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Origin and age of Adirondack anorthosites re-evaluated with Nd isotopes

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ABSTRACT

We report the Sm-Nd systematics in seven whole-rock anorthosites, in plagioclase and garnet mineral separates from one anorthosite, and in five mangerite-norite-charnockite rocks from the Snowy Mountain dome in the south-central Adirondacks. The plagioclase, two garnet separates, and the whole-rock anorthosite define a four-point internal isochron of age 1,098 ± 7 (2σ) m.y. The six whole-rock anorthosites and the anorthositic gabbro in conjunction with the above internal isochron define a similar age of 1,095 ± 7 (2σ) m.y. and an initial $^{143}Nd/^{144}Nd$ ratio of 0.51135 ± 1 (2σ). This age of 1,100 m.y. is considered to be the time of crystallization of the anorthositic rocks. The initial Nd isotope ratio of the combined whole-rock and mineral isochron indicates an ϵ_{Nd} value of +2.5, which suggests a light rare-earth-element–depleted source for the anorthositic parent magma in the upper mantle. The trace-element and isotopic data also support the view that gabbroic anorthosite is the parent magma for the anorthosites. Five whole-rock samples of norite-mangerite-charnockite, found in close association with the anorthosites, do not define a precise isochron. The initial ϵ_{Nd} values of these rocks at 1,100 m.y. show a range from +2.7 to +5.1, which demonstrates that the anorthositic rocks and the mangerite-charnockite are not cogenetic. The isotopic data further demonstrate that the mangerite-charnockite rocks are mantle-derived meta-igneous rocks, and not of sedimentary derivation.

INTRODUCTION

The origin of Adirondack-type anorthosite and associated norite-charnockite has been one of the most debated problems in petrology (e.g., de Waard, 1969; Carmichael et al., 1974). However, there is a remarkable unity of the anorthosite problem in that the massif-type anorthosites in the Adirondacks and throughout the world are characterized by the following unique features (Buddington, 1969): (1) The anorthosite massifs occur as concordant intrusive plutons varying in size from small bodies to batholithic proportions in high-grade metamorphic terranes. (2) They are monomineralic rocks consisting of plagioclase of composition An_{35} to An_{65}; hypersthene and augite make up < 10% of the composition in anorthosite; plagioclase composition is relatively constant through facies that vary from anorthosite through gabbroic anorthosite to gabbro. (3) The anorthosite bodies are usually surrounded by gabbroic border facies. (4) In the field, complete transition from anorthosite through noritic or gabbroic anorthosite, norite, and mangerite (monzonite) to charnockite (hypersthene granite) may commonly be found. (5) Most massif-type anorthosites range in age between 1,100 m.y. and 1,400 m.y. and lie in two principal belts when plotted on a predrift continental reconstruction (Herz, 1969).

A satisfactory explanation of the above set of unique phenomena is, however, yet to be found in any single or multiple hypotheses. Isachsen (1969) has summarized the major hypotheses regarding the origin of anorthosite and related rocks. One group of workers, led by Buddington (1969), believe that the anorthosite suite formed from a gabbroic anorthosite magma or high-alumina basalt magma (Emslie, 1969) and that the mangerite-charnockite rocks are not comagmatic with the anorthosites. A second group of workers suggests that the associated mangerite-charnockite suite is related to the anorthosites by crystallization differentiation of a common magma (e.g., Philpotts, 1966). Other important questions in anorthosite petrogenesis involve the precise ages of crystallization and the nature of the source of the parent magma.

Here we have attempted to answer some of these questions by a study of the Sm-Nd systematics in anorthosites and associated rocks from the Snowy Mountain area in the south-central Adirondacks, New York. This study was undertaken for several reasons: (1) to determine the age of crystallization of Adirondack anorthosites by the whole-rock and internal-isochron method, (2) to determine whether different lithologic members of the anorthosite series and the associated mangerite-charnockite series are comagmatic, (3) to characterize the nature and the source of the parent magma(s), and (4) to determine if crustal contamination of the invading parent magma was significant.

ADIRONDACK ANORTHOSITES AND ASSOCIATED ROCKS

The Adirondacks have been a classic area for the study of massif-type anorthosites because of the pioneering investigations by Bowen (1917), Balk (1930), and, in particular, Buddington (1939). The Adirondack area in New York State is an outlier of the Grenville subprovince of the Canadian shield; the Grenville subprovince, about 375 km wide and 1,500 km long, consists predominantly of high-grade metamorphic rocks and meta-igneous plutonic complexes. The anorthosite massifs in the Adirondacks are considered to be sheet-like, 2 to 3 km thick, with multidomical upper surfaces, and to have invaded the highly metamorphosed sedimentary rocks of the region. The different anorthosite bodies in the Adirondacks usually show finer grained marginal facies more mafic than the core, and locally the anorthosite shows a composition sequence of anorthosite, gabbroic or noritic anorthosite, and gabbro. The latter sequence of rocks belongs to the anorthositic series of Buddington (1969). Further, the rocks of the anorthositic series are in many places bordered by quartz-poor

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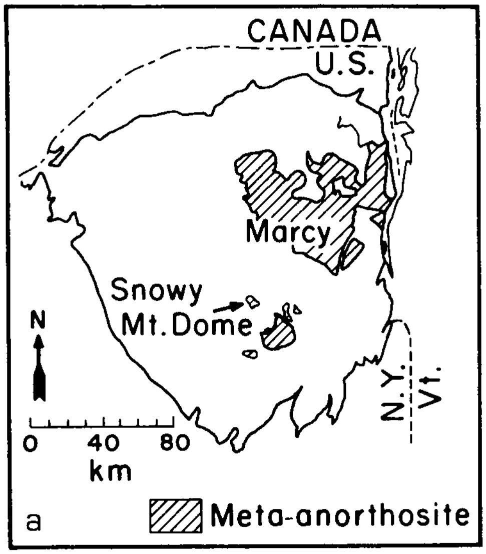

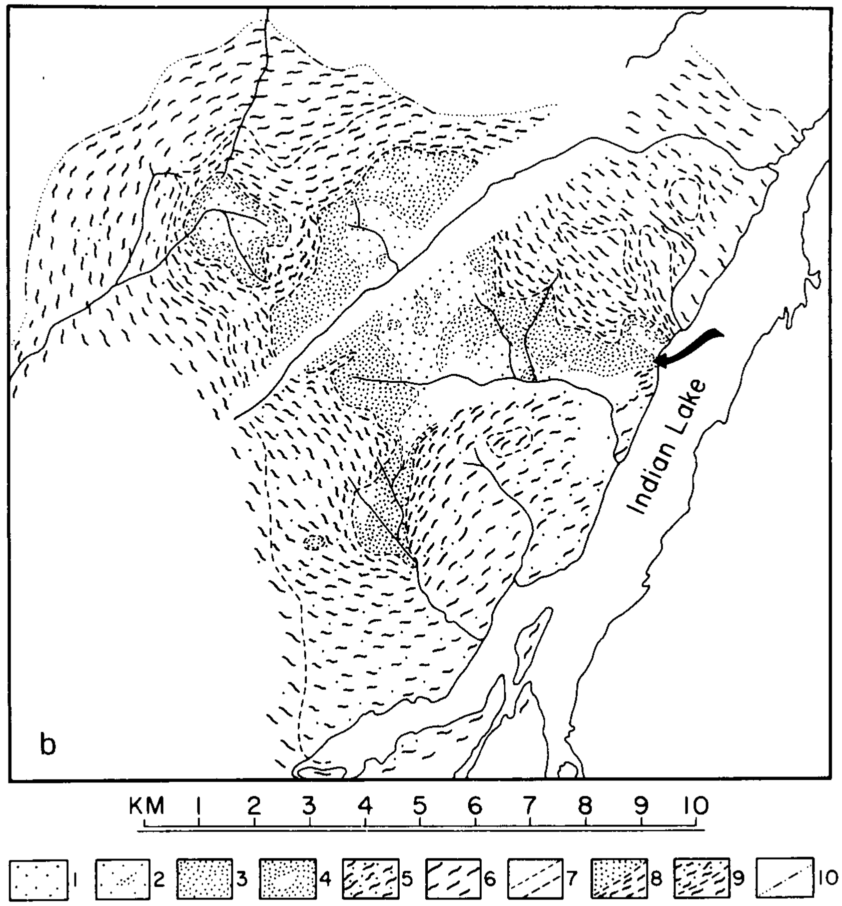

Figure 1. a: Index map of distribution of anorthosite massifs in Adirondack Mountains, New York, showing location of Snowy Mountain dome, after Reynolds et al. (1969). b: Geologic map of Snowy Mountain dome, after de Waard and Romey (1969). 1 = anorthosite; 2 = anorthosite with noritic pockets; 3 = norite-mangerite; 4 = same as 3 with gradational anorthositic blocks; 5 = foliated norite-mangerite with plagioclase augen; 6 = foliated norite-charnockite; 7 = gradational rock boundaries; 8 = limit of foliation; 9 = limit of feldspar augen; 10 = limit of anorthosite-charnockite complex. Arrow indicates location of samples in this study.

syenite gneiss, which, as orthopyroxene-bearing, is called mangerite-charnockite (e.g., de Waard, 1969). The above intimate association of rocks that constitute an anorthosite massif in the Adirondacks and elsewhere was described earlier by Goldschmidt (1916) as an anorthosite-charnockite suite. Buddington (1969), however, separated the anorthositic series of rocks, considered to have intruded early, from the younger mangerite-charnockite series that locally crosscut and intrude the anorthosites.

FIELD RELATIONS IN SNOWY MOUNTAIN OF SOUTH-CENTRAL ADIRONDACKS

Figure 1 shows the location of the Snowy Mountain dome and field relations among the various members of the anorthositic series and the mangerite-charnockite suite of rocks as mapped by de Waard and Romey (1969). The Snowy Mountain massif is similar in lithologic sequence to the main Adirondack pluton, known as the Marcy massif, to the north. Anorthosite forms the core of the Snowy Mountain dome and is surrounded by a shell of hypersthene-bearing rocks grading upward and outward from norite through mangerite to charnockite. The gradation observed between different rock types was considered to be primary by de Waard and Romey (1969), who provided the following detailed descriptions of these gradations in the Snowy Mountain area (Fig. 1).

The contacts between the leucocratic, coarse-grained anorthosite and the mesocratic norite are usually well defined and can be traced in the field. The anorthosite is viewed as a rock consisting of andesine megacrysts and interstitial norite. Near the contact between the anorthosite core and the marginal norite, the amount of interstitial noritic component may increase to the extent that the resulting rock is transitional in nature. Thus, names such as gabbroic (noritic) anorthosite or anorthositic gabbro (norite) may be used to describe these rocks. Outside the boundary zone between the anorthositic core and the noritic shell, however, these transitional rocks are rare.

The actual field relationships among the norite-mangerite and charnockite are poorly displayed in the Snowy Mountain dome because of increasing deformation outward in the shell of rocks that surrounds the anorthosite massif. However, xenoliths of anorthosite and norite have been observed in mangeritic rocks.

Sm-Nd SYSTEMATICS IN ANORTHOSITE AND ASSOCIATED ROCKS OF SNOWY MOUNTAIN

We selected the Snowy Mountain area for this study because this area has been very well mapped by de Waard and Romey (1969) and because within a short distance most of the lithologic members of the anorthositic and the mangerite-charnockite series can be found. We collected samples guided by the field map in Figure 1. The samples range in rock type from anorthosite through gabbroic anorthosite, anorthositic gabbro, mangerite-norite, and mangerite charnockite and were collected within a distance of 0.5 km along the west bank of the Indian lake (arrow in Fig. 1).

Sm and Nd concentrations and the isotopic composition of Nd for twelve whole-rock samples and three mineral separates are given in Table 1. The analytical methods were similar to those of Nakamura et al. (1976). Large, fresh samples were crushed into homogeneous powders. About 100-mg portions of these powdered samples were decomposed for the mass spectrometric analysis. The $^{143}Nd/^{144}Nd$ ratios were normalized to a $^{146}Nd/^{144}Nd$ ratio of

0.7219. Measured blanks were of the order of 85 and 250 picograms (pg) for Sm and Nd, respectively. Errors in the estimation of Sm and Nd contents are 0.1% or less, and those for the $^{143}Nd/^{144}Nd$ ratios reported in Table 1 are 2σ of the mean and correspond to the last figure.

In general, the Sm and Nd contents of the anorthositic and associated rocks reported in Table 1 are typical of other similar rocks reported from North America and Europe (Seifert et al., 1977; Simmons and Hanson, 1978; Ashwal and Seifert, 1980; Fountain et al., 1981; and others). The plagioclase mineral separates (sample 3-1 in Table 1) and the whole-rock leucocratic anorthosite (sample 1-10) show the lowest concentrations of Sm and Nd. The Sm and Nd contents increase in the anorthosite rocks with increasing contents of the ferromagnesian minerals—the highest concentration being found in the anorthositic gabbro (sample 2-7). The Sm, Nd concentration data in Table 1 also imply, as in previous studies cited above, that the anorthositic rocks have fractionated light rare-earth-element enrichment with respect to the chondritic abundances.

Sample 3-1 is a leucocratic anorthosite with sparsely developed small grains of garnet at triple-junction grain margins of andesine crystals and with rare augen-like porphyroclasts of garnet. We analyzed the small garnet grains (garnet a), an augen of garnet (b), plagioclase mineral separates, and a mechanical mixture of plagioclase and garnet to represent the bulk-rock composition of rock 3-1. The Sm-Nd analyses of these four samples define an internal mineral isochron of age 1,098 ± 7 m.y., with an initial $^{143}Nd/^{144}Nd$ ratio of 0.51131 ± 1.

Because anorthosite does not show much variation in Rb/Sr or Sm/Nd ratios, its time of crystallization is extremely difficult to ascertain by conventional radiometric methods. The Sm-Nd data of the seven whole-rock anorthositic rocks (Table 1) do not show sufficient scatter for a meaningful isochron age. These whole-rock data, in conjunction with the internal mineral isochron data of rock 3-1, as discussed above, define an excellent isochron of age 1,095 ± 7 m.y., with an initial $^{143}Nd/^{144}Nd$ ratio of 0.51135 ± 1. This isochron is shown in Figure 2. Although this isochron, in essence, dates the time of crystallization of the garnets, we con-

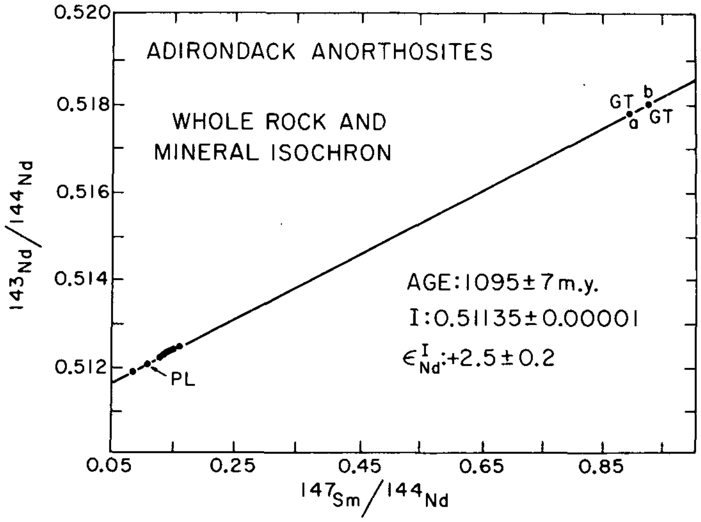

Figure 2. Sm-Nd isochron diagram for anorthositic rocks and mineral separates. PL = plagioclase separate, Gt-a represents small garnet grains, and Gt-b a garnet augen. Other dots represent whole-rock analyses of anorthositic rocks.

TABLE 1. SM-ND SYSTEMATICS IN ANORTHOSITES, GABBROIC ANORTHOSITES, AND ASSOCIATED NORITE-MANGERITE-CHARNOCKITES FROM SOUTH-CENTRAL ADIRONDACKS, NEW YORK

Anorthosites and gabbroic anorthosites		Sm (ppm)	Nd	$^{147}Sm/^{144}Nd$	$^{143}Nd/^{144}Nd$
1-10	Anorthosite (whole rock)	0.301	2.203	0.08267	0.51194 ±0.00002
1-3C	Gabbroic anorthosite (whole rock)	7.399	33.727	0.13254	0.51229 ±0.00003
1-3A	Gabbroic anorthosite	8.977	39.737	0.13652	0.51234 ±0.00003
1-3D	Gabbroic anorthosite (whole rock)	7.564	32.410	0.14105	0.51238 ±0.00004
1-3B	Anorthositic gabbro (whole rock)	23.429	96.834	0.14621	0.51242 ±0.00003
2-7	Gabbroic anorthosite (whole rock)	10.474	39.980	0.15830	0.51252 ±0.00002
3-1	Anorthosite (whole rock)	2.338	10.690	0.13217	0.51227 ±0.00002
	Plagioclase (mineral separates)	1.578	8.787	0.10853	0.51201 ±0.00003
	Garnet (A) (mineral separates)	12.101	8.189	0.89296	0.51775 ±0.00003
	Garnet (B) (augen separate)	10.985	7.177	0.92469	0.51795 ±0.00003
Norite-mangerite-charnockite					
1-9	Mangerite-norite (whole rock)	7.134	35.727	0.12061	0.51225 ±0.00003
1-3E	Mangerite-norite (whole rock)	8.669	38.942	0.13456	0.51245 ±0.00002
1-1	Mangerite-norite (whole rock)	11.574	56.748	0.12324	0.51225 ±0.00004
1-5	Mangerite-charnockite (whole rock)	13.854	63.937	0.13069	0.51239 ±0.00003
1-8	Mangerite-charnockite (whole rock)	14.039	69.225	0.12254	0.51228 ±0.00002

TABLE 2. INITIAL ϵ_{Nd} AT 1100 M.Y. OF NORITE-MANGERITE-CHARNOCKITES FROM THE SNOWY MOUNTAIN DOME, SOUTH-CENTRAL ADIRONDACKS

Sample No.	Rock type	ϵ_{Nd} at 1100 m.y. ago
1-1	Mangerite-norite	+2.7
1-3E	Mangerite-norite	+5.1
1-5	Mangerite-charnockite	+4.5
1-8	Mangerite-charnockite	+3.5
1-9	Mangerite-norite	+3.1

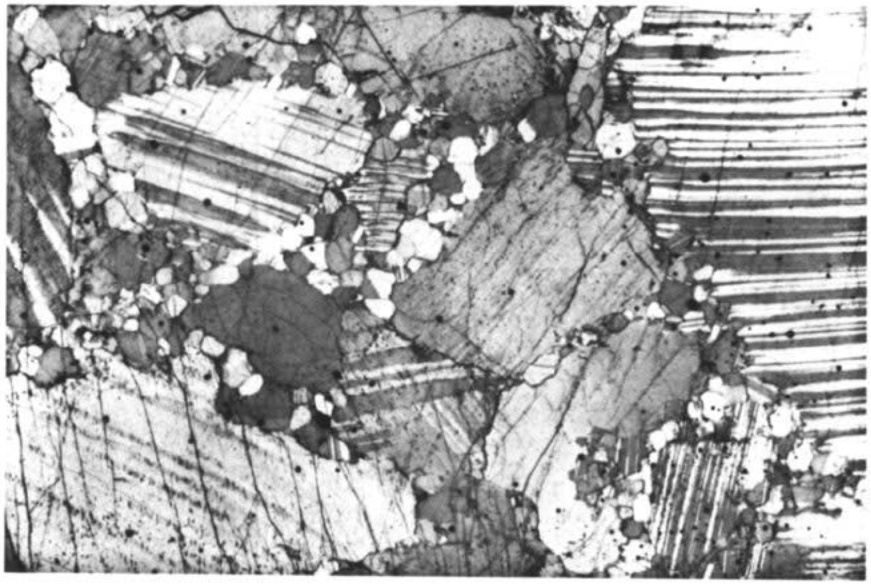

Figure 3. Photomicrograph of anorthosite sample 3-1 showing typical porphyroclastic texture; small garnet grains (Gt-a in Fig. 2) were recovered from finer grained matrix. Crossed nicols, 5 mm × 3 mm.

sider, in the next section, this age of 1,100 m.y. to be also the time of crystallization of the anorthosite massif at the Snowy Mountain dome. A Sm-Nd whole-rock isochron age of 1,190 ± 130 m.y. has also been reported (Ashwal et al., 1980) from the Marcy massif of the Adirondacks. This 1,200-m.y. age is, however, about 100 m.y. older than zircon ages of the adjacent charnockite, reported by Silver (1969).

Sm and Nd data on five norite-mangerite-charnockite samples, collected close to the anorthositic rocks discussed above, are also shown in Table 1. These rocks show, in general, higher total abundances of Sm and Nd than the anorthositic rocks, but with Sm/Nd ratios very similar to those of the anorthosites. These concentration data also indicate that the norite-mangerite-charnockite rocks have highly fractionated, light rare-earth-element enrichment with respect to the chondrites, and that within this series more silicic charnockites have much greater rare-earth-element abundances. It is significant, as discussed below, that the Sm-Nd data for norite-mangerite-charnockite rocks do not yield a precise isochron, although some of the analyses cluster very close to the whole-rock and mineral isochron for the anorthositic rocks in Figure 2. A consideration of the initial $^{143}Nd/^{144}Nd$ ratios for each of these five rocks at the above inferred age of 1,100 m.y. show a range in ϵ_{Nd} values from +2.7 to +5.1 (Table 2). This range of ϵ_{Nd} values is significantly different from the ϵ_{Nd} value of +2.5 ± 0.2 obtained from the isochron of the anorthositic rocks in Figure 2. These findings compare closely with those of Pettingill (1983) and Pettingill and Sinha (1982) in the Blue Ridge of Virginia, where the Roseland anorthosite massif and the associated charnockites yielded positive ϵ_{Nd} values at 1,050 m.y. B.P.

AGE AND ORIGIN OF ADIRONDACK ANORTHOSITES AND ASSOCIATED ROCKS

Figure 3 shows a photomicrograph of the texture of one of the anorthosites analyzed in this study (sample 3-1 in Table 1). This texture, common in massif-type anorthosites, shows large porphyroclasts of plagioclase in a finer grained equigranular, recrystallized groundmass of plagioclase also. Although it has traditionally been interpreted as an igneous texture or "crystal mush" (Buddington, 1931), and later as an autoclastic texture (Williams et al., 1982), we interpret this texture as resulting from dynamic recrystallization during plastic deformation. The garnets we analyzed are associated with the recrystallized groundmass and may have nucleated during the recrystallization of this groundmass. We interpret these garnets as synkinematic with respect to the plastic deformation of the anorthosites. Experimental studies (e.g., Green and Ringwood, 1967) on garnet-forming reactions in mafic compositions indicate positive *dP-dT* slopes, with garnet being stable on the high-pressure side. Therefore, an intrusion at depth followed by cooling at essentially constant pressure could conceivably have produced the garnet in the Adirondack anorthosites (Whitney and McLelland, 1973). The internal mineral isochron age of 1,098 m.y. obtained from the Sm-Nd data of sample 3-1 in Table 1, according to our interpretation, gives the time of formation of the garnets and of the crystallization-deformation of the anorthosite. It is remarkable that the Sm-Nd data of the seven anorthositic whole rocks also define a linear array, identical to that of the mineral isochron. Thus, we accept ~ 1,100 m.y. B.P. as the time of crystallization of the Snowy Mountain massif.

If this age of 1,100 m.y. is the primary crystallization age of the anorthosites, then several important conclusions can be drawn from our isotopic data. First, the fact that all members of the anorthositic series, from anorthositic gabbro to gabbroic anorthosite and anorthosite, show an isochronous relationship in the Sm-Nd system indicates their comagmatic origin. Second, the isotopic and the trace-element data demonstrate the credibility of Buddington's (1939) original hypothesis that the parental magma of the anorthositic series is of gabbroic anorthosite composition similar to the rocks of the border facies and that anorthosite forms by crystal accumulation of plagioclase. Third, the initial ϵ_{Nd} value of +2.5 of the isochron for the anorthositic rocks suggests their derivation from a time-integrated, light rare-earth-element–depleted source in the mantle. Fourth, the differences in the initial ϵ_{Nd} values between the anorthositic and the mangerite-charnockite series also support Buddington's (1939) opinion that these two suites of rocks are not consanguineous. Fifth, the positive initial ϵ_{Nd} values of the mangerite-charnockites at 1,100 m.y. B.P. also indicate their derivation from upper-mantle reservoirs.

An extensive uranium-lead isotopic study in zircons from the Adirondack anorthosite-charnockite rocks by Silver (1969) led him to the conclusion that these two suites of rocks have identical ages of 1,130 ± 10 m.y. In particular, zircon characteristics in charnockites suggested this to be the age of magmatic crystallization. The decay constants of ^{238}U and ^{235}U used by Silver have been revised, and if Silver's data are recalculated using the new decay constants, the times of crystallization of the Adirondack charnockite and anorthosite become identical to the date of 1,100 m.y. B.P. obtained in this study.

Thus, it appears that the anorthositic rocks and the charnockitic rocks in the Adirondacks are coeval and yet unrelated to each other by any scheme of magmatic differentiation. A mechanism is, therefore, necessary to explain the spatial association of anorthosite and mangerite-charnockite without requiring them to be comagmatic. Hargraves (1962) suggested that the acidic rocks were produced by contact anatexis of quartzofeldspathic country rocks due to the intrusion of the anorthosite. Several recent workers (Emslie, 1978; Fountain et al., 1981; Ashwal, 1982; Morse, 1982) have also supported such a proposition. Our isotopic data are consistent with such an origin but provide a constraint to this model in that the supracrustal material being melted by the intrusion of the anorthosite must have been derived from a mantle source also. They are thus meta-igneous, and not of sedimentary derivation.

CONCLUSIONS

A combined whole-rock and mineral isochron age of 1,095 m.y. obtained from seven anorthosites is considered the primary age of crystallization for the Snowy Mountain anorthositic body. The gabbroic or noritic anorthosites constituting the marginal facies are cogenetic with the anorthosites and are considered to be the parent material from which the anorthosite crystallized. This parent material was derived from a depleted mantle source. The emplacement of the anorthositic rocks is considered coeval with the generation of the marginal envelopes of the mangerite-charnockite series of rocks. Both suites are mantle-derived, but they are not consanguineous. The trace-element and Nd-isotope data are consistent with a model of genesis of anorthositic and charnockitic series rock by the intrusion of the anorthositic magma from a mantle source into the lower crust. This intrusion produced partial anatectic melting of the surrounding lower crust. The products of this anatectic melting were the mangerite-charnockite suite of rocks that enveloped the anorthositic massifs.

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