

# NEODYMIUM AND STRONTIUM ISOTOPIC CONSTRAINTS ON THE ORIGIN OF THE PERALUMINOUS GRANITOIDS OF THE SOUTH MOUNTAIN BATHOLITH, NOVA SCOTIA, CANADA

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## Abstract

Clarke, D.B., Halliday, A.N. and Hamilton, P.J., 1988. Neodymium and strontium isotopic constraints on the origin of the peraluminous granitoids of the South Mountain batholith, Nova Scotia, Canada. *Chem. Geol. (Isot. Geosci. Sect.)*, 73: 15-24.

Nd isotopic data from the South Mountain batholith show that its peraluminous granitic rocks have considerably higher  $\epsilon_{\text{Nd}}^t$  ( $t=372$  Ma) values ( $-5.2$  to  $-1.4$ ) than the extensive flyschoid country rocks ( $-11.2$  to  $-8.7$ ). These isotopic data are combined with Sr isotopic measurements to estimate the involvement of the country rocks, either as source materials or as contaminants, in the batholith. Metasedimentary enclaves in the batholith generally have Nd and Sr isotopic compositions intermediate between those of the batholith and the country rocks, and provide evidence of contamination by the country rocks. Integrated with other geochemical data, the isotopic results show at least two possible origins for the South Mountain batholith: either this large batholith is a hybrid of mantle and crustal materials and contains a large proportion of mantle-derived Nd and Sr, or the magma is derived from deeper metasedimentary crustal material, with younger model ages or higher Sm/Nd ratios than the upper crust.

## 1. Introduction

The granites and country rocks of the Meguma Zone of the northeastern Appalachians have been the object of considerable attention in recent years (McKenzie and Clarke, 1975; Clarke and Halliday, 1980, 1985; Muecke and Clarke, 1981; Keppie and Poole, 1984; Clarke and Muecke, 1985). Briefly, this lithotectonic zone consists of an extensive ( $125,000 \text{ km}^2$ ), thick ( $>14$  km) suspect terrane of Cambro-Ordovician turbidite flysch (Schenk, 1978) that was deformed and metamorphosed in the early

Devonian and intruded by many peraluminous granitoid plutons in the late Devonian-early Carboniferous (Fig. 1) (Clarke and Halliday, 1980; Reynolds et al., 1981, 1987).

The granitoid rocks are characterized by modal andalusite, cordierite, and garnet, and by  $A/CNK$  [ $\text{mol Al}_2\text{O}_3 / (\text{CaO} + \text{Na}_2\text{O} + \text{K}_2\text{O})$ ] ratios  $>1$  and, therefore, it might be reasonable to infer some genetic link between them and their enclosing flyschoid rocks, i.e. that they may be typical so-called "S-type" (Chappell, 1984) granitoids derived from deeper levels of the thick flyschoid sequence. The present work

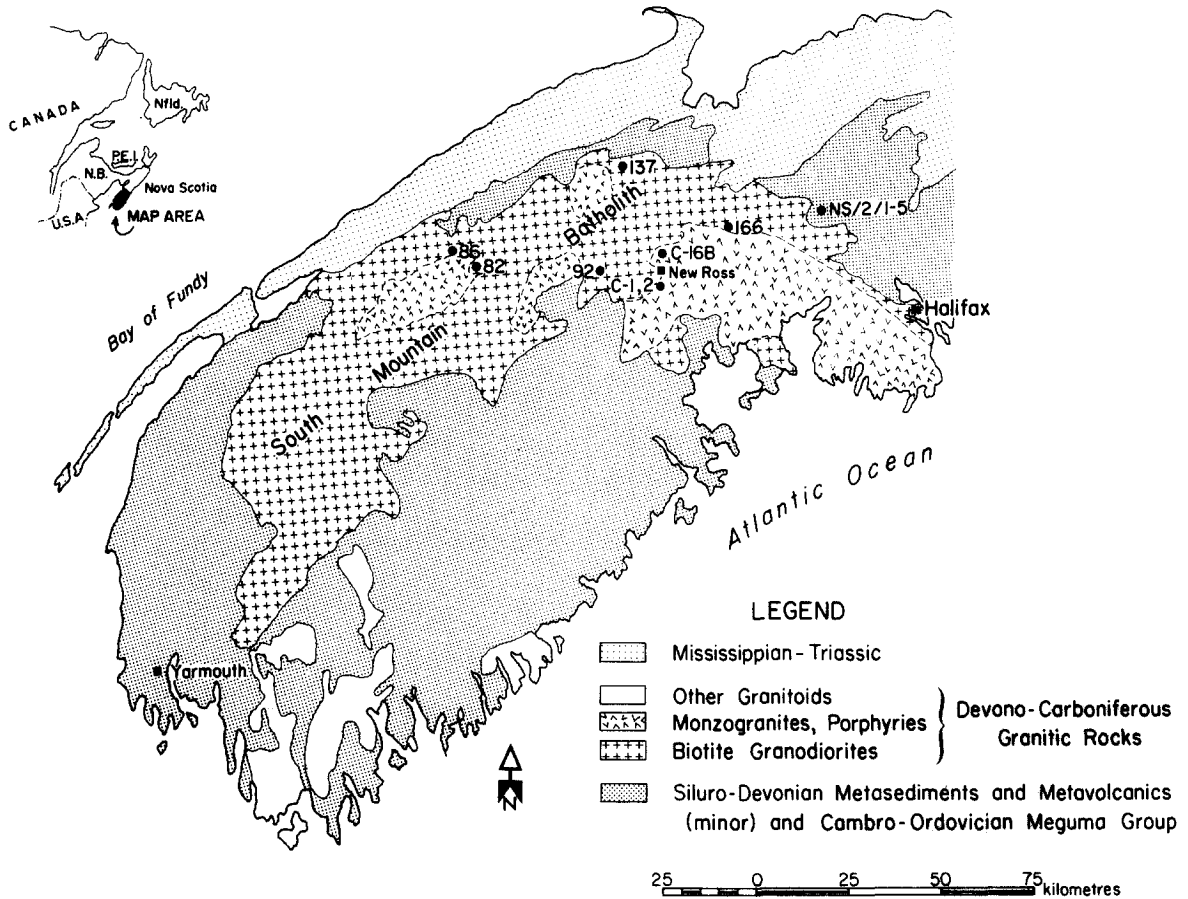


Fig. 1. Simplified geological map of the South Mountain batholith showing location of samples used in this study.

has been undertaken to examine this possible genetic link between the Meguma Zone peraluminous granitoids and their enclosing flysch, to determine the model ages of the granitoids, and to refine the models for the origin and evolution of the largest of the granitic bodies, the South Mountain batholith (SMB).

## 2. Analytical techniques and data

### 2.1. Analytical techniques

Rb, Sr, Sm and Nd concentrations were determined by isotopic dilution techniques. Analyses were performed on an automated V.G. Isomass<sup>®</sup> 54E mass spectrometer and all details of the procedures and calibration data have

been reported previously (Halliday et al., 1984; Clarke and Halliday, 1985).

### 2.2. Data

Samples used in this investigation were selected from the same group as those examined by Clarke and Halliday (1980) in their study of the Rb–Sr whole-rock isochron ages of the several lithological facies of the SMB. From field relations and Rb–Sr dating, the sequence of intrusion is: granodiorite ( $372 \pm 2$  Ma)–monzogranite ( $364 \pm 1$  Ma)–monzogranite porphyry ( $361 \pm 1$  Ma), with corresponding variations in mean  $A/CNK$  (1.09, 1.15, 1.20), and  $^{87}\text{Sr}/^{86}\text{Sr}_i$  (0.7081,  $0.7094 \pm 0.0004$ ,  $0.7102 \pm 0.0012$ ). Table I shows that there is also significant variation in  $\epsilon_{\text{Nd}}^t$  (–2.2, –3.3, –5.1) ( $t=372, 364,$

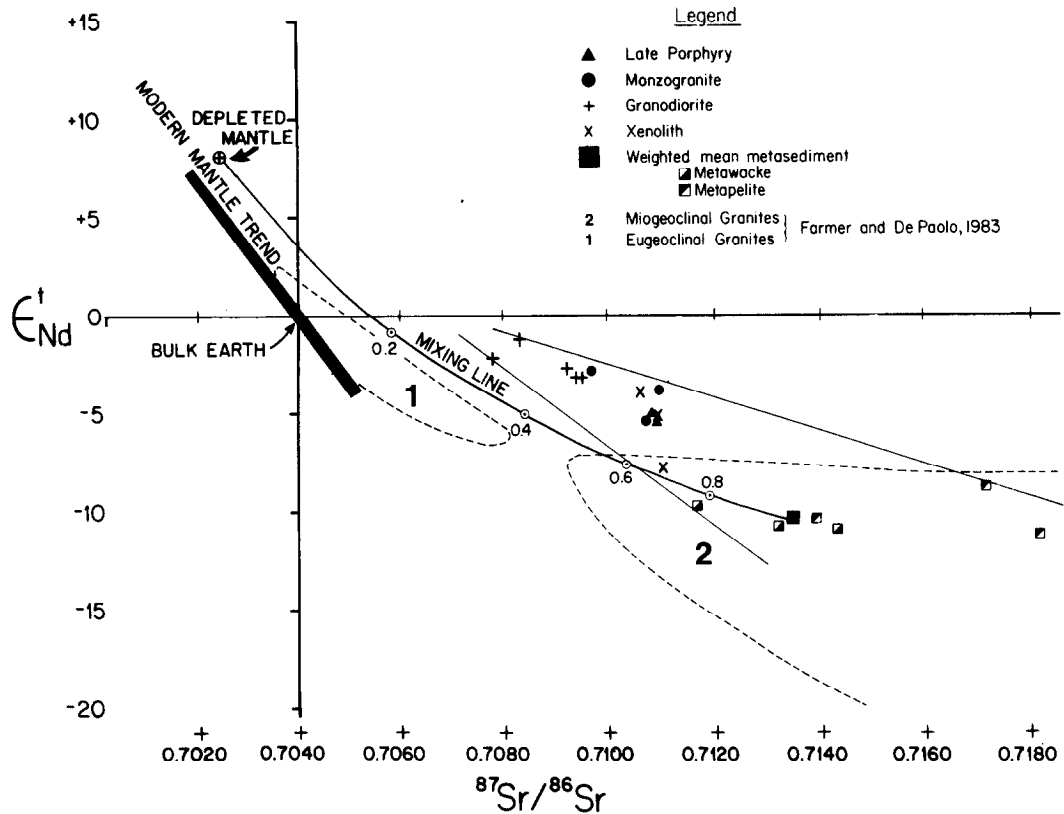


Fig. 2. Conventional  $\epsilon_{\text{Nd}}-^{87}\text{Sr}/^{86}\text{Sr}$  diagram showing the relationships among the major rock types of the Meguma Zone of the eastern Appalachians. Points to note are that the earliest phase of the batholith (granodiorite) is most unlike the country rocks, that the trend from granodiorite through monzogranite to late porphyries could correspond to a mixing of these two components, and that there appears to be partial isotopic equilibration of the enclaves in the granodiorites. Also, a mixing line involving depleted mantle and Meguma metasedimentary rocks does not pass through the SMB array (see text for details).

361 Ma), respectively. In addition, the granitoid rocks have higher  $\epsilon_{\text{Nd}}^t$  than the enclosing metasedimentary rocks ( $-11.2$  to  $-8.7$ ), and the enclaves have intermediate values.

### 3. Discussion

#### 3.1. Relation between granitoids and country rocks: open or closed system?

Many geochemical and isotopic data show that genetic relationships exist among the various phases of the SMB (Muecke and Clarke, 1981; Clarke and Muecke, 1985). Also, the temporal evolution of the SMB is characterized by increasing  $\text{SiO}_2$ ,  $A/\text{CNK}$  and  $(^{87}\text{Sr}/^{86}\text{Sr})_i$ , and

decreasing  $\epsilon_{\text{Nd}}$  and  $\Sigma\text{REE}$  (total rare-earth elements) similar to the Criffell pluton in Scotland, U.K. (Stephens et al., 1985), all of which must be explained in a comprehensive petrogenetic model.

In their study of the Sr isotope geochemistry of the Meguma Zone, Clarke and Halliday (1980) concluded that there are two viable models for the Sr isotopic evolution of the SMB: (1) an open system in which the increase in  $^{87}\text{Sr}/^{86}\text{Sr}$  could be attributed to a combination of assimilation of metasedimentary country rocks coupled with fractional crystallization largely of plagioclase [now termed AFC (assimilation-fractional crystallization) processes], or (2) a closed-system model in which the increase of

TABLE I

Analytical data for granitoids and xenoliths from the South Mountain batholith used in this study

Sample	Lithology	A/CNK	Rb-Sr $t$ (Ma)	$(^{87}\text{Sr}/^{86}\text{Sr})^t$	Sm-Nd		$^{147}\text{Sm}/^{144}\text{Nd}$	$^{143}\text{Nd}/^{144}\text{Nd} \pm 2\sigma_m$	$\epsilon_{\text{Nd}}^t$	$t_{\text{DM}}$ (Ga)
					Sm (ppm)	Nd (ppm)				
<i>Main batholith:</i>										
M72-86	granodiorite	1.06	372	$0.7076 \pm 0.0003$	7.533	33.36	0.1365	$0.512377 \pm 0.000022$	0.51204	-2.2 1.31
M72-137	granodiorite	1.12	372	$0.7081 \pm 0.0004$	8.020	37.13	0.1306	$0.512406 \pm 0.000028$	0.51209	-1.4 1.17
M72-192	granodiorite	1.10	372	$0.7090 \pm 0.0003$	6.607	30.87	0.1294	$0.512326 \pm 0.000016$	0.51201	-2.9 1.29
M72-82	monzogranite	1.14	364	$0.7107 \pm 0.0004$	9.239	41.81	0.1336	$0.512292 \pm 0.000030$	0.51197	-3.8 1.43
M72-166	monzogranite	1.16	364	$0.7095 \pm 0.0003^{*1}$	2.553	8.881	0.1738	$0.512440 \pm 0.000030$	0.51203	-2.8 2.32
C-1	monzogranite									
	porphyry	1.24	361	$0.7102 \pm 0.0012^{*1}$	1.603	5.437	0.1783	$0.512330 \pm 0.000030$	0.51191	-5.2 3.20
C-6	monzogranite									
	porphyry	1.10	361	$0.7102 \pm 0.0012^{*1}$	2.009	6.325	0.1920	$0.512363 \pm 0.000022$	0.51191	-5.2 —
C-16B	monzogranite									
	porphyry	1.26	361	$0.7102 \pm 0.0012$	3.011	9.324	0.1952	$0.512382 \pm 0.000021$	0.51192	-4.9 —
<i>Contact study:</i>										
NS/2/1	granodiorite	1.17	372	$0.70925 \pm 0.00016$	8.792	41.29	0.1287	$0.512309 \pm 0.000028$	0.51200	-3.2 1.31
NS/2/3	xenolith	1.48	372	$0.71072 \pm 0.00016$	8.060	43.53	0.1119	$0.512031 \pm 0.000022$	0.51176	-7.8 1.51
NS/2/4	xenolith	1.23	372	$0.71058 \pm 0.00011$	7.618	31.52	0.1461	$0.512259 \pm 0.000020$	0.51190	-5.0 1.76
NS/2/5a	granodiorite									
	(adjacent to xenolith)	—	372	$0.70922 \pm 0.00012$	7.227	35.76	0.1222	$0.512298 \pm 0.000027$	0.51200	-3.1 1.24
NS/2/5b	xenolith									
	(adjacent to granodiorite)	—	372	$0.70968 \pm 0.00008$	15.31	68.66	0.1348	$0.512279 \pm 0.000021$	0.51195	-4.1 1.47
Mean										
Meguma*2	graywacke/pelite	1.9	372	0.71335	6.74	35.70	0.1142	0.511906	0.51164	-10.5 1.74

Present-day bulk-Earth values used are:  $^{147}\text{Sm}/^{144}\text{Nd} = 0.1966$ ;  $^{143}\text{Nd}/^{144}\text{Nd} = 0.512638$ .\*<sup>1</sup>Regression derived.\*\*<sup>2</sup>Values estimated from Clarke and Halliday (1980, table 4 and unpublished data, 1983) based on Meguma weighted average =  $(0.7 \times \text{mean metawacke}) + (0.3 \times \text{mean metapelite})$ .

$^{87}\text{Sr}/^{86}\text{Sr}$  in the magmatic complex was the result of decay of  $^{87}\text{Rb}$  over the time required to intrude the various members of the batholith. With Sr isotopic data alone, it was not possible to distinguish between these models.

The Nd data presented here make possible a choice between these alternatives (Fig. 2). Although the initial Sr isotopic ratio could have increased from 0.7081 to 0.7102 in the 8–12 Ma between intrusive phases through simultaneous enrichment of Rb and decay of  $^{87}\text{Rb}$  (Clarke and Halliday, 1980), it is not possible to account for the decrease of  $\epsilon_{\text{Nd}}$  from  $-2$  to  $-5$  through closed-system decay of  $^{147}\text{Sm}$  in such a short period of time (typically, the  $\epsilon_{\text{Nd}}$ -value will decrease by only 0.1 in 10 Ma in the granodiorites). Thus Fig. 2 suggests that the Nd–Sr isotopic variation in the SMB might be explained by varying degrees of incorporation of Meguma-like metasedimentary material.

Three other lines of evidence support the idea that Meguma material has been incorporated into the SMB:

(1) There are both magmatic and xenocrystic garnet (Allan and Clarke, 1981) and cordierite (Maillet and Clarke, 1985) in parts of the batholith.

(2) The early granodiorite phase of the SMB contains abundant xenoliths of the Meguma flyschoid rocks, ranging in size from tens of metres to centimetres, and in shape from angular to rounded, respectively. These xenoliths have minerals, textures and compositions which show that they have reacted with the granodioritic magma (Jamieson, 1974; Allan and Clarke, 1981; Woodend, 1985).

(3) Isotopic evidence from the present contact study (see Table I) appears to provide clear geochemical confirmation of the partial equilibration of the xenoliths with the magma. All samples in this subset were taken from one large outcrop on the eastern contact of the SMB. Sample NS/2/1 is a granodiorite remote from any xenoliths. Sample NS/2/5a is a granodiorite immediately adjacent to metawacke xenolith NS/2/5b. Sample NS/2/3 is a medium-

grained metawacke dominated by the assemblage quartz–biotite–plagioclase–K-feldspar and has prominent porphyroblasts of plagioclase. Sample NS/2/4 is a fine-grained metawacke hornfels with anhedral porphyroblasts of garnet. From a mineralogical and textural point of view these samples form a continuum from: granodiorite (remote from the contact) — NS/2/1 — NS/2/5a — NS/2/5b — NS/2/3 — NS/2/4 — average Meguma metasedimentary rock, and the  $^{87}\text{Sr}/^{86}\text{Sr}$  and  $\epsilon_{\text{Nd}}$ -values are (0.7081,  $-1.8$ ) — (0.7092,  $-3.2$ ) — (0.7092,  $-3.1$ ) — (0.7097,  $-4.1$ ) — (0.7107,  $-7.8$ ) — (0.7106,  $-5.0$ ) — (0.7134,  $-10.5$ ), respectively. Because the enclaves are out of isotopic equilibrium with their granitoid hosts, they cannot represent source material for the granitoids themselves, as was proposed for enclaves in the Sierra Nevada batholith (Domenick et al., 1983). Instead, they simply appear to be mineralogically, texturally, and chemically modified fragments of the country rock, assimilation of which could be responsible for part of the chemical variation observed in the SMB.

The question remains as to how much of the Meguma country rocks could have been incorporated into by the SMB magma? One approach to the problem of determining the relative inputs of Meguma, and more primitive sources in the SMB magma, is to make simple assumptions concerning the nature of the primitive material. In the extreme, if the primitive material for the SMB magma were mantle-derived basalt with  $\epsilon_{\text{Nd}} = +8$ , and using isotopic ratios only, then:

$$f(\text{Nd}_M) = (\epsilon_{\text{NdG}} - \epsilon_{\text{NdB}}) / (\epsilon_{\text{NdM}} - \epsilon_{\text{NdB}})$$

where  $f(\text{Nd}_M)$  is the fraction of Nd in the granodiorite magma derived from the Meguma metasediments,  $\epsilon_{\text{NdG}}$  has a value of  $-2.2$  in the granodiorites,  $\epsilon_{\text{NdM}}$  has a value of  $-10.5$  in the Meguma, and  $\epsilon_{\text{NdB}}$  has a value of  $+8.0$  in the basalt. With these values, the fraction of Nd derived from the Meguma is 0.55. This represents a maximum because the more primitive component is unlikely to have had  $\epsilon_{\text{Nd}} > +8.0$ . Us-

TABLE II

Elemental concentrations and isotopic ratios used in mixing calculations to assess the origin of the granodiorite magma

	Strontium		Neodymium	
	(ppm)	$^{87}\text{Sr}/^{86}\text{Sr}$	(ppm)	$\epsilon_{\text{Nd}}$
Depleted mantle	100	0.7025	10	+8.0
Meguma	175	0.7134	36	-10.5
Granodiorite	142	0.7081	33	-2.2

ing a similar relationship for ( $^{87}\text{Sr}/^{86}\text{Sr}$ )<sub>i</sub> and a value for a depleted mantle component of 0.7025, the fraction of Sr derived from the Meguma is 0.51. This, too, represents a maximum degree of involvement by the Meguma in the generation of the SMB magmas. More realistically, if the concentrations of Nd and Sr are also taken into account and standard mixing equations are used (Faure, 1986; Table II), then Fig. 2 shows that the mixing line between depleted mantle and Meguma does not pass through the SMB array. The implication of this calculation is that if both depleted mantle and Meguma components are involved in the SMB, then there must be at least one more component or process, as yet unidentified. Indeed, there are many possible variations in the isotopic compositions of the hypothetical mantle component, and/or the evolutionary processes (e.g., AFC; DePaolo, 1981), to achieve a better fit to the SMB data.

It is now clear, from the strong decrease in  $\epsilon_{\text{Nd}}$  in the cotectic granitic rocks of the SMB, that involvement of Meguma country rocks, either as one contributing source material or as contaminant, has occurred. The presence of partially digested xenoliths, the presence of partial melting in some xenoliths, and possibly the increase of *A/CNK* with fractionation, all point to an open system where the country rocks are involved in the chemical evolution of the batholith. Superimposed on this variation, caused by two or more source components, are both crystal-liquid fractionation (McKenzie and Clarke, 1975), and the evolution of a sep-

arate vapour phase (Muecke and Clarke, 1981) as important causes of the remaining chemical variation in the batholith. These processes have recently been reviewed (Clarke and Muecke, 1985; Clarke and Chatterjee, 1988).

### 3.2. Source of the granodiorite magma

Despite uncertainties concerning the relative inputs to the SMB as a whole, there are several constraints on the source of the SMB granodioritic magma:

(1) As demonstrated above, the host Meguma metasedimentary rocks represent only one of the components in the granodiorite magma.

(2) The granodiorite has generally high  $\delta^{18}\text{O}$ -values (+10 to +12‰ SMOW; Longstaffe et al., 1980) and *A/CNK*, characteristics more readily acquired from low-grade metasedimentary rocks than from mantle-derived materials.

(3) The granodiorite is relatively uniform in composition. It may thus represent derivation from a homogeneous source, or if it is a hybrid, it represents a high degree of homogenization.

(4) High temperatures are required to create granodiorite magmas. If there were mantle material as input to the SMB, then a source of heat to melt the crustal component is not a problem. Mafic intrusions that could be genetically related to the SMB have not been found within the batholith, but do occur around its periphery. These are volumetrically minor dykes and plugs in southwestern Nova Scotia (de Albuquerque, 1977; Rogers, 1985; Douma, 1988), but there are more important gabbroic breccia pipes spatially associated with the nearby Liscomb Complex (Giles and Chatterjee, 1986). These may yet be shown to be extremely important in the magmatic evolution of the Meguma Zone, but at present the evidence is only embryonic. Alternatively, if the other component in the SMB is solely crustal in composition and energy, then the heat necessary to produce the granodioritic magma of the SMB would require considerable overthrusting, most likely during the Acadian deformation.

Given these constraints, we believe that the

SMB granodiorite was probably derived from a deeper crustal source that was largely metasedimentary, but which contained a greater proportion of material with either younger crustal residence ages, or higher Sm/Nd ratios (less fractionated REE patterns), than are found in the Meguma metasediments (see next section). This could happen in one of two different ways: (1) the metasediments of the Meguma Zone represent an inverted time sequence where the younger rocks of a former crustal segment (the African Shield?; Clarke and Halliday, 1985) were eroded first and buried beneath older materials eroded later from the same, or another, source similar to the cases discussed by Hamilton et al. (1983) and Allègre and Rousseau (1984), or (2) there is an unrecognized tectonic boundary in the Meguma Zone between the observed Meguma Group flyschoid metasediments, and unknown crust beneath. If the latter case, there may be a link between possible "thin-skin tectonics", proposed here and elsewhere in the Appalachians (Cook et al., 1979; Brown et al., 1983; Rast, 1984; Williams, 1984), and magma generation, where overriding by the Meguma Group may have been sufficient to cause the raising of isotherms and melting of the underlying crustal material. Whatever the nature of the crustal source material, the high  $\epsilon_{\text{Nd}}$ -values and relatively high  $^{87}\text{Sr}/^{86}\text{Sr}$  ratios rule out a significant contribution from ancient granulites (Farmer and DePaolo, 1983; Harmon et al., 1984; Hensel et al., 1985) such as Grenvillian basement (McCulloch and Wasserburg, 1978) that crops out elsewhere in the Appalachians but is not known to occur in the Meguma Zone. This deduction concerning the absence of granulites agrees with both seismic profiles (Dainty et al., 1966) and depositional models (Schenk, 1970, 1971) for the Meguma, neither of which have allowed for a lower-crustal granulite facies zone. With the present isotopic data, it is not possible to distinguish between the inverted and thin-skin crustal models for the stratigraphy of the Meguma Zone.

### 3.3. Model ages of granitoids, xenoliths and country rocks

Fig. 3 shows a conventional  $\epsilon_{\text{Nd}}-t$  plot for all analyzed rocks from the Meguma Zone. The Meguma metasedimentary rocks show a well-defined evolutionary history with  $\epsilon_{\text{Nd}}^t$  ( $t=372$  Ma) values from  $-11.2$  to  $-8.7$  and  $t_{\text{DM}}=1.74 \pm 0.1$  Ga. All the granodiorites are similarly constrained to  $\epsilon_{\text{Nd}}^t$  ( $t=372$  Ma) values from  $-2.9$  to  $-1.4$  and  $t_{\text{DM}}=1.26 \pm 0.06$  Ga. However, the enclaves show wide variations in their  $^{147}\text{Sm}/^{144}\text{Nd}$  ratios probably related to fractionation of Sm and Nd during partial melting, and this is reflected in a wide variation in  $t_{\text{DM}}$  from 1.47 to 1.76 Ga (Fig. 3), the latter value being similar to the mean Meguma host rocks.

The late monzogranites and monzogranite porphyries, i.e. those probably resulting from fractional crystallization and significant amounts of assimilation of Meguma country rocks, are the most variable of the rock types shown on Fig. 3. Their  $\epsilon_{\text{Nd}}$ -values are displaced toward those of the country rock, but their  $^{147}\text{Sm}/^{144}\text{Nd}$  ratios are very high (Table I). Muecke and Clarke (1981) showed that neither the decrease in  $\Sigma\text{REE}$ 's, nor the decrease in La/Yb ratios, in the monzogranites can be explained by known fractional crystallization processes or bulk contamination by the Meguma. They concluded that late-stage hydrothermal fluids were responsible for these changes, a process which could change Sm/Nd ( $^{147}\text{Sm}/^{144}\text{Nd}$ ), but not affect  $^{143}\text{Nd}/^{144}\text{Nd}$ . However, recent separations of monazite from some of the monzogranites (C. Harper, pers. commun., 1986) may yet show an increased importance for the role of fractional crystallization in the SMB.

### 3.4. I- and S-type granites and the restite model

It has been demonstrated here that there are at least two components in the SMB. One of

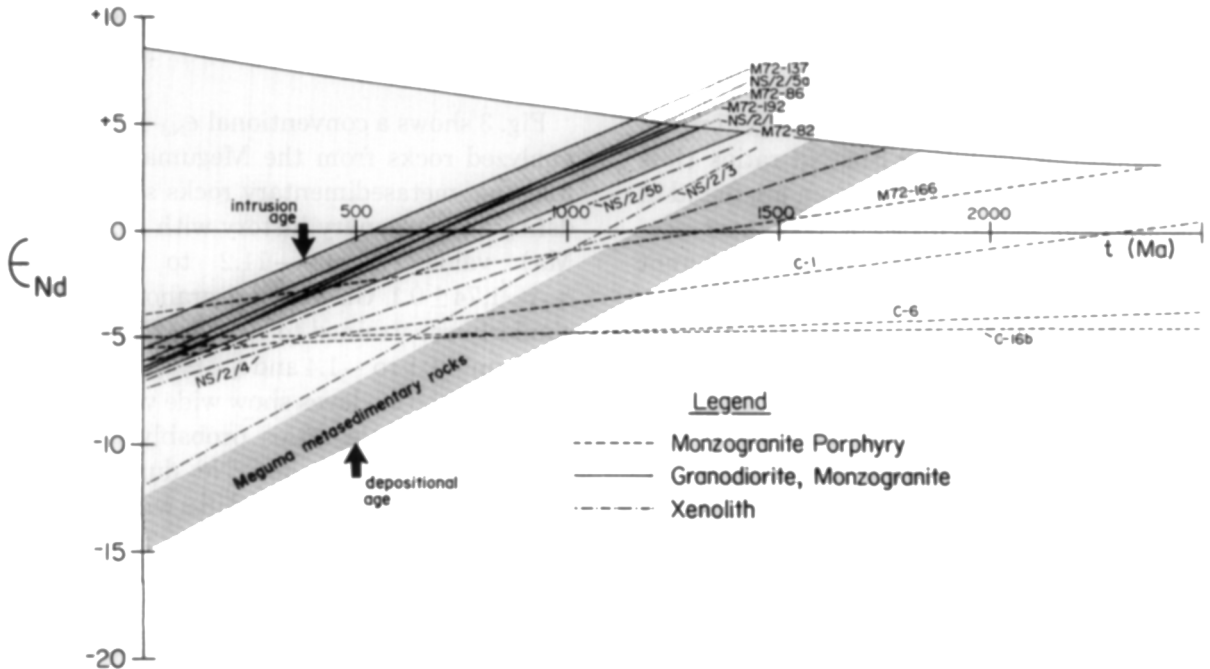


Fig. 3. A plot of  $\epsilon_{Nd}$ - $t$  showing all samples of granitoids, country rocks and xenoliths from the Meguma Zone. Depleted mantle curve is after Farmer and DePaolo (1983). All of the granodiorites define a restricted zone of variation with  $t_{DM} = 1.26 \pm 0.06$  Ga. The country rocks of the Meguma Group (Clarke and Halliday, 1985) have  $t_{DM} = 1.74 \pm 0.1$  Ga. Other granitoids in the batholith and one enclave behave erratically (see text for interpretation).

these components is the highly peraluminous ( $A/CNK = 1.29$ – $3.58$ ) metasediments of the Meguma Group; the other, if mantle-derived, might even have been metaluminous and, if so, the I-S genetic classification for such hybrid magmas is inappropriate. Secondly, because the partial isotopic equilibration of the xenoliths with their granitoid hosts has been clearly demonstrated, and supports the mineralogical, textural and chemical equilibration already described, their link with the country rocks is clear and restite separation in the SMB is not an identifiable process given our data. Clarke and Muecke (1985) have used many other lines of evidence to question the application of the restite model to the SMB, and Wall et al. (1987) have discussed the general problem of restite separation extensively.

#### 4. Conclusions

Many physical and chemical processes have operated to account for the observed geochemical variation in the South Mountain batholith (Clarke and Chatterjee, 1988). The most significant results of the present study are:

(1) The Nd isotopic data provide the first clear chemical evidence that involvement of country rock is responsible for some of the chemical diversity in the batholith. The general absence of metasedimentary enclaves from the later monzogranites and porphyries could be explained alternatively by the failure of the later monzogranite differentiates to come in contact with the metasedimentary rocks (unlikely, in view of their low  $\epsilon_{Nd}$ -values), by partial assimilation and complete gravity settling of the



xenoliths, or even by effectively complete assimilation of the foreign material.

(2) In addition to assimilation, other processes such as fractional crystallization are required to account for much of the major- and trace-element variation, including Rb and Sr, and late-stage fluid phases may explain the variation in REE's, including Sm and Nd, as well as Li and some of the economic elements such as Sn-W-Cu-Mo-U (Strong and Taylor, 1988). Each process undeniably has had an effect on every chemical constituent in the batholith, although it may not yet be quantified, and in some cases two different processes may strongly affect a single parameter, e.g.  $A/CNK$  will be very sensitive to both assimilation and the action of fluid phases, but its variation is severely limited during crystal-melt fractionation (Zen, 1986). So far, our geochemical tools are not sufficiently good to resolve the relative effects of such overlapping processes.

(3) At present, we believe that a deeper crustal source for the SMB best explains its bulk chemical and isotopic characteristics, although the implications are that this source has a younger residence age (inverted crustal residence stratigraphy), or higher Sm/Nd ratios (less fractionated REE patterns), than the metasedimentary rocks of the Meguma Group exposed at the surface. However, because of increasing evidence for a spatial association of some peraluminous granites with mafic intrusive rocks in the Meguma Zone, another possible origin for the SMB is the mixing of mantle melts and upper-crustal materials, the implications of which are that the mixing process is extremely thorough, and that the SMB contains large fractions of mantle-derived Nd and Sr.

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