Trip A-4

QUARTZ-SILLIMANITE VEINS AND NODULES IN LYON MOUNTAIN GRANITE, AND THE OCCURRENCE OF PRISMATINE IN METAPELITIC GNEISS AND QUARTZITE, MOOSE RIVER, WESTERN ADIRONDACKS

by

JAMES McLELLAND
Department Geology, Colgate University, Hamilton, NY, 13346
and
ROBERT DARLING
Department of Geology, SUNY, College at Cortland, Cortland, New York, 13045

INTRODUCTION

The western Adirondacks contain a wide variety of rock types, and this trip will visit representatives of the major lithologies. Stops include units of Lyon Mountain granite recently dated by U-Pb geochronology including multi- and single-grain TIMS and SHRIMP II analyses as well as in-situ dating of monazites.

The Adirondack Mountains represent a southeastern extension of the Grenville Province via the Thousand Islands – Frontenac Arch across the St. Lawrence River (Fig. 1). The region is topographically divided into the Adirondack Highlands and Lowlands separated by the Carthage-Colton Mylonite Zone (CCMZ, Fig. 2). The former is underlain largely by orthogneiss metamorphosed to granulite facies and the latter by upper-amphibolite facies metasediments, notably marbles and calcsilicate. Both sectors have experienced multiple deformations resulting in refolded major isoclines. The intrusion history is summarized by a tripartite division, as summarized below and in Fig. 3. Broadly, the plutonic lithologies fall into the following five groups: 1350-1300 Ma tonalites rifted from Laurentia at ca. 1300 Ma.; 1250 Ma granodiorites; 1160-1150 Ma anorthosite-mangerite-charnockite-granites (AMCG suite); 1100-1090 Ma Hawkeye granite; and 1055-1040 Ma Lyon Mountain Granite (LMG). The four major orogenic events associated with these are: an Andean-type arc along southeast Laurentia, the Elzevirian (ca1250-1220), the Shawinigan (1210-1140 Ma), the Ottawan (1090-1030 Ma), and the Rigolet (1000-980 Ma) orogenies (Fig. 3). The Elzevirian involved a back-arc rift basin with protracted outboard arc magmatism and accretion and was followed by the Shawinigan Orogeny due to the collision between Laurentia and the Adirondack Highlands – Green Mountain Terrane. The Ottawan was a Himalayan-type collision of Laurentia with Amazonia (?). Most of the metamorphic and structural effects present in the Adirondacks are the result of the Ottawan Orogeny, but Shawinigan and Elzevirian features can be recognized where minimally overprinted by the Ottawan. Both the AMCG suite and the LMG are thought to be late- to post-tectonic manifestations of delamination of over-thickened orogens undergoing terminal extensional collapse.

Structurally, the central and western Adirondack Highlands are dominated by the same large, recumbent fold-nappe structures (F_2) as found in the southern Adirondacks (Fig. 2), and with fold axes oriented dominantly ~NE-SW and ~E-W parallel to stretching lineation. As in the southern Adirondacks, these Ottawan fold-nappes are thought to possess sheared-out lower limbs, but this has yet to be demonstrated at map scale. F1 folds of Shawinigan age occur as minor folds within the much larger F2 recumbent isoclines. At least two distinguishable upright fold events are superimposed on the nappes: F3 with shallow plunging ~E-W axes and F4 with shallow-plunging NNE axes. Both of these can be shown to be of late Ottawan (ca, 1050-1040 Ma) origin. All of three fold sets affect Hawkeye and older units, and thus must be of Ottawan age. This is also the case with the strongly penetrative rock fabric, including strong ribbon lineations that are present in these rocks and are largely associated with the large fold-nappes. Intense fabric and nappe structure are largely absent from the ca. 1050 Ma LMG; however, this unit is folded by F3 and F4, and this is interpreted to reflect its intrusion in late, post-nappe stages of the Ottawan orogenic phase of the Grenvillian orogeny. In the northern portion of the eastern Adirondacks the NNE, F4, folds become quite tight and have a strong lineation associated with them. This may be the result of rock sequences being squeezed between large, domical prongs of anorthosite during terminal Ottawan exhumation.

Most of the region likely experienced peak Ottawan temperatures of ~750-850^{o} C and pressures of ~5-8 Kbar (Kitchen and Valley, 1995, Florence et al, 1995, Spear and Markussen, 1997; Storm and Spear, 2005 and Darling et al., 2004). Evidence exists that similar P, T conditions were attained in the Shawinigan orogeny (Heumann et al., 2006). Based upon extensive oxygen isotopic work by John Valley and his students, it appears most likely that Ottawan metamorphism proceeded under fluid-absent conditions

(Valley and O'Neil, 1982, Valley *et al*., 1990). Note, however, that this does not exclude the presence of late, post-peak fluids associated with the emplacement of Lyon Mountain granite.

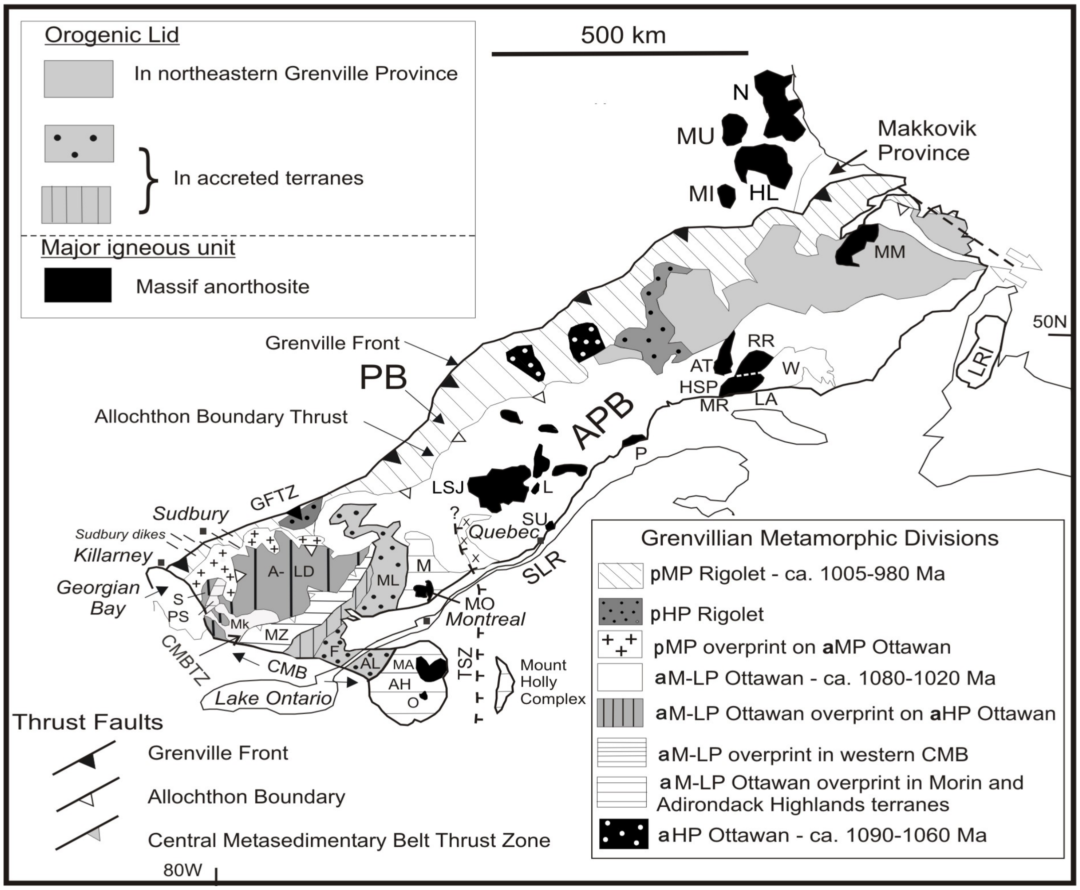


Fig. 1 Generalized map shows the Grenville Province whose three major tectonic divisions (Rivers, 1997) are indicated. The Orogenic Lid of Rivers (2008) is shown in light gray. The accreted ca. 1.3-1.4 Ga Montauban-La Bostonnais arc is shown by X- pattern. **Abbreviations**: A-LD- Algonquin- Lac Dumoine domain; AL-Adirondack Lowlands; AH- Adirondack Highlands; APB- Allochthonous Polycyclic Belt; CMB- Central Metasedimentary Belt; CMBTZ, Central Metasedimentary Belt thrust zone; F, Frontenac terrane; GFTZ- Grenville Front Tectonic Zone; LRI- Long Range inlier; M- Morin terrane; MK- Muskoka domain; ML- Mont Laurier domain; MZ- Mazinaw terrane; O- Oregon dome; PS- Parry Sound domain; RR- Romaine River, S- Shawanaga domain; SLR- St. Lawrence River, TSZ – Tawachiche Shear Zone with its southern projection, W- Wakeham terrane. **Abbreviations for metamorphic divisions**: p-MP- parautochthonous medium pressure belt; aM-LP- allochthonous medium to low-pressure belt; aHP- allochthonous high-pressure belt; pHP- parautochthonous high-pressure belt. **Major anorthosite massifs with ages**: AT- Atikonak (ca 1130 Ma); HL- Harp Lake (ca. 1450 Ma; HSP- Havre-St-Pierre, (ca. 1126 Ma, dashed white line is the Abbe-Huard lineament; L- Labrieville (1060 Ma); LA- Lac Allard HL) (ca. 1060 Ma); LSJ- Lac-St.-Jean (ca. 1155 Ma); MA- Marcy Massif (ca. 1155 Ma), MO- Morin (ca. 1153 Ma), MI- Mistastin (ca. 1420 Ma); MU- Michikamau (ca. 1460 Ma); MR- Magpie River (ca. 1060 Ma); N- Nain-(ca 1383- 1269 Ma); P- Pentecôte (ca 1350 Ma); S- St. Urbain (ca. 1060 Ma). *Modified after Rivers (2008 and McLelland et al. (2010a).*

The most recognizable fold patterns in the Adirondack Highlands are those of the ~E-W F3 and ~NNE F4 folds that span the entire region, e.g., Fig. 2, P (Piseco dome). These upright, relatively open folds exhibit E-W stretching lineations coaxial with the F3 folds. Because both these fold sets affect the ca. 1050 Lyon Mt. Granite and are crosscut by it, they are most likely synchronous with the terminal, extensional phase of the Ottawan orogeny. We interpret them as "a" and "b" domical folds that have been identified in large scale extensional orogens such as the Aegean core complex (Jolivet et al., 2004) and are due to the extension itself. Axes of the "a" folds form parallel to the principle extension due to constriction, whereas the “b” folds form approximately perpendicular to extension and slightly postdate the “a” folds. The axes of F2 folds are approximately parallel to extension and may have formed in this orientation and/or were rotated into it by extensional strain.

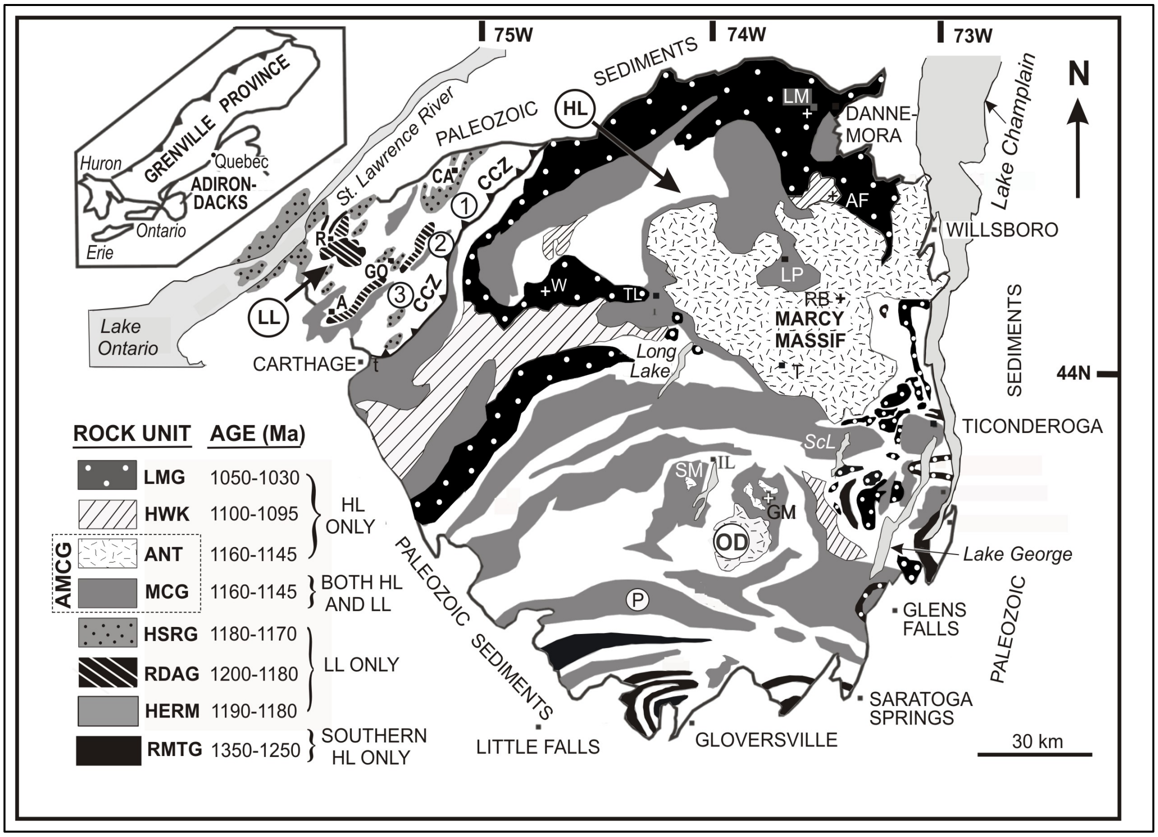


Fig. 2. Map showing generalized geology and geochronology of the Adirondacks. Units designated by patterns and initials consist of igneous rocks dated by U-Pb zircon geochronology with ages indicated in the legend. Units present only in the Highlands (HL) are: RMTG – Royal Mountain tonalite and granodiorite (southern and eastern HL only), HWK -Hawkeye granite, LMG – Lyon Mountain granite, and ANT – anorthosite. Units present in the Lowlands (LL) only are HSRG – Hyde School and Rockport granites (Hyde School also contains tonalite), RDAG – Rossie diorite and Antwerp granodiorite, RMTG – Royal Mountain tonalite and granodiorite (southern and eastern HL only), HWK -Hawkeye granite, LMG – Lyon Mountain granite, and ANT – anorthosite. Units present in the Lowlands (LL) only are HSRG – Hyde School and Rockport granites (Hyde School also contains tonalite), RDAG – Rossie diorite and Antwerp granodiorite. Granitoid members of the anorthosite-mangerite-charnockite-granite (AMCG suite) are present in both the Highlands and Lowlands. Unpatterned areas consist of metasediments, glacial cover, or undivided units. Other abbreviations: CCZ- Carthage-Colton Shear Zone; CL-Cranberry Lake, LL-Lowlands, OD- Oregon dome anorthosite massif, SM – Snowy Mountain anorthosite, IL-Indian Lake, L-Lyon Mountain. *Modified after McLelland et al., 2010a.*

Recent investigations in the Grenville Province demonstrate that the Ottawan orogen (Rivers, 2008) and its Adirondack outlier (McLelland et al., 2010a) underwent terminal extensional collapse that, in the latter case,
was accompanied by emplacement of LMG. The most complete local study of this sort is that of Selleck et al. (2005) that utilized zircon geochronology to document that down-to-the-west displacement along the northwest dipping Carthage-Colton Shear Zone (CCZ, Fig. 2) was coeval with intrusion of Lyon Mt. Granite (Fig. 2) into the fault complex at ca 1050-1045 Ma. It is thought that, at peak Ottawan contraction, the over-thickened lithosphere experienced delamination by foundering, convective thermal erosion, or both. Following delamination of the dense lithospheric keel, the orogen rebounded and hot asthenosphere moved to the crust-mantle interface where it underwent depressurization melting to yield aluminous gabbro

that differentiated into anorthositic crystal mushes that ascended, along with crustal granitic melts, to yield the ca. 1050 Ma AMCG suite that is exposed in Canada (Fig. 2) as the Lac Allard massif and the Labrieville to St. Urbain CRUML belt (Owens et al., 1994, Morrisett et al., 2010, McLelland, 2010b). The asthenospheric diapir likely underwent degassing, and caused fertilization and melting of deep crust to yield A-type LMG. As the granite ascended into the crust, it both lubricated and enhanced low-angle normal faults formed in response to increased topographic elevation, fluids, and anatexis; all leading to orogen collapse. In such situations, it is not uncommon to find that collapse is quasi-symmetrical around the orogen core thus giving rise to a mega-gneiss dome or double-sided core complex such as the Shuswap complex (McLelland 2010a, Wong et al, 2011).

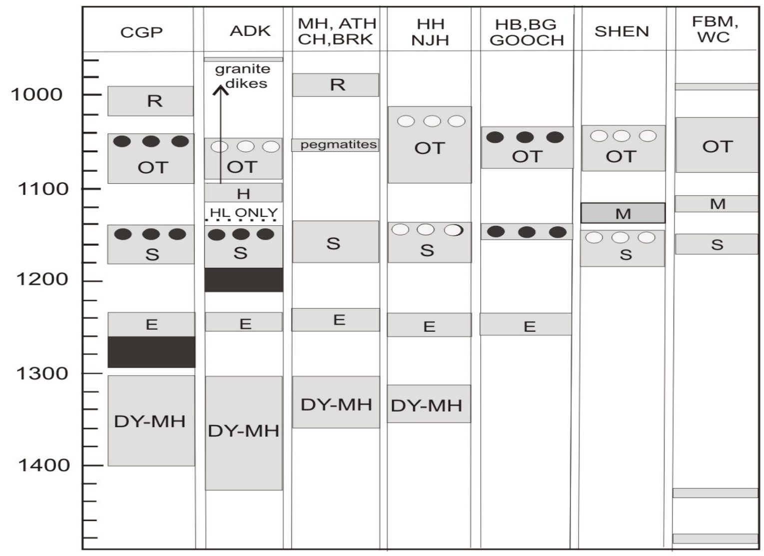


Fig.3 Chart summarizing Mesoproterozoic orogenic events in eastern North America during the interval 1.5-0.9 Ga. The gray blocks labeled R and OT represent the ca 1.09-1.03 Ga Ottawan orogenic phase and the ca. 1000-980 Ma Rigolet phase of the Grenvillian orogeny,respectively (Rivers, 2008). The black circles represent late- to post-tectonic AMCG suites, whereas the smaller, white circles represent MCG magmatism only. The black blocks in the Elzeverian (E) and Shawinigan (S) orogenies represent pre-orogenic arc magmatism. The events labeled DY-MH in the lower gray blocks represent ca.1.45-1.3 Ga continental arc magmatism along the southeastern margin of Laurentia. Portions of the arc rifted during the formation of the Central Metasedimentary Belt (ca. 1.3-1.22 Ga) and are now situated in the Adirondacks and the Mesoproterozoic inliers of the northeast Appalachians where they are known as the Dysart-Mt. Holly suite. Geographic abbreviations from left to right: CGP – Canadian Grenville Province, ADK – Adirondack Mountains, MH – Mount Holly, ATH – Athens dome, CH – Chester dome, BRK – Berkshire Mountains, HH – Hudson Highlands, NJH - New Jersey Highlands, HB – Honey Brook uplands, BG – Baltimore Gneiss domes, GOOCH – Goochland Terrane, WC– Wolf Creek, SHEN– Shenandoah Blue Ridge, FBM– French Broad Massif. *Modified after McLelland, 2010a.*

LYON MOUNTAIN GRANITE

The mineralogy and chemistry of Lyon Mountain granite has been thoroughly reported by Postel (1952), Whitney and Olmsted (1988, 1993), Whitney, 1992, and Valley et al. (2011) who showed it to be a ferroan, A-type leucogranite. McLelland et al. (2001a, 2001b, 2002) addressed the zircon geochronology of LMG and its close relationship with hydrothermal sodic alteration and Kiruna-type magnetite ores. Unequivocal evidence demonstrates that LMG is an igneous intrusive rock emplaced at ca. 1050 Ma (McLelland et al. 2001a,b; Selleck et al. (2005), Valley et al., 2011). The regional outcrop pattern of LMG is significant as it tends to occur around the perimeters of the Adirondack Highlands (Fig. 2) leading McLelland et al. (2010) and Selleck et al. (2005) to propose that it was intruded along, and helped to lubricate and promote, detachment faults formed during ca. 1050 Ma extensional collapse of the Ottawan orogen. The purpose of the first part of this trip is to examine some outstanding river-washed exposures of LMG and some of the interesting features within it including remarkable quartz-sillimanite veins and nodules. To this end further discussion will be presented in the Road Log and Field Stops.

PRISMATINE-BEARING METAPELITES AND QUARTZITES ALONG THE MOOSE RIVER

Prismatine, the boron-rich end-member of the kornerupine solid solution (Grew et al., 1996; ideally $[(\square,Mg,Fe)(Al,Mg,Fe)_9(Si,B,Al)_5O_{21}(OH,F)]$) occurs in metapelitic and quartzitic rocks about 12 km east of Ager's Falls (Stop 2) on the Moose River. Kornerupine-group minerals are generally rare, having been described from nine localities in the Grenville Province (Grew, 1996; Darling et al., 2004; Korhonen and Stout, 2005) including two in the Adirondacks (Farrar and Babcock, 1993; Farrar, 1995; Darling et al., 2004).

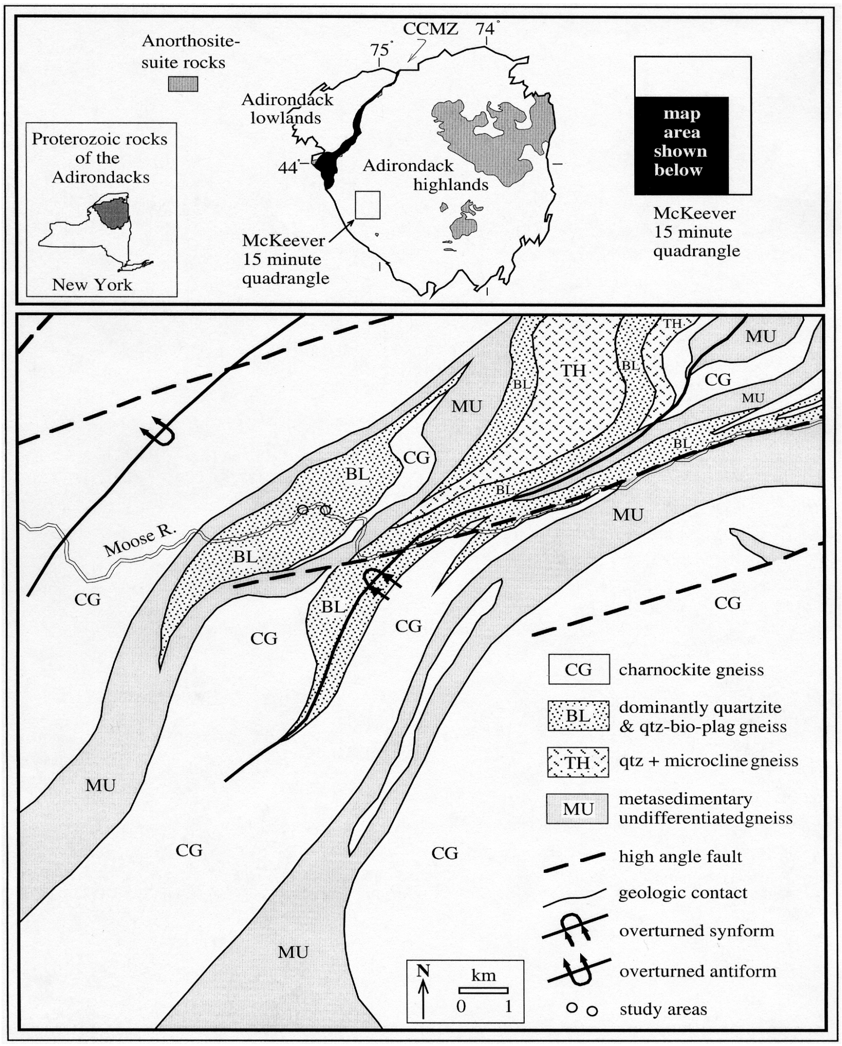


Fig. 4. - Map showing location of prismatine-bearing metapelites and quartzites (open circles on Moose River) and surrounding bedrock geology. Stop 6 is easternmost open circle. Geologic map units, structures, and relations illustrated are from Whitney et al. (2002). *Taken from Darling et al. (2004).* Bio —biotite; CCMZ—Carthage-Colton mylonite zone; pl—plagioclase; qtz—quartz.

Along the Moose River, prismantine occurs at two locations (separated by about 400 meters, Figure 4) within a unit of heterogeneous metasedimentary rocks (Figure 4, unit BL) mapped by Whitney et al. (2002). This unit comprises mostly quartzite and biotite-quartz-plagioclase gneiss with lesser amounts of calcsilicate rocks, and minor amphibolite, quartzofeldspathic gneiss, and calcite marble (Whitney et al., 2002). These rocks are interlayered with: 1) other metasedimentary undifferentiated rocks (Figure 4, unit

MU) that contain relatively more calcsilicate and less quartzite than BL, 2) thick tabular bodies of granitic to locally charnockitic gneiss (Figure 4, unit CG), and 3) quartz-microcline gneiss with quartzite and calcsilicate granulite layers (Figure 4, unit TH). These units occur in a complex, southeast-verging overturned synform bordered on the northwest by a tabular, northwest-dipping body of CG several kilometers thick, and on the southeast by a domical body of batholithic proportions consisting of relatively leucocratic CG. Although the granitic and charnockitic rocks have not been dated, they are lithologically and geochemically similar to felsic rocks of the ca. 1150 Ma anorthosite-mangerite-charnockite-granite (AMCG) suite found throughout much of the Adirondack Highlands (McLelland et al., 2001; Whitney et al., 2002).

In addition to prismantine-bearing assemblages, the surrounding rocks contain metapelitic assemblages of a) cordierite + spinel + sillimanite + garnet + plagioclase + quartz + ilmenite + rutile +/- biotite, b) cordierite + orthopyroxene + biotite + K-feldspar + quartz, and c) orthopyroxene + plagioclase + K-feldspar + quartz +/- biotite, +/- garnet (Darling et al., 2004). Additional descriptions and interpretations are included in the Road Log and Field Stop section.

ROAD LOG

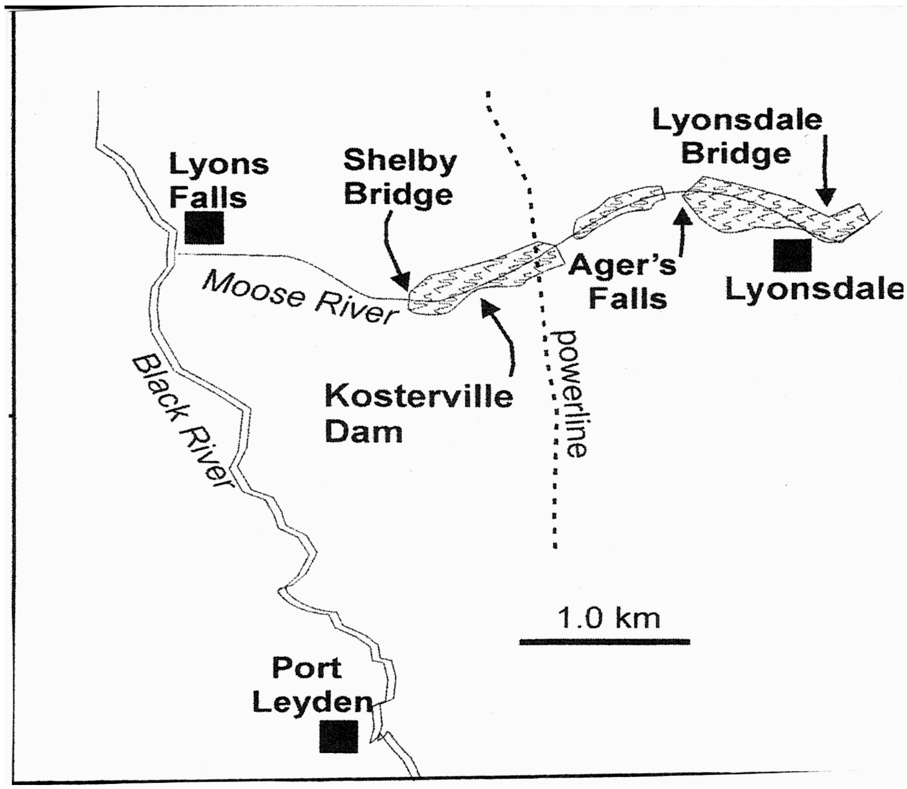


Fig. 5. Location map for Lyonsdale stops

CUMUL-ATIVE MILES	MILES FROM LAST STOP	ROUTE DESCRIPTION
0.0	0.0	Traffic light at intersection Rt. 12 and Main St., Port Leyden. Turn east on Main St.
0.5	0.5	Intersection with River Road. Turn left, Continue for 0.8 miles.
1.3	0.8	River Road forks left; continue straight ahead on Marmon Road.
2.7	1.9	Pass Penny Settlement Road on right; continue straight ahead.
4.5	2.6	Lyonsdale; turn right on Lowdale Road and cross three short one-lane bridges over the Moose River. Just before the third bridge park in parking area on left side of road. If no further room, continue over third bridge and park along shoulder. Meet at bridge.

STOP 1. LYONSDALE BRIDGE (45 MINUTES)

River-washed exposures begin at the bridge over the Moose River that adjoins the Burroughs Paper plant at Lyonsdale. A coarse, steeply east-dipping pegmatite can be seen descending down a steep cliff face and crossing the river onto the exposures immediately beneath the bridge. The pegmatite is zoned with a quartz core containing sillimanite and magnetite. McLelland et al., (2001) report a .single grain TIMS upper intercept age of

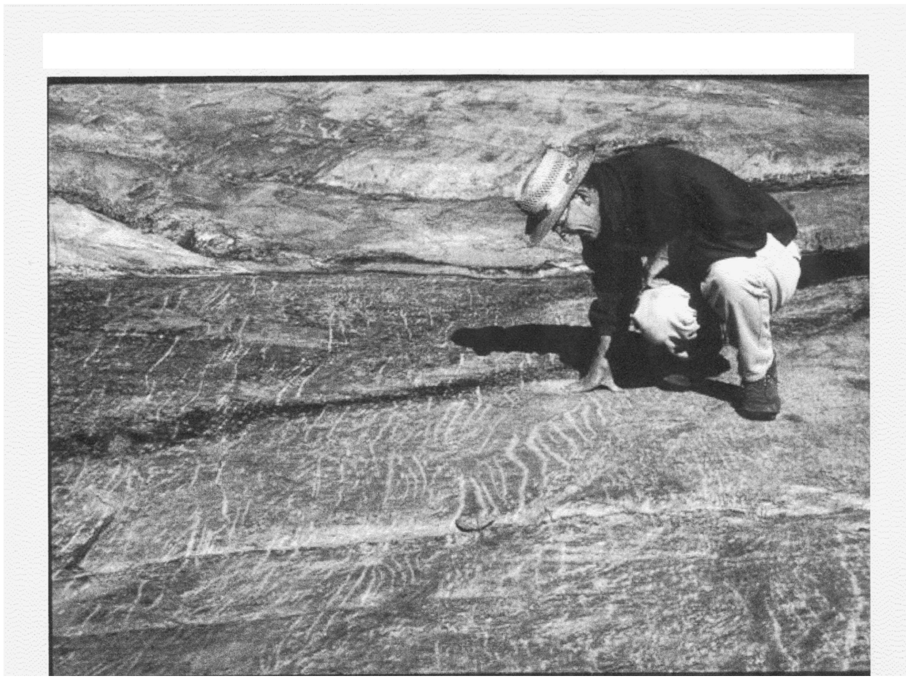


Fig. 6. Dugald Carmichael puzzles over the network of quartz-sillimanite veins and nodules below Lyonsdale Bridge.

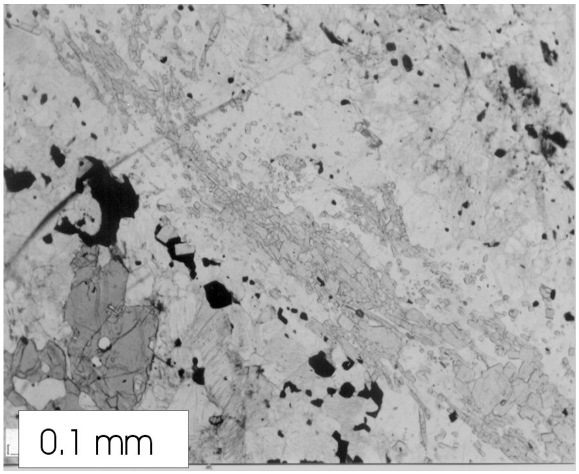
1035 ± 10 Ma for the pegmatite (McLelland et al., 2002). A nearby sample of LMG yielded a SHRIMP and single grain TIMS age of 1046 ± 4.4 Ma (McLelland et al., 2001). The pegmatite age appears to be ~10 Ma too young and redating by SHRIMP would be very desirable. Nonetheless, it overlaps with the average LMG (n = 11) age of 1049 ± 10 Ma (McLelland and Selleck, 2011).

LMG consists of pink equigranular quartz and feldspar with small amounts of magnetite and occasional biotite. It shows virtually no penetrative grain shape fabric (Fig. 7b) and, despite examples of tight folding in the outcrop, appears to be undeformed by the nappe-like folding that affects all rocks older than 1050 Ma and imparts to them pronounced ribbon lineation and grain shape fabric. In contrast, LMG displays a good igneous texture resembling that of hypersolvus granite. Elsewhere it has been shown that late, upright folds trending E-W and NNE-SSW fold some LMG and were formed during the ca. 1050 Ma extensional collapse of the Ottawan orogen (McLelland et al., 2010). We are confident that the tight, disrupted, isoclines defined by quartz and granitic veins in the riverbed are the result of flow folding due to LMG magma emplacement (McLelland et al., 2002a,b).

As shown in Fig. 6, LMG has been penetrated by myriad white veins that consist of sillimanite and quartz with subordinate magnetite (Fig. 7a). There are several distinct generations of these, and it is clear that some groups are more deformed than others (Fig. 8a). The dominant, and perhaps youngest, trend is N50E. Careful examination of quartz nodules will show that they commonly form linear trends that are best explained by disruption or boudinage.

Where LMG intruded country rock, the former contains garnet. The original country rock was a calcsilicate but has been contaminated by the granite and its fluids. It is common to find aligned boudins of this rock in the stream bed. They tend to be angular and separated by granite and most likely represent blocks disrupted by the magma. Other important features to be seen are pegmatites that transition from two-feldspar to albite rich and even to quartz veins with magnetite. At one place a sillimanite-magnetite veinlet can be recognized when sunlight hits it in a certain direction. The same is true with several occurrences of very coarse (~6”) sillimanite.

A **B**



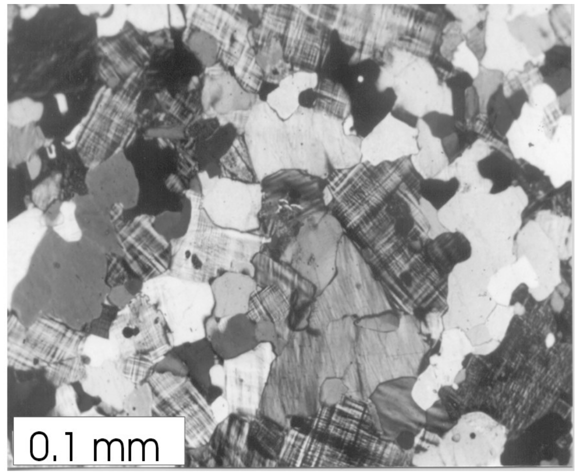


Fig.7. These images show photomicrographs of LMG collected at Lyonsdale Bridge. In 7a a quartz-sillimanite vein is shown with sillimanite needles at its core. Quartz (clear) occurs on either side of the sillimanite, and minor magnetite is sporadically present along the edges. Host LMG can be seen in the lower left hand corner.
7B shows a thin section of LMG under cross-polars. Microcline perthite and quartz dominate the field of view,
and there is no sign of deformation in the rock. *Modified after McLelland et al., 2002a.*

Mileage
4.7 0.2 mi. Return over bridges to Lyonsdale and turn right (west) on Marmon Road
5.1 0.4 mi. Turn right past gate at entrance to Ager's Falls power station. Take an immediate left and continue downhill to parking area.

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STOP 2. AGERS FALLS (45 MINUTES)

This stop exposes riverbed outcrops of LMG immediately southwest of a small hydroelectric facility on the Moose River. Fig. 8 presents some of the important relationships at Ager's Falls. Fig. 8A shows the same multiple, cross-cutting vein sets as seen at Lyonsdale Bridge. Note how the older set has been disrupted into nodules. In Fig 8B trains of nodules are shown crosscutting dark, xenolithic fragments of country rock calcsilicate. A similar scenario is shown in Fig. 8F that also contains late pegmatite veins. The crosscutting of the calcsilicate xenoliths is a critical relationship, because it establishes the post-intrusion origin of the quartz-sillimanite veins and nodules, i.e., they are not due to incorporation of "aluminous quartzite "into the magma. In Fig 8C several vein sets can be seen with the one pointed to by the pen clearly undergoing ductile boudinage consistent with extension in a fairly viscous magma. A very late, thin vein wanders across the field parallel to the pen. Figs. 8D and Fig 8G display a crucially important exposure in which a pegmatite-cored granite dike crosscuts, and ductiley deforms, the quartz-sillimanite vein-nodule system in a sinistral shear zone. The granite in the dike is good LMG identical to that in the country rock, but it contains no veins or nodules. This informs us that LMG magma was still present when the veins and nodules were being formed as a viscous magma was being fractured by rapid strain rate forces associated with emplacement into a fault controlled magma chamber. The granite then evolved a pegmatitic core as the magmatic episode drew to a close. It is likely that these processes were taking place near the top of the pluton, perhaps in a cupola. A self-consistent sequence of events is shown in Fig. 9 where a sheet of magma in a N50E shear zone has plucked off xenoliths parallel to its margins. As fluid pressure built in the crystallizing magma, movement along the shear zone triggered extensional fracturing parallel to sigma-1 and filled with hot, acidic magmatic fluids giving rise to quartz-sillimanite veins via hydrolysis. Sinistral shearing continued into frame 9C and resulted in rotation and boudinage of the earlier veins. By frame 9D, fluid pressure had built up again and a new set of extension fractures were produced along with subsequent rotation, boudinage, etc. In this way, the crosscutting vein system evolved with earlier veins getting rotated and boudinaged into nodules (McLelland et al., 2002 a, b).

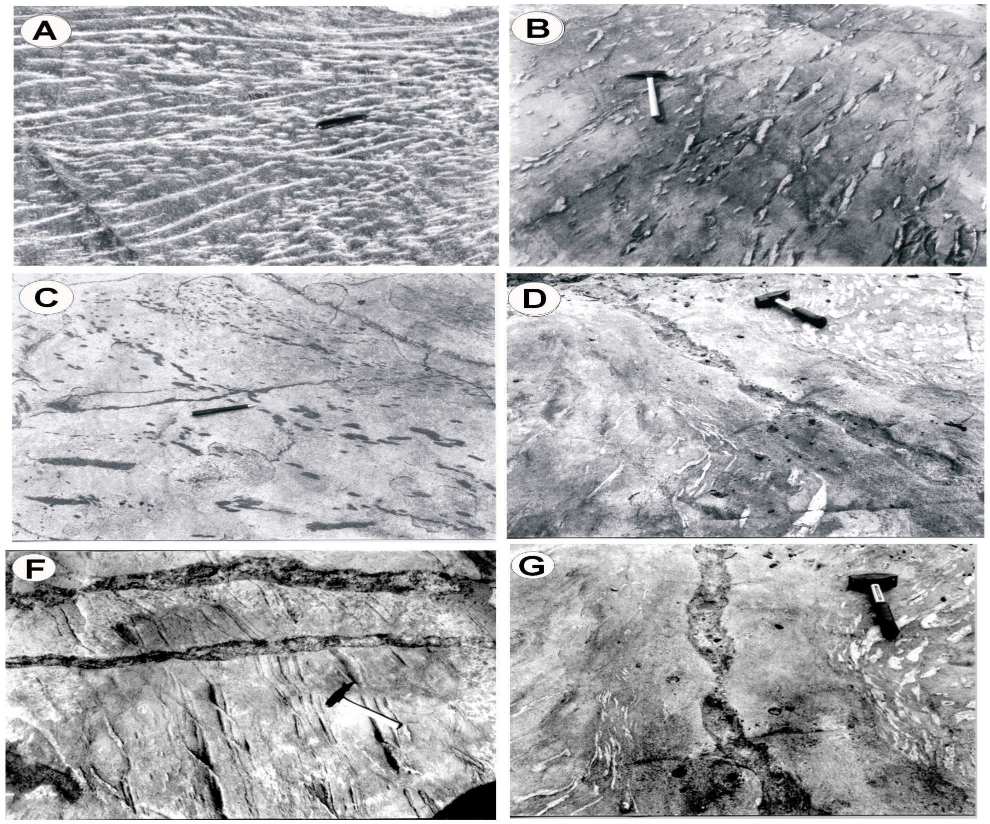

Fig. 8. Some granite-dike relationships at Ager's Falls, See text for explanation.
After McLelland et al. 2002a.

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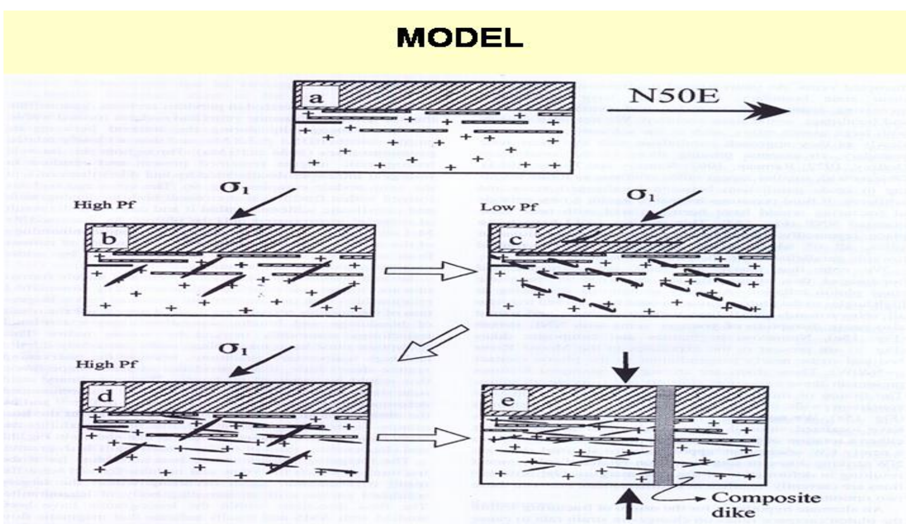

Fig. 9. The model shows the evolution of the vein-nodule complex.
See text for details. *After McLelland et al., 2002b.*

There are places in the Ager's Falls exposures where tight isoclinal folds defined by quartz veins are present, However these are disharmonic and the veins are discontinuous. The best explanation for these folds is that they are the result of flow-rate variations in a magma.

Fig. 10. Closeup showing veins crosscutting calcsilicate xenoliths.

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As the Moose River is followed farther downstream, the quantity of quartz veins increases until the rocks pass into a thick, sillimanite-bearing megaquartz vein complex that we will visit at Stops 3, 4, and 5. The quartzite is clearly of hydrothermal origin, and we interpret it to represent the release of late magmatic fluids through the carapace of a large LMG pluton.

Mileage
5.75 0.65 mi. Proceed west along Marmon/Lyonsdale Road. Park in small parking area for trail access.

STOP 3. QUARTZ VEIN COMPLEX AT FISHING ACCESS SITE (15 MINUTES).

These stream exposures contain quartz veins, pegmatite veins, and veins of granite. The green and red coloration of portions of the rocks is the result of hydrothermal fluids acting on iron oxides and iron-bearing silicates. The wide expanse of quartz is due to widening of the vein system visited at the end of stop 2. The quartzite is interpreted as the end product of leaching of alkalis from the original granite leaving a residue rich in silica and alumina. Magnetite, hematite, and later chlorite result in the pink to green coloration in the rock.

Mileage
6.0 0.25 mi. Proceed west along Marmon Road. Park along east shoulder, walk down dirt road.

STOP 4. QUARTZ-SILLIMANITE ROCK & ILLITE-DIASPORE, KOSTERVILLE DAM (20 MINUTES).

Exposures at the base of the dam display ~100 feet wide coarse grained, massive, sillimanite-bearing quartzite discussed by Selleck et al., 2004). Broken-off fragments show randomly oriented sillimanite crystals up to 6” long. Scattered across the outcrops of quartzite are large (up to 20 cm.), porcellanous, and irregularly shaped salmon- and green-colored platelets consisting of diaspore and illite. It is common for these minerals to psuedomorph sillimanite. These features are interpreted as low T (<200C) alteration features related to later hydrothermal alteration that dissolved and redistributed silica and alumina as fluids permeated the fracture network. Fluid inclusion work indicates oxidizing and highly saline (>20% NaCl) fluids. Interestingly, the illite-diaspore platelets contain high concentrations of altered zircon that we interpret to be the consequence of leaching of labile constituents (e.g., alkalis) from the original granite leaving a residue rich in quartz, alumina, and zircon. A few viable zircons yield ages of ca. 1030-1050 Ma. Although the quartzite is poorly layered, there does appear to be a gently dipping tectonic foliation defined, in part, by the illite-diaspore platelets.

Mileage
6.9 0.9 mi. Continue down Lyonsdale Road to intersection with Shibley Road at Gould’s Mills. Turn right.
7.1 0.2 mi. Turn left at Kosterville Road. Park in open lot on right.

STOP 5. SHIBLEY BRIDGE COMPLEX (30 MINUTES).

These interesting exposures are a continuation of the mega-quartz vein occurrence seen at the last three stops. The border with the granite is visible near the west end of the waterfall. Beneath Shibley Bridge there occurs a rock consisting of what looks like a quartz boulder conglomerate. However, close inspection will prove it to be the megaquartzite that has been deformed in such a manner to produce boulder-size rounded boudins of coarsely crystalline quartz in finer, grain-size reduced quartz that superficially resembles a sedimentary conglomerate.

At the waterfall, staining of the rock with sodium cobaltinitrite reveals the presence of a fine grained, potassic phase that takes the yellow stain and clear quartz grains that do not. Thin sections reveal that the potassic phases consist of muscovite and K-feldspar that were deposited by fluids in fractures that have rendered the quartzite a mass of sand grain-size fragments. Directly above the waterfall, a dark, red-stained band heads in the direction of the road, Careful sampling reveals that it consists of very coarse sillimanite intergrown with magnetite. This assemblage was a principal iron ore at Benson Mines and, given its composition, must be hydrothermal.

STOP 6. PRISMATINE-BEARING GNEISSES (60 MINUTES)

CUMUL-ATIVE MILEAGE	MILES FROM LAST POINT.	ROUTE DESCRIPTION
0.0 mi.	0.0 mi.	Turn around and head back southwest on Shibley Rd.
0.6 mi.	0.6 mi.	Turn left onto River Rd.
1.9 mi.	1.3 mi.	Turn right onto Pearl St. (River Road; Co. Rt. 39) and continue south.
2.6 mi.	0.7 mi.	Make slight left and continue on Pearl St. for 0.1 miles.
2.7 mi.	0.1 mi.	Turn left onto Moose River Rd. and head east.
5.3 mi.	2.6 mi.	North-South Rd. on left.
7.7 mi.	2.4 mi.	Boonville / Moose River Rd. on right.
12.3 mi.	4.4 mi.	1876 Red School House on right.
12.4 mi.	0.1 mi.	Turn left into dirt parking area by Moose River and park.

Follow the all-terrain vehicle path downstream for about 200 meters. The path passes through the stone foundations of the former Moose River tannery and then follows rapids as the Moose River heads southwest. Here, the river cuts through northwest-dipping, calc-silicate gneisses and quartzites. Stay high on the river bank until the rapids disappear. The path will descend and cross a small, wet, muddy creek bed. Afterwards, the Moose River pools and turns north and the first outcrops on the west side of the river are the prismatine-bearing rocks. Please exercise caution while walking among the river boulders and talus at the base of the outcrops. Also, please DO NOT USE HAMMERS at this stop and refrain from collecting prismatine specimens unless you're planning to study them scientifically; a future geologist will be grateful someday.

The feature of geologic interest at STOP 6 is the exceptionally well-developed prismatine crystals in coarse-grained, feldspathic lenses. Here, prismatine crystals form dark greenish-black, euhedral, elongated grains (up to 10 cm in length) that commonly display radiating patterns in feldspathic lenses one to three cm thick (Figure 11A). The prismatine crystals *appear* to have grown only within the plane of the foliation. However, upon closer examination, the prismatine grains are seen to be arranged randomly, but the longest and best-developed crystals formed parallel to the foliation plane. Because of this, Darling et al. (2004) inferred that non-deviatoric pressure conditions prevailed locally during prismatine formation. It should also be noted that a number of prismatine-bearing feldspathic lenses are located adjacent to fine-grained tourmaline + plagioclase + biotite–rich zones near the north end of the exposed rocks. In these locations, the prismatine-bearing feldspathic lenses texturally embay, cross-cut earlier foliation, and appear to form at the expense of the tourmaline-bearing zones (Figure 11B). The embayed country rocks, coarser grain size, and the random arrangement of the prismatine crystals led Darling et al. (2004) to interpret the feldspathic lenses and the prismatine found in them to be of anatectic origin.

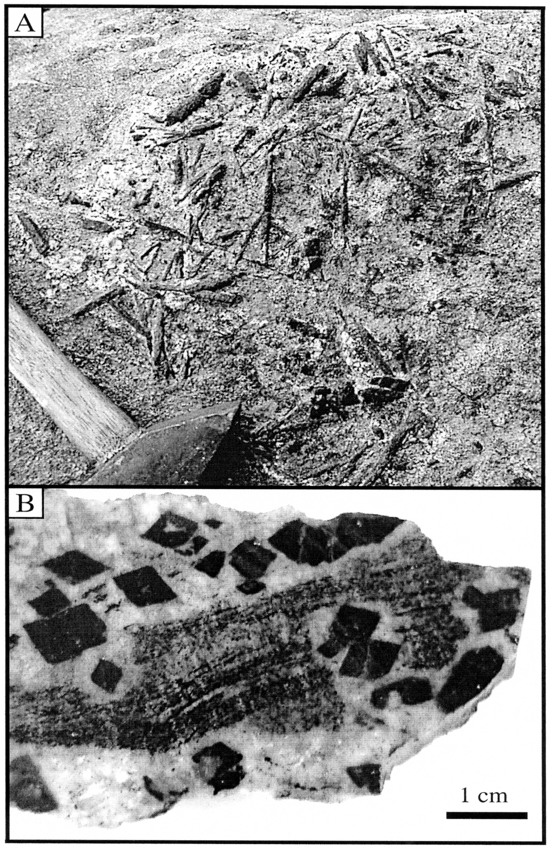

Fig. 11. - (A) Prismatine crystals (black) in coarse-grained feldspathic lens, taken parallel to plane of lens. Hammer for scale. (B) Euhedral prismatine (black) in coarse-grained feldspathic lens embaying fine-grained, foliated tourmaline + biotite + plagioclase–rich zones. *Taken from: Darling et al. (2004).*

Plagioclase, K-feldspar, minor quartz and rutile are the most common phases associated with prismatine, but biotite, cordierite, garnet and rarely sillimanite occur locally as well. The prismatine contains 0.73 to 0.79 formula units of B (out of 1.0) and has Mg / Mg + Fe between 0.70 and 0.73 (Table 3 of Darling et al., 2004). After determining the associated mineral compositions, Darling et al. (2004) proposed the following prismatine-forming reaction:

Tourmaline + sillimanite + biotite + cordierite → prismatine + rutile + melt (1).

This reaction is similar to a number of proposed prismatine-forming reactions from other granulite terranes (Grew, 1996), including those in sapphirine-free rocks found in the Reading Prong, New Jersey (Young, 1995), and in Waldheim, Germany (Grew, 1989). In those cases, garnet rather than cordierite was a proposed reactant.

Metamorphic temperatures and pressures are difficult to estimate from prismatine-bearing mineral assemblages as little is known about the stability of boron-rich kornerupine at pressures less than 10 kb (Schreyer and Werding, 1997). However, the prismatine occurs in proximity to low-variance metapelitic assemblages in the surrounding rocks. Specifically, thermobarometry calculations from net transfer and exchange equilibria record temperatures and pressures of 850° ± 20°C and 6.6 ± 0.6 kilobars for orthopyroxene + garnet assemblages and 675° ± 50°C and 5.0 ± 0.6 kilobars for cordierite + garnet + sillimanite + quartz assemblages (Darling et al., 2004). The former assemblage is interpreted to have formed during partial melting whereas the latter assemblage is interpreted to have formed on the early retrograde metamorphic path (Darling et al., 2004). The ~850°C temperatures derived from the orthopyroxene + garnet assemblage are reasonable for partial melting conditions. Although the cordierite + garnet + sillimanite + quartz assemblage occurs at STOP 6, it and the orthopyroxene + garnet assemblage are better developed further downstream at the second prismatine location (the westernmost open circle in Figure 4). These exposures can be reached by following the footpath on the south bank of the Moose River for a distance of about 400 meters.

Because many of the prismatine-bearing feldspathic lenses are saturated in both quartz and rutile, Storm and Spear (2009) intensely studied the prismatine-bearing lenses as part of a natural test of the titanium-in-quartz geothermometer of Wark and Watson (2006). Storm and Spear (2009) determined a wide range of metamorphic temperatures, specifically from 630 + 63 / -86 to 879 ± 8 °C, but most determinations fell between 700°C and 880°C (see Figure 8a of Storm and Spear, 2009). This is in good agreement with metamorphic temperatures determined by the aforementioned methods (Darling et al., 2004). Storm and Spear (2009) also provide convincing textural evidence that prismatine was locally replaced by leucosomatic quartz, most likely during melting of prismatine. Interestingly, it was the leucosomatic quartz that yielded the highest Ti-in-quartz temperatures (800-880°C; Figure 8a of Storm and Spear, 2009).

The timing of partial melting is unknown but is likely associated with either intrusion of the AMCG suite at ~ 1160-1145 Ma, or burial associated with the Ottawan phase of the Grenville Orogenic cycle and the associated intrusion of Lyon Mtn. granite at ~ 1050-1030 Ma (McLelland et al., 2010a).

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