# Trip A-6

## CORDIERITE-BEARING GNEISSES IN THE WEST-CENTRAL ADIRONDACK HIGHLANDS

**Frank P. Florence**
Science Division, Jefferson Community College, Watertown, NY, USA 13601
fflorence@sunyjefferson.edu

**Robert S. Darling**
Department of Geology, SUNY College at Cortland, Cortland, NY, USA 13045

**Phillip R. Whitney**
New York State Geological Survey (ret.), New York State Museum, Albany, NY, USA 12230

**Gregory W. Lester**
Department of Geological Sciences and Geological Engineering, Queen's University, Kingston, Ontario, CANADA K7L 3N6

### INTRODUCTION

Cordierite-bearing gneiss is uncommon in the Adirondack Highlands. To date, it is has been described from three locations, one near the village of Inlet (Seal, 1986; Whitney et al, 2002) and two along the Moose River further to the west (Darling et al, 2004). All of these cordierite occurrences are located in the west-central Adirondacks, a region characterized by somewhat lower metamorphic pressures as compared to the rest of the Adirondack Highlands (Florence et al, 1995; Darling et al, 2004).

In the Fulton Chain of Lakes area of the west-central Adirondack Highlands, a heterogeneous unit of metasedimentary rocks, including cordierite-bearing gneisses, forms the core of a major NE to ENE trending synform. Cordierite appears in an assortment of mineral assemblages, including one containing the uncommon borosilicate, prismatine, the boron-rich end-member of kornerupine (Grew et al., 1996). The assemblage cordierite + orthopyroxene is also present, the first recognized occurrence of this mineral pair in the Adirondack Highlands (Darling et al, 2004).

This field trip includes stops at four outcrops containing cordierite in mineral assemblages that are characteristic of granulite facies metamorphism in aluminous rocks. Stops 1, 3 and 4 are from those previous described (Seal, 1986; Whitney et al, 2002; Darling et al, 2004) whereas Stop 2 is described here for the first time. Our intention is to consider the different parageneses in cordierite gneisses, and to consider the metamorphic pressure-temperature controls, as well as compositional controls, on the formation of these assemblages. We will also discuss the utility of these low variance assemblages for characterizing the pressure-temperature path of metamorphism (as well as formation conditions for prismatine) and the implications of their moderate pressure conditions of metamorphism for our understanding of the geologic history of this portion of the Adirondacks.

## STRUCTURAL SETTING

The Fulton Lakes Synform is a major structure that extends from the small community of McKeever on the southwest to beyond Raquette Lake in the northeast (Whitney et al., 2002). The axial trend passes through the Fulton Chain Lakes, so that one travels approximately parallel to it while driving along Route 28. Various rock units, most of sedimentary origin, occur in overturned, southeast verging folds that are bounded to the northwest and southeast by charnockitic gneisses. Abundant rock units within this synform include quartzite, biotite-quartz-plagioclase gneiss, and calcsilicate rocks. Also present, but less abundant, are Mg-rich gneisses, amphibolites, biotite-sillimanite schist, and calcite marble. Tight-to-isoclinal folding of these units has pervasively deformed compositional layers. Foliation parallels compositional layering. Centimeter scale gneissic layering is common, as are fine scale laminations in quartzite and ubiquitous, prominent mineral lineations.

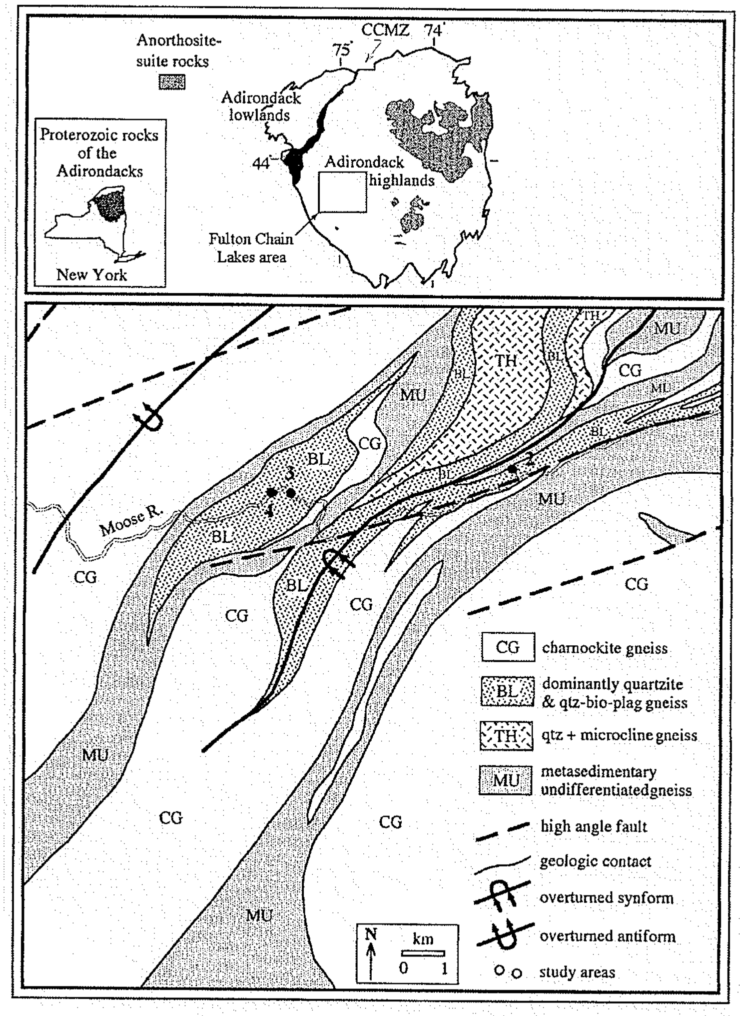


Figure 1. Location map showing the area of the field trip. Geologic map shows the map units, and structures from Whitney et al. (2002) and the last three field trip stops. Stop 1 is to the northeast near the village of Inlet. Its location is described in the road log.

## LITHOLOGIES

The following are general features of the rocks we will visit on this trip.

*Quartzites*: Outcrops of quartzite are some of the most readily recognized metasedimentary lithologies of the Fulton Lakes Synform. They occur throughout the synform, often interlayered with calcsilicate rocks (e.g., Stop 1) and in the vicinity of the Moose River, adjacent to the Mg- and B-rich gneiss containing prismatine (Stops 3 and 4.) Layers vary in thickness from centimeters to tens of meters. Green diopside is a common accessory mineral, especially in calcsilicate layers within the quartzites. Other associated phases include pale needles of tremolite, phlogopite, and tourmaline. Whitney et al. (2002) report the presence of scarce wollastonite in the quartzite in the vicinity of the Moose River.

*Metapelites*: Medium- to coarse-grained biotite-quartz-plagioclase gneisses are found throughout the area, commonly interlayered with quartzites. Garnet and sillimanite are common accessory minerals in these rocks and are sometimes locally abundant. Alkali feldspar, typically, perthitic, may also be present. Anatectic leucosomes are found in these rocks, both parallel to and cross-cutting foliation. Presumably, these formed through fluid-absent melting involving biotite breakdown, as reported for similar rocks in the Port Leyden area, on the western edge of the Adirondacks (Florence et al., 1995.)

*Calcsilicates*: Fine grained, generally equigranular calcareous rocks are abundant throughout the synform and occur both as thick outcrops and as thin layers within the quartzites. These rocks contain abundant diopside, and often include quartz, tremolite, phlogopite, and titanite. Calcsilicates throughout the synform also contain variable amounts of andradite garnet, epidote, scapolite, enstatite, biotite, pyrite, pyrrhotite, and graphite. Layers of calcite marble are less common, but are observed associated with the calcsilicates in the vicinity of the Fulton Lakes Synform.

*Mg-rich gneisses*: Outcrops and layers of dark, Mg-rich gneiss are scattered throughout the synform, either as layers within quartzite units or in close proximity to quartzite. Stop 1 contains distinctive layers within quartzite that contain garnet, cordierite, sillimanite, biotite, and quartz (Seal, 1986). Different horizons within the biotite-quartz-plagioclase gneisses seen at Stops 3 and 4 contain the following assemblages: (1) cordierite, garnet, sillimanite, and spinel; (2) cordierite, orthopyroxene, and biotite, (3) cordierite, garnet, sillimanite, microcline, prismatine, and tourmaline; and (4) garnet, orthopyroxene, and microcline. The presence of prismatine ± tourmaline in assemblage (3) attests to abundant boron, in addition to magnesium, and Whitney et al. (2002) suggest that these rocks may have been metamorphosed from evaporite protoliths.

## SUMMARY OF CORDIERITE-BEARING ASSEMBLAGES

Individual assemblages are discussed in the Road Log, but the following list compares the different mineral association containing cordierite.

Cordierite + Garnet + Sillimanite + Biotite + Quartz + Plagioclase (Stop 1).

Cordierite + Biotite + K-feldspar + Plagioclase ± Quartz ± Magnetite ± Garnet (Stop 2)

Cordierite + Garnet + K-Feldspar + Plagioclase + Quartz + Prismatine ± Biotite ± Sillimanite (Stops 3, 4)

Cordierite + Garnet + Sillimanite ± Spinel + Biotite + Quartz + Plagioclase (Stops 3, 4)

Cordierite + Orthopyroxene + Biotite + K-feldspar + Quartz (Stops 4)

## CONDITIONS OF METAMORPHISM

The presence of low-variance assemblages and a variety of mineral equilibria provide the means to determine the conditions of metamorphism for these rocks. Darling et al. (2004) applied a combination of net transfer and mineral exchange equilibria, along with constraints from petrogenetic grids, to the assemblages along the Moose River that are associated with the prismatine-bearing gneiss. While these results pertain specifically to the outcrops along the Moose River, and the conditions of prismatine formation, we suggest here that they are reasonable indicators for the metamorphic conditions that were experienced throughout the western portion of the synform.

The results for Fe-Mg exchange thermobarometry (Harley, 1984), in garnet-orthopyroxene gneiss, Al solubility in orthopyroxene (Fitzsimmons and Harley, 1994) from the same gneiss, and application of the petrogenetic grids for the formation of orthopyroxene in pelitic gneisses (Vielzeuf and Holloway, 1988; Spear et al., 1999) demonstrate that conditions for the equilibration of garnet-orthopyroxene assemblages correspond to 850 ± 20 °C and 6.6 ± 0.6 kilobars (Darling et al., 2004). These P-T ranges appear to represent the highest preserved conditions of metamorphism. The absence of any evidence of sillimanite in combination with orthopyroxene in these rocks indicates that maximum P-T conditions of metamorphism did not rise above 860 °C and 8.5 kilobars. Figure 2 shows the results of these equilibria calculations and petrogenetic constrains.

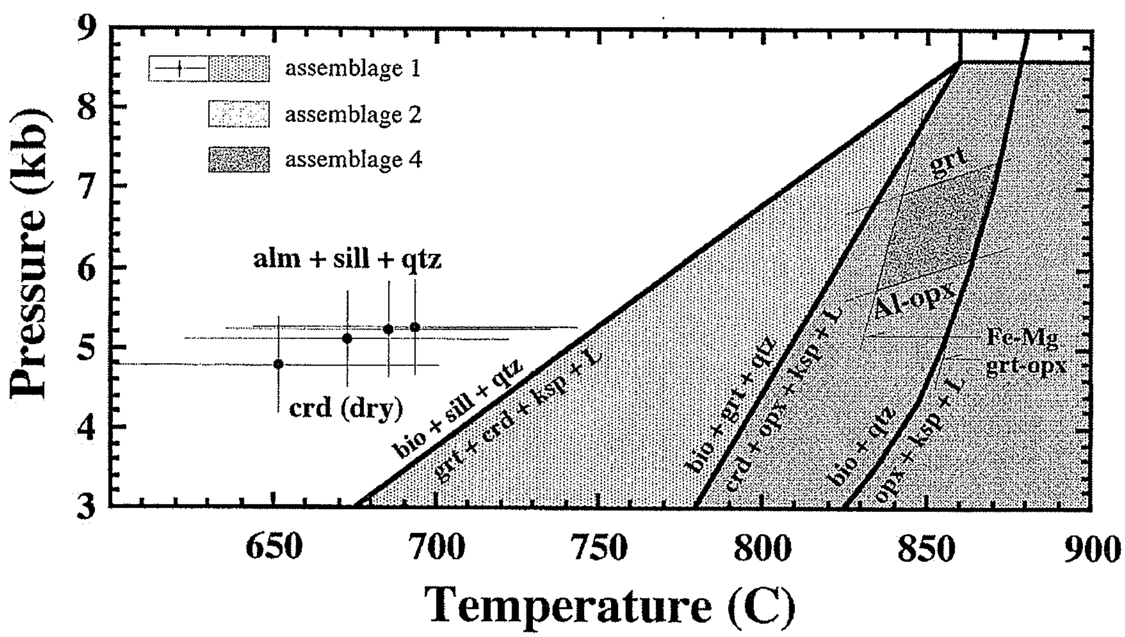


**Figure 2.** Pressure-temperature plot showing petrogenetic constraints, as well as results from net transfer and exchange reaction calculations based on mineral compositions found in assemblages along the Moose River. (From Darling et al., 2004)

Fe-Mg exchange equilibria and net transfer reactions for cordierite-garnet-sillimanite-quartz assemblages (Nichols et al., 1992) from the same outcrops as above reveal conditions of equilibration of 675 ± 50 °C and 5.0 ± 0.6 kilobars. These results are also plotted on Figure 1. Darling et al (2004) interpret the thermobarometry of the cordierite-bearing assemblage to indicate the effects of retrograde re-equilibration. They point out that the stability of the mineral assemblage in the cordierite gneiss is inconsistent with the thermobarometry results. Fe and Mg diffusivities in cordierite are not well known, but have been estimated to be orders of magnitude more rapid than garnet (Lasaga et al., 1977.) Even after temperatures decreased to the extent that retrograde exchange reactions in garnet were effectively stopped, cordierite and biotite are presumed to have continued Fe-Mg exchange. Support for this interpretation comes from the garnet-biotite $K_d$ values, which show Fe-enrichment in biotite.

It should be pointed out that the pressure estimates obtained from the net transfer reaction used to equilibrium conditions for the cordierite-garnet assemblages are very nearly independent of temperature. As a result, it is reasonable to assume that even as retrograde Fe-Mg exchange during cooling altered cordierite compositions, no large uncertainty was introduced to the estimates of pressure conditions. Consequently, we favor the interpretation that the cooling path experienced by these rocks followed a nearly isobaric trajectory. This interpretation conforms to the retrograde cooling paths for the Adirondack Highlands that have been proposed on the basis of other petrologic studies, including Bohlen (1987), Lamb et al. (1991), Spear and Markussen (1997), and McLelland et al (2001).

## DISCUSSION

Although generally rare throughout the Adirondack Highlands, cordierite is recognized in a variety of structurally related gneisses in the Fulton Chain of Lakes region. The bulk of the rocks in the Fulton Lakes Synform derived from sedimentary protolith suggesting that many, if not all, of the aluminous composition gneisses formed from pelitic or semipelitic deposits. At Stops 1, 3, and 4, the cordierite is found in distinctly Mg-rich layers that are associated with quartzites and calcsilicates. Whitney et al. (2002) have suggested that metamorphosed evaporite deposits are the likely protoliths for the calcsilicates in the area and argue on the basis of lithologic similarity that quartzites here can be compared to stromatolite-bearing quartzites in the Adirondack Lowlands. Mg- and B-enrichment, as seen in the prismatine-bearing layers, is consistent with the interpretation of evaporates at least locally present in the protolith. It is also possible that Mg-rich enrichment developed from dolomitization of layers within the original limestone. Cordierite seen at Stop 2 is found in pegmatitic, K-feldspar-, quartz-, and biotite-rich veins that appear to be the result of partial melting. Iron oxides and almandine garnets are also abundant in this exposure, indicating a bulk composition that is different from outcrops seen at the other stops.

It is clear that the cordierite gneisses reflect conditions of granulite facies metamorphism, but detailed analysis of the mineral assemblages suggests that cordierite had the role of either reactant or product in different melt-forming reactions as these gneisses reached conditions favorable for anatexis. In the assemblage cordierite + spinel + sillimanite + garnet, cordierite contains lenses of sillimanite needles and anhedral spinel grains in its core regions. Comparison of this relationship to similar features seen in contact metamorphism around the Laramide anorthosite complex in Wyoming (Grant and Frost, 1990) suggests that cordierite may have pseudomorphically replaced porphyroblasts of sillimanite or sapphirine. In the aluminous gneiss seen at Stop 2, cordierite is restricted to migmatitic leucosomes. Cordierite formed in contact and apparent textural equilibrium with orthopyroxene at Stop 4. Garnet and sillimanite are not present with this mineral pair, constraining the pressure-temperature conditions of formation of the assemblage (as discussed above) and suggesting that the reaction that formed this mineral pair involved biotite breakdown and melt formation. In nearby lenses containing orthopyroxene and plagioclase but without cordierite, orthopyroxene displays well developed ophitic textures.

Prismatine occurs in feldspathic lenses within biotite-quartz-plagioclase gneiss and these lenses extend out into the surrounding gneiss. Many prismatine blades lie randomly oriented within the plane of foliation of the surrounding gneiss, but other grains grew across foliation, suggesting that this mineral crystallized under pressure conditions that locally were close to hydrostatic. Tourmaline occurs in the gneiss away from these lenses and also is preserved as inclusions in garnet. Prismatine formation likely occurred at the expense of tourmaline and probably involved biotite breakdown. The proposed reaction of Darling et al. (2004) for prismatine formation also includes cordierite as a reactant:

tourmaline + sillimanite + biotite + cordierite ⟶ prismatine + rutile + melt

An outstanding issue is the timing of cordierite formation for the rocks studied here. As seen at Stop 2, some cordierite formed as a result of partial melting. Anatexis has been recognized in other pelitic and quartzofeldspathic gneisses in the synform (Whitney et al., 2002), as well as in pelitic gneiss west to the area, near Port Leyden (Florence et al, 1995). A single crystal zircon age determination of 1031±8 Ma from granitic gneiss at Agers Falls (Port Leyden area; Orrell and McLelland, 1996) and similar age monazite from the Port Leyden pelitic gneiss establish the timing of Ottawan granulite facies metamorphism and partial melting in the west-central Adirondacks. Deformation of the cordierite-containing leucosomes at Stop 2 may reflect syn-tectonic anatexis during the Ottawan. Initial cordierite formation elsewhere may predate Ottawan metamorphism. This region has had a complex tectonic history, as demonstrated by the intrusion and deformation of charnockite and granitic gneisses. These rocks have not been dated in this area, but are geochemically similar to ca. 1150 Ma AMCG (anorthosite-mangerite-charnockite-granite) suite rocks that occur elsewhere in the Adirondack Highlands (McLelland et al., 2001; Whitney et al., 2002.) To what extent this earlier magmatic event was responsible for formation of cordierite is not clear.

More evident is the cooling path exhibited by these rocks following Ottawan granulite facies metamorphism, which outlasted ductile deformation. Whether formed during the Ottawan or re-equilibrated then, mineral compositions of cordierite, garnet, biotite, and orthopyroxene reflect the conditions near and subsequent to the thermal maximum of the Ottawan event. The pressure-temperature evolution for the cordierite-bearing rocks followed a nearly isobaric cooling path from 850 ± 20 °C and 6.6 ± 0.6 kilobars to 675 ± 50 °C and 5.0 ± 0.6 kilobars. This path parallels the cooling trajectory identified for the Eastern Adirondacks by Spear and Markussen (1997), and shows a pressure that is lower by about 1.2 kilobars.

It is interesting to compare these thermobarometric results with an earlier study of the western Adirondack Highlands that also suggested lesser pressures here than in the eastern Adirondacks. De Waard (1965) observed that amphibolites in the western Adirondacks invariably lacked garnet, whereas those to the east were garnetiferous. He recognized that the transition from two-pyroxene ampiblities to garnet-bearing varieties was the result of the largely pressure-dependent net transfer reaction:

orthopyroxene + plagioclase ⟶ garnet + clinopyroxene + quartz

Development of this reaction is also dependent on bulk composition, but de Waard's suggestion that it indicates an overall westward decrease in pressure conditions of metamorphism across the Adirondacks is supported by the pressure determinations from the Moose River assemblages. Florence et al. (1995) also obtained moderate pressure-temperature estimates of 735 ± 25 °C and 4-6 kilobars at Port Leyden. Presuming these estimates also reflects Ottawan conditions, this would appear to confirm a gradient of decreasing pressures across the Adirondack Highlands from the High Peaks to the western margin.

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## ROAD LOG FOR CORDIERITE-BEARING GNEISSES IN WEST-CENTRAL ADIRONDACKS

| CUMULATIVE MILEAGE | MILEAGE FROM LAST POINT | ROUTE DESCRIPTION |
|---|---|---|
| 0.0 | 0.0 | Town Park, Village of Inlet, on Route 28. |
| 0.5 | 0.5 | Stop 1. Outcrops on right side of road. |

### STOP 1. BIOTITE GNEISS WITH CORDIERITE

A long series of roadcuts is exposed along this section of road. The rocks immediately to the right are light gray outcrops of calcsilicates. Begin walking in the same direction as you were driving (to the N along this section of Route 28.) The next outcrops are garnet-biotite-quartz-feldspar gneisses containing abundant K-feldspar. Notice the color of these iron-rich garnets.

Proceed to the next outcrop to the north, containing darker gray quartzite and layers of biotite-quartz-plagioclase gneiss. Coarse sillimanite and lavender grains of garnet are found associated with biotite-rich layers. Bluish cordierite, ca. 1 cm in size, can be observed on fresh surfaces on the face of the outcrop or on top, towards the south end. Deformed leucosomes and pegmatite veining is also seen in outcrop.

| | | |
|---|---|---|
| 11.2 | 10.7 | Enchanted Forest, Village of Old Forge |
| 11.6 | 0.4 | Old Forge Hardware Store, downtown Old Forge |
| 13.6 | 2.0 | Thendara Station |
| 21.8 | 8.2 | Stop 2. Outcrops on left (east) side of Route 28. |

### STOP 2. CORDIERITE-BEARING OUTCROP

Pink and gray two-feldspar gneisses outcrop along both sides of the road and exhibit steeply NW dipping to nearly vertical layers. Coarse grains of bluish cordierite are visible within a deformed pegmatite vein at the southern end of the exposure.

These gneisses show strong evidence migmatization. There are numerous K-Feldspar-, biotite-, quartz- rich pegmatite veins parallel to foliation, some of which are deformed into isoclinal or ptygmatic folds. Cm long, thin, discontinuous lenses of biotite and sillimanite (restite?) are abundant on the south end of the outcrop on the west side of Route 28, where it can be seen that the long axis of sillimanite blades are randomly oriented within the plane of foliation. The association of cordierite with the pegmatite veins suggests that its formation was the result of a melt-producing reaction.

These outcrops contain abundant oxides and the coloration of garnet implies a relatively high Fe ontent. Overall, the mineral abundances suggests that these rocks have a different bulk composition than the cordierite gneiss seen at Stop 1 and those that will be shown at Stops 3 and 4.

| | | |
|---|---|---|
| 22.1 | 0.3 | McKeever bridge across Moose River |
| 22.2 | 0.1 | Moose River Road. Turn right.<br>Continue on Moose River Road |
| 24.0 | 1.8 | Lewis County boundary |
| 25.4 | 1.4 | Moose River in view to right |
| 26.2 | 0.8 | Stops 3 and 4. Pull into dirt parking area on right, adjacent to river. |

The next two stops are along the Moose River and require a little more than a kilometer of walking to visit them both. The outcrops are exposed along the river's edge. Caution is advised during periods of high water. Please DO NOT USE HAMMERS at these outcrops. We request that sampling be restricted to collecting loose material.

From the parking area, follow an unimproved fishing trail that leads left out of the parking area and walk downstream on the bank above the south side of the river. Continue for approximately 100-200 m, past NW dipping quartzite beds containing tremolite needles, diopside, and other calcsilicate minerals. The trail passes through the old foundation of a former tannery. After another few 100 m, the river then bends to the north and the trail drops down to the river's waters edge.

Stop 3 consists of the first outcrops along the riverbank that are exposed downstream from the bend.

## STOP 3. MG-RICH METAPELITES

This stop consists of a continuous bedrock exposure along the south side of the Moose River. The first exposures past the bend in the river contain large greenish-gray blades of prismatine that have formed in a biotite-quartz-K-feldspar gneiss containing massive, cm scale "lumps" of garnet. Cordierite was recognized in thin sections taken from these outcrops.

Continuing downstream, biotite-quartz-feldspar gneiss outcrops show elongate segregations of cordierite, sillimanite, and spinel in the layers adjacent to spectacular splays of prismatine. Prismatine is also well displayed in an isoclinal fold that can be seen on a 2 m high vertical face. Notice that prismatine needles grow both parallel to and across the plane of foliation. A little further downstream, outcrops contain zones with abundant small, black tourmaline crystals. Prismatine is also present here, immediately rimmed by tourmaline-free halos. Cordierite is present in this portion of the outcrop as well, sometimes as dark, pinitized (altered) grains and in lumpy-looking symplectite intergrowths with quartz.

The western end of the exposures at Stop 3 rises directly above the Moose River. To continue further west from here, walk directly upslope and return to the fishing trail. Continue in the downstream direction another 400 m to where quartz-rich outcrops are exposed along the river. Follow these outcrops for another 30-50 m. This is Stop 4.

**STOP 4. METAPELITES CONTAINING CORDIERITE + ORTHOPYROXENE**

The first exposures along this section of outcrop contain occasional euhedral grains of prismatine in quartz-biotite-feldspar lenses in quartzite. Just downstream (ca. 10 m) from these are layers locally displaying large blue knots of cordierite and lavender garnets.

Another 10-15 m of downstream travel brings one to a few south dipping rocks that extend a little into the river. Here, cm long, dark green prismatine blades form radiating splays on surfaces of biotite-quartz-feldspar lenses within quartzite. Most grains lie within the plane of foliation but individual crystals are in fact arranged in random orientations with respect to foliation in what appear to be leucosomes. Sillimanite occurs in this assemblage only as anhedral grains included in prismatine, leading Darling et al. (2204) to suggest that sillimanite abundance was the limiting reactant in the melt-forming raction leading to prismatine formation.

Other feldspathic gneiss lenses within these outcrops contain orthopyroxene, garnet, K-feldpsar, and plagioclase in melt zones. In thin section, grains of othropyroxene and plagioclase modrate to well-developed ophitic texture. As with the prismatine-bearing lenses, these mineral assemblages are considered to be the result of partial melting.

Adjacent biotite-rich layers contain bronze colored, weathered orthopyroxene megacrysts and cordierite knots. Grains of unaltered orthopyroxene were seen in thin section, where they appear in textural equilibrium with cordierite, biotite, quartz, and K-feldspar. Some grains of cordierite are rimmed by biotite and quartz symplectites. Presumably, the alteration and replacement of orthopyroxene and cordierite proceeded according to the reaction

orthopyroxene + cordierite + K-feldspar + (hydrous melt or $H_2O$) $\longrightarrow$ biotite + quartz

It is not clear whether this reaction operated during the subsolidus portion of the retrograde path, presumably by the introduction of an aqueous phase, or it was brought on by melt-formation at or near the peak of metamorphic conditions.

From here, walk uphill to regain the fishing trail to return to the parking area.