Granite ascent in convergent orogenic belts: Testing a model

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ABSTRACT

The common spatial relationship in convergent orogenic belts between a crustal-scale shear-zone system, high-grade metamorphic rocks, and granites suggests a feedback relation between crustal anatexis and contractional deformation that helps granite extraction and focuses granite ascent. Such a feedback relation has been proposed for ascent of Early Devonian granites in west-central Maine. This interpretation requires that deformation, metamorphism, and plutonism were synchronous. We have determined precise U-Pb zircon and monazite ages that we interpret to record time of crystallization of syntectonic granite in metric to decametric sheets and kilometric plutons, and of schlieric granite within migmatites. Ages are in the range ca. 408–404 Ma, within 1 m.y. at 95% confidence limits. These ages are similar to extant U-Pb monazite ages of ca. 405–399 ± 2 Ma for syntectonic regional metamorphism in the same area. The coincidence between the age of peak metamorphism and crystallization ages of granite shows tectonics, metamorphism, and magmatism were contemporaneous, in support of the feedback model.

INTRODUCTION

Extraction of granite from lower crust, and its emplacement at shallower levels, is the principal mechanism by which the continents have become differentiated. Thus, understanding how granite moves through the crust is an important step toward understanding crustal evolution. In many convergent orogenic belts spatial and temporal relationships between granite and regional tectonic structures suggest ascent and emplacement during contraction rather than during extension (e.g., Hutton, 1997; Brown and Solar, 1998a). During orogenesis, melting occurs in a dynamic environment in which differential stresses acting upon anisotropic crust lead to heterogeneous deformation at all scales, which enables granite extraction, ascent, and emplacement (e.g., Brown, 1994; Sawyer, 1994). Deformation leads to periodically connected melt flow networks (e.g., Brown and Rushmer, 1997; Brown and Solar, 1998b) and crustal-scale architectures, such as shear-zone systems (e.g., D'Lemos et al., 1992; Brown and Solar, 1998a), that allow melt extraction and focus melt ascent through the crust. Regional tectonic structures are thought to play an important role during emplacement of some granite plutons, either by creating space (e.g., Hutton, 1988) or by arresting ascent (e.g., Clemens and Mawer, 1992).

It is implicit in these relationships and interpretations that crustal anatexis and granite extraction, ascent, and emplacement are syntectonic processes, and that deformation and melt transfer are synchronous. Synchroneity of metamorphism and migmatization, and granite melt extraction, ascent, and emplacement can be tested by precise determination of crystallization ages, which is the purpose of this paper.

GEOLOGY OF WEST-CENTRAL MAINE

The northern Appalachians of New Hampshire and Maine include Ordovician metasedimentary and metavolcanic rocks, Neoproterozoic basement rocks of the Bronson Hill belt, and metasedimentary rocks of the Central Maine belt, which range in age from Llandovery to Emsian (e.g., Moench and Pankiwskyj, 1988; Fig. 1a). The Central Maine belt contains structures believed to have formed primarily during Devonian dextral-transpressive deformation (Brown and Solar, 1998a).

In the Central Maine belt of west-central Maine, zones of enhanced deformation are suggested by a high degree of parallelism between compositional layering and foliation, which maintain a consistent northeast strike and steep southeast dip across the width of the zones, and a well-developed moderately to steeply northeast-plunging mineral elongation lineation (Brown and Solar, 1998a). These steep zones surround zones (Figs.1b and 1c) in which foliation is neither as strongly developed nor generally parallel to variably oriented, moderately dipping compositional layering, although a well-developed moderately to steeply northeast-plunging mineral elongation lineation is pervasive. We interpret these intervening zones to record relatively lower strain (LSZs) within anastomosing zones of higher strain (HSZs) (Solar and Brown, 1998); these are part of the Central Maine belt shear-zone system. In HSZ rocks, a noncoaxial component of deformation is suggested by asymmetric pressure shadow tails around porphyroblasts, by biotite "fish," and by a consistent obliquity between boudinaged granite-pegmatite sheets and layering and/or foliation, and it is required to prevent space incompatibilities between the structural zones. The kinematics suggests the Central Maine belt shear-zone system accommodated dextral-reverse displacement during transpressive orogenesis (Brown and Solar, 1998a). Also, porphyroblasts of biotite, garnet, andalusite, and staurolite contain an included foliation inclined to surrounding matrix foliation, consistent with coeval metamorphism and plastic deformation (Solar and Brown, 1998). Smith and Barreiro (1990) determined the age of this syntectonic regional metamorphism as 405–399 ± 2 Ma, using the U-Pb method on monazite crystallized at staurolite-grade conditions in schists unaffected by later contact metamorphism.

At high metamorphic grade, partial melting formed migmatites within the Tumbledown and Weld anatectic domains (Fig. 1b) (Brown and Solar, 1998a). Stromatic (layered) migmatites contain a lower fraction of leucosome in comparison to foliated inhomogeneous migmatites. Inhomogeneous migmatites vary from mica-rich residual varieties to leucosome-rich schlieric granite, which suggests progressive segregation of melt from residue by granular-flow–induced compaction. The boundaries between these two migmatite types are approximately coincident with boundaries between structural zones (Fig. 1b); stromatic migmatites are in the HSZs whereas inhomogeneous migmatites are in the LSZs. Sheets of granite that are concordant or weakly discordant with respect to foliation in HSZs (Fig. 2) are interpreted to record channeled transfer of melt, and by analogy with veins at a lower metamorphic grade, may be in tensile and dilational shear fractures (Brown and Solar, 1998b).

The Granites

The dextral-reverse kinematics of the Central Maine belt shear-zone system implies that successively shallower structural levels are exposed to the northwest across the study area in west-central Maine (Fig. 1b). Thus, within the block to the southeast of the central HSZ, the Phillips pluton and the associated Weld anatectic domain represent the deepest structural level, while the Redington pluton and the northern lobe of the Lexington pluton in the block to the northwest of the central HSZ represent shallower levels.

The three-dimensional shape of plutons can be deduced by combining geologic information

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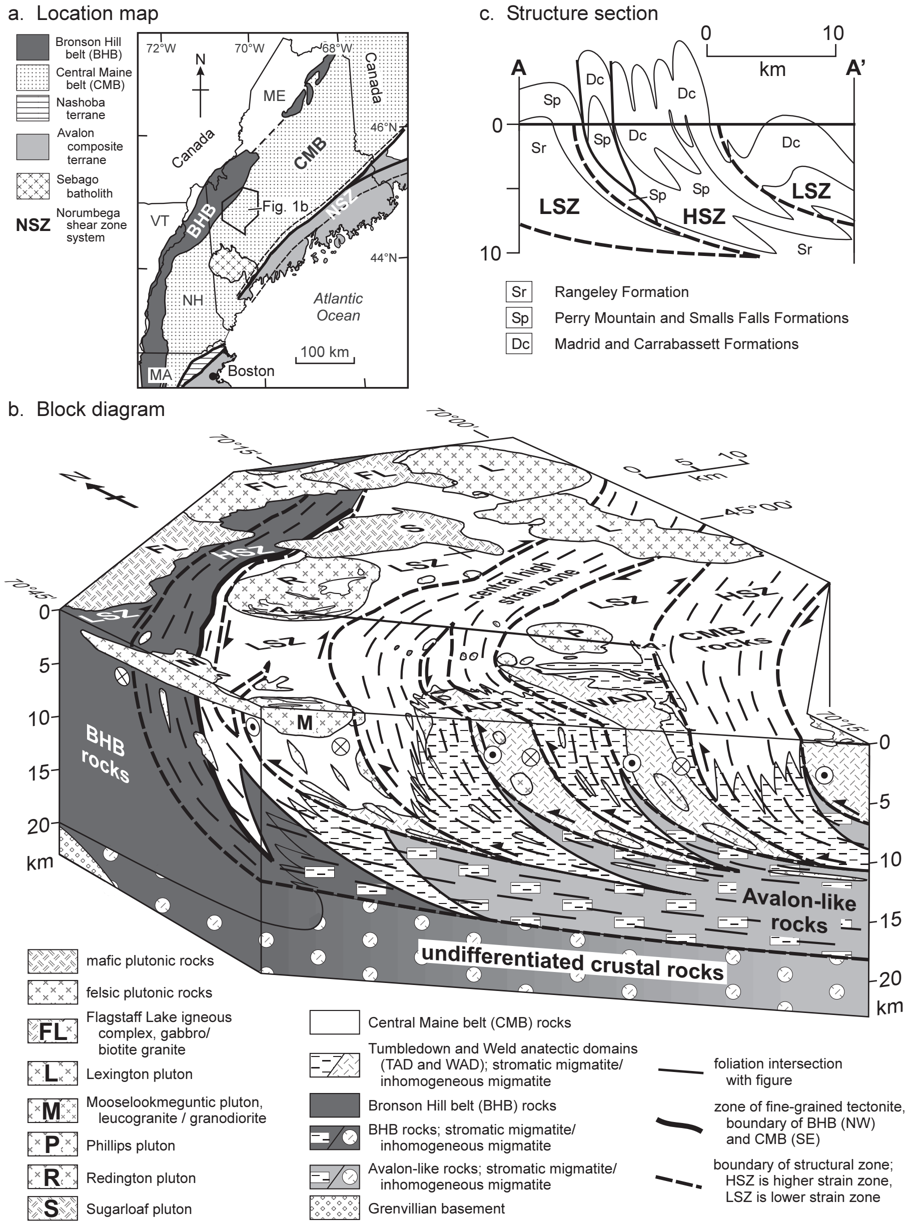

Figure 1. a. Location of Central Maine belt (CMB) of New Hampshire and Maine in relation to Bronson Hill belt (BHB) to northwest, and Norumbega shear-zone (NSZ) system and Avalon composite terrane to southeast. Outlined area north of Sebago batholith corresponds to part b. ME = Maine, VT = Vermont, NH = New Hampshire, and MA = Massachusetts. b. Block diagram constructed from simplified geological map and cross sections of the study area, west-central Maine, to show relationship between granite plutons and Central Maine belt (CMB) shear-zone system. Higher strain zones are indicated by lines representing orientation of foliation and lower strain zones are unornamented; plutons are indicated by inclined crosses. c. Simplified structure section, northwest-southeast, with Redington and Phillips plutons omitted.

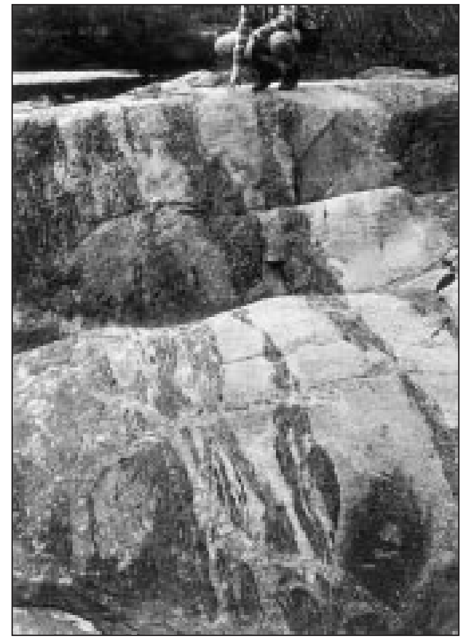

Figure 2. Steeply east-dipping granite sheets in stromatic migmatite within central high strain zone along west side of Tumbledown anatectic domain, Swift River, Roxbury, Maine (view to north).

with models based on geophysical data, gravity studies in particular. Here, we summarize pluton geometries derived by Brown and Solar (1998b) using map information, thermal aureole width and depth of pluton emplacement, cross sections of plutons modeled in a regional gravity study (Carnese, 1981), and a crustal model based on an integrated geophysical study (Stewart, 1989).

The Phillips pluton is a hemiellipsoidal body in an LSZ (Fig. 1b). Where observed, principal contacts between granites and metasediments are concordant with respect to regional structure. Steeply dipping magmatic fabrics (biotite-rich schlieren, and modal and grain-size layering) occur locally and are oriented conformably with the northeast-striking, subvertical foliation in surrounding metasedimentary units (Pressley and Brown, 1998). Although the Weld anatectic domain to the south is poorly exposed, available outcrop data suggest it is composed of inhomogeneous migmatite with lenses of schlieric granite (Brown and Solar, 1998b). Given the northeast-plunging mineral elongation lineation in the Central Maine belt rocks, it is implicit that rocks similar to those exposed in the Weld anatectic domain occur under the Phillips pluton to the northeast (Fig. 1b). The Redington pluton has irregularly northeast-dipping contacts with wall rocks in the northeast and inward-dipping contacts in the southwest, where it is inferred to be in contact with wall rocks along a northeast-dipping surface that represents the base of the pluton. In the southwest, aligned K-feldspar phenocrysts in granite define a moderately northeast-dipping magmatic foliation, subparallel to kilometer-scale screens of weakly strained hornfelsic wall rock. The pluton is in an LSZ (Fig. 1b). Gravity modeling suggests a horizontal wedge as much as 2.5–3 km thick at the northeast margin thinning to the southwest (Carnese, 1981). In contrast, the Lexington pluton has a hybrid geometry in which a hemiellipsoidal northern lobe is in an LSZ, but the central-southern lobe has a tabular form that thins to the south-southeast, cutting discordantly across the shear-zone system (Fig. 1b). Modeling by Unger et al. (1989) suggests the northern lobe is ≈12 km thick, with steep inward dipping contacts, in comparison with the central-southern lobe, which thins from ≈6 to ≈3 km across the strike of the central HSZ. Sporadic outcrops in the center of the pluton exhibit northeast-striking, steeply southeast-dipping magmatic foliation. The eastern part of the Mooselookmeguntic pluton is exposed in the west of the area (Fig. 1b). This is a large tabular pluton, shallowly northeast dipping and thinning to the southwest, that also cuts the shear-zone system.

The Model

On the basis of field mapping and microstructural interpretations in west-central Maine (Fig. 1), Brown and Solar (1998a, 1998b) have proposed a model in which metamorphism, migmatization, and granite melt transfer were synchronous with deformation in a crustal-scale shear-zone system. In nonmigmatitic rocks, porphyroblast-matrix relations show metamorphic crystallization was syntectonic (Solar and Brown, 1998). For anatectic rocks, at melt fractions greater than threshold permeability during active contractional deformation, end-member rheological models are as follows: (1) percolative melt flow parallel to the principal finite elongation direction in the plane of flattening, recorded by the mineral elongation lineation and the foliation, and (2) en masse flow of melt with residue (e.g., by granular flow), in which differential flow rates may enable melt and residue to segregate. Flow may be channeled, as illustrated by centimeter-scale stromatic (layered) migmatite structures and meter-scale sheets of internally layered granite arrested during ascent (Fig. 2). Embrittlement due to a buildup of melt pressure may have enabled tensile and dilatant shear fractures to form in stromatic migmatite, and granular flow may become dilatant, leading to localization of deformation that enables melt exfiltration (Brown and Solar, 1998a, 1998b). Cyclic fluctuations of melt pressure result in pulsed flow of melt consistent with internal layering in granite sheets. Granite exhibits magmatic foliation but does not record solid-state fabrics. This suggests late syntectonic transfer of melt through the shear-zone system as deformation waned, followed by crystallization that proceeded without penetrative strain, although smaller sheets exhibit crenulate margins, and some sheets are deformed into pinch and swell structures (Fig. 2).

Existing Age Data

Previous age determinations on granites in this area include Rb/Sr whole-rock isochron ages of 371 ± 6 Ma (regressed from nine samples of the Mooselookmeguntic pluton and satellite bodies, and recalculated from data in Moench and Zartman, 1976) and 399 ± 6 Ma (based on samples from both the northern and central-southern lobes of the Lexington pluton, H. E. Gaudette, personal commun., cited in Dickerson and Holdaway, 1989, p. 499). A U-Pb monazite age of 363± 2 Ma from the southern part of the Mooselookmeguntic pluton was reported by Smith and Barreiro (1990). DeYoreo et al. (1989) reported Late Devonian through Carboniferous $^{40}Ar/^{39}Ar$ ages from hornblende, muscovite, and biotite mineral separates from the Mooselookmeguntic and Phillips plutons.

RESULTS

Zircon selected for analysis was needle or prism shaped (<75 µm size fraction), of high optical quality, and free of optically visible inclusions. We interpret these zircons to be igneous (Pupin, 1980). On this basis, we expect that the zircons may incorporate the least inherited component, thus permitting the interpretation of ages as recording the time of crystallization. Honey-yellow monazite selected for analysis was round and ~50 µm in grain size. Preparation, chemical purification, and analytical techniques follow the procedures developed by Krogh (1973, 1982), with slight modification (Tucker et al., 1990). In the conventional concordia diagrams of Figure 3, individual zircon fractions plot concordantly or with slight discordance, suggesting modern-day Pb loss. All monazite fractions plot concordantly. The data are given in Table A,[1] and ages, quoted at 95% confidence limits, are summarized in Table 1. The general consistency between zircon and monazite ages and reproducibility of multiple fractions from the same granite samples (Fig. 3) suggest that the ages may be interpreted to record the time of crystallization of the granites.

[1]GSA Data Repository item 9872, Table A, Zircon and Monazite Analyses, is available on request from Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301. E-mail: editing@geosociety.org.

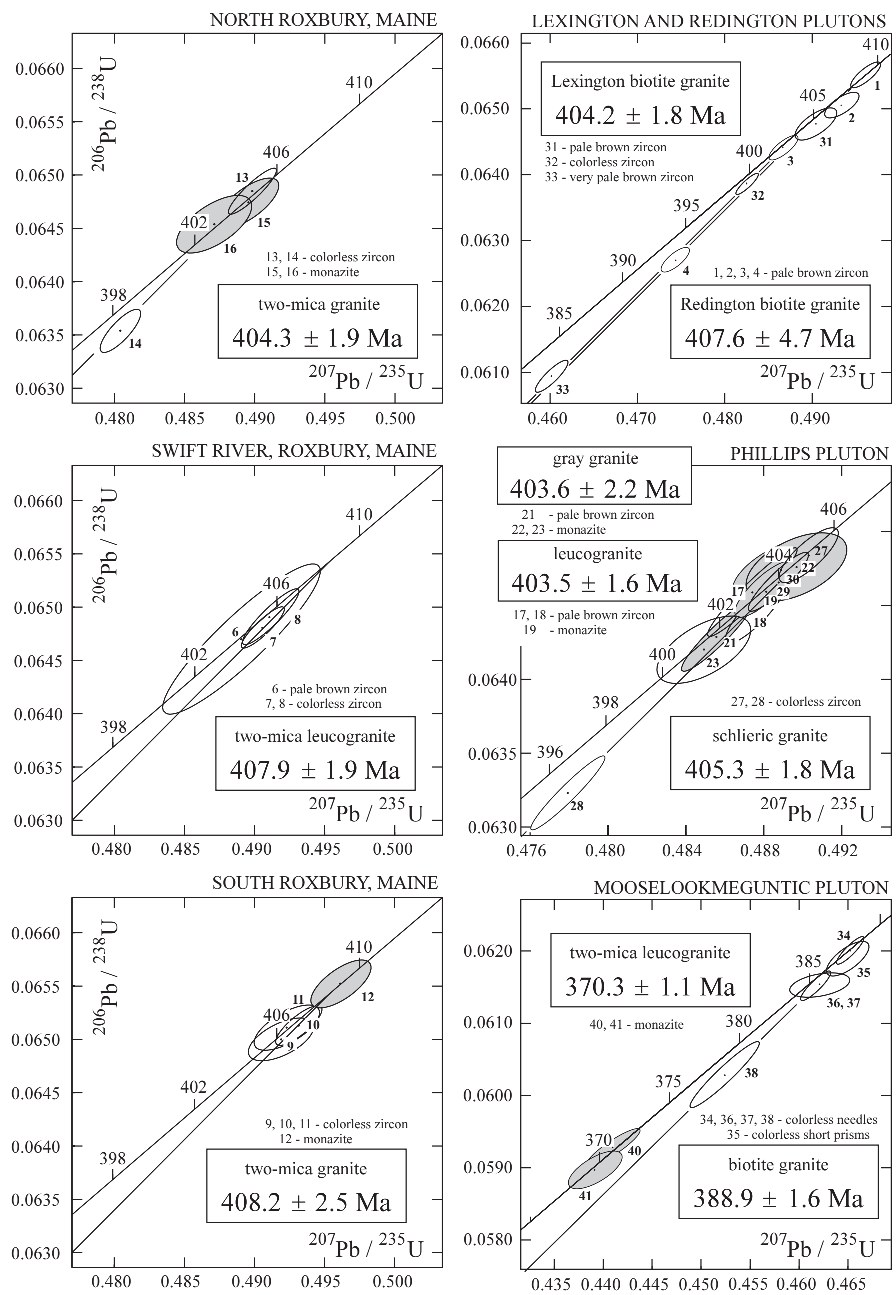

Figure 3. $^{206}Pb/^{238}U$ vs. $^{207}Pb/^{235}U$ concordia plots of analytical data. Three samples from Roxbury area are sheets of granite within the central high strain zone. Ages are given at 95% confidence level.

TABLE 1. U-Pb ZIRCON AND MONAZITE AGES FROM GRANITE SAMPLES

Sample	Mineral (color/morphology)	Age (± 2σ), Ma
Two-mica granite sheet in HSZ	zircon (clear colorless needles), monazite	404.3 ± 1.9
Two-mica leucogranite sheet in HSZ	zircon (clear colorless to pale brown needles, short prisms)	407.9 ± 1.9
Two-mica granite sheet in HSZ	zircon (clear colorless needles, short prisms), monazite	408.2 ± 2.5
Redington pluton (biotite granite)	zircon (pale brown needles)	407.6 ± 4.7
Phillips pluton		
(gray granite)	zircon (pale brown short prisms), monazite	403.6 ± 2.2
(leucogranite)	zircon (clear brown prisms), monazite	403.5 ± 1.6
Schlieric granite within migmatites	zircon (clear colorless needles)	405.3 ± 1.8
Lexington pluton (biotite granite)	zircon (colorless to pale brown needles)	404.2 ± 1.8
Mooselookmeguntic pluton, S lobe		
(biotite granite)	zircon (clear colorless needles, short prisms)	388.9 ± 1.6
(two-mica leucogranite)	monazite	370.3 ± 1.1

Note: HSZ is high-strain zone.

DISCUSSION AND CONCLUSIONS

In west-central Maine, granite sheets in the central HSZ, schlieric granite in migmatites, and granite plutons yield precise crystallization ages in the range ca. 408–404 Ma, consistent within error with the age of 405–399 ± 2 Ma for the synkinematic metamorphism (Smith and Barreiro, 1990) and with the range for plutons farther northeast along strike, 410–400 Ma (Hubacher and Lux, 1987; Bradley et al., 1996). The apparent contradiction between crystallization ages of the granites and fossil ages of the youngest metasedimentary rocks they intrude (Emsian) is resolved by the new Devonian timescale of Tucker et al. (1998), in which the base of the Devonian is ca. 418 Ma and the base of the Emsian is ca. 409.5 Ma. Thus, the new data reported in this paper support a model of contemporaneous deformation, metamorphism, and granite ascent through the crust (Brown and Solar, 1998a, 1998b); viewed at the crustal scale (Fig. 1b), granite extraction, ascent, and emplacement were syntectonic.

Our data for the Mooselookmeguntic pluton show that it is composite, having been constructed by at least two separate plutonic events. The younger age of ca. 370 Ma for leucogranite is consistent with U-Pb monazite ages reported by Smith and Barreiro (1990) of 369–363 ± 2 Ma from metasedimentary rocks within the contact aureole of this pluton and close to the monazite age of 363 ± 2 Ma for a satellite body of leucogranite. Southwest along strike, in New Hampshire, the range of monazite ages reported by Eusden and Barreiro (1988) from metamorphic rocks is ca. 402–376 Ma and from small plutons and sheets of granite and pegmatite is ca. 401–359 Ma. These ages from the Mooselookmeguntic pluton and farther southwest suggest orogen-parallel diachroneity in the age of tectonic events in the northern Appalachians.

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