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SMALLS FALLS REVISITED: A JOURNEY THROUGH A PALEOZOIC SEDIMENTARY BASIN

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INTRODUCTION

Organic-rich marine sedimentary rocks, a.k.a. black shales (e.g., Wignall, 1994), are the subject of great public and scientific attention nowadays. They are source rocks for the world's oil and gas. Current public interest is due in large part to advances in hydrofracturing or "fracking" that have changed the economics of the oil industry. For example, the Marcellus Shale, underlying portions of New York, Pennsylvania, Maryland, West Virginia, and Ohio, is a source rock for oil and natural gas, and is currently exploited by fracking in several of the above states. In Maine and New Hampshire, the Smalls Falls Formation, which once resembled the Marcellus, now appears as sulfidic schist and quartzite, having undergone metamorphism and deformation during the Acadian orogeny. As a result, Smalls Falls rocks have been thermally promoted far beyond the "oil window" of ~60 to 120°C and hence are not candidates for oil and gas exploration. This applies also to black shales and schists elsewhere in Maine, which similarly lack fracking potential for oil and/or gas due to high temperatures experienced during metamorphism.

"The rocks don't change from one generation of geologists to the next" (J. Haller, pers. comm., 1984). Nonetheless, our perceptions of the rocks, and our interpretation of their relations, do change. Figure 1 shows the pre-plate tectonic conception of regional geology as expressed fifty years ago, whereas Figure 2 shows, after decades of work, our current understanding of tectonic subdivisions. Prior to 1970 and the plate tectonic revolution, the geology of the northern Appalachians generally followed the stratigraphic model of Billings (1956) that was based on rocks in New Hampshire. Extending this system to the east into Maine proved problematic, however. At the 1970 NEIGC meeting, Boone, Boudette, and Moench established the now-classic Rangeley to Seboomook stratigraphic model (Boone et al., 1970) that is now widely accepted. Later workers (e.g., Hatch et al., 1983) successfully extended the Rangeley-based stratigraphic system to the west into New Hampshire. In other words, it proved easier to allow our interpretations to evolve from east to west than the reverse, due largely to the extensive deformation and metamorphism in western regions.

In the Silurian, following the Taconic arc-continent collisions, marine conditions persisted to the southeast between the enlarged Appalachian margin of Laurentia and several peri-Gondwanan terranes. The Central Maine Trough deepened rapidly to the east in the vicinity of Rangeley, Maine, as shown by significant increases in the stratigraphic thickness of formations compared to the area west of Rangeley. This abrupt deepening was named the *Silurian Tectonic Hinge* by Boone et al. (1970). The earliest Silurian sediments were the thinly laminated sandstones and siltstones of the Silurian (?) Greenvale Cove Formation, overlain by coarse clastic sediments of the Rangeley Formation, followed by quartz-rich sandstone turbidites of the Perry Mountain Formation. At this time, portions of the basin became so cut off from the general oceanic circulation that bottom waters became oxygen-deprived, including locally (but not pervasively) anoxic conditions and apparently rare euxinic (sulfidic) conditions. This was the depositional environment of the Smalls Falls Formation seen on this trip. Smalls Falls rocks are in turn overlain by the calcareous Madrid Formation (Siluro-Devonian) and the pelitic turbidites of the Devonian Seboomook Group, the latter correlated with the Littleton Formation of New Hampshire (Billings, 1956). Appendix A of this field trip guide contains a formation-by-formation description of the metasedimentary rocks of this region.

The area encompassed by this field trip in western Maine is underlain by metamorphic rocks of Paleozoic age that have undergone complex deformation to the southwest, and been intruded by numerous plutons of mostly Devonian age. In addition to the Bedrock Geologic Map of Maine (Osberg et al., 1985), the reader is referred to the geologic map of Western Interior Maine (Moench and Pankiwskyj, 1988b) that covers all of the field trip stops. A more recent regional geologic map by Moench et al. (1995) also covers the localities we will visit, but at a smaller scale. The reader is also referred to Boone et al. (1970), Moench and Boudette (1970), Moench (1971), and Moench (2006), for more extended descriptions of stratigraphy and structure in this region.

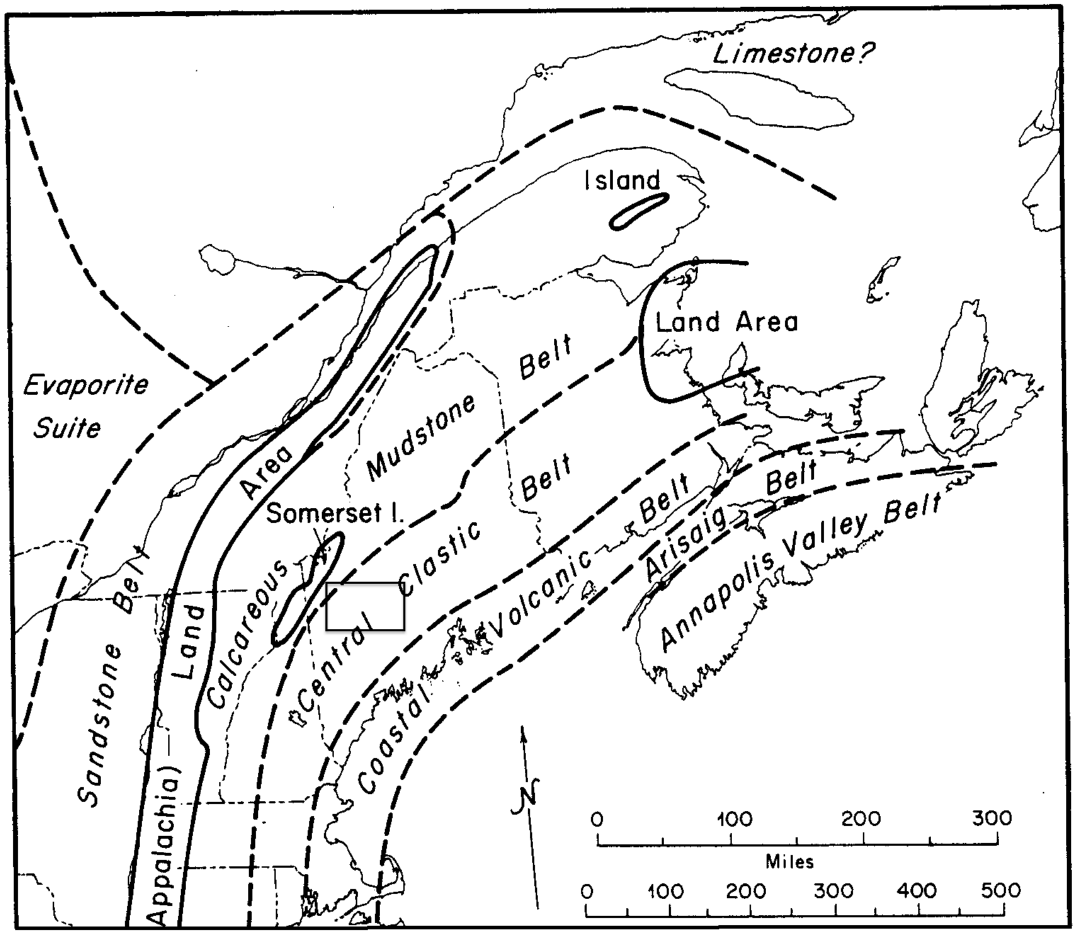

Figure 1. Lithofacies and paleogeography of the Ludlow Stage in the northern Appalachian region (after Boucot, 1968). Box shows area of this field trip.

TECTONIC FRAMEWORK

The Smalls Falls Formation crops out in the Central Maine Trough (CMT), primarily in the northwestern part. The Central Maine Trough, essential to understanding the regional tectonics, comprises marine sedimentary rocks of Silurian-Devonian age (Reusch and van Staal, 2012 and references therein). It extends from Connecticut through Massachusetts and New Hampshire to Maine. On its northwest flank, CMT strata conformably overlie Ordovician marine sedimentary and volcanic rocks of the Bronson Hill belt. Note that the Middle Ordovician volcanic rocks are unconformable on the Dead River Formation that has Gondwanan provenance and displays Penobscottian deformation. Contact relationships along the southeastern margin of the CMT are varied. In southern Maine, CMT strata are difficult to distinguish from strata of the Merrimack Trough. In south-central Maine, CMT strata are in fault contact with the Liberty-Orrington belt. In New Brunswick, CMT strata overlie the Miramichi belt via a Salinic (Silurian) unconformity. Paleocurrent data and stratigraphic relationships strongly suggest the CMT received sediment from the northwest during the Early Silurian, and subsequently also received sediment from the southeast (e.g., the Rangeley Formation along the northwestern margin has northwestern provenance, and the Vassalboro Group along the southeastern margin has southeastern provenance).

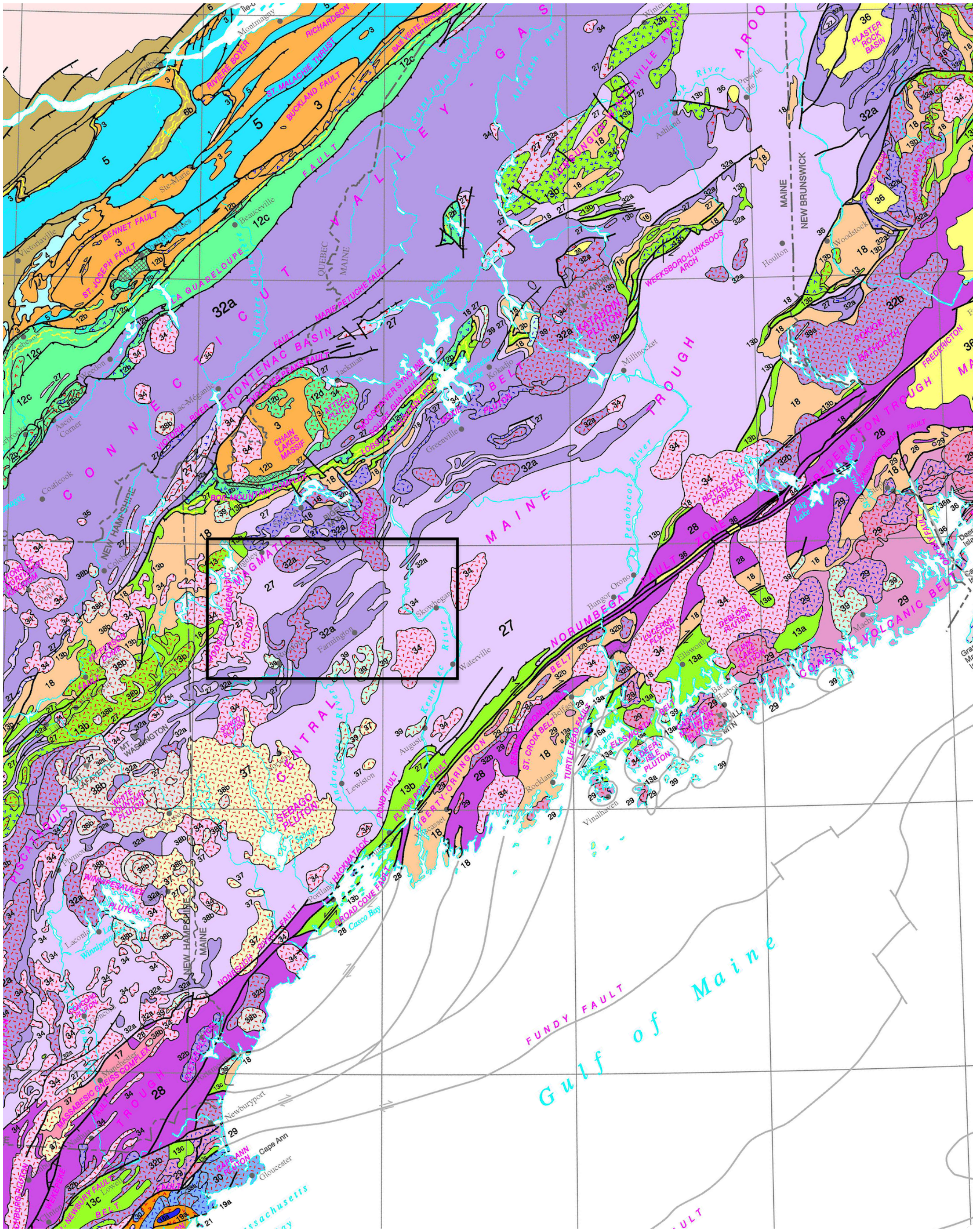

Figure 2. Generalized geologic map of portions of Maine and adjacent regions showing locations of major lithotectonic terranes (after Hibbard et al., 2006). Note correspondence between this map and the Boucot map: Calcareous Mudstone Belt has become Connecticut Valley-Gaspé Trough, Central Clastic Belt has become Central Maine Trough; Coastal Volcanic Belt retains its name. Box shows area of this field trip. See Hibbard et al. (2006) for description of numbered features.

Regional stratigraphic relationships suggest the CMT occupied a forearc setting with respect to a post-Taconic continental arc that lay to the northwest on the Taconic-modified Appalachian margin of Laurentia (Hussey et al., 2010; Reusch and van Staal, 2012). Rocks of the Liberty-Orrington-Miramichi belt constitute a segment of the Brunswick subduction complex between the forearc basin and trench located in the Fredericton Trough farther southeast. Recent detrital zircon results indicate the Fredericton Trough marks the locus of a formerly wide basin (Tetagouche-Exploits). Closure of the basin during the Silurian resulted in emergence of the Brunswick subduction complex, documented by an erosional influx along the southeastern margin of the CMT (e.g., Vassalboro Group).

Early Devonian strata of central and northern Maine, including the Madrid Formation and Seboomook Group, are widely interpreted as a clastic wedge deposited in a foreland basin that lay northwest of a growing Acadian orogen (Bradley, 1983; Bradley et al., 2000; Bradley and Tucker, 2002). The basin migrated northwestward in front of the growing orogen, eventually emerging above sea level and culminating with deposition of the Catskill delta. The Smalls Falls Formation was deformed during this Early Devonian event. The northwestward migration of the basin and the deformation front are constrained by a host of dated plutons (Bradley et al., 2000). All of these rocks display a steeply dipping foliation that is axial planar to map-scale folds such as the Brimstone Mountain anticline and Bear Hill syncline between Rangeley and Phillips (Moench and Pankiwskyj, 1988b). Moench was much interested in early, syn-sedimentary structures that he related to down-to-basin extensional faults such as the Rumford allochthon (Moench and Pankiwskyj, 1988a; Reusch et al., 2010)

"REGIONAL CONTACT METAMORPHISM"

The rocks of west-central Maine are polymetamorphosed and intruded by plutons[1] so numerous that their overlapping contact metamorphic aureoles have in places become regional features. Charlie Guidotti (pers. comm.) coined the term "regional contact metamorphism" to describe this high-T and low-P pattern. Figure 3 shows in outline the major plutons of western Maine and the general nature of metamorphic isograds that surround them. In detail, the metamorphic history in western Maine is highly complicated and involves several thermal events that are variably superimposed on each other. These are commonly referred to as the M1, M2, and M3 events. Guidotti et al. (1996, p. 176) describe M1 as "a regionally pervasive greenschist event, possibly associated with a deformation that produced a crenulation cleavage." They continue: "... these observations indicate development of a micaceous foliation before any of the later events which attained high grades. This implies at least some early recrystallization of these rocks -- probably syntectonically." There is no firm date for the M1 event other than that it preceded the higher grade M2 metamorphism associated with the emplacement of Devonian plutons. The M2 was a low P (~3 kb) - high T static event that produced in pelitic compositions widespread staurolite- and andalusite-bearing assemblages. However, Guidotti et al. (1996, p. 176) caution that "M2 has been associated with the intrusion of early Devonian granites, but this has been demonstrated only locally for the Lexington pluton to the east." M3, which overprinted M2, was a slightly higher P (~3.5 kb) event that produced sillimanite-bearing assemblages. M3 was also associated with emplacement of Devonian plutons, leading to overlapping contact aureoles and the "regional contact metamorphism" described here. To the south of our field trip area, close to the margin of the Sebago batholith, there was also an M4 event that reached sillimanite-K-spar facies. The most recent review that conveys an idea of this complexity is Guidotti and Johnson (2002).

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[1] We note that many igneous intrusions in Maine are called batholiths in the older literature, but plutons in more recent papers. For this field trip there is no practical difference; we use the terms interchangeably.

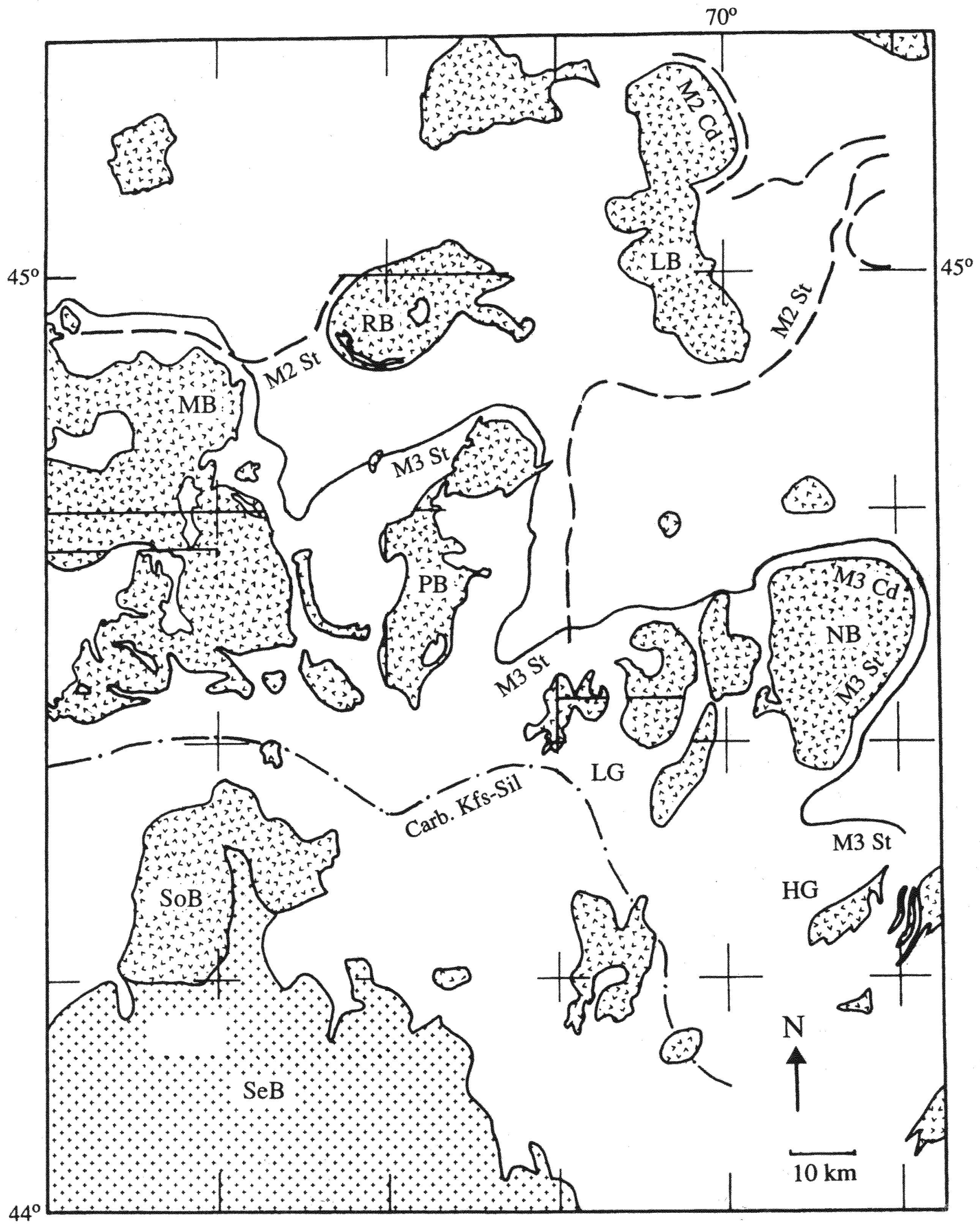

Figure 3. Map showing metamorphic isograds and Devonian intrusives in area of the field trip. This map may be correlated with geologic map in Figure 2 by matching pluton shapes. Metamorphic isograds are M2 (solid) staurolite; M2 (dashed) cordierite; M3 staurolite or cordierite; Carb.Kfs.Sil (dash-dot) Carboniferous sillimanite-K-feldspar. Abbreviations as follows: HG, Hallowell pluton group; LB, Lexington batholith; LG, Livermore Falls pluton group; MB, Mooselookmeguntic batholith; NB, Norridgewock batholith (now called Rome pluton); PB, Phillips batholith; SE, Sebago batholith; SoB, Songo batholith; RB, Redington batholith. After Guidotti and Holdaway (1993).

THE SMALLS FALLS FORMATION

The Smalls Falls Formation was named after its type locality: the Smalls Falls Picnic Area in the Sandy River Plantation between Rangeley and Phillips (Fig. 4). See Appendix A for the original description of this formation. The rocks at these falls, possibly named after Jesse Small, a miller who resided in the area around the time of the Civil War, were mapped as Silurian, Wenlock to Ludlow, by Osberg et al. (1968). This age assignment has been recently challenged (albeit with very limited sampling) by detrital zircon data that suggest a younger Early Devonian (Pragian) age (Bradley and O'Sullivan, 2016). On this trip we will offer ideas on what the basin may have looked like during Smalls Falls time, and how the organic-rich sediments responded to the Acadian orogeny. There are many rusty-weathering schists in Maine, but we only consider rocks part of the Smalls Falls Formation if they have the proper stratigraphic position (see Appendix A). Guidotti and Van Baalen (2001) and Van Baalen (2006) provide a general introduction to many aspects of the Smalls Falls Formation, including environmental issues related to arsenic.

The Smalls Falls and correlative formations units crop out for a distance of over 400 km along strike in New England. In far northern Maine, at the limit of exposures that can reasonably be correlated with the Smalls Falls Formation, the rocks have never been deeply buried, and hence the metamorphic grade is very low (lower greenschist and below). Proceeding along strike to the south and west, however, the metamorphic grade rises considerably, because the rocks now on the surface reflect successively deeper levels in the crust. At its type locality, the metamorphic grade is staurolite (for pelitic rocks) and in western Maine and for much of central New Hampshire, in the so-called sillimanite plateau, the metamorphic grade is sillimanite. Far to the southwest of the area of this field trip, on the Massachusetts-Connecticut border, where rocks from deep in the crust are now exposed on the surface, the metamorphic grade is pyroxene-granulite. As a result of this uplift and erosion, a tilted cross section of a large portion of the crust in northern New England presents a natural laboratory where the response of similar rocks to varying degrees of metamorphism can be studied.

Figure 4. Smalls Falls with lower plunge pool. Note rusty nature of outcrops, due to weathering of abundant Fe-sulfide minerals (pyrrhotite and pyrite).

METAMORPHISM OF SULFIDE-RICH PELITIC ROCKS

The petrologic aspects of black shales are mainly related to the relative abundance of Fe-sulfide minerals commonly present, even if deposition did not involve a truly anoxic environment. Several interesting considerations arise due to the presence of Fe-sulfides in shales that undergo metamorphism. In addition to the more narrowly mineralogical features discussed in the next section, these include: (1) impacts on the silicate bulk composition and resultant silicate and opaque mineral assemblages, (2) effects on reactions between the silicates and Fe-sulfides, and (3) impacts on the composition of the fluid phase present during metamorphism. For metapelitic rocks in New England, descriptive aspects of (1) have been considered by Guidotti (1970), Guidotti et al. (1975, 1977), and Robinson et al. (1982). Thompson (1972) developed the theoretical aspects of (2), and details of specific reactions have been presented by Tracy and Robinson (1988). For rocks in New England, (3) has been discussed by Guidotti (1970) and especially Henry (1981).

The impact of sulfide content on the effective silicate bulk composition is most easily appreciated by considering as a first approximation that Fe^{2+} in a rock that is "tied up" in sulfides is unavailable to enter the silicate minerals. As a consequence, minerals that are Fe^{2+}-rich relative to Mg will be absent (e.g., garnet, staurolite, chloritoid, and ilmenite) and the minerals that are present will be Mg-rich (e.g., phlogopite instead of biotite). As a result, at a given grade of metamorphism, metamorphosed black shales will, in addition to an Al-silicate, contain various combinations of assemblages of Mg-rich minerals: cordierite, phlogopite or Mg-rich biotite, and Mg-rich chlorite. Where the assemblages of such rocks are merged with assemblages in associated metapelites having bulk compositions of common shale, one can define more precisely the metamorphic mineral facies present (Thompson, 1957). By using this approach, Guidotti et al. (1975) defined rigorously the metamorphic mineral facies for the middle metamorphic grades of the low-P and high-T metamorphism that occurred in western Maine.

As an example, referring to Figure 5, "normal" metapelites having bulk composition **x** will contain staurolite, whereas sulfide-rich rocks in which Fe is not available to form silicates, have an effective bulk composition **y** and thus will contain cordierite instead of staurolite. This mineralogical difference explains why Smalls Falls rocks at their type locality, at staurolite grade metamorphism, lack staurolite. The metamorphic facies concept holds that, for a given bulk composition, the mineral assemblage is a function of P and T, whereas for a given P and T the mineral assemblage is a function of bulk composition. The Smalls Falls rocks provide an excellent example of this principle.

A further effect of the increased sequestering of Fe by Fe-sulfide is that it reveals a change in the Ti-saturating phase that occurs in the rocks, resulting in the formation of rutile instead of ilmenite. Accordingly, whereas Smalls Falls rocks may contain rutile, adjacent rocks of the Perry Mountain Formation contain ilmenite. The approach for a theoretical understanding of this change has been developed by Thompson (1972). A key aspect of this development is that as metamorphic grade increases, the pyrite originally present in black shales reacts with the silicate minerals and is converted to pyrrhotite, by the model reaction:

$$FeS_2 + Fe = 2FeS$$

As a consequence, an even larger fraction of the Fe in the rock becomes sequestered into sulfide and so is unavailable to enter the silicates. Thus, the bulk composition and mineral assemblage aspects described above become even more amplified, and as a result the newly formed silicates tend to be Mg-rich. Details of some of these sulfide-silicate reactions are presented by Tracy and Robinson (1988). Such reactions explain why pyrrhotite predominates in metapelites, and why pyrite persists only in rocks that at the sedimentary stage contained particularly large modal amounts of pyrite, e.g. >> 10-15 vol %. Overall, it becomes clear that the specific Fe-sulfide contained in a metamorphosed black shale is a function of both original S content of the rock, and metamorphic grade.

Note also, following Thompson (1972), that the nature of the Ti-saturating phase in sulfide- and graphite-rich rocks changes during metamorphism, from ilmenite to rutile. Once again, the siderophile behavior of Fe is responsible.

Finally, the sulfide-silicate equilibria typically involve the gas species CO_2, H_2S, CH_4, and SO_2 as well as H_2O. Hence, these gases impact the composition of the metamorphic C-O-H-S fluid phase, especially with regard to its deviation from being solely H_2O. The study by Henry (1981) was especially interesting in this context, in showing that sulfidation equilibria affected the composition of the fluid phase such that on the scale of only cm, continuous reactions among silicates were systematically facilitated, thereby demonstrating very local, buffering control by the rocks on the fluid composition.

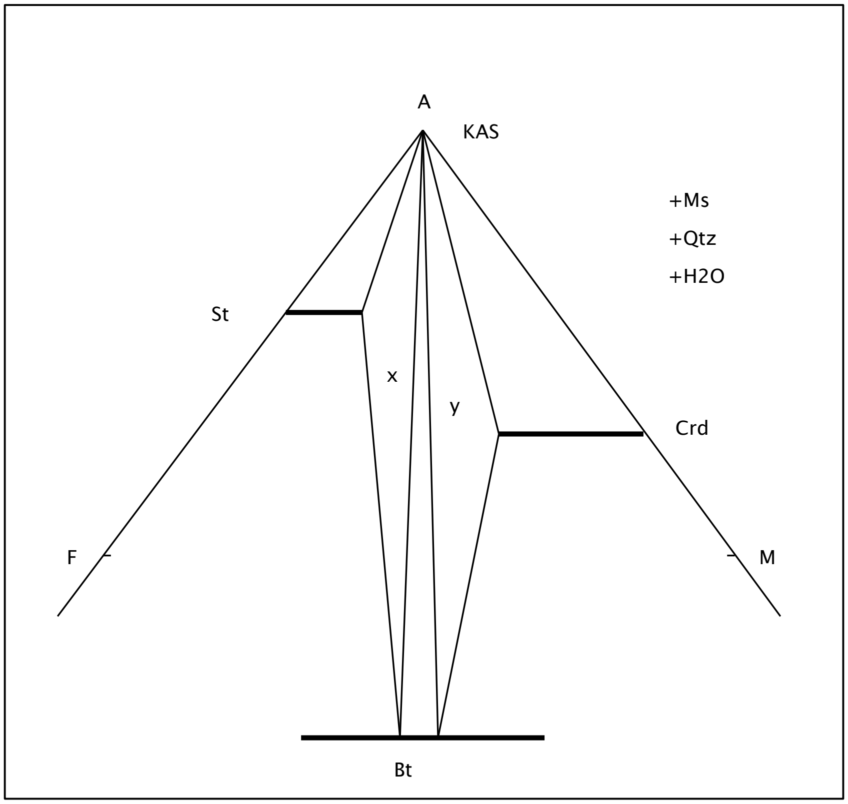

Figure 5. AFM diagram after Thompson (1957) for metapelites at upper staurolite zone. A, Al_2O_3; F, FeO; M, MgO; KAS, either kyanite, andalusite, or sillimanite; St, staurolite; Crd, cordierite; Bt, biotite; Ms, muscovite; Qtz, quartz.

WHOLE-ROCK GEOCHEMISTRY

Whole-rock analyses for major, minor, and trace elements (including rare earth elements, REE) were acquired on 21 samples of black shale and black schist from the Smalls Falls Formation. Most samples were obtained from small cores (drilled in 2015) in order to minimize oxidation and weathering. Basic statistics are listed in Table 1, together with data for average black shale, for comparison. The analyzed samples, from areas of lower to upper greenschist grade and amphibolite grade, were collected in order to evaluate effects of metamorphism on bulk compositions of these strata, and to constrain the redox state of bottom waters and pore fluids during sedimentation (Slack et al., 2016). Distinctive features of these compositions include generally low MnO and P_2O_5 (<0.1 wt % each), plus low TOC (<1.5 wt %) but high total S (1.2-9.7 wt %). Despite the generally high S contents, base and related transition metals are uniformly low (Co <40 ppm, Cu <65 ppm, Ni <85 ppm, Pb <35 ppm, Zn <135 ppm). Relative to median or average contents of black shales worldwide (Table 1), the Smalls Falls samples have significantly lower TOC and V, moderately lower Cu and Zn, and higher Fe_2O_3, Sn, and As.

Table 1. Basic statistics for bulk compositions of black shale and black schist from the Smalls Falls Formation, northern and western Maine

Oxide/Element	Mean	Stdev	Minimum	Maximum	Avg Black Shale*
Al_2O_3 (wt %)	13.89	3.44	7.35	19.65	13.23
Fe_2O_3	7.16	2.30	2.24	12.38	2.86
MnO	0.06	0.06	0.01	0.31	0.05
MgO	2.30	0.77	0.85	3.23	1.16
CaO	1.85	0.88	0.42	3.78	2.10
K_2O	3.06	0.78	1.33	4.34	2.41
P_2O_5	0.06	0.04	0.00	0.11	0.32
TiO_2	0.68	0.15	0.33	0.92	0.33
TOC**	0.82	0.24	0.43	1.48	3.20
CO_2	0.38	0.55	0.01	1.45	n.r.
Total S	3.28	1.82	1.22	9.67	n.r.
As (ppm)	92.5	84.3	30	280	30 ± 3
Au (ppb)	9.1	9.2	5	38.0	7 ± 1
Ba	446	156	187	801	500 ± 20
Ce	68.6	22.3	25.7	107	58 ± 3
Co	22.6	7.48	12.6	38.6	19 ± 1
Cr	69.5	17.7	30	100	96 ± 3
Cu	43.5	11.6	24	64	70 ± 3
La	31.9	10.4	11.7	48.9	28 ± 1
Mo	28.7	17.8	3	61	20 ± 1.5
Ni	56.7	14.5	34	82	70 ± 2
Pb	19.5	6.24	11	34	21 ± 1
Sb	1.6	0.76	0.1	2.6	5.0 ± 0.5
Sc	13.8	4.01	6	21	12 ± 1
Sn	5.9	7.44	1	29	3.9 ± 0.3
Th	11.4	3.28	4.2	17.4	7.0 ± 0.4
U	7.49	3.86	2.87	15.2	8.5 ± 0.8
V	114	39.4	61	217	205 ± 15
Y	26.7	7.86	13.8	45.6	26 ± 1
Zn	65.5	30.4	6	132	130 ± 10
Zr	186	56.0	97.3	331	120 ± 5

*Major elements including TOC (medians) from Vine and Turtelot (1970);
MnO, P_2O_5, trace elements, and REE (means) from Ketris and Yudovich (2009)

**Includes organic C + graphitic C

n.r., not reported; all analyses by fusion ICP-AES (no data for SiO_2 or Na_2O)

In Figure 6 the high S/non-carbonate C ratios of the Smalls Falls samples are especially distinctive. Such uniformly low contents of non-carbonate C suggest one of three processes, as show in the inset (1) hydrothermal S overprint, (2) thermal or metamorphic loss of C, or (3) euxinic marine deposition. Absence in all samples (and outcrops) of epigenetic, sulfide-bearing veins rules out the first possibility. The third possibility is considered unlikely because all of the Mo concentrations (Table 1) are below the threshold of 100 ppm that reflects persistently euxinic (sulfidic) conditions (Scott and Lyons, 2012). A caveat in this context is the presence of uniformly low Mo in modern sediments of the euxinic Black Sea, but this is linked to the isolated nature of this water body, which is essentially cut off from recharge by Mo-rich oxygenated waters of the open ocean (including the Mediterranean). Given these constraints, the most logical explanation for the distribution of data on Figure 6 is a loss of C via thermal or metamorphic effects. The high temperatures (and pressures) of the greenschist- to amphibolite-grade metamorphic conditions of the samples are consistent with this mechanism, but a loss of C (and some metals) after deposition but prior to metamorphism must also be considered. Scott et al. (2017) have recently determined a loss of ca. 30% organic C in one sample from the Late Devonian-Early Mississippian Bakken Formation in North Dakota, attributed to thermal effects during late diagenesis at or above the thermal window for oil generation (~60-120°C). An even greater loss of C may have occurred in the Smalls Falls Formation, reflecting heating during both late diagenesis and multiple episodes of regional metamorphism. Also relevant to this issue are the high contents of V, Ni, and to a lesser extent Mo that occur in many crude oils (e.g., Lewan, 1984; Ventura et al., 2015), which are seldom discussed in studies of black shale geochemistry, but are important to consider because the likely removal of these metals (in unknown proportions) during oil generation means that common redox proxies such as V/(V+Ni) must be used with caution in applications to ancient black shales such those of the Smalls Falls Formation. This caution is supported by the low mean V content of 114 ± 39.4 ppm in our samples (Table 1), relative to that of average black shale worldwide (205 ± 15 ppm), consistent with a loss of substantial V during oil generation and/or later regional metamorphism of Smalls Falls rocks.

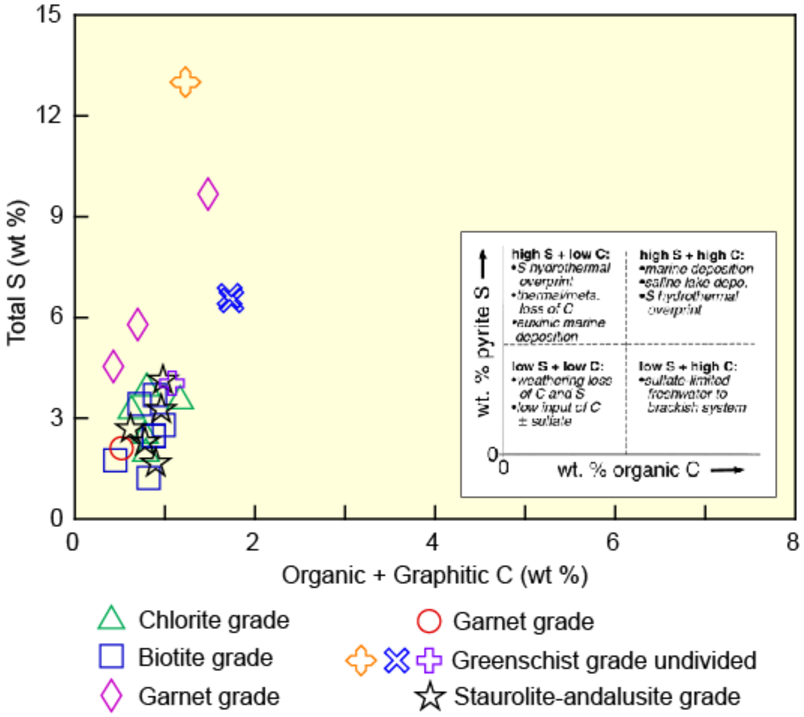

Figure 6. Organic + graphitic C vs Total S plot of bulk compositions of black shale and schist from the Smalls Falls Formation. All samples have high ratios of S/(organic+graphitic C), consistent with thermal and/or metamorphic loss of C (see text). Inset from Lyons et al. (2000).

Numerous geochemical proxies have been used for evaluating the redox states of bottom waters and pore fluids during sedimentation. However, in many cases these proxies yield conflicting results, for a variety of reasons. Among various commonly applied proxies, one of the most robust is a plot of total organic C (including graphitic C) vs Mo (Fig. 7). Based on work by Scott and Lyons (2012), the relatively low Mo contents of the Smalls Falls samples—despite mostly high to very high total S (Fig. 6)—suggest that the bottom waters during sedimentation were mainly suboxic to anoxic, and lacking persistently euxinic (sulfidic) conditions given the absence of Mo concentrations >100 ppm. It is possible that samples having <25 ppm Mo record oxic bottom waters (Scott and Lyons, 2012), but this could also reflect dilution by quartz or other clastic components. Importantly, the above interpretations assume that little if any Mo was lost from the sediments during oil generation, and/or during later metamorphism in the region.

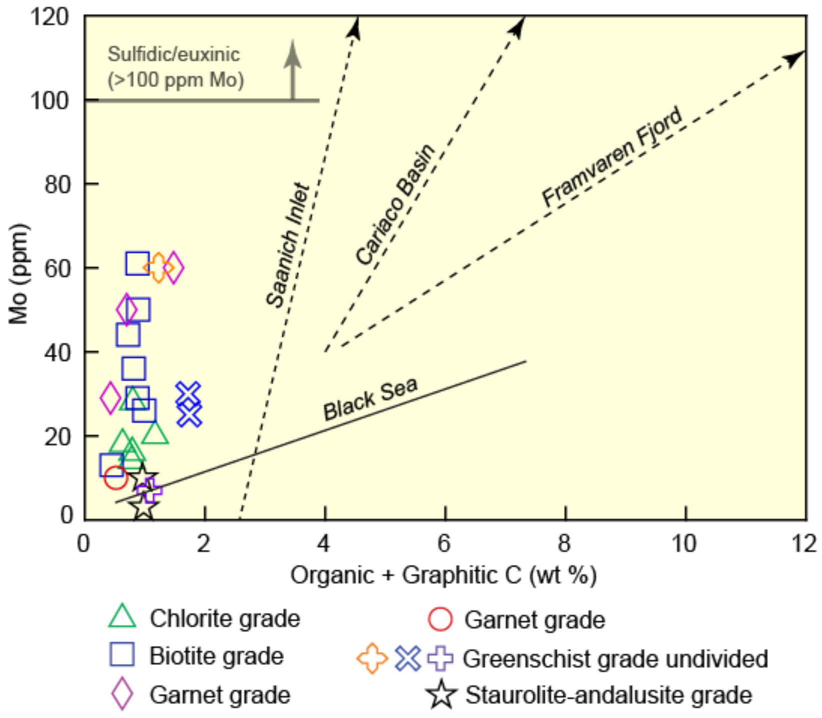

Figure 7. Organic + graphitic C vs Mo plot of bulk compositions of black shale and schist from the Smalls Falls Formation. Relatively low Mo contents suggest a range of redox conditions in bottom waters, from suboxic to anoxic (see text). Trends for anoxic to euxinic/sulfidic sediments of the Black Sea, Framvaren Fjord (Norway), Cariaco Basin (offshore Venezuela), and Saanich Inlet (British Columbia) are from Algeo and Lyons (2006). Mo limit for persistently sulfidic/euxinic conditions is from Scott and Lyons (2012).

PROVENANCE AND ORIGIN OF THE SMALLS FALLS FORMATION

The Smalls Falls Formation originated as organic-rich clastic sediments that were deposited into a basin whose bottom waters underwent seemingly abrupt changes at the beginning and end of Smalls Falls time. There is good evidence that the source region for these sediments probably lay to the north and west (present day coordinates), but the cause of the abrupt changes in bottom water chemistry is more speculative. We consider some modern-day analogues in the context of Silurian tectonics in order to suggest a likely scenario.

Insights into the provenance of the original sediments come from plots of immobile trace elements. Figure 8 shows that, with one exception, all samples have Th/Sc ratios >0.5, which suggests predominantly felsic sources. The trend and range of Zr/Sc ratios is consistent with sediment recycling and zircon addition. A ternary plot of Th-Sc-Zr/10 (Fig. 9) shows that data for all samples from greenschist-grade outcrops have bulk compositions that fall in the field for continental arcs. A source from a predominantly felsic arc is thus proposed, an interpretation supported by the elevated Sn contents of some of the analyzed samples, which range up to a maximum of 29 ppm (Table 1). For comparison, average Sn in black shale globally is 3.9 ± 0.3 ppm (Ketris and Yudovich, 2009). These mostly high Sn contents, together with the elevated Th/Sc ratios, suggest an evolved felsic plutonic and/or volcanic source within a former continental arc. In an earlier study, Cullers et al. (1997) reached a similar conclusion for the Smalls Falls Formation, on the basis of trace element ratios and REE patterns, albeit for a small data set (two samples).

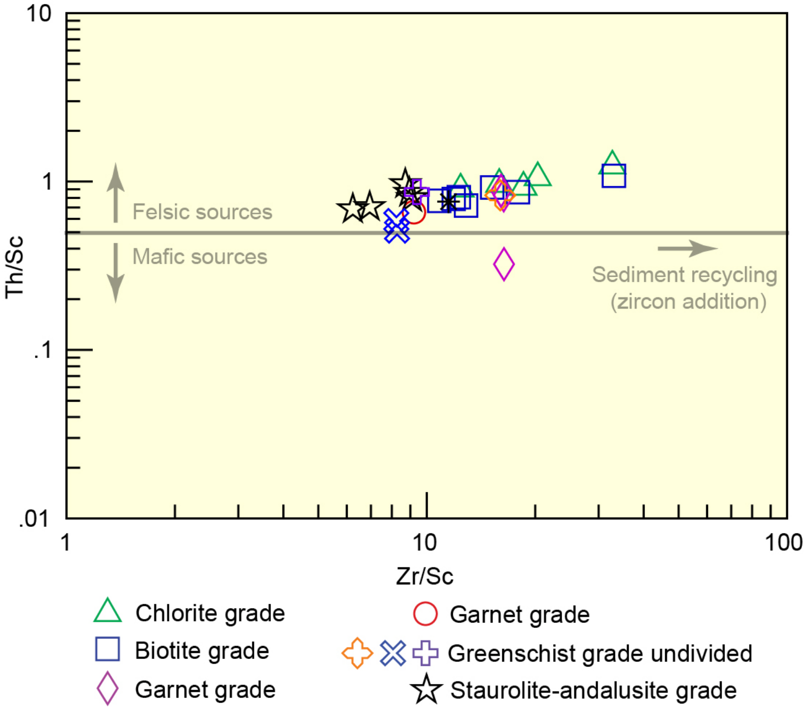

Figure 8. Plot of Zr/Sc vs Th/Sc of bulk compositions of black shale and schist from Smalls Falls Formation. Relatively high Th/Sc ratios of >0.5 suggest predominantly felsic sources; Zr/Sc ratios >30 imply zircon addition via sediment recycling. Plot from McLennan et al. (1993).

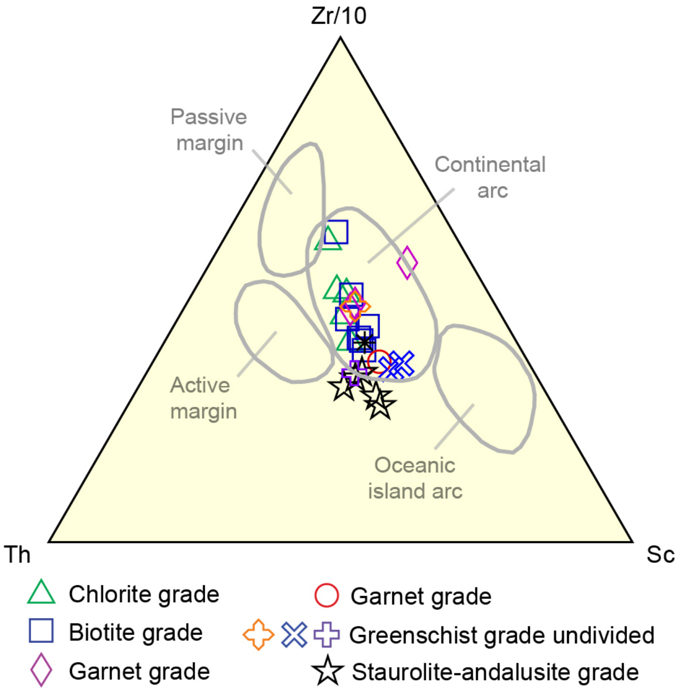

Figure 9. Ternary Zr-Th-Sc plot of bulk compositions of black shale and black schist from Smalls Falls Formation. Except for samples from highest metamorphic grade (staurolite-andalusite), all data fall within field for continental arcs. Plot from Bhatia and Crook (1986).

A source region lying to the northwest is considered most likely (Bradley and O'Sullivan, 2006). Bradley and Hanson (2002) reported predominantly northwest paleocurrent directions for the Smalls Falls Formation. Given the early Ludlow graptolite age of this unit, a Middle Silurian or older arc is required. Potential candidates include Silurian felsic igneous rocks to the northwest, such as the 443 Ma Attean pluton in northwestern Maine (Gerbi et al., 2006) and the Ascot Complex in southeastern Québec. Older Ordovician arcs of this region also are plausible sources, but are undermined by the lack of Ordovician ages in the detrital zircon histogram for the Smalls Falls Formation (Bradley and O'Sullivan, 2006).

Several possible modern analogues can be invoked for the basin—or basins—in which the Smalls Falls sediments accumulated. Certain geochemical signatures (e.g., generally low MnO and locally elevated Mo concentrations) suggest that the basin(s) had suboxic to periodically anoxic bottom waters. Euxinic (sulfidic) conditions are implied, at least locally, by the presence of very small (~5-6 μm) pyrite framboids in one sample from northern Maine (Slack et al., 2016). However, it is important to note that these redox interpretations are greatly constrained by the effects of high temperatures reached prior to and during regional metamorphism, possibly involving the selective removal of unknown quantities of trace elements such as Ni, V, and possibly Mo. Another important point is that the Smalls Falls Formation extends for over 400 km along strike (Osberg et al., 1985), although not in continuous outcrop; this discontinuity may reflect tectonic dismemberment from an original contiguous basin. Alternatively, non-deposition, a Devonian tectonic overprint, or deposition within separate basins may be the explanation[2]. However, the great strike length of the Smalls Falls Formation cannot be attributed solely to tectonic events prior to or during the Acadian orogeny, hence any proposed analogue involving a modern anoxic basin should have similar maximum dimensions. Few candidates are known that exclude sites of oceanic spreading centers floored by basalt (e.g., Red Sea) or that have relatively small diameters (e.g., 150 km for Cariaco Basin north of Venezuela). The large Black Sea (~1200 km diameter) is also ruled out as an analogue because it

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[2] We cannot rule out diachronous deposition into separate basins. The detrital zircon data from Bradley and O'Sullivan (2016) allow this interpretation.

has a restricted setting as an intracontinental rift basin in which the bottom waters are uniformly euxinic/sulfidic (more reducing than anoxic). We suggest that a modern analogue could be the Southern California Borderland, west of Los Angeles, where seven separate suboxic to anoxic basins and intervening rises in total extend over a distance of nearly 400 km (Christensen et al., 1994; Chong et al., 2012). The sediments in most of these basins have several percent or more of organic C, thus being similar to inferred protoliths of the black shales and black schists that make up the Smalls Falls Formation.

More detailed work on the bulk geochemistry of this formation, both stratigraphically at previously sampled sites and at new sites, could help to refine our understanding of how the sediments of this distinctive Paleozoic unit accumulated, and the effects of subsequent diagenesis and regional metamorphism.

The question of what caused abrupt changes in bottom water chemistry, from fully oxygenated to oxygen-deprived, locally anoxic, must be considered in light of what we know of Silurian tectonics in the region. Moench (2006, p. 84) wrote "*The abrupt contact between the Perry Mountain and Smalls Falls Formations marks a change from aerated to strongly reducing conditions, probably the result of abrupt susbidence [sic] that produced a closed, euxinic basin.*" And then, re the sharp contact between Smalls Falls and Madrid, *"These features signal the arrival of energetic, probably oxygenated currents that ended the euxinic conditions of Smalls Falls deposition*." Reusch and van Staal (2012, p. 254) in turn suggested that "*A mechanism for the black shale deposition invokes isolation of the forearc basin as a result of collision-induced uplift of the adjacent, partly subjacent subduction/collision complex (Dickinson and Seeley, 1979). The Central Maine–Matapedia forearc experienced a general shallowing, due to a combination of basin infilling and uplift."*

We suggest four processes that may have been at work, either individually or in combination:

(1) rising sea level;
(2) increased productivity, including a widespread algal bloom that enhanced eutrophication, possibly triggered by changes in marine circulation due to tectonic events;
(3) changing marine circulation that greatly limited, or eliminated, recharge with oxic seawater due to various factors (e.g., newly formed submarine sill or horst as in Southern California Borderland and Cariaco Basin), or different patterns of seawater circulation as in Arabian Gulf; and
(4) a change to very slow sedimentation with minimal detrital influx that produced a 'condensed section.'

For the lower contact of the Smalls Falls Formation, we suggest that uplift accompanied by extension could have produced horsts and grabens (similar to the modern-day North Sea). The grabens would be an ideal site for black shale deposition, as in the Southern California Borderland discussed above. Another mechanism to explain the abrupt transition across the Perry Mountain Formation-Smalls Falls Formation contact is the mid-Silurian emergence of the Brunswick subduction complex (BSC) on the southeastern margin of the Central Maine Trough (Reusch and van Staal, 2012). This tectonic event is critical to understanding the Silurian geology of Maine, as it is the basis for the Salinic system that dominated the Silurian, and culminated with closure of the Tetagouche-Exploits basin on the Dog Bay Line (Reusch and van Staal, 2012). The BSC emergence may have affected sedimentation on the northwestern margin of the basin in several ways: First, it would have modified internal circulation by restricting the exchange with the open ocean to the southeast. Second, extensive erosion as documented by strata of the Vassalboro Group implies nutrient loading and eutrophication. Third, an emergent landmass might have shed a buoyant freshwater lid across the narrowing Central Maine Trough to the northwest, thus further amplifying eutrophication. An alternative mechanism for the onset of black shale deposition entails the formation of isolated basins within an overall extensional upper plate setting (Tremblay and Pinet, 2005; Reusch and van Staal, 2012).

The transition across the Smalls Falls Formation-Madrid Formation contact also begs for an explanation. The map pattern suggests the possibility of sedimentary interfingering, but we believe the map pattern is tectonic and not depositional, as Boone et al. (1970) noted that the contact is sharp and conformable. A simple mechanism is an increase in sedimentation rate, such that dilution by calcareous and siliciclastic sediment terminated black shale deposition in advance of the Acadian orogeny. However, the calcareous nature of the Madrid, and in fact the calcareous uppermost portion of the Smalls Falls, also requires consideration of a source region for the carbonates. Offshore reefs from the eastern approaching landmass are one possibility; another is a carbonate bank akin to the Brionçonnais zone in the Alps (e.g., Hsu, 1994). Increased sedimentation from the source region evidently brought black shale deposition to an end, as reflected by the siliciclastic strata of the Madrid Formation.

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APPENDIX A - STRATIGRAPHY

(a) Greenvale Cove Fm. [Sg], Silurian, Lower Llandoverian? Mainly a slightly rusty weathering, light grey, laminated and thinly bedded feldspathic meta-sandstone and meta-siltstone, commonly calcareous. The thickness is 200 m. Originally mapped as Upper Ordovician by Boone et al. (1970), Moench et al. (1995) mapped it as Silurian.

(b) Rangeley Fm. [Sra, Srb, Src], Llandoverian to Wenlockian? A thick formation subdivided into three members, A, B, and C with a total thickness of about 3 km in its type area near Rangeley. A coarse conglomerate followed by moderately rusty-weathering, thin to thick, interbedded metapelite and impure quartzites; commonly showing graded interbeds. Some massive arkosic sandstone and thin conglomerate beds throughout. Member A, containing coarse boulder conglomerate, is 1200 m thick, and correlates with the Clough Quartzite of western New Hamphshire. Rangeley A conformably overlies the Greenvale Cove. Member B has a similar thickness, and represents a generally finer grained, more distal facies. Member C is yet finer-grained, with a thickness of about 600 m. The rusty weathering reflects the presence of minor-up-to-5% pyrrhotite . Graphite and ilmenite are other typical opaque accessory minerals. Many Rangeley rocks weather to a characteristic brick-red color.

(c) Perry Mountain Fm. [Sp], Silurian, Wenlockian? Thin to thick, graded interbeds of metapelite and fairly pure quartzite. Ilmenite is the typical opaque mineral, with pyrrhotite and graphite sparse or absent in some samples. Hence, outcrops have a grey weathering surface. A very few samples have magnetite present. Thickness is about 400 m. The boundary between this unit and the overlying Smalls Falls Fm. is sharp and conformable.

(d) Smalls Falls Fm. [Ssf], Silurian, middle Wenlockian to lower Ludlovian?.

As originally defined by Boone et al. (1970),

> The Smalls Falls Formation is a rusty-weathering unit composed of black sulfidic metashale cyclically interbedded with sulfidic quartz-rich metasandstone. The upper few hundred feet is calcareous. Thick graded beds of commonly calcareous quartz granule metaconglomerate are abundant in northern outcrops, particularly near the faults northwest of Madrid (Moench, 1970). The Smalls Falls Formation is about 2500 feet thick west and south of Madrid, but thins and wedges out northward. The contact between the Smalls Falls and Madrid Formations is sharp and conformable.

The age of the Smalls Falls has recently been challenged: see discussion in trip text. Thin to thick interbeds of calcareous quartzite and very rusty-weathering metapelite characterize the formation. The pelitic beds especially have very abundant amounts of pyrrhotite and graphite, typically 5-10 % and 1-3 modal %, respectively, with rutile as the Ti phase rather than ilmenite. Moreover, due to abundant muscovite and a lesser amount of Mg-rich biotite, the pelitic samples are basically white in color on unweathered surfaces. Typical metapelitic minerals such as garnet and staurolite are absent, but Mg-rich cordierite is common. On this field trip we will encounter the graptolite-bearing Parkman Hill Fm at Stop 1, correlated with

Smalls Falls. In Western New Hampshire, the well-known arenaceous Clough Quartzite (Billings, 1956) is considered a time-equivalent, proximal facies of the more distal Smalls Falls Fm.

(e) Madrid Fm. [DSm], Upper Silurian to Lower Devonian. Medium to thick, immature interbeds of biotite granofels and calc-silicate granofels, with actinolite common at lower metamorphic grades, diopside at higher. The Madrid formation is correlated with the Fitch Formation of western New Hamphshire. The age of the Madrid is somewhat in doubt: originally it was considered Silurian, but now (Moench et al., 1995) it is mapped as Devonian. See discussion in Moench (2006). The thickness of the Madrid is about 600 m.

(f) Carrabassett Fm. of the Seboomook Group [Dc], Devonian? This is the basal unit of the Seboomook Group, whose type locality is in the Little Bigelow Mountain quadrangle (Boone, 1973). We will not visit this formation on this trip. Variable thickness interbeds of metapelite and impure feldspathic quartzites, commonly showing graded bedding. The accessory opaque minerals are ilmenite, graphite, and minor to moderate amounts of pyrrhotite, the latter in some cases being reflected by moderately rusty weathering surfaces.

(g) Seboomook Fm. [Ds], Devonian. Thickly bedded turbidites with primary sedimentary structures preserved, showing an easterly source. Seboomook Group is correlated with the well-known Littleton Formation of New Hampshire.

ROAD LOG

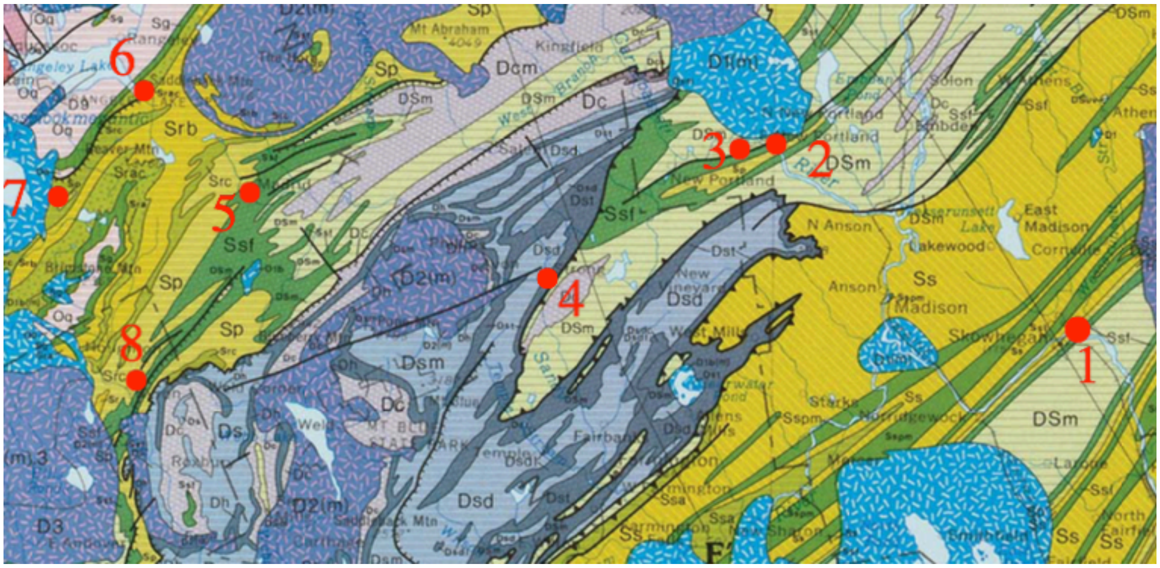


Figure 10. Portion of Maine state geological map showing field trip stops. After Osberg et al. (1985).

Starting Point: Coburn Park, a public park along the Kennebec River in Skowhegan. 44°46.3 N, 69°42.6 W. The park is about 0.5 miles east of the center of town along US 2 (Water St.); it has a gazebo and a Porta Potty. Muffin alert: there is a fine bakery on Water St. called *The Bankery*! There is also a Dunkin Donuts on Water St.

From the park entrance, walk 500 ft. east on Water St. to a trail that enters the woods on the right at a sign "433". Follow obvious path through the woods along the river to large stream outcrops on the north shore of the Kennebec River. Watch out for poison ivy here!

STOP NO. 1, Great Eddy. (30 minutes) We are at the Great Eddy of the Kennebec River below the Skowhegan Dam (formerly Falls). Exposed here are the steeply dipping, rusty weathering rocks mapped as the Silurian Parkman Hill Formation by Ludman (1977), but remapped as the eastern facies of the Smalls Falls Formation on the Moench and Pankiwskyj (1988b) map. Here we also see the underlying metagreywacke and pelite of the Silurian Sangerville Formation, in the same stratigraphic position as the Perry Mt. Formation. The contact between these formations is exposed here. We are on the north limb of the Currier Hill Syncline; the tops point south, towards the river. Therefore the north limb of the syncline is overturned. This syncline was first recognized by Charlie Guidotti (unpublished mapping, 1964). The Parkman Hill ~ Smalls Falls rocks, closest to the river, are rusty weathering schists, at biotite grade of metamorphism. Here the sulfides include pyrrhotite (dominant) and pyrite (subsidiary), as well as minor amounts of chalcopyrite and sphalerite. Table 4 contains analyses of these sulfides. Higher up and in the woods are the Sangerville ~ Perry Mt. rocks.

After examining the outcrops, return to the vans in Coburn Park. Exiting the park, reset odometers to 0.0 as you turn left onto Water St.

0.0 Exit Coburn Park, turn left onto Water St.

0.2 Bear right onto High St., pass through a traffic light.

0.5 At second traffic light turn right onto Madison St. (US 201). Move into the left lane.

0.8 Turn left onto Spring St. with a car wash on the corner.

0.9 Turn right onto Russell Rd. at old warehouse, then pass Skowhegan fairgrounds at 1.4 miles.

6.2 Carefully turn left onto Rt. 148 at crossroads with unique radar-assisted stop sign.

7.7 Note distant views to the north towards the Saddleback massif, underlain by the 407 Ma Redington Pluton (Solar et al. (1998).

9.6 Pass straight through the town of Madison and its now-closed paper mill, cross Kennebec River.

10.3 Turn right onto US 201A northbound. Continue along the scenic Kennebec River. Note sign commemorating the route of Benedict Arnold's invasion of Quebec in 1775.

14.9 Cross bridge as you enter village of North Anson, turn left onto Rt. 16, noting outcrops of Madrid Formation in the river. This is the Carrabassett River. We will see more of these rocks at Stop 3.

16.6 Note antique wooden observation tower in cornfield.

17.9 Note more roadside outcrops of Madrid Formation on right.

20.3 Pull into small parking lot on the left side of highway, taking care for high speed traffic on this road. There is parking for 6-8 vehicles here. 44°53.6 N, 69°59.4 W. Cross road very carefully and walk back along highway 300ft. to:

STOP NO. 2, Carrabassett River Valley (20 minutes) Here we have 3m high vertically dipping, rusty weathering outcrops of the Smalls Falls Formation, and at the eastern end of the outcrop, massive Perry Mt. Formation lacking the normal repeating quartzite beds. This locality is close to the western margin of the Lexington Batholith, dated at 404±2 Ma, Solar et al. (1998). We are within the contact aureole, with nearby calcsilicate rocks of the Madrid Formation containing diopside, and farther out, actinolite. More pelitic rocks might contain garnet and staurolite, except that in the sulfide-rich Smalls Falls there is no garnet! The contact between Smalls Falls and Perry Mt. is exposed in this outcrop. Look for garnet and staurolite in the Perry Mt. rocks - so far we have not found them, but they may be there.

Cross road very carefully and return safely to the vans in the parking lot. Continue westbound on Rt. 16 for a short distance, preparing for immediate left turn.

20.4 Turn left onto Katie Crotch Rd. (derivation unknown). Follow along the Carrabassett River.

22.4 At stop sign, travel straight ahead, joining Rt. 146 in the village of East New Portland. Cross the river on a concrete bridge that is in poor repair.

22.7 At far end of bridge, turn left onto dirt road and park beside river. 44°53.9 N, 70°01.3 W. Scramble down to the river at:

STOP NO. 3, East New Portland (30 minutes) Extensive exposures of the Devonian Madrid Formation form the river bottom here in an area of rapids. These calcareous rocks are gently dipping to the north, as we are on the north limb of the Strickland Hill Anticline, containing Smalls Falls rocks at its core. The rock type is biotite granofels and calcsilicate granofels. As we are still close to the western margin of the Lexington Batholith, the metamorphic grade here is actinolite. A prominent granitic dike crosscuts the Madrid Formation in the river bed. This dike is a two-mica granite, probably anatectic. Look for tourmaline, garnet, and other aluminous phases in the granite. Although there is no date for this dike, it is likely related to emplacement of the Lexington Batholith at 404±2 Ma (Solar et al., 1998), and if so, places an important constraint on the depositional age of the Madrid Formation.

Return to the vans, turn around and head back to the paved road at the end of the bridge.

22.8 Continue straight ahead, following Rt. 146 to. the town of New Portland, where road winds around a bit. Note sign in village for the Wire Bridge, a local curiosity.

27.2 At stop sign, turn left onto Rt. 27 southbound, a high speed road. Watch for trucks!

31.4 Note low, dark outcrops of Madrid Formation on left.

33.3 Pass the "Maine Wood Turning" factory, that produces handles, dowels, and other parts as forest products of the North Woods. At the south end of the factory turn right onto Rt. 234 towards Strong.

35.9 Strong town line.

38.6 At bottom of a steep hill as we enter the village of Strong, turn into parking lot of the Harry Gordon Lumbering Co., and park. 44°48.2 N, 70°13.0 W. Carefully walk back uphill 200 ft. to some low outcrops at roadside. Watch out, this is a blind corner, so keep off the road! Fortunately there is relatively little traffic on this road.

STOP NO. 4, Strong (10 minutes) We may skip this stop if the group size is too large. The outcrops here are very graphitic, steeply dipping rocks that have been confused with Smalls Falls Formation. The metamorphic grade here is garnet but of course there is no garnet due to the high sulfide content of the rock. There are horizons of pyrrhotite that is only weakly magnetic. In pyrrhotite, a non-stoichiometric compound, the magnetic susceptibility is related to the Fe concentration, with lower concentrations more strongly attracted to magnetic fields. Our structural position here is just west of the Winter Brook Fault (back up the hill, but not exposed), marking the boundary of the Rumford allochthon (Moench and Pankiwskyj, 1988a). Temple Stream rocks are lithologically similar to Smalls Falls rocks, but lie in a higher structural setting.

Return safely to the vans, watching out for traffic on the road as vehicles descend the hill.

Continue west on Rt. 234 into the village of Strong.

38.9 Turn left onto Rt. 145 in center of village.

39.3 Cross Sandy River on modern bridge, bear right and at a yield sign join Rt. 4 towards Rangeley. The highway crisscrosses the Sandy River as it passes through the towns of Phillips and Madrid.

53.1 Note the tiny village of Madrid, with an abandoned hotel and Mobil station. On the right Reeds Mill Rd. crosses the river at a bridge. Under this bridge is the type locality of the Madrid Formation, but as we saw excellent exposures of this formation at Stop 3 we will not stop here. 44°51.8 N, 70°27.7 W for reference, at the former Mobil gas station.

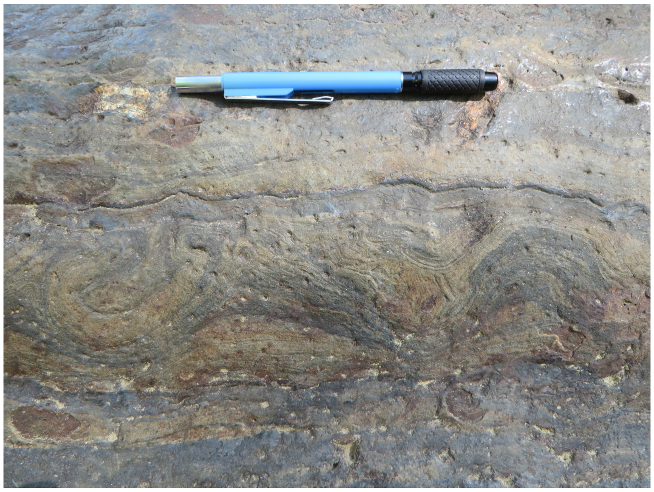
55.1 Note 5-m-high road cuts of Smalls Falls rocks on right. Slow down, approaching a left turn that comes up suddenly.

56.0 Turn left into the Smalls Falls Picnic Area (sign) and park vehicles. 44°51.4 N, 70°30.9 W.

STOP NO. 5, Smalls Falls Picnic Area (90 minutes, including lunch) The scenic picnic area (with bathrooms) is also the type locality of the Smalls Falls Formation, where the Sandy River descends over a series of cascades. **This is a no-hammer stop!**

There are several waterfalls here, the highest of which is just above the picnic area. During the warm period of the year this is a popular swimming hole. The river has forced its way through the weakest portions of the rusty weathering Smalls Falls Formation. We will cross the footbridge and ascend the trail that follows the right bank of the river, with chain link fences protecting the most dangerous places. On smoothed surfaces look for a variety of pseudomorphs. In the bottom of an enlarged pothole there are some very well displayed pseudomorphs after cordierite. They consist of coarse-grained muscovite, Mg-rich chlorite, and phlogopite. Please do not hammer on them - take a picture instead! Higher up, look for large chiastolite crystals - except that, as shown by Guidotti and Cheney (1976) they are now pseudomorphs composed mainly of margarite. As your eyes become more focused on the details of the textures present, you will see that other 2 cm pseudomorph knots are present. These consist of aggregates of chlorite and phlogopite after cordierite. The original chiastolite and cordierite formed during M2 but during M3 they have been pseudomorphed (ibid.)

Continuing along the right bank of the river, within sight of a wooden bridge, there are smoothed surfaces containing examples of submarine soft sediment deformation (see photo).



Cross the wooden bridge on a dirt road that joins the paved highway. If time permits, we will follow the former route of Rt. 4, now grass, to a set of 5 m high outcrops at the boundary between the Smalls Falls Formation and the underlying Perry Mt. Formation. The contact lies in the woods and is unfortunately not exposed here. Here the rock has thin to thick, graded interbeds of metapelite and fairly pure quartzite. Perry Mountain itself, which gives its name to the Perry Mt. Formation, lies just across Rt. 4. We will see the Perry Mt. Formation again at Stop 8.

Return to the vans via the trail we used during the ascent.

56.3 Exit the parking lot and turn left, westbound, on Rt. 4 towards Rangeley. Note large roadcuts of Smalls Falls rocks on the right.

58.8 Appalachian Trail crossing.

61.4 Note 3-m-high outcrops of Perry Mt. Formation on the left.

61.8 Pass Long Pond on the left. The bedrock geology here is now Rangeley C Formation, the upper, more distal portions of the Rangeley Formation. We will see these rocks again at Stop 7.

64.8 Note sign for Rangeley Lakes State Park, as road ascends to a height of land. Slow down.

65.7 Near height of land, at 3-m-high roadcuts on the right, turn left into a dirt driveway, taking care for oncoming traffic. Park here. 44°55.9 N, 70°37.4 W.

STOP NO. 6, Rangeley Conglomerate (20 minutes). The roadcuts here display the spectacular polymictic conglomerate of the Silurian Rangeley Formation. This stop is the same as Stop 4 of NEIGC 1970 Trip A1 (Moench and Boudette, 1990), as well as Stop 1 of NEIGC 2006 Trip C4 (Van Baalen, 2006). The rocks are the Rangeley A Formation, close to their lower contact with Silurian (?) and pre-Silurian rocks to the west. The rock here includes a spectacular polymictic boulder conglomerate with clasts derived from source regions to the northwest of here. At first glance one might assume this to be a basal conglomerate above the Taconic Unconformity, but Moench and Boudette (1970) argue that the sequence is in fact conformable. Some of the clasts are coarse-grained igneous rocks. There are also graded beds here, indicating tops to the east. In general, the lowest part of the Rangeley Formation (Rangeley A) contains the coarsest conglomerates and sandstones; the formation fines upward and eastward into deeper portions of the basin into which it was deposited, probably as a result of a marine transgression (see Fig. 1).

Cross back to the vans, watching out for traffic. The dirt loop where the vans are parked rejoins Rt. 4 in a short distance. Turn right on Rt. 4, back the way we came.

66.4 Turn right onto South Shore Rd., noting sign for Rangeley Lakes State Park. Follow this road along the shore of Rangeley Lake, with occasional views and many lake camps.

74.0 Turn left at stop sign intersection onto Rt. 17 south, towards Rumford.

75.5 Pass scenic overlooks on left, at which we will stop only if time permits.

80.9 At height of land, pull into well-marked scenic overlook on right and park, 44°50.2 N, 70°42.6 W.

STOP NO. 7, Scenic Overlook (10 minutes) This scenic overlook with expansive views to the west over Mooselookmeguntic Lake and other distant lakes, underlain by the 388 Ma Mooselookmeguntic Pluton (Solar et al., 1998) and beyond, the pre-Silurian rocks that are beyond the scope of this trip. Across the road are outcrops of Rangeley C, the relatively fine grained, most distal portion of the Rangeley Formation. The bedrock here contains staurolite. Note perched two-mica granite boulder of the Mooselookmeguntic Pluton on top of the outcrop.

Re-board vans and descend south along Rt. 17 towards Rumford.

92.4 Pull into parking lot for Coos Canyon rest area in the small village of Byron, 44°43.2N, 70°37.9 W. There is a public restroom here, across the bridge on the left. The small store across the road has a nice collection of hand lenses and mineral specimens, as well as ice cream.

STOP NO. 8, Coos Canyon (30 minutes). This stop is the same as Stop 4 of GSA 2001 Trip F1, Guidotti and Van Baalen.

The beautiful rocks in the river bed are the Perry Mt. Formation that we saw at its type locality but are actually better displayed here. Note the well-defined thin bedding of metapelite and fairly clean quartzite, commonly in a gradational fashion. Although these rocks have been subjected to two high-grade metamorphisms, some of the quartzite beds still display very nice delicate, fine-scale cross beds. The present grade here is Upper Staurolite Zone and the main AFM mineral assemblage is staurolite + garnet + biotite + chlorite with muscovite + plagioclase + quartz also abundant. Accessory opaque minerals are ilmenite and very sparse pyrrhotite and graphite. The main thing to note is the very abundant staurolite, garnet, and dark colored biotite, all Fe-rich minerals, something that never occurs in the Mg-enriched silicate bulk compositions of the Smalls Falls Formation. The occurrence of pseudomorphs (now composed of coarse muscovite) (to 1 cm x 5 cm) after andalusite indicates that the earlier M2 event was somewhat higher grade than the second M3 event to which the rocks are now approximately equilibrated.

If time permits, we will continue 0.2 miles south along Rt. 4 to a small dirt road on the right immediately before a bridge over the Swift River. There is a parking area, possibly with some construction equipment here. Descend to the river by a rough trail to some additional outcrops of the Perry Mt. Formation showing variable Al-content as evidenced by presence or absence of staurolite on different horizons. Additionally, there are some lovely open folds here.

Return to the vans, continue to Bethel via Rt. 17 and US 2, about 50 minutes.

END OF TRIP

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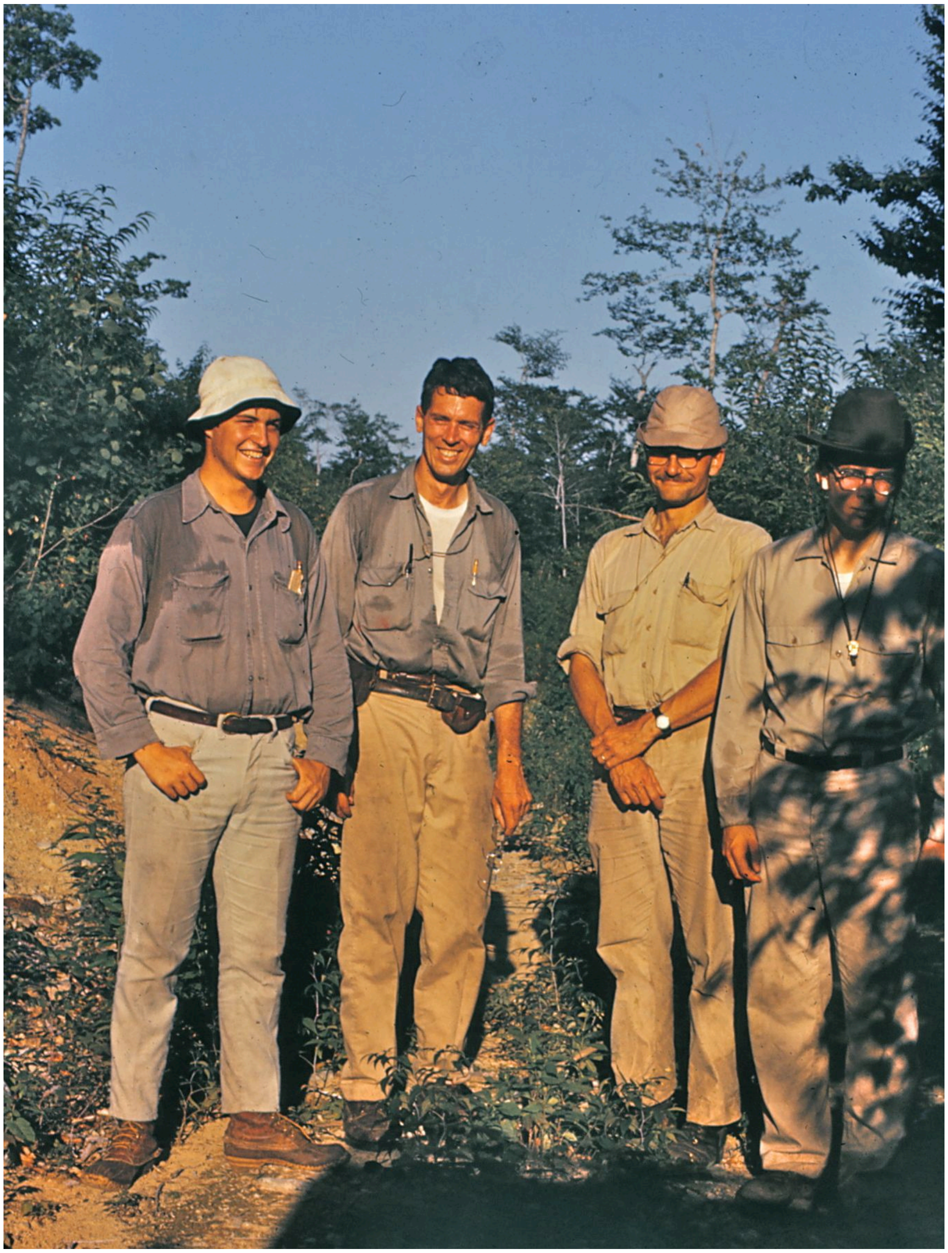

Photo: Peter Lyttle, Gary Boone, Bob Moench, and unidentified geologist, ca. 1968