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Sm–Nd ISOTOPE SYSTEMATICS AND THE DERIVATION OF GRANITIC PEGMATITES IN SOUTHWESTERN MAINE

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ABSTRACT

The Nd isotopic compositions of monazite and apatite are used to assess the initial isotope systematics of approximately 270 Ma granitic pegmatites in the Topsham area of southwestern Maine. The isotopic compositions are compared to values of spatially associated granites and country-rock migmatites to constrain potential sources of the pegmatites. The pegmatites form two groups: (1) the Northern series, which comprise the majority of the pegmatites exposed in the area, lack abundant rare-earth-element-enriched minerals, and have ϵ_{Nd}(270 Ma) in the range –2.2 to –1.4; (2) the Standpipe Hill series, distinguished by an enrichment in rare-earth-element minerals, displays a ϵ_{Nd}(270 Ma) in the range –3.4 and –3.3. Data for each group are internally consistent and suggest that the different pegmatite series were not derived from a single isotopically uniform source. The source of the Standpipe Hill series resembles adjacent biotite leucogranite [ϵ_{Nd}(270 Ma) between –3.9 and –3.7]. The Northern series pegmatites have Nd isotopic characteristics similar to both migmatites that they intrude [ϵ_{Nd}(270 Ma) between –2.9 and +0.8], and fine-grained biotite granites located *ca.* 15 km east of the pegmatites [ϵ_{Nd}(270 Ma) between –2.5 and –1.7]. The isotopic data demonstrate that spatially and temporally related pegmatites need not be derived from identical sources.

Keywords: apatite, monazite, neodymium isotopes, granitic pegmatites, Topsham, Maine.

SOMMAIRE

La composition isotopique du Nd de la monazite et de l'apatite sert à évaluer les caractéristiques initiales des pegmatites granitiques mises en place il y a environ 270 Ma dans la région de Topsham, dans le sud-ouest du Maine. On compare leur composition isotopique à celle des granites associés dans la région, et des roches encaissantes migmatitiques, afin d'en définir la source. Les pegmatites se répartissent en deux groupes: (1) les pegmatites de la série du Nord, qui comprend la majorité des pegmatites affleurant dans la région, ne possèdent pas une abondance de minéraux de terres rares, et ont une valeur ϵ_{Nd}(270 Ma) comprise entre –2.2 et –1.4; (2) les pegmatites de la série de Standpipe Hill, enrichies en minéraux des terres rares, possèdent une valeur ϵ_{Nd}(270 Ma) de –3.4 à –3.3. Les données pour chaque groupe montrent une concordance interne, et semblent indiquer que les deux séries ne pourraient pas avoir la même source isotopiquement uniforme. La source des venues de la série de Standpipe Hill ressemble à celle des massifs de leucogranite à biotite adjacents [ϵ_{Nd}(270 Ma) entre –3.9 et –3.7]. Les pegmatites de la série du Nord possèdent des caractéristiques isotopiques semblables à celles des migmatites qu'elles recoupent [ϵ_{Nd}(270 Ma) entre –2.9 et +0.8] et des granites à biotite à grains fins, situés environ 15 km à l'est des pegmatites [ϵ_{Nd}(270 Ma) entre –2.5 et –1.7]. Les données isotopiques démontrent que des pegmatites granitiques associées dans l'espace et dans le temps ne sont pas nécessairement dérivées de sources identiques.

(Traduit par la Rédaction)

Mots-clés: apatite, monazite, isotopes de néodyme, pegmatites granitiques, Topsham, Maine.

INTRODUCTION

Granitic pegmatites are of interest for their economic potential (*e.g.*, Li, Cs, Ta), but their sources and petrogenesis are poorly understood. In many cases, a genetic relation between granite plutons and bodies of pegmatite is assumed on the basis of spatial proximity. If a candidate "parental" granite is not exposed, the origin of a given granitic pegmatite is generally conjectural. Models of pegmatite genesis include: (1) magmatic fractionation of a granitic parent (Černý 1991), (2) segregations produced by direct anatexis of

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country rocks (Stewart 1978, Fowler & Doig 1983, Simmons *et al.* 1996), or (3) products of crystallization from a fluid phase (Kretz *et al.* 1989).

Established approaches to the study of pegmatite petrogenesis involve the use of major and trace elements, analogous to the use of liquid lines of descent in classical petrology (Goad & Černý 1981, Shearer *et al.* 1987, 1992, Černý & Meintzer 1988, Walker *et al.* 1989, Jolliff *et al.* 1992, Breaks & Moore 1992, Mulja *et al.* 1995). The capacity of these models to clarify pegmatite genesis is seriously limited by difficulties in estimating the bulk chemical composition of these exceedingly coarse-grained rocks and by a lack of relevant crystal – melt – fluid distribution coefficients.

Isotopic studies of granitic pegmatites are not common for several reasons. First, the potential for oxygen and hydrogen isotope exchange between magma and surrounding rocks limits the extent to which these data may be used to assess pegmatite sources. The extent of this exchange is likely quite significant, owing to the combination of a high ratio of country rock to pegmatite and the volatile-enriched bulk compositions (Taylor & Friedrichsen 1978, Longstaffe 1982). In addition, there is commonly little isotopic contrast between pegmatite and potential source-rocks (Walker *et al.* 1986a, Krogstad & Walker 1996). Such volatile-aided open-system behavior also creates uncertainties in the interpretation of Rb–Sr data from pegmatites (Clark & Černý 1987). The extreme enrichment of Rb in micas and feldspars (*e.g.*, Černý *et al.* 1985) and the likelihood of subsolidus transfer of radiogenic Sr into lower Rb/Sr minerals can disturb Rb–Sr systematics in granitic pegmatites, although valid geochronological information may still be preserved (*e.g.*, Riley 1970, Walker *et al.* 1986a, Trumbull 1993, Černý *et al.* 1995).

In several studies, chemical data from bulk samples of wall zones of pegmatites have been used in order to assess petrogenetic details (Walker *et al.* 1986b, Jolliff *et al.* 1992). The wall zone is a thick exterior margin of the pegmatite that displays leucogranitic bulk composition and, commonly, a somewhat finer grain-size than the more interior zones. Despite the smaller average grain-size of the wall zone, a modally representative sample of the wall zone is difficult to obtain because accessory minerals are sparse and widely distributed. Inasmuch as the rare-earth elements (*REE*) in granitic rocks reside dominantly in accessory minerals (*e.g.*, Gromet & Silver 1983), wall zones of granitic pegmatites tend to have low concentrations of *REE*. Hence, the introduction of small amounts of *REE* after pegmatite crystallization (*e.g.*, by later hydrothermal alteration or regional metamorphism) will disturb the Sm–Nd systematics of wall-zone samples.

In this study, the initial Nd isotopic compositions of pegmatite bodies from the Topsham area of southwestern Maine are estimated with *REE*-rich accessory minerals, specifically monazite and apatite. Von Blanckenburg (1992) found that accessory minerals in granitic rocks have an initial Nd isotopic composition equivalent to that of the bulk sample. Furthermore, the capacity to select the interior portion of *REE*-enriched minerals offers the best prospect of circumventing possible late-stage chemical and isotopic disturbances.

The Topsham pegmatites are a rare example of multiple spatially related bodies of granitic pegmatite with overlapping ages of crystallization (Tomascak *et al.* 1996). Age relations are fundamental constraints on granite – pegmatite relations, although these are seldom obtained (*e.g.*, Romer & Wright 1992, Krogstad & Walker 1994). Where a temporal link between pegmatites and granites is established, the assessment of genetic relations by chemical and isotopic means can be made.

GEOLOGY

Regional context

The granites and pegmatites of this study are the final products of the latest magmatic event (Alleghanian orogeny) in the northern Appalachians. The granitic rocks of the Topsham area intrude amphibolite-facies rocks of the Coastal Lithotectonic Belt in Maine (Hussey 1988; Fig. 1). Leucogranites and granitic pegmatites in the Topsham area are separated from bodies of fine-grained biotite granite (age unknown) in Phippsburg, *ca.* 15 km to the east, by the Flying Point fault. West *et al.* (1993) estimated approximately 4 km of post-Paleozoic, west-side-up displacement on the Flying Point fault.

The bedrock in the Coastal Lithotectonic Belt in the Topsham area is the Falmouth – Brunswick sequence, a group of quartzofeldspathic to semipelitic gneisses (migmatites), with associated amphibolite and calc-silicate. The conditions of peak metamorphism were greater than 550°C and 230–330 MPa (Lang & Dunn 1990). Granitic rocks east of the Flying Point fault intrude the Casco Bay Group, which consists largely of pelitic schists, metamorphosed at a T above 590°C and P in the range 280–330 MPa (Lang & Dunn 1990). On the basis of U–Pb data from zircon of presumed igneous origin, Hussey *et al.* (1993) have suggested an age for part of the Falmouth – Brunswick sequence of 471 ±3 Ma.

Metamorphic muscovite from rocks of the Falmouth – Brunswick sequence in the Topsham area record ^{40}Ar/^{39}Ar ages of 249 to 246 Ma (West *et al.* 1993). This interval of ages reflects cooling after the climax of the Alleghanian orogeny, the final orogenic event in the development of the Appalachians. High-temperature (>400°C), dominantly strike-parallel ductile deformation in the Topsham area, associated with the regionally extensive Norumbega fault zone, is evident up to the time of intrusion of the leucogranites and pegmatites to be described here (Tomascak & Solar 1996). The pervasive structures associated with the

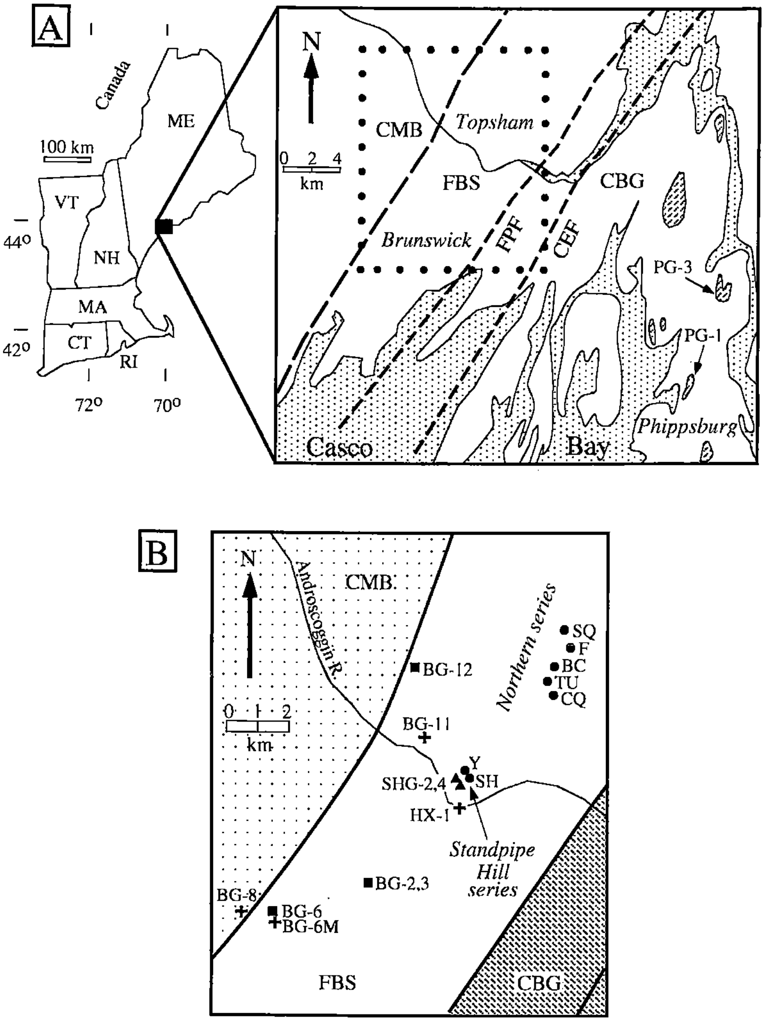

FIG. 1. A. Location of the study area in northeastern U.S.A. (Abbreviations of state names: CT, Connecticut; MA, Massachusetts; ME, Maine; NH, New Hampshire; RI, Rhode Island; VT, Vermont). Detail shows the general geological framework of the area, with the Topsham area (dotted box) in its regional context, which includes: predominant lithotectonic groups (Central Maine Belt, CMB; Falmouth – Brunswick sequence, FBS; Casco Bay Group, CBG), faults that are the local manifestations of the regionally extensive Norumbega fault zone (FPF, Flying Point fault; CEF, Cape Elizabeth fault), and bodies of fine-grained biotite granite in Phippsburg (patterned shapes; those marked PG are those for which samples have been analyzed). Town names are in italics. B. Location of samples in the Topsham area, from the box in A. Circles mark pegmatite localities. Northern series: SQ, Square Pit; F, Fisher; BC, Biotite Crystal; TU, Trebilcock; CQ, Consolidated. Standpipe Hill series: SH, East and Main Standpipe Hill; Y, Yedlin. Squares and triangles mark locations of leucogranite samples (squares, two-mica leucogranite; triangles, biotite leucogranite). Crosses designate locations where samples of country-rock migmatite were taken for analysis. See text and Table 2 for further descriptions of the samples.

development of shear zones associated with the Norumbega fault zone largely overprint structures interpreted to have been developed during the Mid-Paleozoic Acadian orogenic event (Hussey 1988). Evidence for multiple episodes of high-temperature metamorphism is preserved in schists in southern Phippsburg, but only discovered at one locality.

Granites and country rocks

Leucogranites in the Topsham area are divided into two groups: biotite leucogranite and two-mica leucogranite (Fig. 1). Exposures of biotite leucogranite are restricted to the Topsham side of the Androscoggin River, along the shore and at higher elevation (Fig. 1). The biotite leucogranite contains the assemblage oligoclase + quartz + K-feldspar + biotite ± garnet, and is characterized by up to about 1% magnetite (octahedra up to 2 cm in diameter) and accessory allanite (prisms up to 4 cm in length).

Two-mica leucogranite crops out throughout the Topsham area in irregularly shaped pods that range from 6 to >80 m in length. These were sampled at three locations. They comprise the assemblage oligoclase + quartz + K-feldspar + biotite + muscovite ± garnet, and have, in places, schlieren comprised predominantly of biotite. Monazite from a two-mica leucogranite sample (BG–6) yielded a mean $^{207}Pb^{*}/^{235}U$ age of 278 ± 1.5 Ma (Tomascak *et al.* 1996). Both groups of leucogranites are medium to fine grained, with igneous textures, and are commonly weakly foliated. Bodies of biotite granite that crop out about 15 km to the east, in Phippsburg (Fig. 1), are generally finer grained and areally more extensive than the leucogranites in the Topsham area.

The migmatites of the Topsham area are divided into two groups: regular migmatites and schlieren-rich granites. Regular migmatites are predominantly stromatic migmatites. They have a tripartite structure (leucosome, melanosome, mesosome), and have been interpreted as representing unsegregated granitic melts without entrained restite (Sawyer 1995). The schlieren-rich granites are hosted by the regular migmatites. They are deformed leucogranites with heterogeneous grain-size and abundant biotite-rich schlieren. They crop out as pods and sills that are either concordant or discordant with the planar fabric of the host. The generation of the migmatitic rocks is interpreted to predate the generation of the granites, on the basis of field evidence and Devonian Rb–Sr ages (Brookins & Hussey 1978).

The Topsham pegmatites

Granitic pegmatites in Topsham occur generally as lenticular bodies 100–600 m long. Although boundaries with country rocks are commonly covered, detailed mapping of pegmatites that accompanied feldspar mining (*e.g.*, Shainin 1948, Cameron *et al.* 1954) revealed the size and shape of many of these bodies. Overall, the pegmatite dikes are concordant with the planar fabric of the host migmatites, although many display irregular and discordant contacts.

The pegmatites are characterized by simple, well-developed internal mineralogical and textural zonation. The outermost part of each body consists of a thick wall-zone composed of very coarse-grained, graphically intergrown perthite and quartz, with plagioclase (An_{11} to An_{21}), biotite and minor garnet and magnetite. The biotite occurs in elongate crystals, some >1 m long, oriented subnormal to the contact of the pegmatite and its host rock. The wall zone forms a shell that completely surrounds the interior zones. The pegmatites have large cores, which consist primarily of the bimineralic assemblage perthite + quartz, with observed crystal dimensions up to 3 m. A discontinuous intermediate zone occurs between the wall zone and core. This intermediate zone consists of quartz, blocky perthite, and muscovite. It also commonly contains albite, biotite, apatite and garnet. Minerals characteristic of moderately evolved granitic pegmatites, such as beryl and columbite – tantalite, are concentrated in the intermediate zone. The intermediate zone adjacent to the core also hosts miarolitic cavities ranging from millimeters to *ca.* 1 m across (very rare; Palache 1934). A more detailed description of the mineralogy of pegmatite bodies in the Topsham area is given by Francis (1987).

The lenses of granitic pegmatite are separated into two series with slightly contrasting mineral assemblages: the Standpipe Hill and Northern series. Outcrops of Standpipe Hill series pegmatites are restricted to a small area in southern Topsham. Contacts between these pegmatite bodies and biotite leucogranite are gradational (Fig. 1), although contacts are generally poorly exposed. The Standpipe Hill series quarries show a greater abundance and diversity of *REE* minerals than the Northern series pegmatites, although monazite is the only mineral we examined from this series. Among Northern series pegmatite bodies, monazite and apatite are the only prevalent *REE*-rich minerals, and their occurrence is restricted (Francis 1987). Monazite and apatite samples for this study come from near the cores of the pegmatites, although this could not be rigorously substantiated in certain monazite specimens (museum crystals without matrix).

Two Standpipe Hill series pegmatites (the East Standpipe and Yedlin quarries) have ages of crystallization that range from 273 ± 1.5 Ma to 271 ± 2 Ma (all reported ages are $^{207}Pb^{*}/^{235}U$). Two pegmatites of the Northern series (the Square Pit and Trebilcock quarries) have ages of crystallization in the interval 272 ± 2 Ma to 270 ± 2.5 Ma. These ages are consistent with the U–Pb apatite age of sample BC–1 (Biotite Crystal pegmatite; Tomascak 1995). Hence, the available geochronological data suggest that the pegmatites examined in this study crystallized over a restricted time-interval, from approximately 274 Ma to 268 Ma.

Monazite and apatite are well-suited for a Sm–Nd isotope investigation of the Topsham pegmatites. Both occur as euhedral inclusions in crystals of other large, primary minerals (typically K-rich feldspar and biotite). Magnetite and samarskite were not examined, owing to their abundant inclusions and, in the case of magnetite, the difficulty in separating visibly pure samples. Allanite, which occurs in some Standpipe Hill series dikes, was not analyzed because grains are typically metamict.

ANALYTICAL METHODS

The monazite separates used for Sm–Nd isotope study are from the same samples as those used in Tomascak *et al.* (1996) for U–Pb geochronology. Each monazite sample comprises material from a single crystal, 3–15 mm across. Samples TU–1D and TU–2B are different crystals from the same body of pegmatite. Individual crystals were carefully broken, and 0.10–0.28 mg of 0.1–0.5 mm chips of visibly homogeneous core material were separated under 50× magnification. Samples were then rinsed in dilute HNO_3 and digested in Krogh-type bombs with concentrated HCl at 180°C for 12 hr.

Short prismatic crystals of apatite selected for study range from 3 to 5 mm in width, and from 7 to 12 mm in length. As with the monazite, individual samples comprise material from the cores of single crystals. Single, visibly inclusion-free fragments of crystals, each weighing 1 to 4 mg, were selected. Sample BC–1A is from the same crystal as used for U–Pb analysis by Tomascak (1995). Apatite separates were washed in cold, distilled water and dissolved completely in 0.1 mL 6M HCl. Monazite and apatite samples were spiked prior to dissolution with a mixed *REE* tracer.

Large blocks of bulk wall-zone (5–10 kg) were reduced and homogenized for *REE* analysis. Sample powders (0.2–0.3 g) were fused with $LiBO_2$ in 1:4 proportion at 1000°C and dissolved completely in 1M HNO_3, to which a mixed *REE* spike solution had been added. The *REE* were coprecipitated with Fe hydroxides by titration with NH_4OH. The *REE* in all samples were purified and separated with two stages of cation-exchange chromatography (HCl and 2-methyllactic acid). Considering the *REE* abundances being processed, no blank correction was warranted.

Isotope ratios were measured in the Isotope Geochemistry Laboratory of the Department of Geology, University of Maryland. *Bobcat II*, a VG Sector 54 mass spectrometer with 7 in-line faraday collectors, was used for measurements of the isotopic composition of Nd, with a multi-dynamic routine followed by off-line correction for spike contribution. Isotope-dilution analyses of the remaining *REE* were performed using *Bobcat I*, an NBS-design 68° sector, 12" radius of curvature, single-collector mass spectrometer. Samples were loaded on either single Ta filaments (Ce, Sm, Eu) or on Re side filaments, run in triple-filament assemblies.

On the basis of periodic analyses of the USGS standard BCR–1, *REE* reproducibilities were less than or equal to ±2.4% for Eu, Gd and Yb, ±2.0% for Nd, and ±1.5% for Ce, Sm, Dy and Er. Reproducibility of $^{147}Sm/^{144}Nd$ was less than ±1.2%. Analyses of the La Jolla Nd standard ($n = 21$) during the study yielded a mean $^{143}Nd/^{144}Nd$ of 0.511849 ± 13. Nd isotopic compositions $[\epsilon_{Nd} = ((^{143}Nd/^{144}Nd_{sample}/^{143}Nd/^{144}Nd_{CHUR}) - 1) \times 10^4]$ discussed in the text are calculated for 270 Ma, and use the measured ($^{147}Sm/^{144}Nd_{sample}$). Propagated

TABLE 1. Sm–Nd CONCENTRATIONS AND Sm–Nd ISOTOPE DATA FOR MONAZITE AND APATITE FROM THE TOPSHAM GRANITIC PEGMATITES

sample number (locality name)	mineral*	Sm, ppm	Nd, ppm	$^{143}Nd/^{144}Nd$	$^{147}Sm/^{144}Nd$	$f_{Sm/Nd}$	ϵ_{Nd} (270 Ma)
Northern series							
SQ–C (Square Pit)	Mnz	42070	128300	0.512566(9)	0.1983	+0.008	−1.4
TU–1D (Trebilcock)	Mnz	41200	106400	0.512626(8)	0.2343	+0.191	−1.5
TU–2B (Trebilcock)	Mnz	34570	91920	0.512610(8)	0.2274	+0.156	−1.6
BC–1 (Biotite Crystal)	Ap	647	1220	0.512765(9)	0.3208	+0.631	−1.8
CQ–1 (Consolidated)	Ap	769	1280	0.512816(9)	0.3634	+0.847	−2.2
Standpipe Hill series							
ESH–C (East Standpipe)	Mnz	24680	73000	0.512477(8)	0.2044	+0.039	−3.4
Y–C (Yedlin)	Mnz	19360	56300	0.512486(8)	0.2080	+0.057	−3.3

$^{143}Nd/^{144}Nd$ is the measured value, with uncertainty in the last digit (2σ) in parentheses; $f_{Sm/Nd}$ is the chondrite-normalized $^{147}Sm/^{144}Nd$ value.

* Mnz: monazite, Ap: apatite. Monazite samples have the following Harvard Mineralogical Museum identifiers: ESH-C = 92-65-5-1 ; Y-C = 125356; SQ-C = 131455; TU-1D = 117531; TU-2B = 131857.

uncertainties in the Sm–Nd data are approximately ±0.35 ϵ unit. Fractionation of Nd isotope ratios during analysis was corrected using a value of ^{146}Nd/^{144}Nd = 0.72190. Uncertainties of all stated mass-spectrometer measurements are given at the 2σ (population) level.

RESULTS

In order to compare values for different rock types, the Sm–Nd isotope data were normalized to the chondritic value at 270 Ma (Table 1; Jacobsen & Wasserburg 1980). For leucogranites in the Topsham area, which crystallized at approximately 278 Ma, the difference between ϵ_{Nd}(270 Ma) and ϵ_{Nd}(t) amounts to about 0.1–0.2 units, depending on ^{147}Sm/^{144}Nd.

Relative to one another, the pegmatite minerals have somewhat variable Sm and Nd concentrations and restricted ranges of ^{147}Sm/^{144}Nd (Table 1). The monazite samples have nearly chondritic to slightly suprachondritic ^{147}Sm/^{144}Nd, which is contrary to the findings of most investigators, who report enrichment in the light rare-earths (*LREE*) relative to chondritic values (*e.g.*, Getty & Gromet 1992, Bea *et al.* 1994, Bea 1996). However, certain studies suggest variability in *REE* patterns of monazite, especially in response to magmatic differentiation (*e.g.*, Wark & Miller 1993, Casillas *et al.* 1995). Because the samples selected are small, hand-picked fragments of larger crystals that lack any visible inclusions or adhering grains, their *REE* concentrations were likely not contaminated by low-*LREE* minerals.

Both monazite and apatite from the two pegmatite series display different initial Nd isotopic compositions. Minerals separated from four different bodies of Northern series pegmatites have ϵ_{Nd}(270 Ma) that range from –2.2 to –1.4. In contrast, monazite from two separate dikes of the Standpipe Hill series have ϵ_{Nd}(270 Ma) ranging from –3.4 to –3.3.

DISCUSSION

Nd isotope systematics of pegmatites

If the experimental method employed here is to provide meaningful results, each pegmatite body should have a restricted, characteristic isotopic signature. This can be tested by examining the isotope systematics of multiple crystals from a single pegmatite dike. The one pegmatite from which two monazite grains were examined (the Trebilcock quarry, samples TU–1D and TU–2B) gives identical results within analytical uncertainty [ϵ_{Nd}(270 Ma) = –1.6 and –1.5]. This suggests that monazite records a single, characteristic Nd isotope signature of a pegmatite body.

The other monazite and apatite samples from Northern series pegmatites come from three separate dikes. Apatite CQ–1 has a slightly lower ϵ_{Nd}(270 Ma) of –2.2, yet this is within analytical uncertainty of the minerals from other Northern series bodies. The difference between the ϵ_{Nd}(270 Ma) of CQ–1 and the other Northern series pegmatites may be attributed to slight heterogeneity in the isotopic composition of the melt that formed the Northern series pegmatites.

Alternatively, the difference between the isotopic composition of apatite CQ–1 and the other Northern series minerals could be the result of slight contamination of the pegmatite-forming magma by interaction with wall-rocks of different Sm–Nd isotopic characteristics. In order to model this contamination, the bulk Nd concentration of the pegmatite-forming melt must be known. An estimate of this value can be made only with better characterization of the mode of *REE* minerals in the pegmatites. Using the composition of the wall zone as a proxy for the bulk pegmatite is, as indicated above, inherently problematical. For example, two samples of wall zone from the same Northern series pegmatite (the Fisher quarry) yielded Nd concentrations of 0.845 and 27.8 ppm (Tomascak 1995; see below, Fig. 4).

On an isochron plot, the differences in isotopic composition among the samples are evident (Fig. 2). The Northern series data lie close to a 270 Ma reference line with an initial ϵ_{Nd} of –1.8. Data for the Standpipe Hill series fall on a reference line with an identical slope and demonstrate an isotopic signature (initial ϵ_{Nd} of –3.4) distinct from the Northern series.

Linear arrays in isochron plots such as Figure 2 may also be interpreted as evidence for contamination by country rocks produced by mixing between the pegmatite-forming melt and the host rocks. Although there is insufficient spread in ^{147}Sm/^{144}Nd among the samples examined here to yield precise information on age, the fact that the data fall close to 270 Ma reference lines suggests that monazite and apatite preserve magmatic isotopic signatures. A linear regression of the

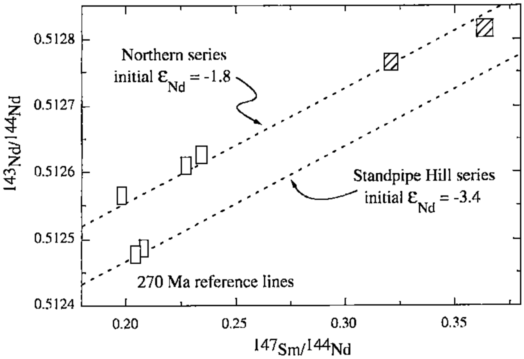

FIG. 2. Sm–Nd isochron diagram for the Topsham suite of pegmatites. Apatite error boxes are striped, monazite error boxes are white. Two reference lines are plotted, both corresponding to an age of 270 Ma, the mean age of crystallization of the pegmatites in both series. The Northern series data fall close to the reference line with an initial ϵ_{Nd} of –1.8. The Standpipe Hill series data plot on a line with an initial ϵ_{Nd} of –3.4.

Northern series mineral data (MSWD = 0.72 using the algorithm of Ludwig 1994) has a slightly shallower slope than the 270 Ma reference line (237 ± 15 Ma) and a proportionally higher initial ϵ_{Nd} of –1.4. If this deviation from the age of crystallization of the pegmatites was produced by minor country-rock contamination, it would indicate that the difference in initial ϵ_{Nd} brought about by the contamination was negligible relative to analytical uncertainty.

Sources of the pegmatites

The Sm–Nd isotope data provide specific evidence about potential differences among the sources of the pegmatite bodies. The monazite and apatite samples from four Northern series pegmatites display similar initial Nd isotopic compositions, which are distinct from those of the monazite samples from two bodies of pegmatite of the Standpipe Hill series (Fig. 3). This distinction could be due to a difference in sources for the two series, or could result from one isotopically heterogeneous source.

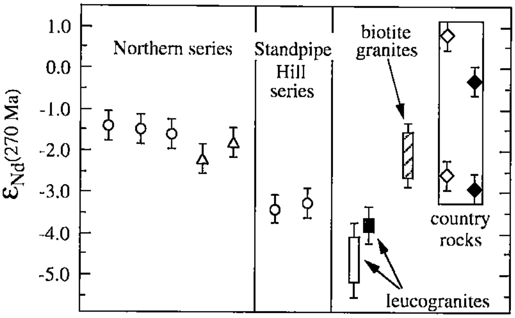

FIG. 3. Summary of Nd isotope data for samples from this area. All data are presented as ϵ_{Nd}(270 Ma). The pegmatite data are grouped by series and keyed to sample type (circle, monazite; triangle, apatite). The right side of the plot shows data for potential source-rocks in the area: open box, two-mica leucogranite; black box, biotite leucogranite; striped box, fine-grained biotite granite in Phippsburg; white diamond, schlieren-rich granite; black diamond, regular migmatite.

The Nd isotopic compositions of the samples within the two series cluster rather tightly. If the difference in isotopic signatures of the two series is to be a reflection of a heterogeneous source, the intraseries homogeneity would require sources with regional heterogeneity, yet local *homogeneity* in Nd isotopic composition. If the source was originally sedimentary, this sort of fortuitous isotopic segregation is not anticipated given the scale of mixing commonly exhibited in sedimentary basins (McDaniel *et al.* 1994, Hemming *et al.* 1995). The difference in bulk chemical composition between the Northern and Standpipe Hill series, as inferred by their mineralogical contrast, is also consistent with derivation of the two series from geochemically dissimilar sources.

If pegmatite-forming magmas are derived *via* fractionation of a parental granitic magma, Sm–Nd isotope data can be used to investigate the potential genetic link. This requires identical initial Nd isotopic compositions for the granite and its pegmatitic differentiates. Samarium – neodymium isotope data for granites and other rocks exposed in the study area are summarized in Table 2 and Figure 3. The two-mica leucogranites in the area define a narrow range in ϵ_{Nd}(270 Ma) (–5.2 to –4.1). The biotite leucogranites also have limited variability in ϵ_{Nd}(270 Ma) (–3.9 to –3.7). There is slight overlap between the initial Nd isotopic compositions of the two groups of leucogranites, considering the analytical uncertainty.

TABLE 2. REPRESENTATIVE WHOLE-ROCK Sm–Nd ISOTOPE DATA FOR GRANITES AND COUNTRY ROCKS FROM THE TOPSHAM AREA

sample	$^{147}Sm/^{144}Nd$	ϵ_{Nd} (270 Ma)
two-mica leucogranites		
BG–2	0.1418	–4.3
BG–3	0.1621	–5.2
BG–6	0.1319	–4.1
BG–12	0.1296	–5.1
biotite leucogranites		
SHG–2	0.1675	–3.7
SHG–4	0.3035	–3.9
fine-grained biotite granites, Phippsburg		
PG–1	0.0876	–2.5
PG–3	0.0815	–1.7
FBS* migmatites		
BG–8 (sg)	0.1476	–2.6
BG–11 (sg)	0.1079	+0.8
BG–6M (rm)	0.1660	–0.3
HX–1 (rm)	0.1230	–2.9

Data from Tomascak *et al.* (in press); uncertainties identical to data in Table 1.

* Falmouth – Brunswick sequence. Symbols: rm regular migmatite, sg schlieren-rich granite.

The biotite leucogranites are indistinguishable isotopically from the Standpipe Hill pegmatite series, to which they are adjacent in the field. This permits the magma that crystallized as biotite leucogranite to be parental to the Standpipe Hill pegmatites. That the isotopic signatures of the biotite- and two-mica leucogranites show slight overlap therefore permits the two-mica leucogranites to be related to the Standpipe Hill pegmatites as well.

The volumetrically more abundant Northern series pegmatites are isotopically similar to fine-grained biotite granites in the Phippsburg area, with ϵ_{Nd}(270 Ma) of –2.5 to –1.7 (Fig. 3). However, factors other than the isotope systematics must be taken into consideration when assessing the viability of a genetic link between those granites and the pegmatites. The fine-grained biotite granites lack many of the major- and trace-element attributes (Tomascak *et al.*, in press) associated with granites that are parental to pegmatite populations (Černý & Meintzer 1988). The apparent geochemical discrepancy makes the fine-grained biotite granites a tenuous choice as parental granites.

The only other rocks in the area with Nd isotopic compositions similar to the Northern series pegmatites are the metamorphic country-rocks. Migmatitic rocks of the Falmouth – Brunswick sequence have ϵ_{Nd}(270 Ma) of –2.7 to +1.0 (Fig. 3). This is consistent with derivation of the Northern series pegmatites from sources similar to the migmatites in the area, which could be interpreted two ways: (1) the pegmatites were derived from granites whose source was the migmatitic sequence, (2) the pegmatites were derived directly from the migmatites. The first interpretation requires parental granites not currently exposed. Nevertheless, field evidence for the *in situ* production of the pegmatites is, at the current level of exposure, equivocal. Available geochronological and geochemical data also are insufficient to rigorously evaluate an anatectic origin for these pegmatites.

The spatial association of pegmatites with *REE*-enriched (Standpipe Hill series) and *REE*-poor (Northern series) mineralogical characteristics is uncommon (Bergstøl & Juve 1988, Smeds 1990). In the opinion of Černý (1991), these "mixed" pegmatite series could result from contamination of a single pegmatite-generating magma or through melting of a depleted or partially depleted protolith. The relatively *REE*-enriched magmas that formed the Standpipe Hill pegmatites would require unreasonably large proportions of a low-ϵ_{Nd} contaminant to yield the difference in isotopic composition between the two pegmatite series. Similarly, the large volume of the individual bodies that make up the Northern series would require contamination by huge volumes of high-ϵ_{Nd} material in order to produce the isotopic shift between the series. Hence, the observed isotopic differences between the two series are not likely the result of contamination of a single batch of magma.

Magmas derived from sources that have undergone multiple episodes of melting may display heterogeneity in initial Nd isotopic composition if there was a sufficient time-gap between melting events. However, this mechanism is unlikely to be viable in the Topsham area, owing to the lack of ancient melting events. Even so, it is not likely that a magma of "minimum" melt composition would be produced during subsequent melting.

Whether or not the Topsham pegmatites constitute a "mixed" series of pegmatites, the Sm–Nd isotope data are most consistent with derivation of pegmatites from isotopically distinct sources. Černý (1989) interpreted a lack of extreme fractionation in a pegmatite field in terms of a source with a short residence-time in the crust ("primitive" sources). Taken as a whole, the "primitive" Nd isotope signatures of the Topsham pegmatites are consistent with their overall restricted degree of rare-metal enrichment.

General applicability of Nd isotopes to pegmatite problems

By way of comparison, in the Tin Mountain pegmatite, South Dakota, Walker *et al.* (1986a) found some heterogeneity of initial Nd isotope systematics in apatite (approximately 3 ϵ units). This pegmatite body yielded a Sm–Nd errorchron age which is >10% older than the U–Pb age of the pegmatite and its parent granite (Krogstad & Walker 1994). These data were interpreted to reflect contamination of the primary Sm–Nd isotope systematics of the pegmatite-forming melt by host rocks with variable Nd isotopic characteristics. Walker *et al.* (1986a, b) have suggested that the *REE*-depleted pegmatite-forming melt was open to *REE* exchange with surrounding schists and amphibolites through a magmatic volatile phase. Unlike the Topsham pegmatites, the Tin Mountain pegmatite is strongly enriched in rare alkalis (Li, Rb, Cs) and F. The Tin Mountain pegmatite preserves a protracted late-stage history of crystallization under fluid-enriched conditions. This is underscored by the occurrence of Li-mineralized fracture fillings that extend from the pegmatite into the country rocks. In contrast, spodumene is absent from Topsham pegmatites, and other Li-rich minerals occur rarely and are paragenetically late.

Walker *et al.* (1986a) used relatively large samples of bulk, powdered apatite for their Nd isotope analyses. Krogstad & Walker (1994) used both bulk powders and small, hand-picked fractions of single crystals of apatite for U–Pb geochronology. The powdered bulk samples of apatite all had discordant U–Pb systematics, whereas fragments from cores of crystals were concordant. Therefore, it is apparent that careful selection and preparation of samples are essential in the acquisition of the most representative isotopic data.

The Topsham pegmatites exhibit *REE* patterns with highly variable shapes and negative kinks at Nd (Fig. 4). Similar complex distributions of the *REE* have been demonstrated in wall-zone samples from many pegmatites (*e.g.*, Goad & Černý 1981, Černý & Meintzer 1988), including the Tin Mountain occurrence. This complexity has not yet been thoroughly explained, although Walker *et al.* (1986b) have suggested the potential for differential *REE* complexation *via* volatile-enriched fluids. The poorly understood *REE* geochemistry of bulk wall-zone samples further justifies the use of *REE*-rich accessory minerals for Sm–Nd isotopic study. On the basis of a comparison of

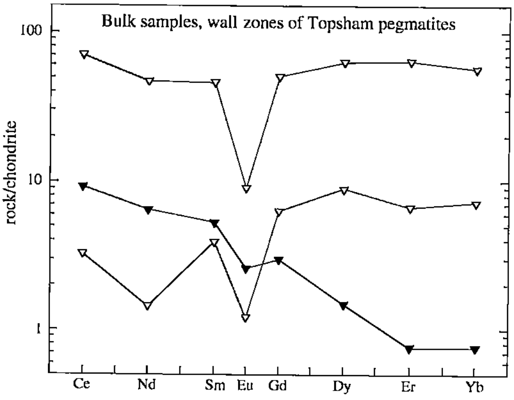

FIG. 4. Isotope-dilution-derived rare-earth-element patterns from bulk samples of wall zones of selected samples of the Topsham pegmatites, normalized to the chondritic values of Masuda *et al.* (1973), multiplied by 1.2. The black symbols are for samples from the Main Standpipe Hill quarry (interpreted to be connected to the East Standpipe Hill locality). The white symbols represent two different samples taken more than 10 m apart in the Fisher quarry (of the Northern series). Note the negative kinks at Nd and the obvious within-pegmatite variability in abundance and distribution of the *REE*.

results for the Tin Mountain and Topsham occurrences, pegmatites that are relatively *REE*-enriched and lack profuse rare alkali mineralization and profound alteration by late-stage volatile-enriched phases have optimal potential for retaining initial Nd isotope systematics.

SUMMARY

Unaltered, carefully selected *REE*-enriched accessory minerals yield internally consistent Nd isotopic compositions for bulk granitic pegmatites in the Topsham area of southwestern Maine. On the basis of Nd isotope data from monazite and apatite, Standpipe Hill series pegmatites were not derived from the same, isotopically homogeneous source as spatially associated pegmatites of the Northern series. The source of the pegmatites of the Standpipe Hill series seems to have been the same as that of proximal biotite leucogranite. The Northern series pegmatites show Nd isotopic characteristics similar to the Falmouth – Brunswick sequence migmatites that they intrude. The isotopic data do not preclude a genetic link between the Northern series and fine-grained biotite granites to the east.

If the two series of pegmatites in the Topsham area were indeed derived from distinct sources, temporally related pegmatites that occur together in the field need not be strictly cogenetic. The use of the Sm–Nd isotope system seems particularly well suited to terranes that contain pegmatites with contrasting lithophile element signatures (the "mixed" pegmatite series). The prospect for probing pegmatite sources with Nd isotopes is improved in pegmatites with modest enrichment in volatile elements and with the selection of interior portions of single crystals.

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