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*108<sup>th</sup> Annual Meeting*

Guidebook for Field Trips along the Maine Coast  
from Maquoit Bay to Muscongus Bay

*Edited by*

Henry N. Berry IV and  
David P. West, Jr.

*Hosted by*

The Maine Geological Survey and  
The Middlebury College Geology Department

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The cover photograph is by Arthur M. Hussey II, to whom this guidebook is dedicated. Arthur Hussey was an accomplished photographer and his numerous photo collections highlighted many aspects of the natural beauty of southwestern Maine. The photo was taken by Arthur at a location about a kilometer south of Lookout Point along the western shore of Harpswell Neck. Arthur first began mapping in this area in 1962, and his 1965 NEIGC field trip visited exposures nearby. The view in the photo is towards the south and the exposures are east-dipping metamorphosed Ordovician volcanic rocks of the Cushing Formation. Arthur's hammer for scale.

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**THE MIGMATITE-GRANITE COMPLEX OF SOUTHERN MAINE: ITS STRUCTURE, PETROLOGY, GEOCHEMISTRY, GEOCHRONOLOGY, AND RELATION TO THE SEBAGO PLUTON**

By

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**INTRODUCTION**

Structural, geochemical and geochronological data from transpressive orogenic belts show regional deformation and the emplacement of plutons to be coeval processes. Therefore, it is important to consider the relation between these processes in order to understand what must be fundamentally connected orogenic processes. If magma flow through deforming rocks is recorded by structures in migmatites and associated granites, study of such rocks requires multiple scales of observation. Crustally derived granites are important probes of the unexposed cores of orogens. Although the structural record may be reconstructed in the field, questions remain regarding the ascent mechanisms, and the timing of magmatism vs. deformation and metamorphism.

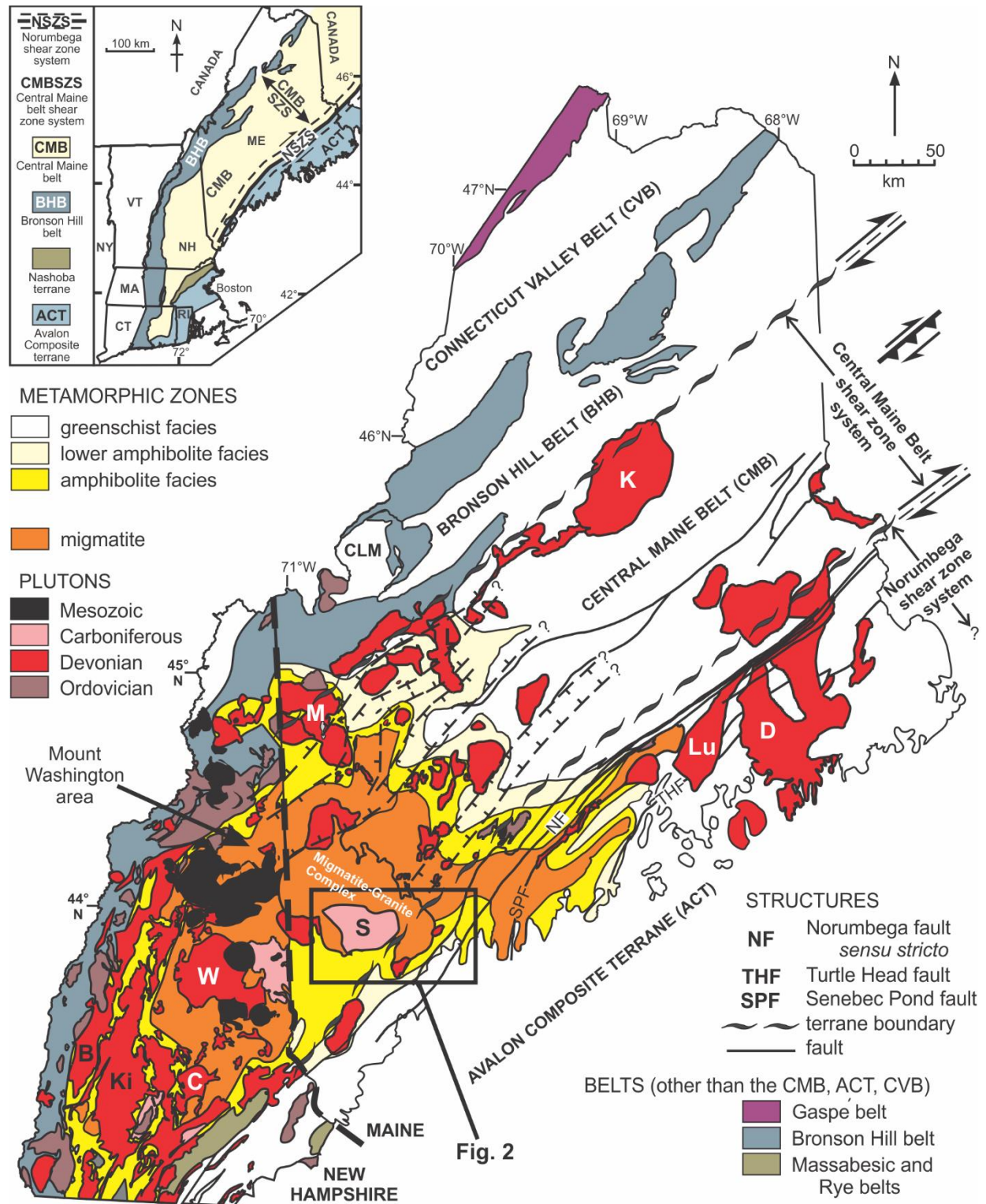
In southern Maine a variety of magmatic and deformational textures characterize the diverse granites that crop out within and adjacent to the Norumbega shear zone system (NSZS; Fig. 1). Existing regional maps do not address relations between granites of various scales and their host structures. Field evidence for synkinematic transport and emplacement of granite is abundant, hence we seek to define the extent to which regional metamorphism and deformation accompanied granite magmatism, and whether these processes were phased or diachronous. In order to consider such problems appropriately, we integrate thorough field and structural analysis with precise geochronology and isotopic/elemental geochemistry.

**This Field Guide and Trip**

This guide represents the current interpretation of results of a ~20 year multi-disciplinary study of rocks of the northern Appalachian migmatite-granite belt. The study comprises several ongoing concurrent and related projects that together form a database of fine-scale documentation of the 400 km<sup>2</sup> Permian Sebago pluton and its surrounding Migmatite-Granite complex (MGC, Devonian, on the W, N and E of the pluton and related rocks in southern Maine and New Hampshire. The larger-scale goals of the project are realized through detailed field and laboratory work, where we document variations of mineral content, structures and fabric at the meter- to millimeter-scales in rocks of the pluton and MGC. The results are expected to be useful in understanding the nature of the Sebago pluton and its construction, as well as the interrelation of the processes of metamorphism, melting/melt segregation/magma flow, magma ascent and emplacement, and plastic deformation in southern Maine and the northern Appalachians.

This work is based significantly on earlier works, updated as new data have been generated. Parts of this present trip guide (STOPS 1, 2, 4, 5 and 8; Fig. 2) were included on previously trips for National GSA (Solar et al., 2001) and NEGSA (Solar and Tomascak, 2009). Beginning in 2002, the work has been dominated by undergraduate student projects in our research group, much of which has been in studies parallel with the current authors' work. Most of the details reported in this guide were compiled and interpreted as a direct result of those studies, and we acknowledge the significant efforts put forth by our students at Buffalo State and Oswego State in the success of the project goals.

Our studies have concentrated on single large exposures or closely-spaced sets of exposures (and specimens collected from these; *e.g.*, STOPS 3, 4, 5, 6 and 8) in order to permit study at meter- and centimeter-scales at outcrops and in the laboratory. Laboratory study has focused on both petrography in hand specimen and thin section, and geochemistry and geochronology in order to augment field data and relations. After regional study reported in Solar and Tomascak (2001, 2002), more detailed field studies of the eastern MGC (Hays and Solar, 2006; Gulino et al., 2007; Bohlen and Solar, 2010; Luther et al., 2015; Tomascak and Solar, 2016), western MGC (Kalczynski and



**Figure 1.** Simplified pluton, metamorphic zone and structural zone map of Maine and New Hampshire (modified after Guidotti, 1989; Lyons *et al.*, 1997; Solar and Brown, 1999; Solar and Tomascak, 2001). The plutonic rocks are apparently independent of metamorphic zone, and arranged into belts that parallel regional strike. Pluton names: D is Dublois, K is Katahdin, L is Lexington, Lu is Lucerne, M is Mooslookmeguntic, S is Sebago, C is Concord, W is Winnepesaukee, B is Bethlehem gneiss, Ki is Kinsman quartz monzonite.

**ROCK TYPES**

- Sebago pluton (Ms-Bi granite, Bi granite, schlieric granite, pegmatite)
- Migmatite-Granite Complex (MGC) (stromatic migmatite, diorite w/ associated gabbro, metagabbro)
- other granites (Ms-Bi granite, schlieric granite, pegmatite)
- metasedimentary rocks (non-migmatitic, undifferentiated) of the CMB and ACT

**STRUCTURE SYMBOLS**

- 33 trend and plunge of mineral lineation in metasedimentary rock, migmatite, granite gneiss
- 33 trend and plunge of fold hinge line

**ZONE BOUNDARY SYMBOLS**

- structural boundaries of the transition zone between the NSZS (SE) and the rocks of the Sebago area
- western boundary of the domain SE of the Sebago pluton
- SE of the Sebago pluton

**STEREOGRAM SYMBOLS**

- pale to foliation
- mineral lineation
- + fold hinge line
- x bedding plane, long dimension

**STOP 1** total: 53  
 ● 38 ● 15  
 + 2  
 x 2

**STOP 2** total: 180  
 ● 142 ● 29  
 + 2

**STOP 3** total: 180  
 ● 87 ● 59  
 + 19

**STOP 4**

**STOP 5**

**STOP 6**

**STOP 7**

SW and S of the Sebago pluton total: 131  
 ● 117 ● 10  
 + 10  
 x 2

domain SE of the Sebago pluton total: 53  
 ● 38 ● 15  
 + 2

transition zone total: 180  
 ● 142 ● 29  
 + 2

NSZS total: 180  
 ● 87 ● 59  
 + 19

G. Solar, P. Tomascak 2002, 2007, M. Kalczyński, 2007  
 D. Naschke, 2010 + M. Hain, 2011

G. Solar, P. Tomascak 1996, 2000, 2001, 2002  
 Guilmo, 2006; Hays, 2006 + Luther, 2014

G. Solar, P. Tomascak 1995, 1996, 2000, 2002, 2007, 2008

G. Solar, P. Tomascak 1995, 1996, 2000, 2001

**Figure 2** (preceding page). Geological, structural and field stop map of the Sebago pluton and the Migmatite-Granite complex, area north of Portland ME, and south of Lewiston, ME (see Fig. 1 for location). Grid areas are towns (*e.g.*, Standish, ME). Field trip stops are indicated, as are many of the roads used in the road log. The thick dashed line that is the boundary of the Sebago pluton is the mapped limit of granites we associate with that body. The contact is seen only at STOP 8 in the northeast. The thick dashed line that is the boundary of the Migmatite-Granite complex is the limit of migmatitic rocks in the map area; migmatitic rocks extend to the north and west of the map space. Structural data on the map are representative; stereograms show all data.

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Solar, 2008) and the northeastern contact of the pluton (LaFleur et al., 2008; Nyitrai et al., 2009; Naschke et al., 2010). Geochemical and geochronological studies have been performed in tandem (Cirimo et al., 2006; Tomascak et al., 2008, 2013; McAdam et al., 2009).

### REGIONAL GEOLOGICAL SETTING

The northern Appalachians are divided into NNE-SSW-trending tectonostratigraphic units (Fig. 1; Zen, 1989; Robinson et al., 1998). The Central Maine belt (CMB) is the principal unit that occupies most of the eastern part of New England and New Brunswick, Canada, composed of a Lower Paleozoic sedimentary succession, deformed and metamorphosed at greenschist to upper amphibolite facies conditions, and intruded by plutons of Devonian age (*e.g.*, Osberg et al., 1968; Williams, 1978; Moench et al., 1995; Bradley et al., 1998; Robinson et al., 1998; Solar et al., 1998; Dorais and Paige, 2000; Dorais, 2003). The CMB is composed of a Lower Paleozoic sedimentary succession, deformed and metamorphosed at greenschist to upper amphibolite facies conditions, and intruded by plutons of Devonian age (*e.g.* Moench et al., 1995; Bradley et al., 1998; Solar and Brown, 2001a). The CMB is located between Ordovician rocks of the Bronson Hill belt (BHB) to the W and NW that were deformed and metamorphosed during the Ordovician Taconian orogeny, prior to deposition of the CMB sedimentary sequence. To the SE of the CMB, rocks are Neoproterozoic to Silurian age of the Avalon Composite terrane (ACT).

Deformation in the northern Appalachian orogen was partitioned heterogeneously during dextral transpression in response to Early Devonian oblique convergence (van Staal and de Roo, 1995; West and Hubbard, 1997; van Staal et al., 1998). Dextral transpression (SE-side-up displacement) was accommodated within the CMB shear zone system in Maine (Brown and Solar, 1998a; Solar and Brown, 2001a) while dextral–transcurrent displacement was accommodated within the Norumbega shear zone system (West and Hubbard, 1997; West, 1999) along the southeastern side of the CMB (Fig. 1). By the Carboniferous, deformation had ceased within the CMB shear zone system and strain had localized into the Norumbega shear zone system (Hubbard et al., 1995; West and Hubbard, 1997; Ludman, 1998; West, 1999).

As the NE-SW-trending structures in the CMB and ACT developed in response to dextral transpression, metamorphism and migmatite formation were coeval in the CMB Siluro-Devonian sedimentary succession (see Moench, 1970a and Moench et al., 1995; Solar and Brown, 1999, 2001a, 2001b). In the CMB rocks, Brown and Solar (1999) and Solar and Brown (2001b) related migmatite structures and plutons, and the geochemistry of migmatites and their separates (melansomes and leucosomes) and of granites from various associated plutons to this structural context. In eastern New Hampshire and western Maine, much effort has been made to document metamorphic reactions, and to separate periods of metamorphism (*e.g.*, Guidotti, 1974, 1989; Holdaway et al., 1982; Eusden and Barreiro, 1988; Smith and Barreiro, 1990) and plutonism (*e.g.*, Tomascak et al., 1996b; Bradley et al., 1998; Solar et al., 1998). Plutons have been studied more recently (*e.g.*, Pressley and Brown, 1999; Dorais, 2003; Tomascak et al., 2005) in order to better understand how they have, or have not, recorded periods of orogenesis.

#### Regional metamorphism

Polymetamorphism of the pelitic stratigraphic sequence is well documented in both the CMB and the ACT in Maine (see Guidotti, 1989, for a review; Holdaway et al., 1997; Johnson et al., 2003) and in parts of contiguous New Hampshire (*e.g.*, Chamberlain and Lyons, 1983). Greenschist facies pelitic rocks in central Maine to the northeast increase in grade to upper amphibolite facies (and migmatite) within 20 km along strike to the southwest (Fig. 1; Guidotti, 1989). The metamorphic field gradient is the product of polymetamorphism (*e.g.*, Chamberlain and Lyons,



1983; Guidotti, 1989, 1993) classically considered related to local pluton-driven thermal pulses (De Yoreo et al., 1991) overprinted on a regionally elevated thermal gradient that resulted from transpression (Brown and Solar, 1999; Solar and Brown, 1999, 2001b).

### **Migmatite**

Migmatites in Maine and New Hampshire are the core of a diachronous ‘metamorphic high’ that extends from eastern Connecticut to Maine (Schumacher et al., 1990; Fig. 1). Migmatites are in two types that correspond with structures: stromatic migmatites – parallel-layered leucosome-melanosome-host rock; and diatexite, a rock in which the protolith structures are not observed, suggesting destruction by diatexis. Migmatite domains in western Maine vary from strongly-foliated metasedimentary rock with a few mm-scale leucosomes per m<sup>2</sup>, in which relict primary structures are preserved, to rocks structurally disrupted by advanced melting (diatexis) and schlieric granite (Solar and Brown, 2001b). Migmatites are separated into varieties based upon internal structure, *e.g.*, stromatic and heterogeneous (*e.g.*, Brown and Solar, 1999; Solar and Brown, 2001b), and these rocks grade into diatexite. In western Maine, the types of migmatite map into discrete zones that correspond with the structural zones (Solar and Brown, 2001b). Migmatites appear to be less well organized in southern Maine and New Hampshire, however, mapping of migmatite varieties in those areas is less complete (Allen, 1996; Solar and Tomascak, 2001, 2002), although petrogenetic studies in New Hampshire migmatites are much more complete (*e.g.*, Chamberlain and Lyons, 1983; Dougan, 1979, 1981, 1983). Within the ‘metamorphic high,’ the protolith of the migmatites is interpreted to be rocks of the CMB stratigraphic sequence based upon relict structures and geochemistry (Solar and Brown, 2001b; Johnson et al., 2003). All migmatites have discrete to diffuse trondhjemitic leucosomes. Solar and Brown (2001b) compared the geochemistry of metapelite source rocks, migmatites and leucogranites to evaluate the hypothesis that migmatites and leucogranites in western Maine are cogenetic. From structural, geochemical and geochronological data, interpretations and arguments presented in Brown and Solar (1998a; 1998b; 1999), Solar et al. (1998), Pressley and Brown (1999), Solar and Brown (1999; 2001a; 2001b) and Johnson et al. (2003), a syntectonic model was progressively constructed for the CMB to explain the relation between orogenic deformation and granite melt flow and pluton emplacement in Maine.

### **Granites**

Granite plutons are kilometer-scale (Fig. 1). Some larger plutons cut across the regional structures without either significant deflection of structural trends or formation of a significant deformation aureole, particularly in Maine (Brown and Solar, 1999). Some have taken this relation to illustrate that the plutons are post-tectonic (*e.g.*, De Yoreo et al., 1991) whereas others consider these relations due to the erosional “cut” effect of pluton shapes on maps (Brown and Solar, 1999). In Maine, the close association between smaller plutons (by area) and heterogeneous migmatite in similar structural zones (Solar and Brown, 2001a, 2001b; see Fig. 2 - stereograms), has been used to suggest a relation between structure, granite ascent and emplacement (Brown and Solar, 1998a, 1998b, 1999; Pressley and Brown, 1999; Solar and Brown, 2001b). In southern Maine, Tomascak and Solar (2001) reported a close spatial relation between migmatites and the Sebago pluton (Figs. 1 and 2) where the pluton is enveloped by a migmatite terrane that has many internal smaller (km-scale) bodies of granite. In New Hampshire, granites show a similar relation to their Maine counterparts. In the Mount Washington area (Fig. 1), the “Wildcat granite” is a diatexite at the high-end part of the metamorphic field gradient, and shows a gradational relation with the surrounding more stromatic migmatite. Geochemical studies (*e.g.*, Dorais, 2003) have focused upon the petrogenesis of the plutonic suite in New Hampshire suggesting that the source of these granites may have significant components from basement rocks. This is similar to geochemical findings in western Maine where plutons have discrete basement-source components, but are otherwise probably sourced from melting rocks similar to those of the CMB (Pressley and Brown, 1999; Tomascak et al., 2005).

### **The Sebago batholith?**

Previous work to our own shows the Sebago pluton and most of its surrounding migmatites and associated granites as a single, much larger body (by area) known as the Sebago batholith (see Fig. 2 – the pluton and most of the MGC combined). The exception to this is the area just outside the SW limit of the Sebago pluton – these rocks were not mapped previously as part of the Sebago pluton, yet migmatites and granites are present (Kalczynski and Solar, 2008). This “batholith” shape of the body is on the Geological Map of Maine (Osberg et al., 1985), and other large-scale compilations, including the updated Lithotectonic Map of the Appalachian Orogen (Hibbard et al., 2006) making the body the largest (by mapping) exposed igneous complex in New England (>1600 km<sup>2</sup>).

The studies of Tomascak et al. (1996a, 1996b) put a framework in place for the area based on the geochronology and elemental and isotope geochemistry of granitic rocks. Using U-Pb TIMS analysis of a multi-grain monazite fraction from near STOP 1, Tomascak et al. (1996b) determined a concordant age of  $293 \pm 2$  Ma. This was taken to represent crystallization of the chemically- and texturally homogeneous, two-mica “core” of what was then mapped as the Sebago batholith. Tomascak et al. (1996a) began by using the mapped extent of the batholith (Osberg et al., 1985), but concluded that this lithological division was at odds with the geochemical data. Surrounding the 293 Ma “core” (their group 1 granites), a wide expanse of migmatitic rocks are intruded by granites that are texturally heterogeneous and this is reflected in their elemental and isotope geochemistry.

Starting with the geochemistry results of Tomascak et al. (1996a), new mapping by Solar and Tomascak (2001, 2002), supported by the existence of a plutonic “core” (gravity study by Behn et al., 1998), called for the separation of the Sebago pluton (*sensu stricto*;  $<400$  km<sup>2</sup>), restricted to the south-central portion of the “batholith”, from the complex of heterogeneously textured migmatites and granites that surround it on the east, north and west (*e.g.*, Solar and Tomascak, 2009; Tomascak and Solar, 2016). These surrounding rocks are collectively within the Migmatite-Granite complex (MGC, Fig. 2; Tomascak et al., 2001, 2002, 2013; LaFleur et al., 2008; Luther et al., 2015. [Note: we previously called that domain the “Sebago Migmatite domain” (Solar and Tomascak, 2009; shown in this guide on Fig. 2 as the “Migmatite-Granite complex”) because of the null hypothesis that the migmatites and granites surrounding the pluton were related in timing to the pluton emplacement, not just in space.] The fundamental goal of the continuing research in this area is to understand the interplay between melt generation, extraction, and transport, and regional-scale deformation. Work has focused on integrated structural geology, petrography and geochemistry of specific outcrops, or closely-spaced outcrops in parts of the pluton and/or MGC (Hays and Solar, 2006; Gulino et al., 2007; Kalczynski and Solar, 2008; LaFleur et al., 2008; Nyitrai et al., 2009; Bohlen and Solar, 2010; Naschke et al., 2010; Luther et al., 2015), or the comparative geochemistry of the rocks in both parts (Cirimo et al., 2006; Tomascak et al., 2008, 2013; McAdam et al., 2009), in order to answer questions about the relation of the Sebago pluton and the MGC.

### **THE SEBAGO PLUTON, THE MIGMATITE-GRANITE COMPLEX, AND THE NORUMBEGA SHEAR ZONE SYSTEM – RESULTS OF OUR EARLY WORK**

In southern Maine, the crystallization of the Sebago granite (ca. 293 Ma; Tomascak et al., 1996a) was coeval with strain accommodation within the dextral-transpressive Norumbega shear zone system (NSZS) located immediately to the southeast (Solar and Tomascak, 2001, 2002; Figs. 1 and 2). Early mapping in the SE contact zone of the batholith and surrounding areas showed no simple cross-cutting relation between the pluton and the NSZS. Instead, subconcordant granite sheets, migmatites and metamorphic rocks are interlayered within the NW boundary zone of the NSZS (similar to other mapping, *e.g.*, Creasy and Robinson, 1997; Berry and Hussey, 1998).

Granites in the “Sebago migmatite domain” correspond to petrochemical group 2 rocks of Tomascak et al. (1996b; Fig. 4). Structures in the migmatites SE of the pluton, in the area immediately NW of the NSZS are sub-parallel to the local fabric of the NSZS (NE-SW striking and steeply dipping; Fig. 2). On a regional scale, our traverses across strike to the SE from the Sebago pluton into the NSZS show a progressive change in planar structures from NNE-striking, moderately SE-dipping to NE-SW-striking and steeply SE-dipping, with sub-horizontal lineations. We found these structural changes are concurrent with a progressive increase in outcrop of plastically deformed concordant granite sheets and schlieric granites, and an increase in fabric intensity (Solar and Tomascak (2001, 2002). If the Sebago granites were related to the NSZS, we suggest that these observations, in concert with geochemical and geochronological data, illustrate granite ascent via structural control, but that deformation outlasted granite crystallization as the ascent conduit closed. However, our early stages of work on the Sebago-NSZS relations had no timing constraints to be able to assess a coeval, process-relation between the Sebago granites and the structure.

Building on the geochemical and geochronological work of Tomascak et al. (1996a, 1996b) on the Sebago body and related granites and pegmatites, and on mapping of parts of the NSZS (*e.g.*, West and Hubbard, 1997), our early, regional-scale mapping efforts had a simple, yet broad focus. The main question we had was how the Sebago group 1 granites (now designated the Sebago pluton) relate to the migmatites that surround it that we had dubbed “the Sebago Migmatite domain”, that include the group 2 granites, but also rocks immediately southwest of the Sebago pluton not before mapped as part of the Sebago batholith. What was the relation between the pluton emplacement history and the relatively coeval major crustal structure, the NSZS? Existing maps, including Tomascak et al.

(1996b), show the pluton just inboard of the NSZS which begs the question of any relation between them. We traversed a ~70 km across-strike transect from the core of the Sebago pluton SE into the highest strain portion of the NSZS in its deepest regional exposure near Brunswick and the necks to the south (Fig. 2). New mapping of the pluton confirmed a clearly separate central body of homogeneous granite (<400 km<sup>2</sup>) derived from Avalon-like sources (Tomascak et al., 1996b; Solar and Tomascak, 2002), flanked by a migmatite-granite complex where migmatite is permeated by smaller bodies of more geochemically heterogeneous granite (the “Sebago Migmatite domain”). In effect, the “batholith” map pattern is not supported in outcrop, geochemistry or gravity data (Behn et al., 1996). The separation of the Sebago pluton (*sensu stricto*) as a clearly separate central body of homogeneous granite (<400 km<sup>2</sup>) is clearly supported by the combination of geochemical and compositional data of Tomascak et al. (1996b; group 1 granite) relative to the area of group 2 granites (see Figs. 3 and 4), a complex dominated by migmatites and subordinate heterogeneous granites. We, therefore, referred to this complex as the “Sebago Migmatite domain”, and make a clear separation of the complex from the “batholith” map pattern and the Sebago pluton proper (Fig. 2).

Extant geochemical data (*e.g.*, Tomascak et al., 1996a, 1996b) are consistent with derivation of these subconcordant granites from materials similar to their host metasedimentary rocks (CMB source; Fig. 1). In the “Sebago Migmatite domain”, deformational fabrics in amphibolite facies country rocks are relatively variable in orientation (Fig. 2, see stereograms). However, the area SE of the pluton, adjacent to the NSZS, contains penetratively parallel structures at all scales, including fabrics in metamorphic rocks, migmatites and concordant granite sheets (Fig. 2). Fabrics are consistently NE-SW-striking and steeply- to moderately SE-dipping, similar in orientation to those in the NSZS suggesting control of granite ascent by deformation in the NSZS. Within this well-constrained structural framework, geochemical and geochronological studies can provide meaningful tectonic constraints.

Field work in seasons 2000-2002 focused on obtaining the appropriate coverage of the Sebago pluton and the migmatites and group 2 granites, and their contact relations. These data were added to our previously-collected data to (1) find the limits of the Sebago pluton proper, and (2) identify key localities that deserve closer inspection and detailed analysis both in the field and in the lab at the outcrop-scale and below. Much of the work in both the field and the lab has been focused on several targeted projects performed by our students in tandem, in a team effort. Field projects and supporting hand-specimen analyses have focused on single large exposures (*e.g.*, STOPS 5, 6 and 8 of this trip), or on a restricted region of closely-spaced outcrops. Geochemical and geochronological projects have focused on collected specimens of both granites of the Sebago pluton and granites in the migmatites, and migmatite components in the method of Solar and Brown (2001b), looking at comparative geochemistry. All project work was aimed at an integration of these projects, including the integration of field work with detailed mapping and petrography, hand-specimen and thin-section petrography, geochronology, and elemental and isotope geochemistry.

### **THE SEBAGO PLUTON, THE MIGMATITE-GRANITE COMPLEX, AND THE NORUMBEGA SHEAR ZONE SYSTEM – RESULTS OF MORE RECENT STUDIES**

#### **The Sebago pluton**

The Sebago pluton of southern Maine has been considered previously as the largest pluton in New England, however poorly exposed, composed of bodies of granite to granodiorite and granitic pegmatite. Others have shown that igneous rock types are either distinct bodies of 1 to 100 km<sup>2</sup> in area, or as complexes on the same scale of mixed types (Berry and Hussey, 1998; Creasy and Robinson, 1997). However, as noted by those studies and confirmed by our mapping, outcrops of schlieric granite and migmatite are at least as common in outcrop as are granitic rocks in the area of the mapped batholith where Tomascak et al. (1996b) mapped group 2 granites.

From our work, we conclude that the Sebago pluton (*sensu stricto*) is delineated based on geochemistry and textures, and is a distinct pluton <400 km<sup>2</sup> in area. The combination of whole-rock geochemistry and isotopic composition corresponds with the group 1 granites of Tomascak et al. (1996b; see Figs. 3 and 4). The rocks of the pluton are typically homogeneous in texture and composition (fine- to medium-grained 2-mica granite), but with local schlieric textures and biotite foliation (see STOPS 1 and 7). The age is *c.* 293 Ma based on one sample (from the rocks near STOP 1; Tomascak et al., 1996a). The presence of a pluton with the limits shown in Fig. 2 is consistent with the gravity interpretations of Behn et al. (1998).

### **The Migmatite-Granite complex we had called the “Sebago migmatite domain”**

In contrast with the Sebago pluton rocks, rocks of the migmatite-granite complex surrounding them are mostly metapelitic or metapsammitic migmatite and diatexite with subordinate centimeter- to meter-scale bodies of granite with compositions from medium-grained 2-mica granite to pegmatite, and more variable geochemistry (Tomascak et al., 1996a, 1996b). Fabrics in the granites range from unfoliated (but low % in outcrop) to augen gneiss and schlieric granite (dominant granitic rocks in outcrops; see STOPS 2, 3, 4, 5 and 6). The so-called “Sebago migmatite domain” rocks are cut by centimeter-scale granite dikes of similar composition and texture as the Sebago pluton rocks (although a connection is not made on that basis). On the northwest, the migmatite-granite complex is apparently part of the NE-SW-trending Devonian central Maine-New Hampshire migmatite belt (Fig. 1). On the southeast, they are apparently part of the NE-SW-trending ACT within the NSZS. Thus the age of the complex of migmatites and granites was uncertain and subsequent work has addressed this unknown. The eastern part of the migmatites is bounded on the SE by the Devonian crustal-scale NE-SW-striking dextral NSZS (e.g., West & Hubbard, 1997). Structure of the eastern migmatite-granite complex is consistent with that zone (Figs. 1 and 2).

The group 2 granites of the “Sebago migmatite domain” (Tomascak et al., 1996b; see Fig. 3) are discrete bodies of various compositions as described above, but always in distinct m- to 10 m-scale layers sub-concordant with host rock structures (e.g., STOPS 5 and 6). Otherwise, the rocks of the “domain” are dominated by stromatic migmatite with well-distributed penetrative plastic deformation fabrics. Leucosomes are commonly seen folded with the fabrics, and with solid-state fabrics and boudinage – illustrating subsolidus fabric formation (*i.e.* deformation continued after migmatite formation, and at subsolidus conditions). Adjacent to the NSZS, fabrics and concordant granite sheets are penetratively parallel at all scales, consistently NE-SW-striking- and steeply- to moderately SE-dipping, similar in orientation to those in the NSZS (Fig. 2; see STOP 4). These relations suggest control of granite ascent by deformation in the NSZS.

The complex of migmatites and group 2 granites mantles the discrete Sebago pluton, but only on its west, north and east (Figs. 1 and 2). The combination of the poor exposure of the pluton (very low outcrop % and density; see Fig. 2), the absence of migmatitic rocks south of the pluton, and the presence of Sebago Lake over much of the southern part of the body (Fig. 2), leave uncertain exactly how much of the area within our interpreted pluton limit on Fig. 2 is Sebago pluton rocks and just what the shape of the pluton is on the map. However, it became clear as detailed mapping progressed, that the migmatites and granites in the “Sebago migmatite domain” are ubiquitously deformed in the solid-state, after migmatite formation. The evidence of this is (1) the penetrative solid-state fabrics in all of these rocks, including in leucosomes, and (2) the folded migmatite structures (STOP 6 has excellent examples of these). When coupled with the observation of igneous-textured granites that cut these structures, it became obvious and unavoidable to us that the migmatite-granite complex that surrounds much of the Permian Sebago pluton is composed of older melted and deformed rocks, making the migmatite-granite complex. It appears the “Sebago migmatite domain” has no structural, time or geochemical connection to the Sebago pluton, and the only remaining relation is geography. Hence, we abandoned the designation “Sebago” in the name of the complex in favor of the generic “Migmatite-Granite complex” (MGC) that we now use, and use in this field guide. We concluded that the Sebago pluton intruded rocks that were already migmatites with subordinate granites within them (*i.e.* the complex is country rock to the pluton). Further geochronological evidence for this is in the next section.

### **SUMMARY OF GEOCHEMICAL AND GEOCHRONOLOGICAL RESULTS ON ROCKS OF THE SEBAGO PLUTON AND MIGMATITE-GRANITE COMPLEX**

The elemental and isotope data are clear in identifying a central pluton that we refer to as the Sebago pluton (formerly group 1 granites of Tomascak et al., 1996a; Figs. 3 and 4). The pluton has a limited range in initial Nd isotopic compositions ( $\epsilon_{Nd} = -3.7$  to  $-1.6$ ; Fig. 4). Initial Pb isotopic compositions of Sebago pluton granites are relatively radiogenic and homogeneous ( $^{207}\text{Pb}/^{204}\text{Pb} = 15.58$  to  $15.68$ ). Coupled with the Nd isotopes, these provided strong evidence for crustal sources with characteristics akin to many circum-Gondwanan terranes, such as Ganderia and Avalonia. The marked chemical and isotopic homogeneity of the Sebago pluton requires that the melts underwent substantial homogenization prior to or concurrent with final consolidation.

The chemical and isotopic homogeneity of the Sebago pluton contrasts with texturally heterogeneous bodies of granite (m to 100 m scale) exposed within the remaining MGC. These rocks have dispersed initial Nd isotope ratios ( $\epsilon_{Nd} = -6.2$  to  $-0.8$ ; Fig. 4) and show comparatively broad ranges in trace elements, including the REE (Fig. 3). For

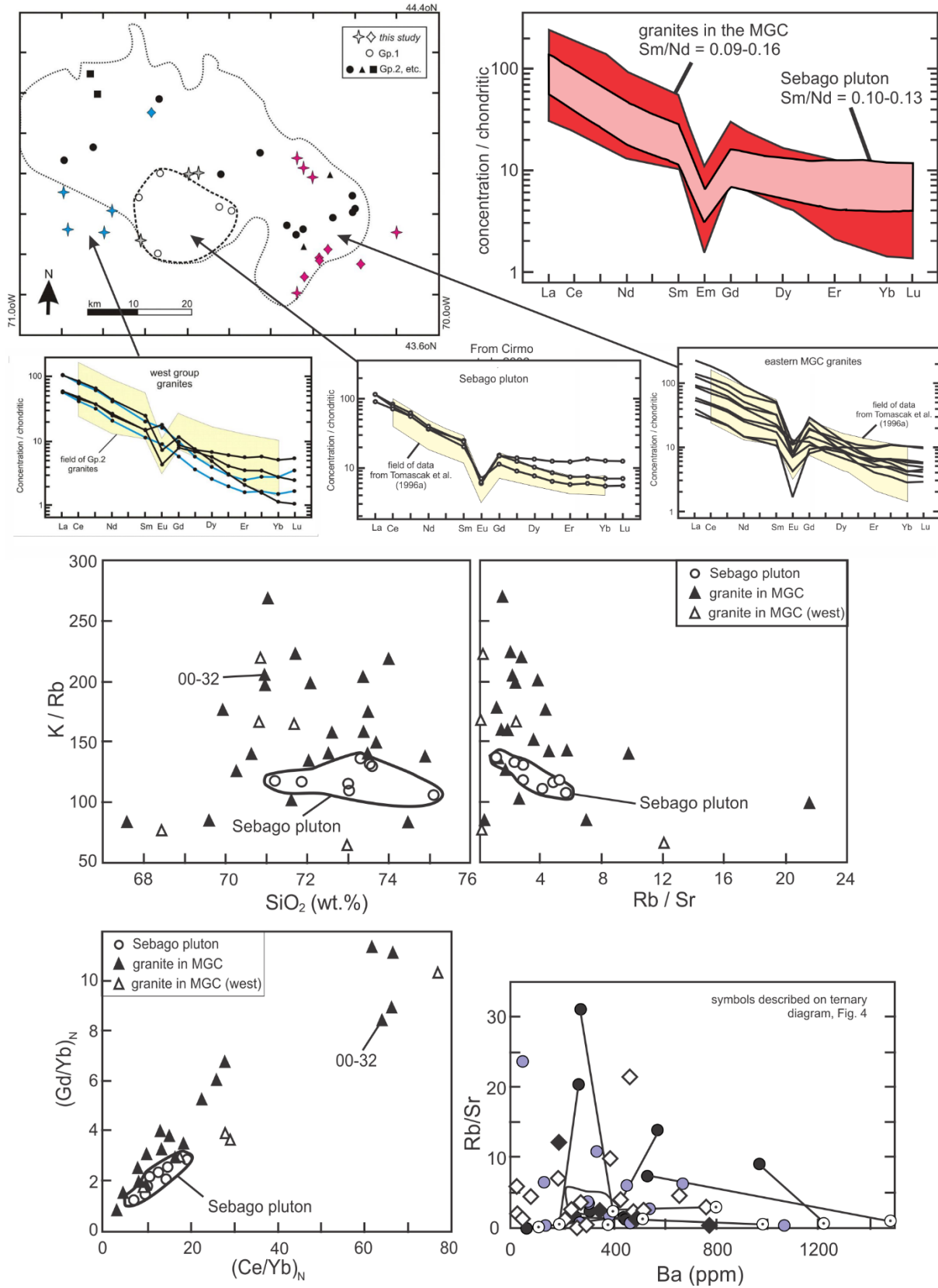
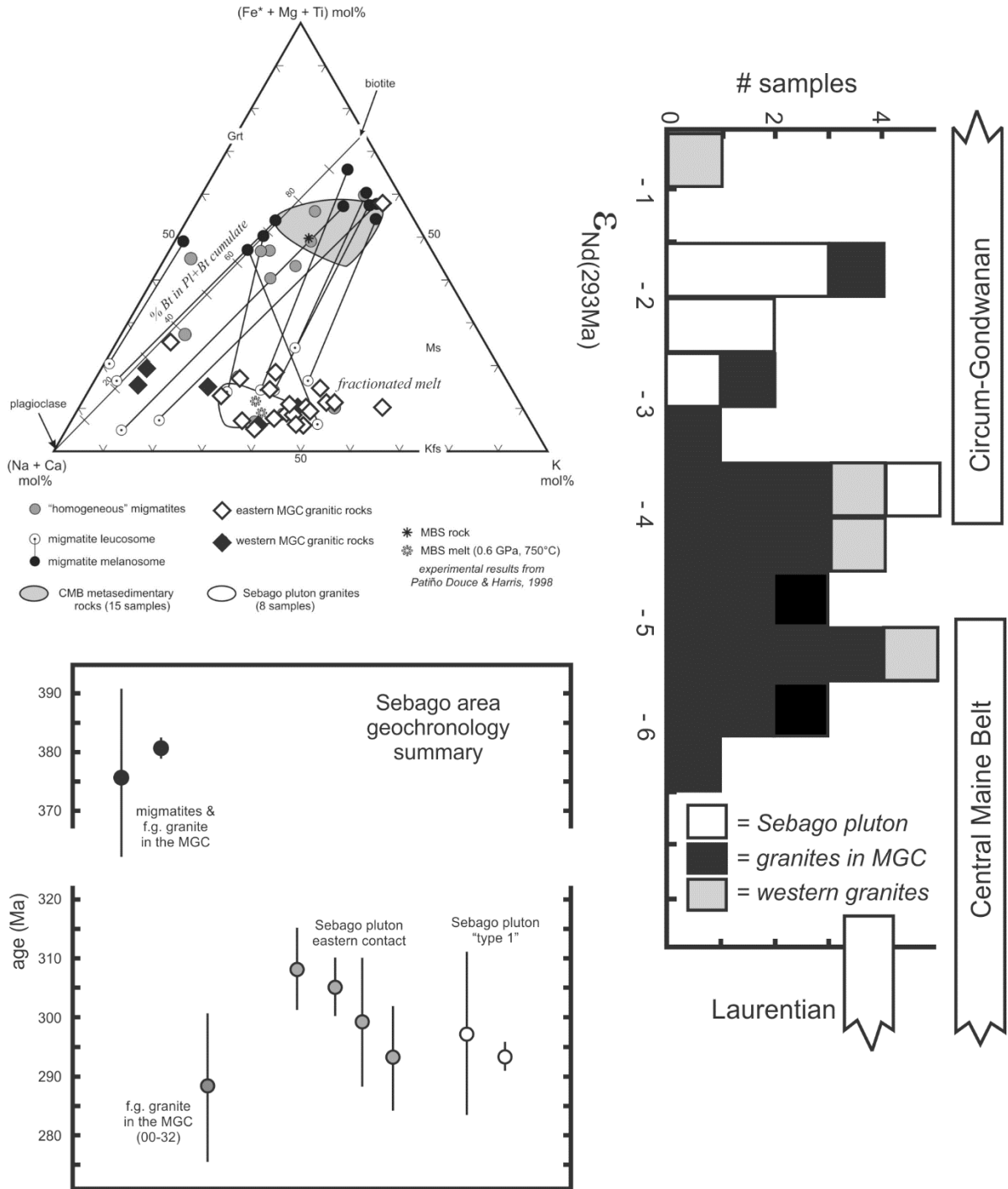


Figure 3. Summary of main geochemistry results for the Sebago pluton and the Migmatite-Granite complex.



**Figure 4.** Summary of geochemistry and geochronology results for the Sebago granites and Migmatite-Granite complex granites. The ternary diagram is modified after Solar and Brown (2001b) to include our results.

example, the lack of strong or variable LREE fractionation in the Sebago pluton samples ( $^{147}\text{Sm}/^{144}\text{Nd} = 0.110$  to  $0.132$ ) is in contrast with the granites in the MGC (ranges to  $0.164$ ).

Understanding granite magmatism in the MGC is complicated by the primarily semipelitic metasedimentary country rocks which do not permit the determination of meaningful thermobarometric constraints. Nevertheless, exposure of the rocks in several key portions of the  $\sim 5000$  km<sup>2</sup> area is very good. Chemical compositions of migmatites from the MGC range from rocks that appear to contain granitic melt arrested in transit to samples that are residual, retaining only fractionated remnants of granite components (mainly biotite and plagioclase). Although derivation of Sebago pluton magmas from the MGC migmatites is not easily reconciled with the gravity signature of the area (Behn et al., 1998), the more texturally, chemically and isotopically variable melts that ultimately became the small-scale granites within the MGC may have a petrogenetic link with the migmatites. This can be further evaluated with geochronology.

The geochronology of the area has been explored using a variety of methods: U-Pb TIMS monazite (multi-grain) and zircon (single grain), and LA-MC-ICP-MS (zircon rims and cores). Zircon from four samples from the eastern Sebago pluton contact zone (Fig. 4; STOP 8) were analyzed. They range from fine-grained granite that occurs as cross-cutting dikes to garnet- and tourmaline-rich pegmatitic granite. Individual parts of crystals do not show appreciable (analytically-resolvable) age differences (i.e., no signs of old, inherited cores). Ages determined by this method range from  $308 \pm 5$  Ma to  $293 \pm 9$  Ma. These data suggest crystallization over a relatively restricted time span (10-15 Ma).

Zircon from two additional granite sample were analyzed by LA-MC-ICP-MS. A Sebago pluton sample from the western portion of the body yielded a mean crystallization age of  $297 \pm 14$  Ma. A fine-grained granite sill from the eastern MGC (sample 00-32) yielded a mean crystallization age of  $288 \pm 13$  Ma. These ages are mutually consistent with contemporary crystallization with the Sebago pluton.

The U-Pb TIMS monazite multi-grain age determination of the Sebago pluton ( $293 \pm 2$  Ma; Fig. 4; Tomascak et al., 1996b) barely overlaps, within  $2\sigma$  uncertainty, the mean age of zircon grains from the eastern border samples ( $304 \pm 8$  Ma). Although it is possible that the Sebago pluton is not expressly comagmatic with the granites exposed at the mapped eastern margin of the pluton (STOP 8), it seems very likely that the older multiple-crystal monazite age has slightly larger uncertainty than originally determined, due to a combination of geological and analytical factors. The age of sample 00-32 further demonstrate that some component of granitic magmatism in the MGC is *not* older than the pluton. Previous work farther east, outside the MGC, established granite and granitic pegmatite crystallization in the range 280-269 Ma (Tomascak et al., 1996b), so this finding should not be particularly surprising, but it begs the question of the age of other granites in the MGD, as well as the age of migmatite formation.

The U-Pb TIMS age of a single abraded zircon from a sample of undeformed two-mica granite from the eastern edge of the MGC (Torrey Hill, Freeport) is  $381 \pm 1$  Ma, more characteristic of broadly Acadian plutonism in this area. Interestingly, this sample is petrographically indistinguishable from sample 00-32. Hence, no simple petrographic criterion can be applied to granites in this area to recognize Sebago-age rocks from those  $\sim 100$  Ma older.

Zircon from migmatites may be difficult to use to date melting, as inheritance is probable and leucosomes can be both zircon-poor and difficult to deal with from a sample preparation standpoint. Thus, finding totally neocrystallized zircon may be impossible. An alternative that may be viable is to analyze neocrystallized rims on inherited cores. If rim thickness is large enough, and laser spot size small enough, these rims can be used to constrain crystallization of melts. We used this method with three migmatite melanosomes and pooled the youngest ages to generate a best estimate of the age of migmatite formation at  $376 \pm 14$  Ma (Tomascak and Solar, 2016). This age is consistent with the one older fine-grained granite in the MGD, and confirms the interpretation based on the geological evidence that the migmatite-forming process in the Sebago area was complete long before the event that led to the formation of the Sebago pluton.

### THE RELATION BETWEEN THE SEBAGO PLUTON AND THE MIGMATITE-GRANITE COMPLEX

Based on our combination of field and laboratory data, there is no question that the formation of migmatites in the MGC, as well as some volume of granite therein, predates intrusion of the Sebago pluton by on the order of 100 Ma. Thus, Sebago pluton magmatism cannot be connected to the predominant regional metamorphism and high temperature deformation. Field and laboratory data suggest that migmatite formation and granite magma flow accompanied deformation of the melting rocks in the MGC, but that deformation outlasted or overprinted the fabrics and the granite textures. This is evident in the pinch-and-swell and solid state boudinage of the granitic rocks, all with plastic deformation textures within. Either the deformation simply outlasted the migmatite formation, or occurred later, or both. It appears that the foliation of the migmatites and the foliation in the granites both have recorded similar strain histories when the rock was subsolidus, perhaps during the same time. However, draping suggests the migmatites were hot enough to be nudged aside during emplacement of the granite, then both rocks record a similar strain history upon continued cooling. Deformation fabrics are consistently oriented with the regional structure (NSZS-related fabrics or otherwise; Fig. 2).

Solar and Tomascak (2001; 2002) placed a limit on the extent of the pluton based on the limit of exposures at the time. The limit line shown in Fig. 2 is the current interpretation of the location of what may be the pluton contact. After 2005, re-routing of Rt. 26 north of Gray, in New Gloucester, exposed rocks virtually exactly along our previously-mapped NE limit of the Sebago pluton (STOP 8). Those exposures were mapped and analyzed at a variety of scales (LaFleur et al., 2008; McAdam et al., 2009; Nyitrai et al., 2009; Bohlen and Solar, 2010).

Mapping of the exposure by LaFleur et al. (2008), and in comparison with related outcrops nearby, illuminates relations between all of the regional rock types, and we define a ~ 3 km-wide, NNW-SSE-trending zone where rock assemblages are distinct from both the pluton and the MGC. Many varieties of granites, mostly very coarse-grained, dominate the exposure. They mostly define consistently-oriented shallowly-N- or S-dipping cm- to 10 m-thick sheet-like bodies. The bodies are sub-concordant to, but encapsulate, pod- to sheet-shaped somewhat migmatitic country rocks. The two main types of granite are fine-medium grained fairly homogeneous 2-mica granite, and course-grained to pegmatitic heterogeneous granite. Granite bodies are undeformed, have no evident solid-state fabrics at outcrop (LaFleur et al., 2008), or hand specimen scales, but show some solid-state deformation in thin section (Nyitrai et al. 2009). Centimeter-scale bodies found inside the migmatites are deformed. The relation between the granites and the non-granites show structural conformity (ghost stratigraphy) as if preserved during construction of a pluton's contact zone where country rock is progressively displaced. Where granite intruded the migmatite pods, granite bodies are pinched and swelled or boudinaged suggesting ongoing deformation.

These relations, particularly in contrast to the rocks outside this "contact zone," suggest rocks at the E contact of the Sebago pluton recorded progressive contact effects with no distinct contact. These rocks record a progressive assembly of the pluton's boundary, whereas rocks outside the pluton were already deformed and melted (migmatite formation), and subsequently deformed sub-solidus. In effect, these rocks, with their ghost stratigraphy defined by the consistently-oriented country rock pods whose fabrics mimic the flat aspect of the pods, and the sheet-like intrusive nature of the main granites, suggest together that these rocks have recorded the emplacement of the Sebago pluton with edge effects as it intruded rocks that were hot enough to deform plastically during intrusion (middle crust). Results of studies performed immediately east and west of this location are consistent with this interpretation as rocks in those areas are regionally typical as described.

From these data, we interpret these rocks at STOP 8 (Figs. 2 and 7) to be part of a contact zone, approximately 3 km wide, that defines the edge of the Sebago pluton at its NE extent. The distinction of granites in this zone from the pluton itself despite overlap in time is interpreted to result from crystallization of unhomogenized batches of magma, many under more volatile-rich conditions (promoting textural and mineralogical extremes). Additional edge effects of pluton emplacement delivered a final textural dissimilarity with the granite of the main body of the pluton. Due to subsolidus deformation evident in the MGC rocks (STOPS 2 through 6), it is clear that the pluton intruded country rocks that previously attained temperatures above the solidus (partially melted) and subsequently fell subsolidus, coeval with plastic deformation which generated solid state fabrics in the migmatites and associated granitic components.



### ACKNOWLEDGEMENTS

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### ROAD LOG

Assemble at the Gray, Maine, Park and Ride at the Gray exit off I-95 (exit 63). Departure time is 8:00 a.m. All stops are indicated on the geological map of Fig. 2. The trip begins within the Sebago pluton near its northern limit, then moves to the east, across the pluton’s SE contact (we travel a significant distance), into the Migmatite-Granite complex (MGC), starting far to the southeast where it is within the Norumbega shear zone system (STOPS 2 and 3). We then travel back to the west toward the pluton, but within the MGC (STOPS 4, 5 and 6). The pluton is visited again at STOP 7, just inside the pluton’s eastern contact, and the trip finishes with outcrops we interpret to have exposed the contact relations of the Sebago pluton (at its northeastern limit, STOP 8). There is significant distance between the assembly point and STOP 1, and again between STOPS 1 and 2. However, each of the other stops are in sequence east to west, so distances between stops are relatively shorter.

#### Mileage

0.0	Park and Ride, Rt. 202, Gray, Maine. From the Park and Ride, turn left onto US 202 W.
3.3	Continue straight onto ME 115 W.
6.3	Turn right onto US 302 W.
18.8	Turn right onto ME 11 N.
19.5	Turn left onto Edes Falls Rd.
21.2	Continue straight/slight left onto River Rd.
21.3	Park on the right side along granite boulders. Parking is limited. Walk along the path to the outcrops along the river.

#### **STOP 1: TWO MICA GRANITE OF THE SEBAGO PLUTON (SEBAGO GROUP 1 OF TOMASCAK et al., 1996b), STREAMCUTS IN CROOKED RIVER, NAPLES, ME.** (UTM 4873025N 0373846W)

The main granite is homogeneous-textured two-mica granite of the Sebago pluton near its north contact (Fig. 2). The main granites here are typical of the petrochemical ‘group 1’ granites of the Sebago pluton (Figs. 1, 2 and 3; cropping out primarily on the north, west and northeast sides of Sebago Lake; Tomascak et al., 1996a; Solar and Tomascak, 2001, 2002). Outcrops of rocks typical of ‘group 1’ include massive two-mica granite, without pervasive magmatic (few occurrences of local schlieren) or metamorphic fabric. This type of granite is generally equigranular to locally porphyritic, with K-feldspar phenocrysts up to 2 cm in length. A specimen collected from a nearby outcrop in Naples, ME, yielded a

concordant U-Pb monazite crystallization age of  $293 \pm 2$  Ma (Fig. 4; Tomascak et al., 1996a). Locally granitic/pegmatitic dikes cut the main granites. Late dikes here are basaltic (diabase) associated with Mesozoic extension.

### Mileage

- 21.3 Turn around, and backtrack to Edes Falls Rd.
- 21.4 Bear right onto Edes Falls Rd.
- 23.2 Turn right onto ME 11 S.
- 23.5 Turn left onto Sand Rd.
- 24.1 Turn left onto US 302 E.
- 36.2 Turn left onto ME 115 E.
- 40.2 Turn right onto Lawrence Rd.
- 41.5 Turn left onto Center Rd. and a quick right onto Dutton Hill Rd.
- 43.4 Just after crossing over I-95, turn right onto Rt. 26 S.
- 45.0 Turn left onto Skillin Rd. (We will be coming back through here later.)
- 45.9 Turn right onto Blanchard Rd.
- 48.7 Continue straight onto Tuttle Rd at the traffic light in Cumberland, ME.
- 50.6 Turn right onto Harris Rd.
- 51.5 Park along Harris Rd. at the powerline crossing. Outcrops are pavement along the east side of the road.

### **STOP 2: STROMATIC MIGMATITE AND DIATEXITE OF THE SOUTHEASTERN MIGMATITE-GRANITE COMPLEX (MGC) IN THE NORUMBEGA SHEAR ZONE SYSTEM, HARRIS ROAD, CUMBERLAND, ME.**

(UTM 4846907N, 0400516W)

A series of pavement outcrops on the east side of Harris Rd. are pelitic-protolith migmatites of the MGC. Exposures at the power line crossing are classic stromatic migmatites with tripartite, sub-parallel structures of the leucosomes, with well-developed melanosomes that separate them from the host metasedimentary rocks. Farther S along Harris Road are pavement exposures of diatexite, but time will likely see these exposures covered due to new home construction. Pegmatite dikes are also present, the larger of which are boudinaged. Fabric in the migmatite is folded locally, but otherwise consistent in orientation with Norumbega Shear zone system fabrics in the NW wall zone of the structure (NE-SW-striking and moderately SE-dipping; Fig. 2). Bt-dominated selvages are common at the contacts of leucosomes, but larger granite sheets do not have selvages. Some leucosomes are Grt-bearing. Leucosomes are also commonly boudinaged, or at least pinched-and-swelled with solid-state deformation evident by grain-size reduction textures. The migmatites are deformed in the solid state (subsolidus) and leucosomes have recorded fabrics. This and the boudinaged granites are consistent with migmatite formation and intrusion preceding the latest deformation. The structure here is consistent with regional Norumbega shear zone system structures.

### Mileage

- 51.5 Return north on Harris Rd. (back the way you came).
- 52.4 Turn right to continue southeast on Tuttle Rd.
- 53.7 Cross Middle Rd. (traffic light) and then over I-295.
- 54.0 Turn left toward US 1, and in under 0.1 miles turn right onto US 1 N.
- 55.2 Park at northern side of the intersection of US 1 and Tyler Dr. Walk to roadcuts on the on-ramp for I-295 S.

### **STOP 3: MIGMATITES AND GRANITES OF THE SOUTHEASTERN MGC IN THE NORUMBEGA SHEAR ZONE SYSTEM, YARMOUTH, ME.**

(UTM 4848559N, 0404378W)

These are relatively new (ca. 2013) roadcuts along the on-ramp on both sides. The ramp curvature provides a 3-D view of the rock structure, especially in the main roadcut on the outside (SE) of the ramp. Similar to rock at STOP 2, the dominant rock here is migmatite with local sill-forming granites that are boudinaged and pinched-and-swelled along the structural grain. These granites have solid-state fabrics. The migmatite has penetrative shallowly E-dipping fabrics subparallel to the rock structure as a whole. The

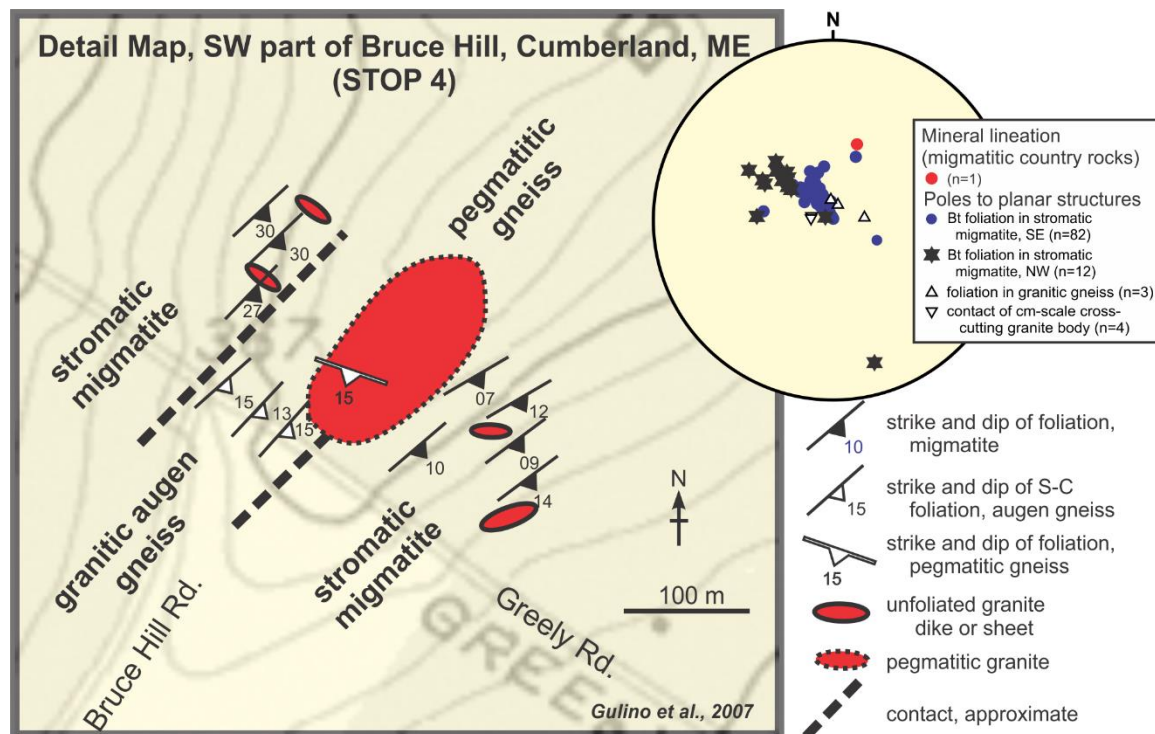
central part of the roadcut features a steeply NE-dipping granitic dike that is strongly discordant to migmatite structures, but appears to be continuous with a structurally-concordant granitic sill near the top of the exposure. For the most part the migmatite is similar here as at STOP 2, however, the protolith was psammitic, and the migmatite lacks the usual tripartite structure (melanosomes are few and local). Solid state structures in both the migmatite and granites are consistent with both migmatite formation and granite intrusion preceding the latest deformation. The structure is consistent with dextral transpression in the NW wall rocks of a restraining bend of the Norumbega zone.

#### Mileage

- 55.2 Reverse direction and return south on US 1 S.
- 56.3 Turn left to return to Tuttle Rd. (from whence we came).
- 56.4 Turn right onto Tuttle Rd.
- 56.5 Again cross over I-295
- 56.6 Again proceed straight through the traffic light at Middle Rd. to continue on Tuttle Rd. toward Cumberland, ME.
- 59.8 Continue straight through the traffic light onto Blanchard Rd. in Cumberland, ME.
- 61.5 Turn right onto Bruce Hill Rd.
- 62.5 Park at the intersection of Bruce Hill Rd. and Pleasant Valley Rd. (outside of the left-hand bend). Walk to the pavement outcrops in the woods along the path north of the northern-most driveway on Bruce Hill Rd.

#### STOP 4: MIGMATITE, GRANITIC GNEISS, PEGMATITE, AND GRANITE OF THE EASTERN MIGMATITE-GRANITE COMPLEX, BRUCE HILL EXPOSURES, CUMBERLAND, ME. (UTM 4852870N, 0397425W)

Pavement exposures and a cut in the back and side yards of the house just north display most rocks at Bruce Hill. Chris Gulino studied the exposures here in detail (Gulino et al., 2007; Fig. 5), and delineated five rock units that are all typical of the MGC in general, but particularly of the eastern MGC. Stromatic migmatite is the dominant rock unit on the NW (the side we park on) and SE flanks of the hill (Fig. 4), and



**Figure 5.** Geological and structural map from Gulino et al. (2007), Bruce Hill area (STOP 4).

is uniformly plastically deformed, including boudinaged leucosomes and granite layers with S-C fabrics. The other units are local semipelitic schist, and granites of three varieties: (1) S-C augen gneiss that composes the SW flank of the hill (this is the first exposure one comes to straight out of the vehicle, and likely the only rock seen on the day of our trip) that have fabrics sub-concordant to the fabrics in the migmatites, (2) pegmatite (locally with solid-state fabrics) that dominates the hill top, and (3) unfoliated to weakly foliated 2-mica granite in dikes that are cut across the main structures. Where fabrics exist, they are consistently NE-SW-striking and shallowly to moderately SE-dipping (Fig. 5).

Stromatic migmatite has mafic melanosomes at the contacts with leucosomes, and the leucosomes are plastically deformed. The granitic gneiss units have foliation defined by ribbon quartz and mica aggregates, and occur in localized bodies, some of which are pods showing pinch along the migmatite structure, and draping of migmatite folia over them (typical of such relations in the MGC). Where augen-bearing, the gneiss has strong S-C fabric and biotite foliation. The pegmatitic gneiss has coarse plagioclase and quartz ribbons, mats of biotite, and muscovite, and occurs in local zones and in meter-scale veins, usually associated with the granitic gneiss, and with variable mineral content including garnet and tourmaline where fabrics are strongest. The 2-mica granite is relatively homogeneous with weak or no visible fabric. Where fabric exists it is defined by somewhat planar-aligned micas. This rock is subordinate in outcrops, and typically strongly discordant to fabrics in country rocks. These granites are in discrete bodies and have textures similar to that of the Sebago pluton rocks to the W.

#### Mileage

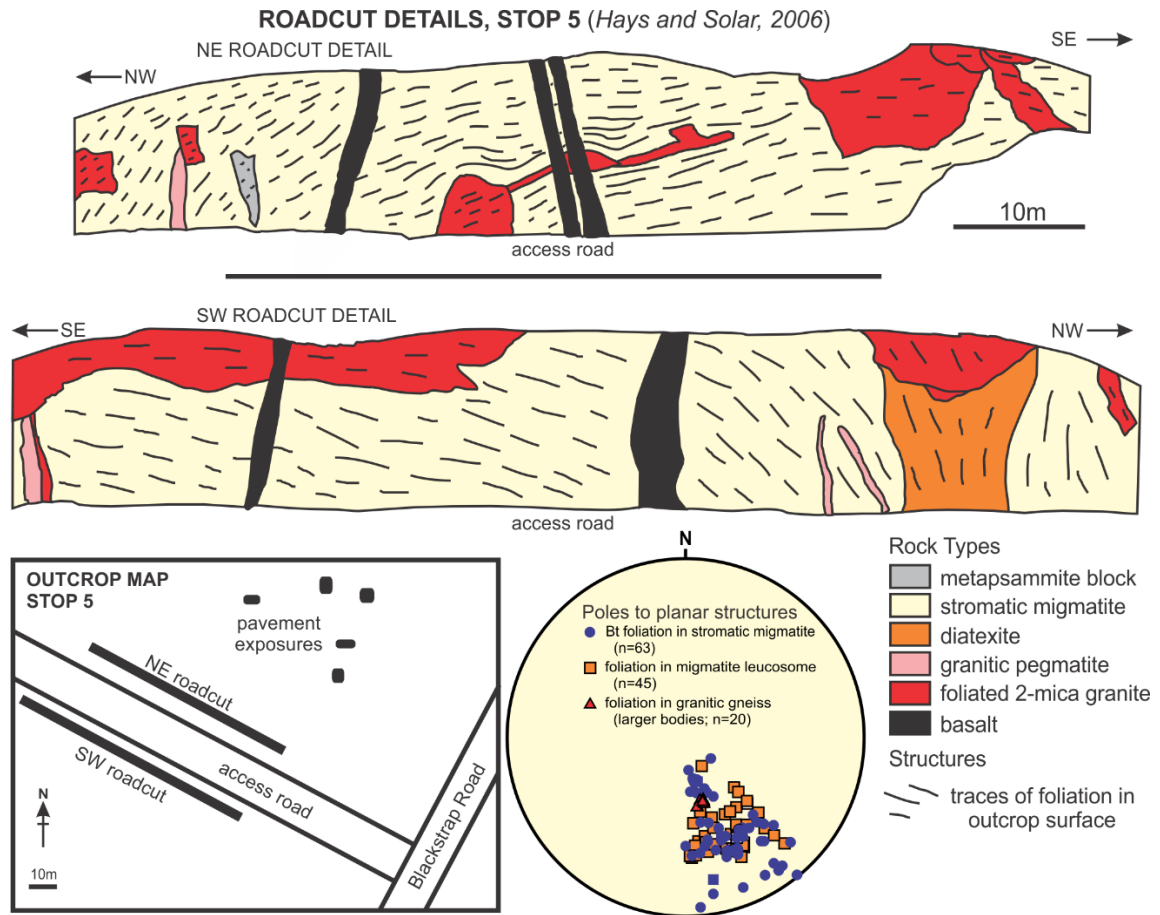
- 62.5 Reverse direction and return southwest on Bruce Hill Rd.
- 63.5 Turn right onto Blanchard Rd. to go NW.
- 64.6 Turn left onto Skillin Rd.
- 65.5 Cross Rt. 26 and continue straight onto Blackstrap Rd.
- 65.7 Cross over I-95.
- 66.6 Turn right onto Old Colony Lane and park. The roadcuts for STOP 5 are along this access road to the subdivision and at the top of the hill.

#### **STOP 5: STOMATIC MIGMATITE, DIATEXITE, GRANITE GNEISS AND GRANITE OF THE EASTERN MIGMATITE-GRANITE COMPLEX, OLD COLONY LN. AT BLACKSTRAP RD., WEST CUMBERLAND, ME.**

(UTM 4851028N, 0393103W)

The roadcuts along both sides of Old Colony Lane and the pavement exposures above the north exposure was studied in detail in 2006 by S. Hays (Hays and Solar, 2006; Fig. 6). He documented variations at the centimeter- to meter-scale of mineral fabrics and the geometry of granitic bodies in this ~150 x 75 x 5 m exposure, and identified seven principal rock types. The majority of the exposure is stromatic migmatite. Leucocratic granitic gneiss is next most abundant with subordinate pegmatitic granite, meta-psammitic schist blocks and cross-cutting sub-vertical basalt dikes (~ 50 cm wide; see Fig. 6 for details). Diatexite is also dominant, seen best in pavement exposures. The stromatic migmatite here is typical of the eastern MGC (*cf.* STOPS 4 and 6) with plastically deformed leucosomes, and fabrics (and overall structure of the rocks) with generally NE-SW strikes and shallowly- to steeply-NW-dipping, varying with distance across strike (Fig. 6, see stereogram and roadcut detail). Lineations (defined by grain shape fabrics) are shallowly NE- or SW-plunging. Using cut samples, Hays measured leucosome long and short axes on mutually perpendicular cuts (Hays and Solar, 2006). Calculations show an overall > 48% leucosome in samples, long dimensions strike-sub-parallel, and flat aspects sub-concordant with migmatitic foliation.

Granitic gneiss is plastically deformed, having a strong foliation defined by ribbon quartz and mica aggregates. Foliation is sub-concordant to the foliation in the migmatite. Granitic gneiss occurs in localized bodies, some of which are pods showing pinch along the migmatite structure, and draping of migmatite folia over them. Pegmatitic gneiss has coarse plagioclase and quartz ribbons, mats of biotite, and muscovite, and occurs in local zones and in meter-scale veins associated with the granitic gneiss. Diatexite is composed of plagioclase, K-feldspar, quartz, biotite, and muscovite, and is plastically deformed,



**Figure 6.** Outcrop map, roadcut detail sketches and structural data from Hays and Solar (2006), Old Colony Rd. at Blackstrap Road, STOP 5.

appearing as granitic gneiss. Granite bodies are typically schlieric. Hays identifies a single “meta-psammite block” in the exposure (see Fig. 5) composed of quartz and plagioclase, with a disjunctive mica foliation, distinct from the rocks of the rest of the exposure (that are otherwise migmatitic or granitic).

#### Mileage

- 66.6 Reverse direction and return east on Blackstrap Rd.
- 67.5 Cross over I-95.
- 71.8 Turn right onto Rt. 26.
- 72.2 Pass intersection with Mill Rd.
- 72.3 Turn left onto dirt road and proceed toward the outcrops ahead. Park before the ‘beach’ in front of the pond below the house. We are on private property with permission of the land owner. Future visits are by advance permission only.

#### **STOP 6: STOMATIC MIGMATITE, AMPHIBOLITE MIGMATITE, GRANITE GNEISS AND GRANITE OF THE EASTERN MIGMATITE-GRANITE COMPLEX, RT 26 AT MILL RD., CUMBERLAND, ME.** (UTM 4851490N, 0394646W)

The outcrop here is special (to say the least). The land owner has in recent years (starting in 2010) removed a deep pile of glacial till to reveal the glacially-polished rocks underneath including a 20m-tall and 80m-long, west-facing cliff (on top of which they built their home), and the clean (lichen-free) pavement exposures below. This is very different from our first visit here in 2001 when we found an

exposure that was less than 40m<sup>2</sup> in one large knob-type outcrop, and lichen-covered. That former exposure is now part of the driveway to the house at the top of the cliff. Rocks here were studied in detail by Brandon Luther (Luther et al., 2015). Visiting the exposures is by permission of the land owner exclusively.

The rocks here represent all rock types found within the MGC, including amphibolite and amphibolite gneiss (migmatitic) and late basalt dikes. The pavement exposure is dominated by solid-state-deformed stromatic migmatite whose structure is moderately SE-dipping, with concordant amphibolite layers. Granitic rocks are within, as is usual in the MGC, and also as usual are found with solid-state fabrics that are sub-parallel to the structure of the migmatite. Leucogranitic gneisses and leucosomes are ubiquitously boudinaged, and many are folded with sub-horizontal hinge lines that trend along the structural grain (NE-SW). Locally fold forms illustrate dextral kinematics that include delta porphyroclasts of feldspar. Where measurable, mineral lineations are also sub-horizontal and NE-SW-trending. Larger granite gneiss bodies are discordant to the migmatite structures, the largest of which cross-cuts the migmatite near cliff face-pavement interface.

### Mileage

- 72.3 Return to Rt. 26, and turn right toward Gray, ME.
- 72.8 Continue past Rt. 26 intersection with Skillin Rd.
- 78.2 In the town of Gray, turn slightly right and then left to continue on Rt. 26 N.
- 79.3 Turn right to remain on Rt. 26 N.
- 80.8 Turn left onto N. Raymond Rd.
- 81.8 Turn left onto Egypt Rd.
- 85.8 Turn left onto Rt. 85 S.
- 86.8 Turn left onto Tarkiln Hill Rd.
- 87.0 Turn left to remain on Tarkiln Hill Rd. and follow the road uphill.
- 87.5 Park along Tarkiln Hill Rd. The pavement outcrops are on the left side of the road, continuing east into the woods.

### **STOP 7: TWO-MICA GRANITE AND PEGMATITE OF THE EASTERN PART OF THE SEBAGO PLUTON, TARKILN HILL RD., RAYMOND, ME.** (UTM 4863906N, 0385276W)

Homogeneous textured two-mica, medium-coarse-grained granite typical of the petrochemical group 1 granites of the Sebago pluton. Rocks here are similar to granites of the Sebago pluton (*e.g.*, at STOP 1), but, in this case, these outcrops are located nearer to the Sebago pluton's northeastern limit, where it is in a contact zone with the eastern MGC (Fig. 2; *cf.* the location of STOP 8). We are here mostly to revisit the pluton after seeing the MGC rocks, and before seeing the contact zone at STOP 8. Granites are locally weakly foliated (Bt) with variable orientations, and contain locally distinct pegmatite bodies that have gradational to sharp cusped margins with the main granite.

### Mileage

- 87.5 Reverse direction and return downhill on Tarkiln Hill Rd. to Rt. 85.
- 88.3 Turn right onto Rt. 85.
- 89.3 Turn right onto Egypt Rd.
- 93.3 Turn right onto N. Raymond Rd.
- 94.3 Turn left onto Rt. 26 N.
- 95.2 First roadcut on left of the STOP 8 sequence of roadcuts. Continue uphill to the second set of exposures to where there are roadcuts on both sides of Rt. 26.
- 95.7 Park on the right shoulder at the top of the hill, at the roadcuts on the right side of Rt. 26. Be careful of traffic on Rt. 26. Attention is directed first on the view across the road to the south-bound-side roadcut.

**STOP 8: N-S SERIES OF ROADCUTS, RT. 26: GRANITES AND METASEDIMENTARY ROCKS (AND MIGMATITES) AT THE NORTHEASTERN CONTACT OF THE SEBAGO PLUTON, NEW GLOUCESTER, ME.**

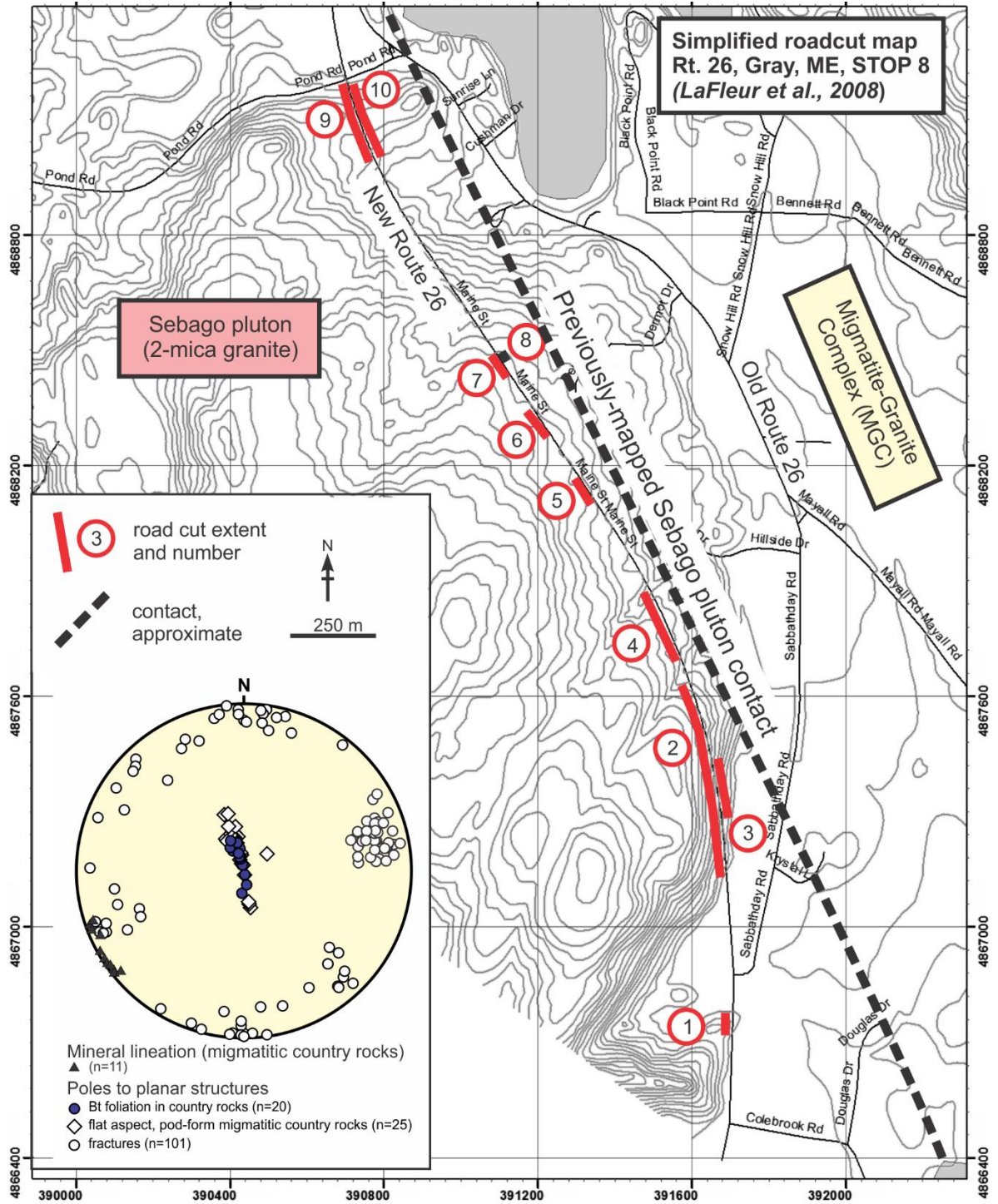
(south end: UTM 4866764N, 0391725W – north end: UTM 4869165N, 0390703W)

These exposures are nearly 100% new as of 2005 when Rt. 26 was re-routed a short distance to the west (Fig. 7). The newly exposed rocks are a set of roadcuts extending along new Rt. 26 here for 2.3 km (NNW-SSE oriented). Fortuitously, this rerouting has exposed rocks nearly precisely along what Solar and Tomascak (2001, 2002) had mapped previously as the eastern limit (contact?) of the Sebago pluton with the eastern MGC (Fig. 2). There is a lot to see here, so plan to spend some time at this set of outcrops. But, more importantly, rocks here did not yield data as expected based on our early mapping. We expected to find some combination of Sebago granite and MGC-typical exposures (or one or the other). Instead what we find here is a suite of rocks that are distinct from both the Sebago pluton rocks and the MGC rocks. Detailed study of the exposure was performed in both the field (LaFleur et al., 2008; Bohlen and Solar, 2010) and the lab (*e.g.*, Nyitrai et al., 2009) in order to best document these rocks. The field results are summarized below, and in Fig. 7 where the locations and extents of the ten roadcuts of this outcrop are illustrated.

The exposures are dominated by granite sheets, some of which show interconnectedness (connecting at shallow angles to the overall layered, shallowly- to moderately-S or N-dipping structure), that envelop layered country rock pods that are locally migmatitic pelitic to semi-pelitic metasedimentary rocks. The overall structure is one of a ghost stratigraphy, where migmatitic, country rock pods have fabrics that show a stromatic (layered) type in pelitic protoliths to diatexite in the smaller bodies. Internally, plastic deformation in the pods is evident, including meter- and centimeter-scale folds, some of which are ptygmatic, of all rock types, including granite sheets and leucosomes. The smallest pods (meter-scale) are disrupted, appearing “wispy” as ends appear as if frayed, perhaps anatectically eroded and disaggregated (frozen in process). The migmatite has biotite foliation, selvage melanosomes, and sub-concordant cm-scale leucosomes that have varied solid-state fabrics. Leucosomes are folded and foliated where cm-thick or more. Within the country rock pods, granitic gneiss layers (cm-scale) are sub-concordant, and show ‘pinch-and-swell’ or boudinage (this outcrop’s exposures 2 and 10 – see Fig. 7 – have excellent examples).

Granite types are delineated into 5 varieties based on the combination of mineral content and texture (Nyitrai et al., 2009). Of the granite types, coarse-grained, texturally heterogeneous 2-mica granite to granodiorite dominates, with the exception of the southern-most exposure (exposure 1) where the main granite is medium-grained 2-mica granite with ubiquitous mm- to cm-scale mica clusters. Exposure 1 is also marked by m-scale pegmatite dikes with distinct contacts. The granites at exposure 1 have an appearance that is most typical in these outcrops of the Sebago granites (except for the mica clusters). Granite sheets outside country rock pods are only locally foliated, but without evidence of solid-state deformation. The main granites occur as sheets, locally cross-cutting the country rocks. Meter-scale (thick) granite bodies inside country rock layers are nearly uniformly boudinaged or ‘pinched-and-swelled.’ Where tapered at their tips, country rock pods appear as if frozen in process of disaggregation, perhaps by anatectic erosion (good examples in exposure 2, Fig. 7), but clearly from N to S along exposure 2 on the west side of the road, coherent bodies of country rocks taper over a short distance to smaller, discrete ‘wisps’ and schlieren. A country rock pod at exposure 10 has a granite layer within that is continuous with the 10m-thick granite sheet structurally above the pod.

Late granite dikes and sills occur locally, but throughout the outcrop (as do some sub-vertical basalt dikes). These granites are fine- to medium-grained 2-mica granites that cross-cut all other rocks (and are also sills partially). These granites are most similar to Sebago granites, but clearly have a later intrusion age than the main granite bodies. One such dike at exposure 2 cross-cuts the outcrop structure, extending from the base to the height of the roadcut. This dike alternates orientation between a moderately S-dipping dike and a sub-horizontal sill. Orientation varies with layer the dike is crossing at that level. These late granites are similar to those found to the W of Rt. 26 where rocks of the Sebago pluton are found (*e.g.*, STOP 7), and in migmatites and granite gneiss exposures in the MGC to the southeast (*e.g.*, STOPS 5 and 6).



**Figure 7.** Outcrop map of the roadcuts along the rerouted Rt. 26, north of Gray, ME (in New Gloucester; STOP 8). Map and data modified after LaFleur et al. (2008).



Of particular note in this outcrop is a granite body in exposure 2 at coordinates 4867319N, 0391663W. Here a ~10 m-wide dike of medium-grained 2-mica granite that opens upward into a sub-horizontal sill. The S edge of this body has a distinctive mafic selvage dominated by Bt. At this same location, the edge of the dike had granite that progressively coarsens in grain size with proximity to the dike contact over about 35 cm distance. There is another such dike, but thinner (3-4 m) at exposure 8 (4868445N, 0391093W).

Results of mapping of the exposure reveals illuminating relations between all of the regional rock types, and we define a ~ 3 km-wide, NNW-SSE-trending zone where rock assemblages are distinct from both the pluton (to the W) and the MGC (to the E). Many varieties of granites, mostly very coarse-grained, dominate the exposure, and mostly define consistently-oriented shallowly-N- or S-dipping cm- to 10 m-thick sheet-like bodies. The bodies are sub-concordant to, but encapsulate, pod- to sheet-shaped somewhat migmatitic country rocks. Granite bodies appear undeformed at outcrop (LaFleur et al., 2008; Bohlen and Solar, 2010), but have some solid state deformation evident in thin section (Nyitrai et al., 2009). Some magmatic fabric is evident locally. The relation between the granites and the non-granites show structural conformity (ghost stratigraphy) as if preserved during construction of a pluton's contact zone where country rock is progressively displaced. Where granite intruded the migmatite pods, granite bodies show pinch-and-swell or boudinage suggesting ongoing deformation. Cross-cutting all of the rocks is fine- to medium-grained 2-mica granite to granodiorite in the form of dikes and sills of cm- to meter-scale thickness. These cross-cutting granites resemble closely the rocks typical of the Sebago pluton proper and are of identical crystallization age as all of the other granitic components in the contact zone of STOP 8.

#### END OF TRIP

The assembly point at the Gray Park and Ride is found by travelling south on Rt. 26 for 3.9 miles to Rt. 26A (stay straight/bear right) that leads directly to the Park and Ride at US 202 (in 1.2 miles).

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