HOW IS THE GRANITE MELT FLOW NETWORK RECORDED IN MIGMATITES AND BY ASSOCIATED GRANITE PLUTONS?

PROJECT DESCRIPTION

A. Introduction

The process of generation, segregation, ascent and emplacement of granite magma during orogeny has important implications because melt transfer affects the thermal and rheological behavior of the crust during orogenesis (*e.g.*, Collins and Vernon, 1991; Stüwe *et al.*, 1993; Brown and Solar, 1998b, 1999). Our models of how melt is generated and segregated are well developed (*e.g.*, Wickham, 1987; Johannes, 1988; Allibone and Norris, 1992; Sawyer, 1994; Brown *et al.*, 1995; Rushmer, 1996; Milord *et al.*, 2001; Barraud *et al.*, 2001a, 2001b). We also understand well how granite magma is emplaced in both extensional and contractional tectonic settings (*e.g.*, Hutton & Reavy, 1992; Grocott *et al.*, 1994; Paterson *et al.*, 1996; Paterson and Miller, 1998; Brown and Solar, 1998b; Benn *et al.*, 1998; Cruden, 1998). However, the mechanism by which melt is transferred from source to sink during orogeny remains a matter of debate, perhaps mostly due to the apparent variability in the rock record of these processes that is specific to geographic area (*e.g.*, Clemens and Mawer, 1992; D'Lemos *et al.*, 1992; Brown, 1994; Rutter, 1997; Sawyer, 1998; Brown and Solar, 1999; Miller and Paterson, 1999; Weinberg, 1999; Kalbeek *et al.*, 2001; Solar and Brown, 2001b; Barraud *et al.*, 2004). There is, however, strong textural, compositional and geometrical commonality in observations from migmatitic rocks and their associated granite bodies.

Within migmatites, the geometry of leucosomes and smaller-volume granites (less than a few kilometers wide or long) may record the melt flow network through the crust (*e.g.*, Brown and Rushmer, 1997; Sawyer, 1998; Brown and Solar, 1999; Brown *et al.*, 1999), particularly so if the leucosomes do not record solid state strain. Regardless, it is apparent that leucosome-granite sheet networks may have recorded a quasi-steady network of melt migration, controlled for the most part by deformation of the melt-bearing rocks. However, experiments have shown that the geometry of leucosomes in migmatites may be only fragments of the conduit geometry since conduits likely close and open periodically during melt flow, and some vein-like leucosomes may travel as a whole during deformation of the host (Barraud *et al.*, 2004). At the outcrop scale, the presence of granite located in structurally-controlled sites within migmatite, such as interboudin partitions and strain shadows (*e.g.*, Stromgard, 1973), fractures and fold hinge zones (*e.g.*, Collins and Sawyer, 1996), and dilatant shear surfaces (*e.g.*, Brown, 1994) suggests melt flow through the migmatite during deformation (*e.g.*, Brown and Rushmer, 1997). This is supported by experiments (*e.g.*, Barraud *et al.*, 2001a, 2001b, 2004). In a partially molten rock, melt is segregated during deformation by moving down gradients in melt pressure to create leucosomes (Brown, 1994; Brown *et al.*, 1995; Rutter, 1997; Marchildon and Brown, 2001). If deformation and melting are coeval, cyclic inflation and collapse of melt flow conduits caused by build up of melt pressure and periodic draining of the source moves melt through the crust (*e.g.*, Brown and Solar, 1998a, 1999; Weinberg, 1999). As deformation progresses, strain will be localized by the changing rheology that results from such factors as reaction-enhanced ductility (*e.g.*, White and Knipe, 1978; Rutter and Brodie, 1995) and melting (*e.g.*, Rutter and Neumann, 1995; Brown and Rushmer, 1997; Brown and Solar, 1998a). Further, the introduction of melt into shear zone systems is widely postulated as a weakening mechanism that will concentrate strain within the system (Hollister and Crawford, 1986; D'Lemos *et al.*, 1992; Grocott *et al.*, 1994; Pavlis, 1996).

Clearly, in order to understand the rock record of the melt transfer process in contractional orogens, it has become important to be able to document the geometry of migmatitic structures and associated plutons. There have been several recent studies published that have illustrated the benefits of such efforts (e.g., Sawyer, 1999; Mengel *et al.*, 2001; Milord *et al.*, 2001; Solar and Brown, 2001b; Marchildon and Brown, 2003). If the leucosome shapes and extents relate to some sort of plumbing, with migmatitic fabrics as the conduits (Sawyer, 1999; Barraud *et al.*, 2004), our best efforts at understanding how melt has flowed through this system would be to document that geometry to the best of our abilities. Despite the likely possibility that this geometry may be fragmentary or composite, the base of understanding can come only from this type of detailed work. Ideally, we should study and measure each square centimeter of migmatites, at three dimensions in order to understand three-dimensional and scale-variant paleomelt-flow structures. The same can be said of studying shapes of plutonic bodies, and internal structures in granites (perhaps defined by differing compositions and textures of discrete granite bodies). Realistically, of course, we have only a small percentage exposed.

One of the primary (although seldom rigorously satisfied) tests of granite-migmatite relations is precise geochronology (*e.g.*, in western Maine: Smith and Barreiro, 1990; Solar *et al.*, 1998). With fundamental field relations developed in studies in the zone of distributed ductile strain of the Central Maine Belt shear zone system (Figs. 1 and 2; Solar and Brown, 2001a) and the Norumbega shear zone system of southern Maine (Fig. 1; Solar and Tomascak, 2001), samples can be readily targeted that will provide an essential geochronological framework using U/Pb in the common accessory minerals zircon and monazite.

Geochemistry of migmatites and granites permit further expansion of the understanding gained from in-depth field characterization of migmatite terranes. Major element componsitions can be used to test basic hypotheses on migmatite petrology (Solar and Brown, 2001b). To the extent that accurate distribution coefficients allow, major and trace elements can be a further test of migmatite and granite connections. Combined, elemental geochemistry seeks to define the extent to which migmatite leucosomes can be considered liquids or cumulates, as well as establishing potential lines of descent amongst groups of spatially related granitic rocks.

Initial ratios of long-lived radioisotopes (*e.g.*, Nd, Pb) permit additional detailed testing of hypotheses of granite-migmatite linkages, although phase relations need to be taken into account as to the potential for disequilibrium effects in a region in which melting reactions may have been locally heterogeneous (Nabelek and Glascock, 1995; Hogan and Sinha, 1989). Above and beyond their usefulness in assessing granite-migmatite relations, combined Nd-Pb isotope data have been effective in western Maine in placing firmer constraints on the nature of source materials (Tomascak *et al.*, in press), which must be factored into the development of more viable tectonic models for the orogen.

An integrated approach is justified in order to understand the rock record of melt transfer in contractional orogens. Each aspect of this type of work can be fully understood only after beginning with the detailed analysis of individual exposures within an area. Such studies are usually ideal for small-scale field and laboratory studies that can be performed by many workers, operating simultaneously within a given region. Each study, therefore, becomes part of a larger-scale project aimed at a singular goal. Hence this work is especially appropriate for a team of undergraduate students focused on individual projects that are integrated into a master regional effort. Not only does it work toward the goal of involving students in meaningful research, but the research itself is better off for the approach of detailed field characterization as the basis for hypothesis testing by more technical means. Both PIs' institutions are primarily 4-year undergraduate colleges, and the PIs are actively involved with mentoring undergraduate students in research (please see the **RUI Impact Statement**).

The **goals** of this proposal are two-fold as follows:

1. A better understanding of the paleomelt-flow network in the cores of collisional zones, in the form of migmatite leucosome geometries, migmatite textures, leucosome and associated granite compositions and geochemisties, and the geochronology of migmatites and associated granites. The field work will be focused on either single large exposures, small sets of closely-spaced outcrops or along a series of transects in order to properly document these variables.

2. Research experiences for undergraduate students in the form of year-long Honors Theses and one-semester Independent Study projects with foci related to distinct, and well-constrained parts of the project goal #1.

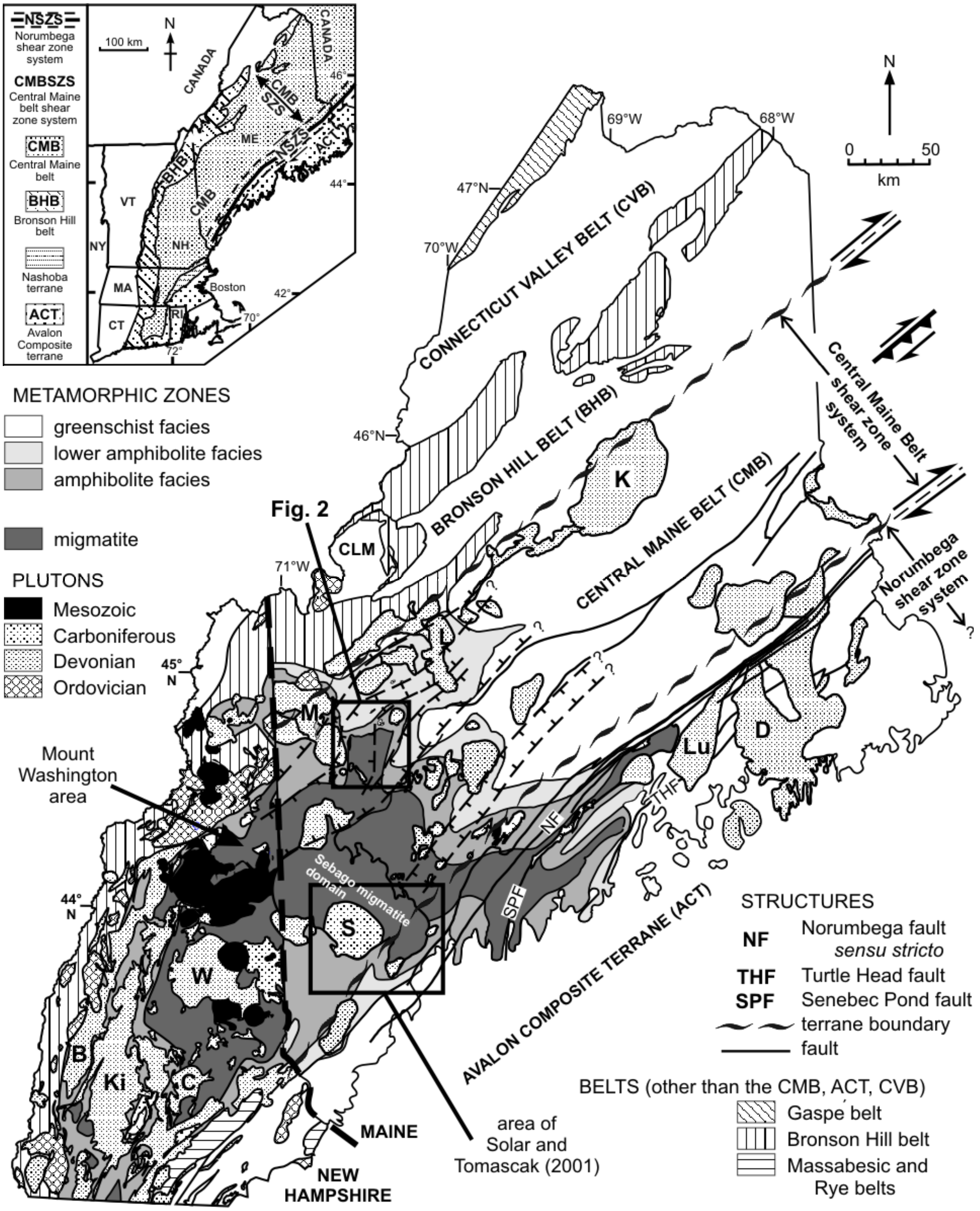

Figure 1. Simplified pluton, metamorphic zone and structural zone map of Maine and New Hampshire (modified after Guidotti, 1989; Lyons *et al.*, 1997; Solar and Brown, 1999; Solar and Tomascak, 2001). The plutonic rocks are apparently independent of metamorphic zone, and arranged into belts that parallel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

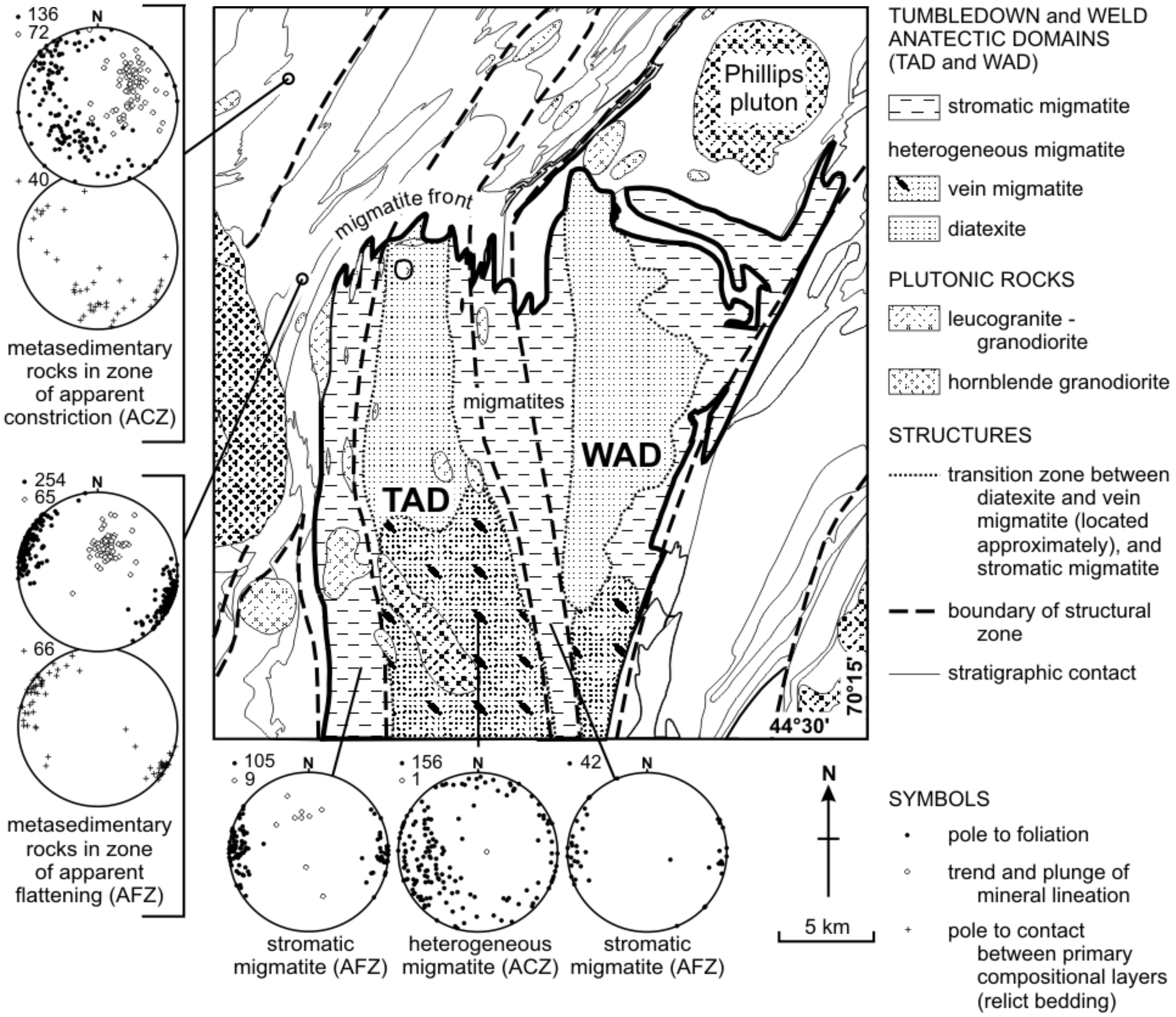

Figure. 2. Map showing the distribution of migmatite in a portion of western Maine (TAD and WAD). Stereograms are lower-hemisphere, equal-area (Schmidt) projections (selected from Solar & Brown, 2001a). Orientation data for fabric elements in metasedimentary rocks (left of map) show the alternation of zones of contrasting strain as explained in text (AFZs = zones of apparent flattening strain or 'straight' belts; ACZs = zones of apparent constrictional strain or intervening zones). Orientation data for fabric elements in migmatites (below map) show the same alternation for stromatic and heterogeneous types, respectively.

B. Geological Setting: Paleozoic migmatite and granite in Maine and New Hampshire

The northern Appalachian orogen.

The northern Appalachians are divided into several 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. 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.*, 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 located between Ordovician rocks of the Bronson Hill belt (BHB) to the WNW, which were deformed and metamorphosed during the Ordovician Taconian orogeny (Ratcliffe *et al.*, 1998, and references therein), and Neoproterozoic to Silurian rocks of the Avalon Composite terrane (ACT) to the SSE (*e.g.*, Stewart, 1989; West *et al.*, 1995; Cocks *et al.*, 1997). 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; van Staal *et al.*, 1998). Dextral–SE-side-up displacement was accommodated within the CMB shear zone system (Fig. 1; Solar, 1999; Brown and Solar, 1998a; Solar *et al.*, 1998; Solar and Brown, 1999, 2001a) while dextral–transcurrent displacement was accommodated within the Norumbega shear zone system (Swanson, 1992; 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).

The geology of western Maine and New Hampshire.
Structures in the CMB and Avalon Composite Terrain (Fig. 1) developed in response to dextral transpression associated with oblique convergence (*e.g.*, van Staal and de Roo, 1995; West and Hubbard, 1997) that caused deformation and metamorphism in the Siluro-Devonian sedimentary succession (see Moench, 1970a and Moench *et al.*, 1995). Solar and Brown (2001a) used revised stratigraphic mapping (Solar, 1999), structural field data and microstructural fabric observations from an area in western Maine to investigate the nature of deformation partitioning. 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.*, 1996; 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.*, in press) in order to better understand how the plutons have, or have not, recorded periods of orogenesis.

Regional structure. A strong NE-plunging penetrative mineral elongation lineation is in metasedimentary rocks across all metamorphic grades, including in migmatites (Fig. 2, stereograms). In contrast, the intensity and orientation of foliation vary to define alternating zones across strike of different fabrics (Fig. 2); a zones of intense, ‘straight’ and steeply dipping foliation, flanked by intervening structural zones where lineation is intense, but foliation is not. This structural style occurs in 'straight' to arcuate belts at outcrop and map scales that collectively make up the CMB shear zone system that includes the rocks of Maine and New Hampshire that are the focus of this proposal (CMBSZS, Fig. 1). Boundaries between the structural zones appear sharp at map scale, but are gradational in outcrop over meter-scale transition zones (Kerr and Solar, 2001). Shapes of granite bodies within the migmatite domains (see below) vary consistently with structural zone, where stromatic migmatite and sheets of granite are largely within 'straight' belts, while heterogeneous migmatite and cylinders of granite occur exclusively within intervening zones (Solar and Brown, 2001b). Kinematic indicators (*e.g.*, strain shadow tails around porphyroblasts) show consistent shear sense along the steeply dipping foliation, in the up-direction of the lineation (dextral-SE-side-up oblique kinematics; Solar and Brown, 1999).

Regional metamorphism. Polymetamorphism of the pelitic stratigraphic sequence is extremely well documented, particularly regarding the rocks to the northwest and east of the migmatite domains in western Maine, and in parts of contiguous New Hampshire (Fig. 1; Guidotti, 1970, 1974, 1989; Holdaway *et al.*, 1982, 1997; Chamberlain and Lyons, 1983; Johnson *et al.*, 2003). 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; see summary in Guidotti, 1989). The metamorphic field gradient is the product of polymetamorphism (*e.g.*, Chamberlain and Lyons, 1983; Guidotti, 1989, 1993) 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 separated into varieties based upon internal structure, e.g., stromatic and heterogeneous (*e.g.*, Brown and Solar, 1999; Chmura and Solar, 2001; 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 (see above; Fig. 2; 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; Tomascak and Solar, 2001), 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 (Fig. 3). 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.

Migmatite domains in western Maine vary from strongly-foliated metasedimentary rock with a few mm-scale leucosomes per m^2, in which relict primary structures are preserved, to rocks structurally disrupted by the migmatization process (diatexis) and schlieric granite (Solar and Brown, 2001b). Leucosome density and disruption of relict primary structures both increase across strike from the migmatite front (Fig. 2; Solar, 1999). Similarly, sheets and cylinders of granite progressively dominate outcrops of migmatite both along and across strike of migmatite layers. Many outcrops of migmatite consist of domains and/or blocks in which some relict primary pelite-psammite interlayers are preserved. Layers in such blocks resemble those common in the stratigraphic succession outside the migmatite domain, down-field gradient from the migmatite front, which suggests the protolith of the migmatites is the CMB metasedimentary succession, supported by the continuation of the regional structure across the migmatite front (Fig. 2; Solar and Brown, 2001b).

Migmatites are in two types that correspond with structural zones. Stromatic migmatites are parallel layered leucosome-melanosome-paleosome and are found in apparent flattening zones. Heterogeneous migmatites do not show this structure and are found between zones of stromatic migmatite (Fig. 2). This structural relation led Brown & Solar (1999) and Solar and Brown (2001b) to interpret heterogeneous migmatite to be within the cores of regional thermal antiforms, flanked by stromatic migmatites. In the northern part of the migmatite domain, layers are progressively eliminated across strike from the migmatite front by increasing volume of trondhjemitic leucosome and disruption by apparent flow, as stromatic migmatite grades into diatexite (melt-disrupted structure).

The orientation of migmatite layers and mineral fabrics are concordant (Chmura and Solar, 2001), as reflected by the consistent steeply dipping orientation of these structures at all scales within each structural zone (Fig 2, see stereograms). At the regional scale, the layers are parallel to those of metasedimentary rocks in the same structural zone (Solar and Brown, 2001b). The northern parts of the migmatite domain in Maine, and parts of the Mount Washington area of New Hampshire (Fig. 1) are underlain by diatexite, a rock in which the protolith structures are not observed, suggesting destruction by diatexis. Contacts between leucocratic and melanocratic domains in diatexite are diffuse and gradational at the cm-scale (Solar and Brown, 2001b). Diatexite varies at outcrop from 'patchy' leucosome-dominated to biotite-sillimanite-dominated rock, and outcrop to outcrop from schlieren-rich migmatite

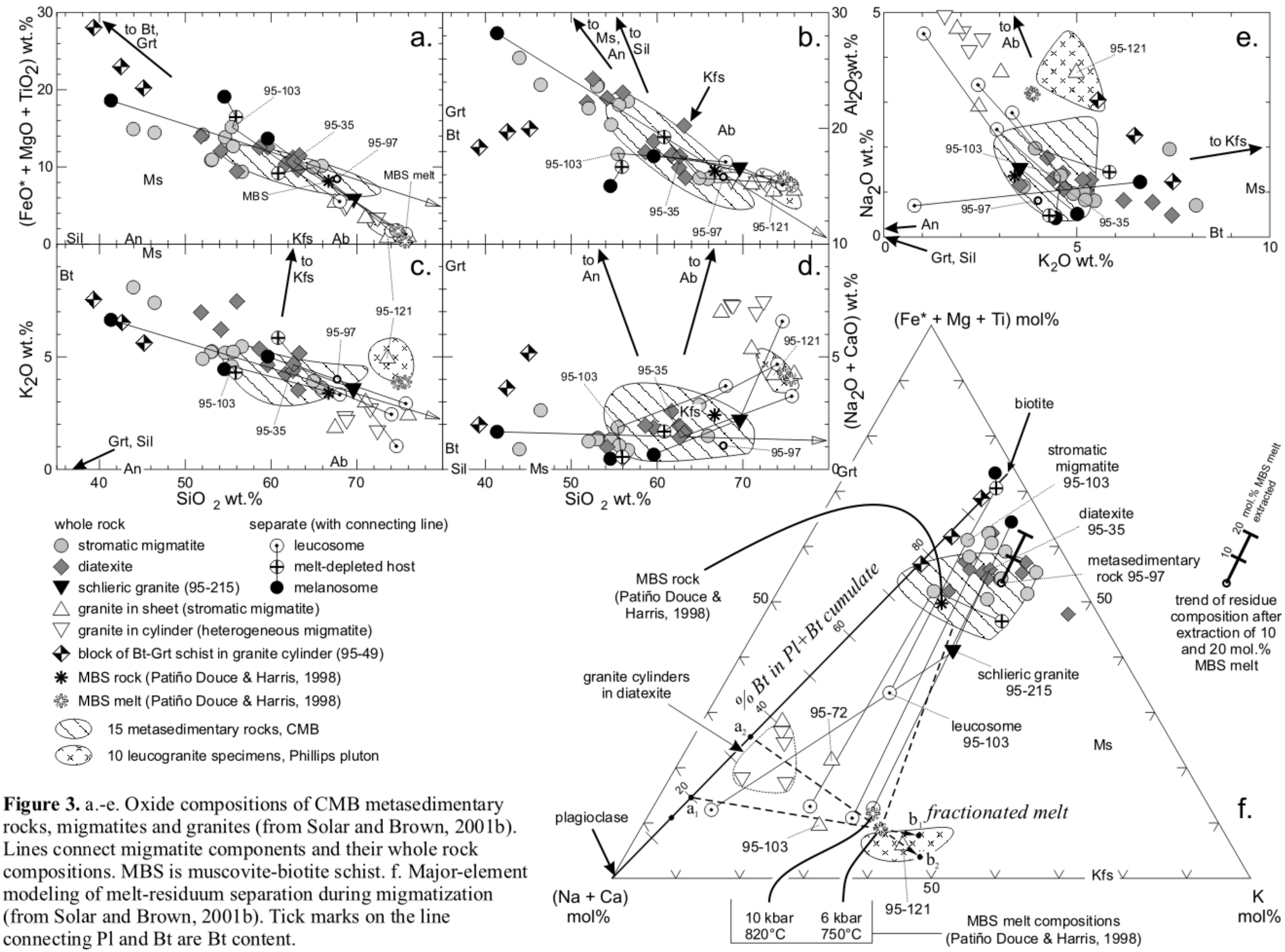

Figure 3. a.-e. Oxide compositions of CMB metasedimentary rocks, migmatites and granites (from Solar and Brown, 2001b). Lines connect migmatite components and their whole rock compositions. MBS is muscovite-biotite schist. f. Major-element modeling of melt-residuum separation during migmatization (from Solar and Brown, 2001b). Tick marks on the line connecting Pl and Bt are Bt content.

to schlieric granite with schollen of vein migmatite and unmigmatized calc-silicate-rich psammite. Most types are characterized by a discontinuous, weakly defined foliation of variable attitude (Solar and Brown, 2001b).

Granite. Granite plutons are kilometer-scale (Figs. 1 and 2). Unlike country rocks, the granites record only local evidence of solid-state deformation internally, although foliation is apparently deflected in rocks around some of the plutons (Pressley and Brown, 1999; Solar and Brown, 2001a, 2001b). 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 take 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), 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, much recent work has focused upon the age and geochemistry of the Sebago pluton (Tomascak *et al.*, 1996). Tomascak and Solar (2001) reports a close spatial relation between migmatites and the Sebago pluton (Fig. 1) where the northern and northeastern parts of the pluton are surrounded 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. Recent 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 the rocks of the CMB (Pressley and Brown, 1999; Tomascak *et al.*, in press).

Centimeter- to meter-scale sub-vertical tabular bodies of granite cut outcrops of stromatic migmatite at concordant to weakly discordant angles to the planar structures (*e.g.*, in western Maine, Fig. 2). Many of these granite sheets are composite (Brown and Solar, 1999), and, in western and southern Maine, most have a 'pinch-and-swell' structure with a longer wavelength in the sub-horizontal direction. In one area of western Maine, within 1 km along strike a progressive increase occurs in the proportion of meter-scale composite granite sheet to host stromatic migmatite such that the migmatite becomes disrupted ultimately to occur only as isolated schollen in granites that make up a sheeted granite complex (Solar, 1999).

Most outcrops of diatexite are cut by meter-scale, cylindrical granite bodies. These granite bodies are elongate subparallel to the mineral lineation in the diatexite, and to the rod-shaped leucosomes (Brown & Solar, 1999). Entrained blocks of strongly foliated biotite-garnet schist are found in the interior of the granite cylinders. The granite cylinders lack a fabric, except proximal to the margin of these blocks.

Timing of orogenesis. Smith and Barreiro (1990) determined U-Pb monazite ages from samples of pelite collected from staurolite zone rocks in western Maine. Their results demonstrate two distinct concentrations of metamorphic ages that are interpreted to reflect regional metamorphism at 405-399 ± 2 Ma and contact metamorphism related to the Mooselookmeguntic pluton (Figs. 1 and 2) at 369-363 ± 2 Ma. Solar *et al.* (1998) determined U-Pb zircon and monazite ages (interpreted to date crystallization) from samples of granite sheets and lenses in stromatic migmatite, and plutons. These ages are concordant, and are similar in the range *c.* 408-404 Ma, except the younger Mooselookmeguntic pluton, which yielded ages of *c.* 389 and *c.* 370 Ma from two discrete granite types. These data support a model of contemporaneous deformation, metamorphism, and granite ascent through the crust in the study area (Brown and Solar, 1999; Solar and Brown, 2001b).

In Maine and New Hampshire, metamorphism and granite crystallization are apparently contemporaneous; and syntectonic magma ascent was controlled by deformation and development of strain fabrics (Solar and Brown, 2001a, 2001b). Mineral assemblages and geochemical data from Maine (Fig. 3; see Solar and Brown, 2001b) are consistent with muscovite-dehydration melting (Johnson *et al.*, 2003), and suggest that migmatite leucosomes and smaller volume granites represent cumulate rocks (+/- residual material and some retained fractionated melt; Fig. 3, see ternary diagram) that complement common leucogranite in the Phillips pluton (Pressley and Brown, 1999). The residual geochemistry of stromatic migmatite and diatexite relative to the metasedimentary rocks, and the 'pinch and swell' structure of granite sheets, are consistent with melt loss from those rocks, perhaps driven by the accommodation of deformation. Rare schlieric granites suggest some melt redistribution prior to melt loss, in this case leaving a more felsic cumulate than the more residual migmatites.

Exposed migmatites preserve evidence in cumulate leucosomes of the flow network that drained these rocks of an evolved melt. Migmatites similar to those exposed are postulated to represent the source of common leucogranite in the Phillips pluton. Thus, the Phillips pluton may be connected at depth to granites similar to those found in the migmatites in the manner described by Brown and Solar (1999) where the heterogeneous migmatites and granites in ACZs formed in the cores of thermal antiforms developed during regional contraction. However, the relation between migmatite leucosomes, smaller-volume granites and leucogranite in plutons is not straight-forward (Solar and Brown, 2001b).

PROPOSED RESEARCH

The main objective of this proposal is to document the relation between migmatite and associated granites in order to determine how these rocks have recorded melt transfer during contractional orogenesis, an apparently common process active during mountain-building at collisional zones. The PIs, along with collaborators and students have performed this type of work on rocks in Maine, and have performed reconnaissance field and laboratory work on rocks of southern Maine (see Fig. 1) and parts of New Hampshire. The PIs have identified appropriate field areas for extending this type of work into those areas less well studied for migmatite-granite relations. PI Solar has had 4 undergraduate student projects completed in the last 4 years on rocks of western and southern Maine (Chmura, Kerr, Klauk, Ribeiro), the latter with the collaboration of PI Tomascak (please see the **RUI Impact Statement**).

The specific objectives of the project proposed herein are to (1) document the geometry of migmatite structures (leucosomes and melanosomes) and associated granite bodies, and (2) to rigorously test the results through geochronology and geochemical analyses. This will be accomplished through separate quantitative studies to answer focused questions such as quantification of the variations in fabrics in differing migmatite outcrops and orientation variations across particular regions where much of the variation is already documented (*e.g.*, western Maine), and less well documented (New Hampshire and southern Maine). The shapes of granite bodies within single outcrops and between closely spaced outcrops are to be major foci of field work, along with targeted sampling for petrography, geochemistry (*e.g.*, in ways shown in Fig. 3) and geochronology. Each aspect of this work is suitable to be defined as a series of small projects with a common theme. Therefore, such work is excellent for involvement of undergraduate researchers who will work independently, but as part of a research team.

As suggested in the Project Description, there are many important uncertainties regarding migmatites and associated granites in the Maine and New Hampshire 'metamorphic high.' We propose to carry out a focused set of projects that will permit us to address some of these issues directly and may provide broader constraints on migmatite-granite issues globally. We list below what we consider to be the most pressing questions and we comment briefly on what we anticipate being able to contribute to their answers.

- **What does the leucosome network record about the melt flow network during formation of migmatites?**

- **Is there a connection between leucosomes in migmatites and granites in associated bodies, and is there a connection of these to granites in plutons?**

- **What is the timing between formation of the leucosomes in migmatites and the crystallization of granites in associated plutonic bodies at several scales?**

- **How do these rocks relate to others of the northern Appalachians?**

- **How do the rocks of the 'metamorphic high' relate to the process of melt transfer during collisional orogenesis in general?**

We intend to involve a large team of undergraduate students over two years. The project will yield multiple independent projects that will collectively begin to answer the questions. Students will be involved in field work and laboratory studies that will support either full-year research Theses or single-semester Independent Studies (see **RUI Impact Statement**). Each student will be independent in his or her own project, but will be an integral part of a team led by the PIs. The total number of proposed independent projects over two years is eight.

Thesis projects will require both field and laboratory work (approximately four weeks in the summer field season, and continued laboratory work during the remainder of the summer, and the following academic year). The goal of field work is to collect quantitative field data, and perform targeted field sampling in order to execute laboratory tests of field relations that will be performed by the Thesis students, and other Independent Study students who will use some of these data and specimens. Each student will be concerned with (1) mineralogical, textural and structural data collection across single large outcrops, between several closely spaced outcrops, or along across-strike transects, that will be augmented by microscopy of selected rock thin sections upon returning to the laboratory, (2) the field determination of the size, shape and distribution of granite bodies at the outcrop scale (illustrated by observations between outcrops) that will be augmented by geochemistry and geochronology upon returning to the laboratory, or (3) mapping in detail the fabrics in migmatite outcrops as they relate to the distribution of granite bodies in outcrops. Independent Study projects will be focused upon (1) hand-specimen textural analysis, and thin-section microscopy of those specimens returned to the lab from the field studies, (2) geochemical handling and data from those specimens, or (3) geochronology handling and data. Regardless of scope, each student will be independent in their own projects, but will be an integral part of a team led by the PIs.

The research will be conducted by two separate teams, one at each of the PIs' institutions. PI Solar's team will focus on field work and petrography, and supporting whole rock geochemistry. PI Tomascak's team will focus on field work, and supporting isotope geochemistry and geochronology. The research team as a whole will be in contact throughout, but the total team will meet twice a year at each others' institutions, for face-to-face discussion, and student presentations to the group and other interested faculty and students. Students in year 1 will actively recruit and help mentor students for year 2.

The nature of the design of the projects will facilitate an excellent research experience for undergraduates, particularly since the results will be publishable in journal articles (either individually, or as part of the team), and/or as part of national and/or specialist and campus conferences where each student will present the results in a public professional setting. Each student will be required by the PIs to present the results of their research to the geological community.

A key component to larger-scale models of melt-migmatite-granite research is found at very fine scales, from the outcrop scale down to the microscope. Hypotheses based on the quantification of these observations can be tested with geochronology and geochemistry. The extant framework of mainly field data on migmatite and granitic rocks in Maine and New Hampshire justify the more detailed studies proposed herein. Clearly, migmatites and granites in Maine and New Hampshire record melt migration processes that are specific to the northern Appalachians. Nonetheless, observations of those rocks and the subsequent development of models to explain them are also consistent with migmatite-granite terrains in many other convergent orogens (*e.g.*, the Himalayas, the Alps). Therefore, a detailed understanding of Maine and New Hampshire rocks would benefit the global research effort on melt migration.

The work proposed here is a natural next step in the process, and is perfectly suited for using focused student projects, each of which is meant to be part of a collaborative undergraduate student effort. Logistically, the proximity of the PIs' institutions makes working on Maine and New Hampshire rocks simple. For the most part, the field work will be completed in the summer months, and the supporting laboratory work will be performed during the academic year, including the winter breaks. Winter breaks are also good times for students to travel to other labs to perform some of the work. Laboratory work is done either in-house, or at Syracuse University (see letter of support from SD Samson). The proposed research plan includes many excellent opportunities for undergraduate students to complete small well-defined research projects. In fact, the kind of detail required for answering our questions is perhaps best performed by undergraduate students who are best equipped to spend time focused upon a singular question that may involve only one large outcrop, or a few carefully collected specimens (*e.g.* for examining variations between leucosomes or between leucosomes and paleosomes in migmatites). This arrangement works well for interested undergraduates since their time constraints do not allow for more involved research. Since each works as part of a research team, spanning two years and two institutions, the results from any one project has a much larger context. Indeed, the project has a strong starting point given the amount of work already performed on the rocks of western Maine by both the PIs and four undergraduate student projects already completed (2 Honors Theses and 2 Independent Study; Chmura, Kerr, and Ribeiro, respectively – see Table 1 in the **RUI Impact Statement**). Therefore, we are confident that increased involvement by undergraduates will only serve to strengthen our understanding of the processes we are studying.

Each project will be closely supervised and will be based strongly on hands-on experiences for the students. The students will learn valuable skills including (1) detailed mapping and field techniques; (2) quantitative data collection techniques; (3) thin sectioning and petrographic/microstructural analyses; (4) sample handling and laboratory techniques for geochronology and geochemistry. In so doing, each student involved in this work will also benefit from the experience of designing, implementing and seeing-through-to-completion thesis-style research projects. Many of these projects will either build upon existing work, or will evaluate critically models put forth by previous workers. Undergraduate students under the supervision of the PIs have been very successful, as is illustrated by the long list of completed projects (see the **RUI Impact Statement**). This list also demonstrates the high level of interest in our undergraduate students toward doing research in the fields of structure/petrology/geochemistry. The long-term benefit to these students is also illustrated by the number of students currently in graduate programs or whom are currently applying to graduate programs. The projects proposed here will greatly enhance the expanding undergraduate research environment at each of the PIs' departments in their predominantly undergraduate institutions.

In order to address the questions listed above, we plan to integrate field work with detailed petrography, geochronology, and elemental and isotope geochemistry, with the work to be performed almost solely by undergraduate student projects. Specifics of each project will be directly supervised by one or both PIs according to expertise (Solar: structure, petrology, elemental geochemistry; Tomascak: petrology, elemental and isotopic geochemistry, geochronology). Each project is part of a collaborative effort; no project will stand completely alone, and data from one project may be essential to another project. For example, some field data and/or rocks collected by a Thesis student may become the basis for an Independent Study project. This is certainly likely to be the case for the part of the total project focused upon geochronology, since the students involved with that aspect of the work will likely spend much of their time in the lab and less time in the field. However, by design, each project will be field based due to project collaboration. The following is a list of methods to be applied to the questions above.

1. Field work and sampling. The PIs and each Thesis student will begin the first field season after already defining projects based upon previous work in western and southern Maine (*e.g.*, Solar and

Brown, 2001b; Solar and Tomascak, 2001; Tomascak *et al.*, in press). During the first field season each Thesis student will collect detailed field relation data and document geometrical relations. Students will also be collecting representative specimens both for their own laboratory use and for use by other students in the group for Independent Studies. The specimens will be collected for microstructural analyses, petrography of migmatites and granites, geochronology and geochemistry. The main goal of the field research is to document the full range of mineralogical, textural and structural variations associated with the migmatites and granites at either a few large exposures or across a transect. Mapping of individual outcrops will become a focus during this time in order to document the geometry of migmatite and granite bodies, and to give strong field constraints to specimens collected for laboratory analyses. We will also spend a portion of time in the field doing reconnaissance for projects in year 2 in adjacent New Hampshire.

An important observation from the Maine migmatite domains is that the shapes of the granite bodies correlate both with migmatite type and with structural zone (subconcordant tabular shapes in stromatic migmatites, in zones of apparent flattening; subconcordant cylindrical shapes in diatexite migmatites, in zones of apparent constriction; Chmura and Solar, 2001; Solar and Brown, 2001b). Although the observation is apparent by inspection and consequent regional synthesis, it remains an important test of such relations to map the granite bodies and the fabrics in their surrounding migmatites in suitable outcrops, or in a series of appropriately located outcrops. It will be important to evaluate differently oriented surfaces in both outcrop and in hand specimen in order to visualize a complete three-dimensional data set for these rocks.

If leucosomes in migmatites have recorded the melt flow network, the need to document the three-dimensional extent and shape of the leucosome network is required. Documentation of variation in the fabric ellipsoid shape and intensity, and how these relate to the metamorphic textures, may be achieved by several transects, including across-strike transects that enable evaluation of changing strain patterns and relations of strain to migmatites and granites in the belt.

2. Hand-specimen petrography. Students will begin specimen analyses with detailed investigation of each collected specimen. This will be done primarily once rocks are cut to reveal several two-dimensional views of the three-dimensional structure (if any) of the rock. This will be especially important in analyzing migmatite specimens. Students will be able to compare each cut surface using standard techniques, which may include analysis of mineral orientation using the inverse SURFOR wheel (Panozzo, 1987).

3. Microscope petrography. Undergraduate Thesis and Independent Study students alike will participate in petrographic analyses of thin sections cut from collected specimens. For the Independent Study students, this may form the bulk of their research. For other students this work may be the basis for study of geochronology or comparative geochemistry between specimens. Each student will characterize in detail the petrography of all specimens according to their specific project. Those working on migmatites may compare and contrast textures between migmatite parts (leucosome v. paleosome, etc.), and those working on granites may compare and contrast composition, crystallization sequence and textures. Students will be able to compare textures in thin sections using the inverse SURFOR wheel analysis (Panozzo, 1987) on photomicrographs. Of course, the geochronological and geochemical analyses to be performed cannot be understood without these data.

Documentation of meso- and micro-scale structures in collected specimens is central to understanding of how the structure of the rock may have played a part in producing melt zones, collecting melt into ‘pockets’ and allowing melt to escape into leucosomes and beyond. It is the experience of the PIs that even if melt is lost from migmatites evidence remains, at least at the microscope scale (e.g., zones of anastomosing sillimanite + plagioclase around grain boundaries, but elongated sub-parallel to matrix foliation; Solar and Brown, 2001b). These represent either zones of melt production or more likely melt escape, and this texture is the record of the melt having occupied those zones. Petrography will also establish if there are melt textures in the migmatites, if there are igneous textures in the leucosomes and associated granites, or if there are solid-state deformational overprints on these textures.

4. Geochronology. Students will participate in sample handling and analysis for U/Pb geochronology in accordance with established laboratory techniques in the Radiogenic Isotope Lab at Syracuse University (see letter of support from S.D. Samson). The results of this work will test field relations regarding the timing of events like leucosome crystallization vs. granite crystallization. These data will also be used to distinguish between textural zones in granites at all scales. One of the primary (although seldom rigorously satisfied) tests of migmatite-granite relations is precise geochronology. With fundamental field relations developed in studies in the zone of distributed ductile strain of the CMB in Maine, samples can be readily targeted that will provide an essential geochronological framework using U/Pb in the common accessory minerals zircon and monazite. Age precision at the <1% level (i.e., ± 1-2 Ma for Paleozoic samples) on analyses of individual crystals is essential to this framework.

If the field relations suggest a cogenetic relation between migmatite leucosomes, associated small-scale granites and granite in plutons, a suite of ages from the granitic rocks is in order. Single zircon U/Pb geochronology will certainly help us to determine whether or not a suite of rocks is related in time. This is a simple, but essential test that we cannot do without if we are to fully address the other issues.

5. Elemental geochemistry. Variation in major and trace element abundances (including lanthanides) for whole-rock granites and migmatites, and migmatite separates (leucosomes vs. paleosomes) will be determined by a combination of XRF and ICP-MS techniques using the GeoAnalytical Laboratory at Washington State University. Students will spearhead the specimen preparation process. Students will then process the geochemical data, and perform comparisons among the analyzed rocks according to established methods (*e.g.*, Hanson, 1978; Nabelek *et al.*, 1999; Sawyer, 1999; Milord *et al.*, 2001; Solar and Brown, 2001b). They will also compare the geochemical data to field data in order to understand better the field relations between these rocks.

We will critically assess the potential geochemical connection between migmatite leucosomes and paleosome. We will ask questions concerning whether or not the migmatite paleosome has melted, and if so, has it lost melt? We will then ask whether the leucosome and smaller-body granites are the locations for the lost melt or are they cumulates, as suggested by Solar and Brown (2001b)? Are the larger-body granites the fractionated melt from this segregation? We acknowledge the limitations on these data, which is why we will depend heavily on field relations to be augmented by the geochemistry, not the other way around.

6. Radiogenic isotope geochemistry. Analysis of initial Nd and Pb isotopic compositions will be carried out at Syracuse University, with students doing the work under supervision of PI Tomascak. Initial Nd isotopic compositions will be determined on whole rock samples, and Pb will be determined in leached K-feldspar separates (preparations as per Tomascak *et al.*, 1996). Samples will be selected from those for which elemental data were generated.

Initial ratios of Nd and Pb isotopes permit additional detailed testing of hypotheses of migmatite-granite linkages, although phase relations need to be taken into account as to the potential for disequilibrium effects in a region in which melting reactions may have been locally heterogeneous (Hogan and Sinha, 1991; Nabelek and Glasscock, 1995). Above and beyond their usefulness in assessing migmatite-granite relations, combined Nd-Pb isotope data have been effective in western Maine in placing firmer constraints on the nature of source materials (Tomascak *et al.*, in press), which must be factored into the development of more viable tectonic models for the orogen.

It has been established that the likely protolith for migmatites and much of the granites in Maine is the CMB metasedimentary rocks (Solar and Brown, 2001b), with a component of basement rocks in the granites (Tomascak *et al.*, 1996, in press; Dorais, 2003). For each concentrated suite of specimens, a geochemical comparison between migmatites and granites, and between whole rock migmatites and their separate leucosomes and paleosomes (and melanosomes), will be made.

WORK PLAN

The proposal seeks to integrate a group of undergraduate researchers into an ongoing integrated study of granite petrogenesis in northern New England. In each year of the proposal one student from each of the participating institutions will conduct research that will constitute an undergraduate Thesis at his/her institution. In addition to this, the research team will be boosted by participation from one-semester Independent Study students, each institution contributing one per year. Thesis students will conduct four weeks of field work (Maine in year 1, New Hampshire in year 2), during which suites of samples will be collected for laboratory analysis of meso/microstructures, geochronology, and chemical and isotopic composition. The division of laboratory work amongst Thesis and Independent Study students will be based on student interests. Student participation in laboratory work at Buffalo State and Oswego State, in addition to work at the radiogenic Isotope Lab at Syracuse University, provide important experiences for students that are otherwise not commonly (or ever) available. We anticipate that suites of samples for major and trace elements will be sent off after processing in early autumn of each year. Based on team discussions of field relations, samples will be selected for U/Pb zircon/monazite geochronology and this work will carry on throughout academic year 1 and 2, with a significant portion of the analytical work planned for the winter breaks. Samples will be selected for Nd (bulk rock) and Pb (K-feldspar) isotope measurement from those analyzed for elemental concentrations, after consideration of those data. This work will carry on in tandem with the geochronological work. By mid-2005 the Oswego State lab will be capable of supporting small-scale trace element clean environments, so initial stages of the Nd and Pb isotope preparation can take place there, but ultimately the ion exchange work will have to take place in the Syracuse University clean lab. Although students will do their own work in the Syracuse lab, it will be under the supervision of PI Tomascak.

The nature of the design of the projects will facilitate an excellent research experience for undergraduates, particularly since the results will be publishable in journal articles (either individually, or as part of the team), and as part of scientific conferences where students will present their results in a professional setting. Each student will be required to present the results of their research to the geological community, both in the team meetings to be held each semester and at regional/national conferences. Such transferable skills are infrequently acquired at the undergraduate level, although they are proven to be invaluable regardless of career track.

BROADER IMPACTS

Buffalo State College is a non-doctoral degree granting institution of over 10,000 students (8,000 undergraduate). The Earth Sciences program (part of the Department of Earth Sciences, together with Meteorology and Astronomy) is fundamental on campus in producing undergraduate research products, and students are regularly involved in presenting on campus. Over the past two years c. 20% of Earth Sciences graduates go on to graduate school. This proposal would provide attractive possibilities for students with interests in structural geology/tectonics, petrology and geochemistry.

Oswego State University is a non-doctoral degree granting institution of 8500 students (6500 undergraduate). The Geology program (part of the Department of Earth Sciences, together with Meteorology and Astronomy) was the first in the University to require all students complete a senior Capstone experience, satisfied by most with a research Thesis. Over the past two years c. 25% of Geology graduates go on to graduate school in the Earth sciences. Given the need for diversity in choices of Capstone Thesis topics, this proposal would provide attractive possibilities for students with interests in structural geology/tectonics, petrology and geochemistry.

Undergraduate students will benefit from Thesis and Independent Study research projects on multiple levels. The emphasis on team effort set out in the work plan will give students valuable experience in integrating data sets and thinking as a team. At the same time, students experience independent research in which they must bring their own creativity to bear on an individual problem. The plan to bring the Buffalo State and Oswego State students and PIs together for regular meetings each semester fosters communication between students working on different aspects of the overall project, provides added support for students through contact with other PI and students, and gives additional mentoring opportunities to the PIs. Students will further polish their scientific communication skills by making presentations at regional and national geological conferences. Regardless of career goals, this work will set students up for success in the job market and in top graduate programs.

SUMMARY AND IMPORTANCE

This proposal seeks to examine the fundamental processes of granite pluton formation. The method to be used begins with detailed analysis of field and mesoscale structures of key outcrops in Maine and New Hampshire. Based on these findings, petrography, geochronology and elemental and isotopic geochemistry will be used to test hypotheses of migmatite-granite interrelationships. The work integrates not only multiple techniques, but input from multiple undergraduate researchers, each of whom has an equivalent stake in the outcome of the overall project. The work is well suited to an approach that connects detailed findings from multiple areas within a larger region. Although the data are collected by low-level scientists, through close supervision and association with top analytical facilities the results should add considerably to the global discussion on melt transfer through the crust in orogenic belts.

RESULTS FROM PRIOR SUPPORT

Gary Solar has no prior NSF support.

Paul Tomascak

EAR0208012 Lithium Isotopic Investigations of the Crust; PI RL Rudnick, WF McDonough and PB Tomascak; $279,922, 06/01/02 - 05/31/05

With this grant we investigated different suites of samples that allow a better characterization of Li isotopes in the Earth system, and improved chemical and analytical techniques for challenging sample types. Through these studies we now for the first time have firm constraints on the bulk Li isotope signature of the upper continental crust, which is a major step toward achieving a planetary Li budget. We additionally began investigations into Li isotopes in various types of and components in stony meteorites, which give us another means of assessing bulk Earth Li and the potential heterogeneity of Li in the early solar system. To date there are four peer reviewed journal articles published or in press from this work:

Rudnick RL, Tomascak PB, Njo HB, Gardner LR (in press) Extreme lithium isotopic fractionation during continental weathering revealed in saprolites from South Carolina. *Chem Geol*

Teng FZ, McDonough WF, Rudnick RL, Dalpé C, Tomascak PB, Gao S, Chappell BW (2004) Lithium isotopic composition and concentration of the upper continental crust. *Geochim. Cosmochim. Acta,* 68 (20), 4181-4192.

Tomascak PB (2004) Developments in the understanding and application of lithium isotopes in the Earth and planetary sciences. In: Johnson CM, Beard BA, and Albarede F (eds) Geochemistry of Non-Traditional Isotope Systems, *Min. Soc. Amer. Reviews Mineralogy Geochemistry*, vol. 55, p. 153-195.

Zack T, Tomascak PB, Rudnick RL, Dalpé C, and McDonough WF (2003) Extremely light Li in orogenic eclogites: The role of isotope fractionation during dehydration in subducted oceanic crust *Earth Planet Sci. Let.,* 208, 279-290.

Contributions to education and development of human resources: This grant supported laboratory work by Alexander von Humboldt research fellow **T Zack**. The ongoing Ph.D. research of **F Teng** was supported, and the undergraduate research of **H Njo**. The funding supported undergraduate laboratory assistance from **E Baker**, separating minerals and performing sample digestions.