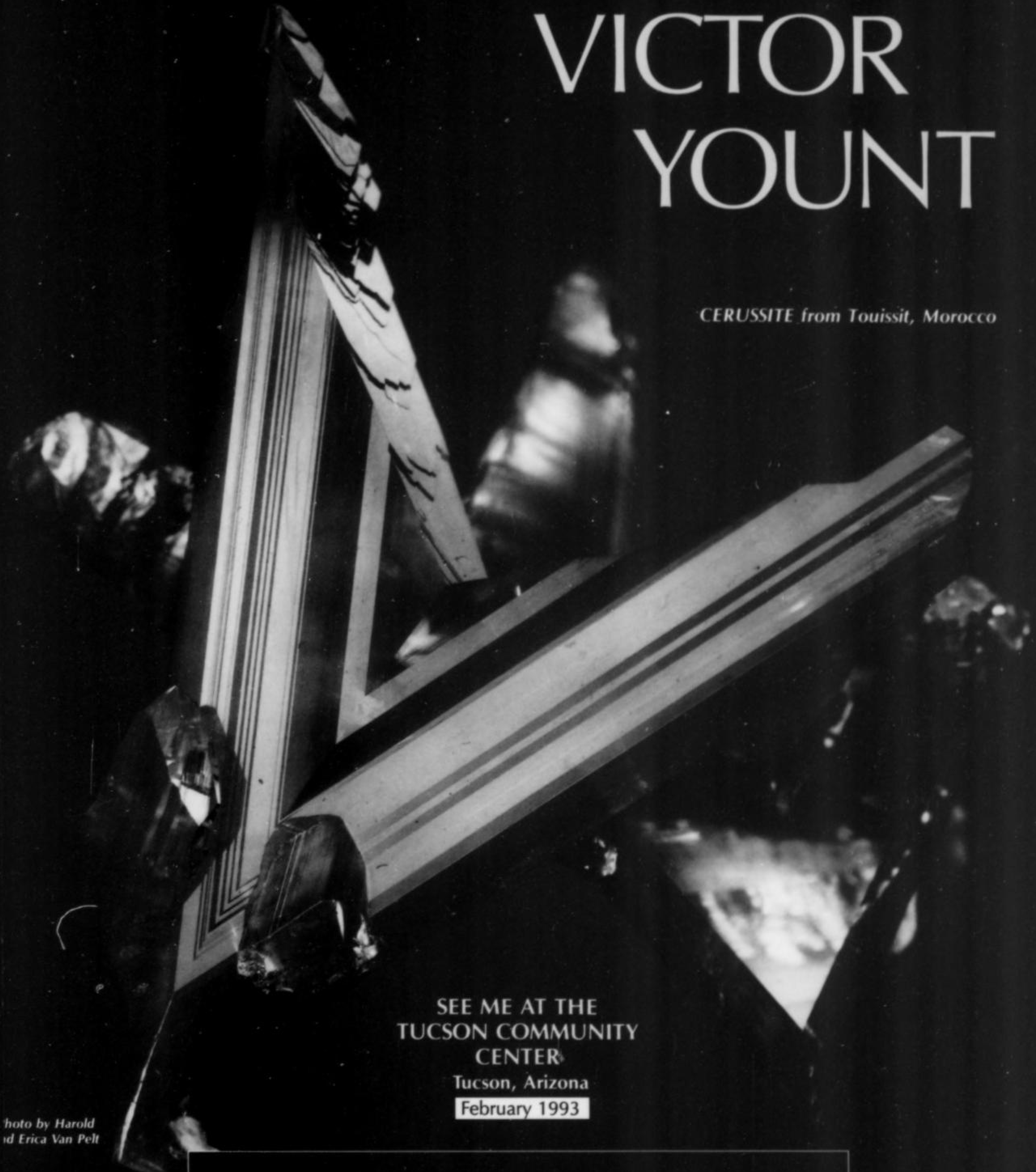

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