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Local equilibrium of mafic enclaves and granitoids of the Turtle pluton, southeast California: Mineral, chemical, and isotopic evidence

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ABSTRACT

Major element and trace element compositions of whole rocks, mineral compositions, and Rb-Sr isotopic compositions of enclave and host granitoid pairs from the Early Cretaceous, calc-alkaline Turtle pluton of southeastern California suggest that the local environment profoundly affects some enclave types. In the Turtle pluton, where the source of fine-grained, mafic enclaves can be deduced to be magmatic by the presence of partially disaggregated basaltic dikes, mineral chemistry suggests partial or complete local equilibrium among mineral species in the enclave and its host granitoid. Because of local Rb-Sr isotopic equilibration between fine-grained enclaves and host granitoid, one cannot use Sr isotopes to distinguish an enclave source independent of its host rocks from an enclave source related to the enclosing pluton. However, preliminary Nd isotopic data suggest an independent, mantle source for enclaves.

INTRODUCTION

Fine- to very coarse-grained mafic rocks commonly occur in calc-alkaline plutons as enclaves (inclusions) and dikes (Didier, 1973, 1987; Reid et al., 1983; Vernon, 1983; Cantagrel et al., 1984; Frost and Mahood, 1987; Kumar, 1988). Although mafic enclaves vary in composition, mineral content, and texture, fine-grained enclaves in metaluminous to weakly peraluminous rocks share numerous features (see references above). There are several models to explain the source of enclaves and the relationship of enclaves to the surrounding pluton. Models of chemical evolution from diorite to granite invoke fractional crystallization or removal of restitic or source material (Bateman et al., 1963; White and Chappell, 1977; Bateman and Chappell, 1979; Chen et al., 1989). Other models propose mixing and mingling of mantle-derived mafic magma and crust-derived granitic magma to generate the range of granitoid and enclave compositions (for example, Barbarin, 1988; Stewart et al., 1988). Field observation of partially disaggregated, synplutonic, basaltic dikes supports the mixing-mingling model (for example, Reid et al., 1983; Barnes et al., 1986; Frost and Mahood, 1987; Kumar, 1988). Lastly, some mafic enclaves are thought to be xenoliths of older plutonic rocks (Jurinski and Sinha, 1989).

The ability to decipher whether mafic enclaves in a given pluton are representative of (1) early crystallizing liquids, or (2) magmas that have contributed to the evolution of a pluton on a gross scale through mixing, or (3) unrelated, accidental magmas and xenoliths that have not affected granitoid compositions (except locally) is contingent on the degree of physical and chemical interaction between enclaves and host granitoid magmas, i.e., the lack of local equilibration of enclaves with surrounding granitoid.The preservation of synplutonic mafic dikes in plutons and their textural similarity to fine-grained enclaves suggest an igneous origin for these enclaves; however, enclaves commonly display a very similar mineralogy and crystallization sequence to those of their granitic host (Vernon, 1983). This suggests equilibration of the mafic enclaves and host granitoid. Equilibration is thought to be a complex process. Exchange can be accomplished by magma mixing, or by chemical exchange through diffusion or reaction or both. Exchange can be between magma and crystals, between fluid and crystals, or between crystals (Eberz and Nicholls, 1990). In this study, the degree of chemical interaction among enclave types and their host pluton, and the amount of source information retained by enclaves, is examined using data from the mesozonal, 130-m.y. Turtle pluton of southeastern California (Fig. 1 and Table 1; Allen, 1989). This study utilizes field relations, whole rock geochemistry, Rb-Sr and Nd-Sm isotopes, and mineral compositions.

FIELD OBSERVATIONS

The Turtle pluton is a reversely zoned intrusion, meaning it has a granitic to granodioritic rim and more mafic, granodioritic core (Fig. 1; Allen, 1989). It can be divided into four facies. The rim sequence is an arcuate unit that grades inward from biotite granite to hornblende-biotite granodiorite. The schlieren zone is a zone of high strain tens of meters wide along the contact of the rim sequence and core facies. The core facies is a relatively homogeneous unit of biotite-hornblende granodiorite and quartz monzodiorite. The fourth facies is exposed in the Four Deuce Hills and forms the eastern lobe of the Turtle plu-

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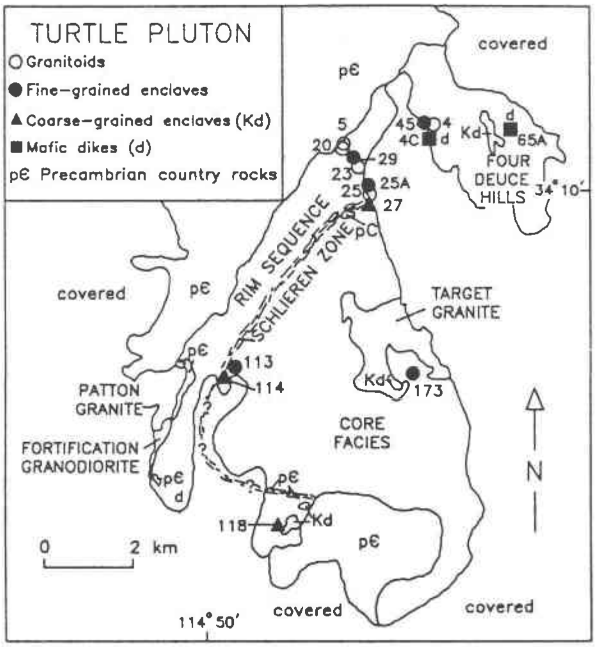


Fig. 1. Simplified geologic and sample location map.

ton. It consists of granite and granodiorite with mineral content and composition like the other facies, but this facies has an unknown intrusive relationship with the rest of the pluton. The Turtle pluton is intruded by two significantly younger intrusions—the Fortification granodiorite and Target granite, and the pluton intrudes the Patton granite of unknown age (Allen, 1989).

Three types of enclaves occur within the Turtle pluton: xenoliths, fine-grained microgranitoid enclaves, and coarse-grained dioritic to gabbroic enclaves. Xenoliths are angular blocks of quartzofeldspathic gneiss, like the surrounding Precambrian country rock. These xenoliths are found only within tens of meters of the contact of the pluton with the country rock and within the schlieren zone. This type of enclave has sharp contacts and shows no evidence of assimilation; it is not considered in further discussion. Fine-grained microgranitoid enclaves are found in all units, either singly or in swarms (Fig. 2a), and this enclave type composes 4–5% by area of the pluton based on measurements of enclave numbers and sizes (Waugh, 1985; Allen, 1989). They are characterized by average grain size less than 3 mm, by greatest observed dimension less than 2 m, and by discoidal shape although digitate shapes are present (Fig. 2a). Contacts are generally sharp. These enclaves are basaltic to andesitic in composition and are common in all outcrops. Coarse-grained enclaves principally occur in a few regions within the pluton as ovoid to angular blocks (see Fig. 1) but are present in all facies. This enclave type probably composes a similar proportion of the pluton as the fine-grained variety, but its distribution is much different, as noted above. Coarse-grained enclaves are characterized by average grain size greater than 5 mm and by smallest dimension greater

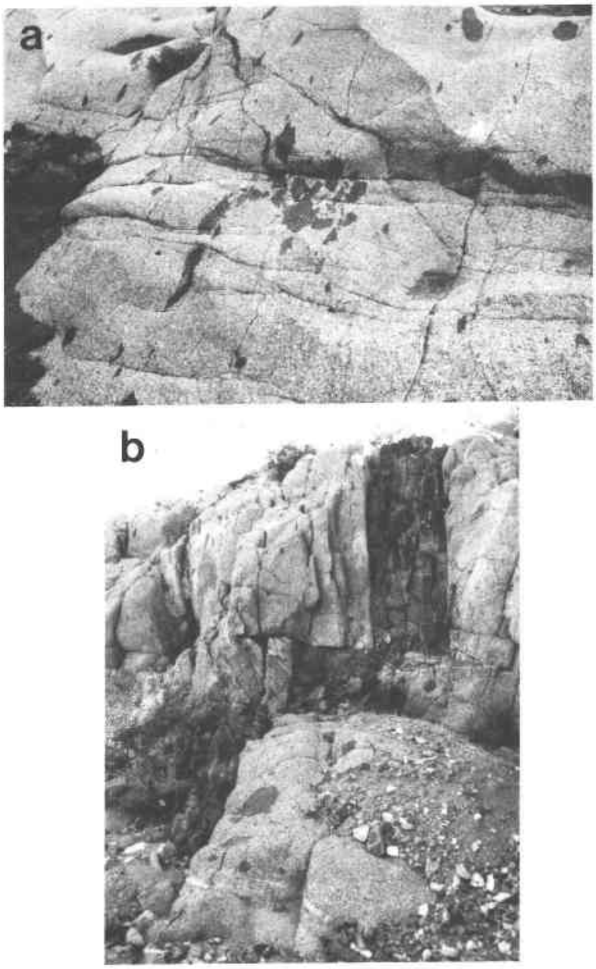


Fig. 2. Field photographs of (**a**) typical fine-grained enclave swarm in granodiorite (outcrop 3 m across), and (**b**) synplutonic mafic dike (sample CA85-4C) intruded by aplites and offset on low angle normal faults. Hammer handle is 48 cm long.

TABLE 1. Sample descriptions

Sample No.	Rock type
CA85-5	Bt granite
BW84-20	Bt granite
BW84-20A	Bt granite and fine-grained enclave
CA85-4	Hbl-Bt granodiorite
CA84-45	fine-grained enclave in CA84-4
BW84-23	Hbl-Bt granodiorite
BW84-29	fine-grained enclave in BW84-23
BW84-25	Bt-Hbl granodiorite
BW84-25A	fine-grained enclave in BW84-25
BW84-27	coarse-grained enclave in BW84-25
CA84-113	fine-grained enclave in Bt-Hbl granodiorite
CA84-173	fine-grained enclave in Bt-Hbl Qtz monzodiorite
CA84-114	coarse-grained enclave in Bt-Hbl granodiorite
CA85-118	coarse-grained enclave in Bt-Hbl granodiorite

Note: Adjacent samples marked by brackets. Bt = biotite. Hbl = hornblende.

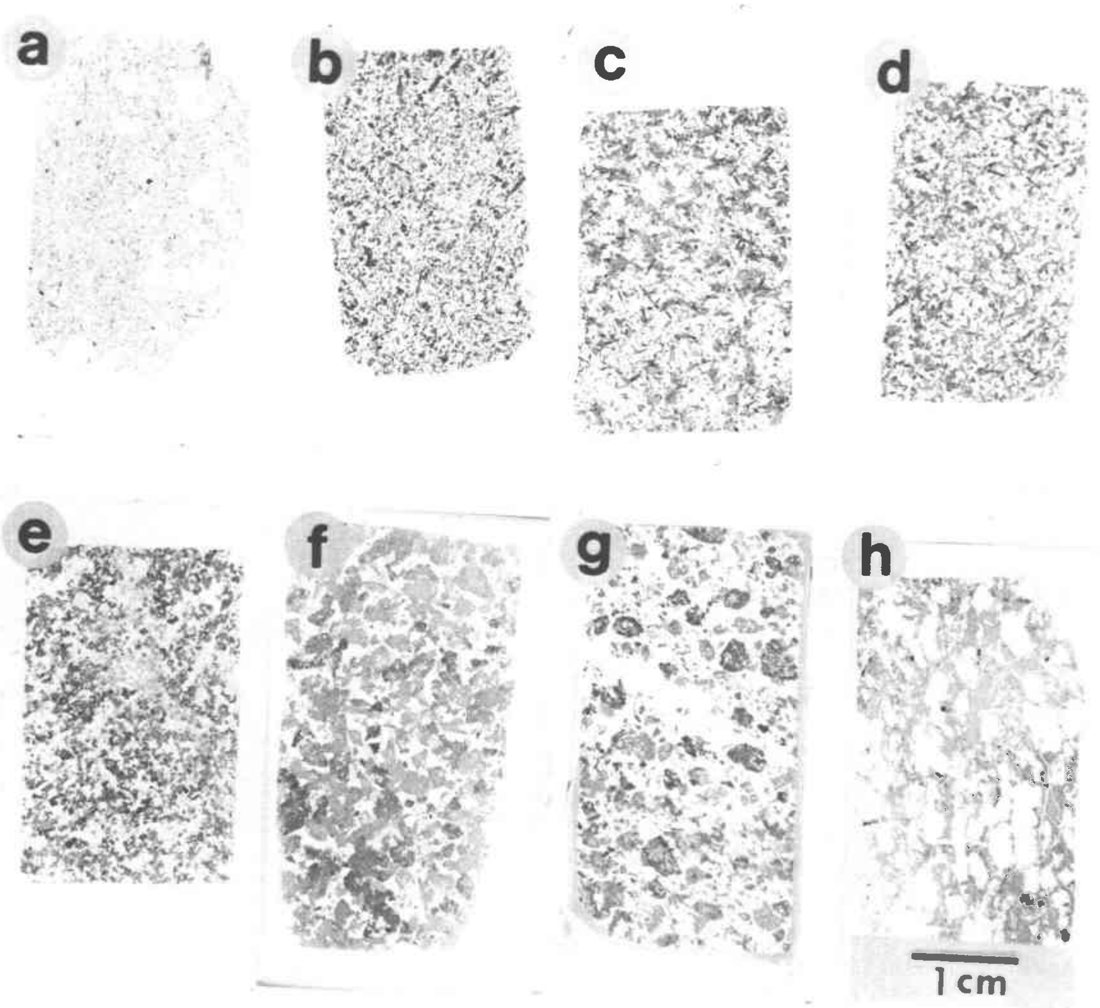


Fig. 3. Photograph of thin sections showing the textural variety of mafic rocks: (**a**) hornblende-free, fine-grained enclave in granite near wall rock contact; (**b**) and (**c**) fine-grained enclaves in granodiorite; (**d**) synplutonic mafic dike, CA84-65A; (**e**)–(**h**) coarse-grained enclaves, BW84-27, CA84-114, CA85-118, and example of cumulus texture, respectively.

than 2 m. Rock type and texture vary from coarse-grained hornblende ± clinopyroxene diorites and gabbros to hornblendites with crystal size in the centimeter range.

Aside from aplitic and pegmatitic dikes that intrude all facies of the pluton, one other kind of synplutonic dike was recognized by mutually cross-cutting relationships with host granitoids. These dikes are basaltic, and they range in thickness from a few centimeters to 2 m (Fig. 2b). Some have finer-grained margins. These dikes only occur in the periphery of the pluton (Fig. 1) and, in most cases, they are texturally and mineralogically very similar to some fine-grained enclaves (Figs. 3b–3d). A genetic relationship of dikes to fine-grained enclaves is probable given the textural similarity and field evidence for dike disaggregation (Fig. 4). Thus a model of enclave formation from disaggregation of basaltic dikes is favored for the fine-grained enclaves of the Turtle pluton (though a specific source like sampled dikes for all enclaves is not intended). Field evidence, such as crosscutting relationships and intermediate textural types, that could aid in understanding the relationship of coarse-grained enclaves to either the fine-grained enclaves or the granitoids of the Turtle pluton was not observed.

Fine-grained enclaves

The mineralogy of the fine-grained enclaves reflects that of their host granitoids. These enclaves contain the mineral assemblage plagioclase (Pl) + quartz (Qtz) + potassium feldspar (Kfs) + biotite (Bt) + apatite (Ap) ± hornblende (Hbl) ± magnetite (Mag) ± ilmenite (Ilm) ± titanite (Ttn) ± zircon (Zrn). Enclaves in ilmenite-biotite granite lack hornblende, magnetite, and titanite, whereas those in magnetite-titanite-biotite-hornblende granodiorite contain the same assemblage as the host granodiorite

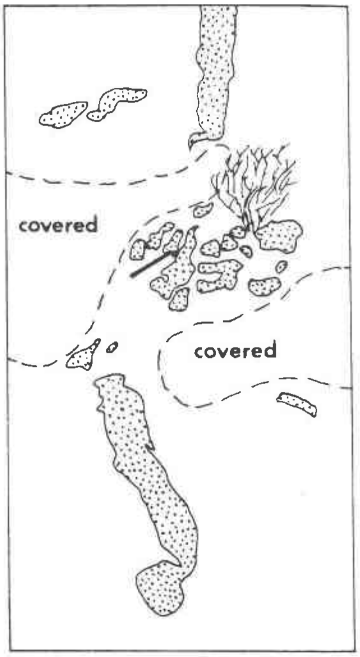


Fig. 4. Line drawing of foreshortened photograph of disaggregated mafic dike and enclaves (both stippled) in granodiorite. Bar in center = 15 cm.

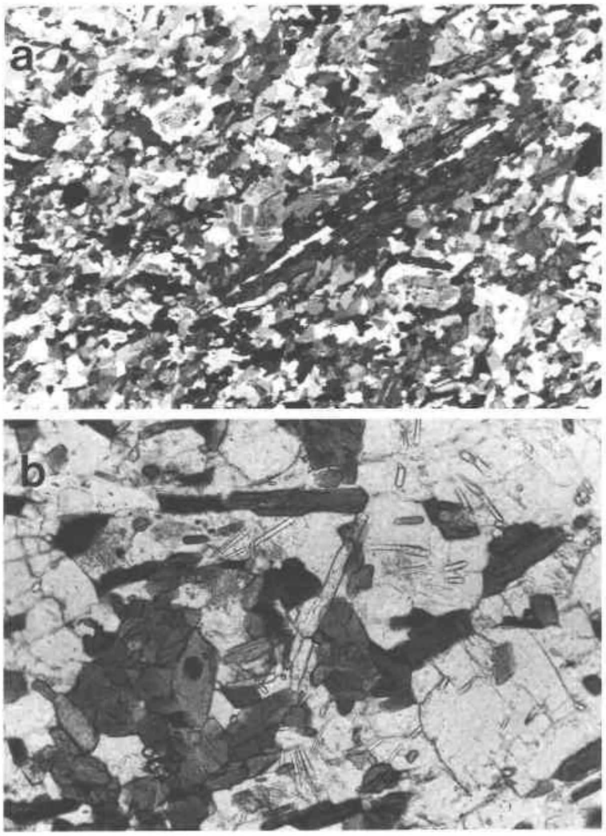


Fig. 5. Photomicrographs showing typical textures of fine-grained enclaves, particularly (**a**) hypidiomorphic-granular texture with acicular hornblende (photo 5 mm across), and (**b**) common acicular apatite, which is segmented in many cases (photo 1.8 mm across).

(Table 2). The color index of these enclaves is generally 35 to 55 (Table 2, Figs. 3a–3d) and textures are hypidiomorphic-granular (Fig. 5a). Because this texture is common in granitoid rocks, Vernon (1983) applied the term micrograntoid to mafic enclaves. Enclaves commonly contain phenocrysts (xenocrysts?) of plagioclase, quartz, or hornblende (Fig. 5a). Crystallization sequences based on petrographic observation of grains other than phenocrysts are presented in Figure 6. Plagioclase occurs as subhedral to euhedral crystals which have oscillatory zonation and an overall normal chemical trend. Some plagioclase shares mutual 120° junctions, suggesting textural equilibrium. Quartz is subhedral to anhedral and has undulose extinction and subgrain development. Potassium feldspar is interstitial. Biotite is brown pleochroic and occurs as subhedral flakes dispersed throughout the rock and as ragged flakes in hornblende. Hornblende is acicular and green pleochroic and commonly contains optically continuous inclusions of biotite that suggest a biotite-consuming reaction. Opaque minerals (primarily magnetite) have a blocky morphology, and titanite is subhedral and commonly contains opaque minerals. Euhedral zircon is present in some specimens. Apatite is an ubiquitous accessory mineral and is acicular (length : width up to 100:1), commonly segmented, and typically contains fluid inclusions (Fig. 5b). Some grains with Y-terminations were observed. Acicular apatite is recognized as a common feature of micrograntoid enclaves (Didier, 1973; Vernon, 1983; Reid et al., 1983), and its morphology and inclusion in all other major minerals suggest it crystallized early as a result of thermal (Wyllie et al., 1962) or compositional undercooling (Lofgren, 1974). Secondary minerals [chlorite (Chl) + epidote (Ep) + sericite ± calcite (Cal)] generally compose less than 5% of this rock type.

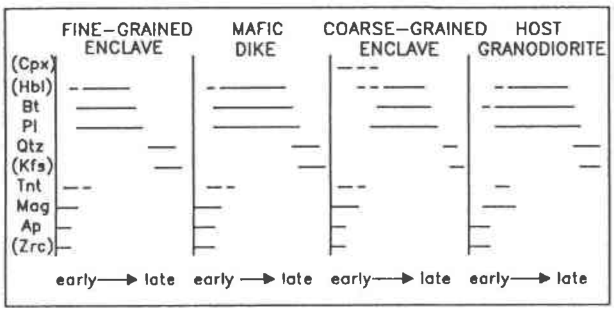


Fig. 6. Crystallization sequences for mafic rocks and granitoids. Minerals given in parentheses may be present or absent in a given sample.

TABLE 2. Modal analyses

Sample	Type	Pl	Kfs	Qtz	Bt	Hbl	Cpx	Ttn	Opq	Ap	Aln	Seric	Ep	Chl	Cal
BW84-20	granite	43.5	23.1	29.1	3.5	0	0	0	0.4	0	0	0.3	0	0.1	0
84-45	fg encl	39.8	0.4	3.8	11.0	41.1	0	0.1	0.2	0	0	2.8	0.4	0.4	0
CA85-4	gdiorite	46.4	18.2	24.3	7.1	2.8	0	0.4	0.2	0.1	0	0.3	0	0.1	0
85-4C	m dike	21.4	0	2.2	4.2	44.6	0	1.8	0.2	0.8	0	18.4	0.2	5.6	0.6
BW84-29	fg encl	39.8	0.6	10.7	11.1	26.1	0	1.2	0.3	0	0	10.0	0	0.1	0
BW84-23	gdiorite	54.5	9.9	21.1	9.8	3.7	0	0.3	0.3	0	0.2	0.1	0.1	0	0
BW84-25A	fg encl	46.2	0.5	1.1	11.3	34.8	0	1.1	0	0	0	3.1	0.3	1.6	0
BW84-25	gdiorite	57.6	7.1	17.7	8.8	6.9	0	0.5	1.0	0	0.1	0.1	0.1	0.1	0
84-27	cg encl	29.6	0.6	6.2	0.2	51.2	3.0	1.6	0.2	0	0	7.0	0	0.4	0
84-113	fg encl	55.8	0.3	0.4	19.0	20.9	0	0.9	1.1	0.0	0	0.9	0.6	0	0.1
84-173	fg encl	44.6	0.7	3.8	11.0	29.0	0	0.9	0.6	0.2	0	6.5	2.8	0	0
84-118	cg encl	31.8	0.0	10.4	1.2	41.4	0	1.2	0	0.0	0	12.6	0.4	1.0	0
84-114	cg encl	26.1	0.9	8.9	8.8	49.5	0	0	0	0.2	0	5.1	0.5	0	0
84-65A	m dike	30.1	0	4.8	0.3	37.5	0	0.7	0.3	0.1	0	18.9	3.3	4.1	0

Note: Pl = plagioclase, Kfs = potassium feldspar, Qtz = quartz, Bt = biotite, Hbl = hornblende, Cpx = clinopyroxene, Ttn = titanite, Opq = opaque minerals, Ap = apatite, Aln = allanite, Seric = sericite, Ep = epidote, Chl = chlorite, Cal = calcite.

COARSE-GRAINED ENCLAVES

Coarse-grained enclaves range in composition from hornblende diorite and gabbro to hornblendite, and they contain the assemblage Pl + Qtz + Kfs + Hbl + Bt + Mag + Ttn + Ap ± Clinopyroxene (Cpx). This assemblage is independent of the mineral content of the surrounding granitoid (Table 2). The color index varies from approximately 43 to 55. Hornblendite was not analyzed chemically and is not considered in further discussion. Coarse-grained enclaves contain tabular, normally zoned plagioclase. Potassium feldspar is interstitial to all other minerals. Quartz, a conspicuous modal mineral in these enclaves, displays undulous extinction and subgrain development and appears to be in textural equilibrium with surrounding minerals. Hornblende is prismatic and green

TABLE 3. Whole rock geochemistry

Sample Rock type	Error (%)	BW84-20 granite	CA84-45 fg encl	CA85-4 gdiorite	CA85-4C m dike	BW84-29 fg encl	BW84-23 gdiorite
SiO_2	1	73.32	50.83	68.18	52.09	53.35	66.90
TiO_2	1	0.20	0.98	0.36	1.52	1.21	0.45
Al_2O_3	1	14.55	16.20	15.41	15.47	18.31	16.31
FeO	1	1.49	10.33	2.62	9.17	7.51	3.43
MnO	3	0.08	0.48	0.09	0.15	0.32	0.10
MgO	3	0.46	6.85	1.25	7.05	5.00	1.77
CaO	1	1.87	7.33	3.35	9.50	7.52	4.12
Na_2O	3	3.92	2.10	3.73	2.34	2.74	3.16
K_2O	1	3.47	2.00	3.72	1.55	1.90	2.82
P_2O_5	<1	0.09	0.29	0.15	0.36	0.30	0.19
LOI	<5	0.30	1.54	0.63	0.96	0.76	0.84
SUM		99.75	98.93	99.49	100.16	98.92	100.09
Ba (ppm)	3	1100	139	985	—	190	688
Rb (ppm)	1.5	102	108	112	54	91	90
Sr (ppm)	1.5	276	284	357	473	346	439
			C.I.P.W. norms				
AN		20.76	61.90	31.00	57.81	58.03	41.79
Q		31.63	0.00	21.92	0.00	2.49	24.18
Or		20.51	11.82	21.98	9.16	11.23	16.67
Ab		33.17	17.77	31.56	19.80	23.19	26.74
An		8.69	28.87	14.32	27.13	32.05	19.20
C		1.16	0.00	0.00	0.00	0.00	1.02
Di		0.00	4.64	1.11	14.51	2.73	0.00
Hy		3.70	28.28	6.94	24.48	23.49	10.15
Ol		0.00	3.48	0.00	0.40	0.00	0.00
Il		0.38	1.86	0.68	2.89	2.30	0.85
Ap		0.21	0.67	0.35	0.83	0.70	0.44
			Isotopic data				
$^{87}Rb/^{86}Sr$	1	1.08	1.10	0.90	0.31	0.76	0.60
$^{87}Sr/^{86}Sr$	0.015	0.71021	0.70894	0.70816	0.70548	0.70833	0.70823
SRI		0.7082	0.7069	0.7065	0.7049	0.7069	0.7071
$^{147}Sm/^{144}Nd$	0.20	0.1124	—	—	—	0.1321	0.1202
$^{143}Nd/^{144}Nd$	0.002	0.512259	—	—	—	0.512478	0.512375
ϵ Nd		−7.39	—	—	—	−3.12	−5.13
$^{143}Nd/^{144}Nd(t)$		0.51216	—	—	—	0.51237	0.51227
ϵ Nd(t)		−6.00	—	—	—	−2.05	−3.86

Note: Major elements in wt%.

pleochroic. One gabbro was observed to contain clinopyroxene in reaction relationship with rimming hornblende (BW84-27); no clinopyroxene was observed in Turtle pluton granitoids. Brown pleochroic biotite commonly occurs adjacent to or within hornblende. Accessory phases are titanite, subhedral to anhedral opaque minerals, and acicular and prismatic apatite. Secondary minerals (Chl + Ep + sericite) generally compose much less than 10% of most of the samples. The fundamental differences between fine- and coarse-grained enclaves are the sizes of individual enclaves, grain size, and the presence of clinopyroxene in coarse-grained enclaves.

Mafic dikes

Mafic dikes have color indices greater than 40 and contain Pl + Qtz ± Kfs + Hbl + Bt + Mag + Ttn + Ap regardless of the mineral content of surrounding granite or granodiorite (Table 2). In many cases, these rocks are lithologically indistinguishable from fine-grained microgranitoid enclaves that lack phenocrysts (see Figs. 3b and 3d) except for the lower abundance of biotite and the greater abundance of secondary phases, Ep + Chl + Cal + sericite (approximately 20–25%, principally sericite after plagioclase), in the dikes. The petrographic similarity of dikes to fine-grained enclaves includes rare examples of biotite mantled by hornblende.

Whole rock geochemistry

Whole rock, major element, Rb, Sr, Ba, Rb-Sr isotopic and Nd-Sm isotopic analyses of fine-grained enclaves, coarse-grained enclaves, host granite, and granodiorite are given in Table 3. The average dimension of fine-grained enclaves sampled for whole rock chemistry averaged about 40 × 40 × 20 cm. The outer 1–2 cm region of the enclave was not analyzed. Coarse-grained enclaves (>4 m in minimum dimension) and dikes (about 1–2 m in thickness) were sampled from core regions. Host granite and granodiorite were sampled 10–50 m from analyzed enclaves, and were free from recognizable enclaves. Major and trace element analyses were performed by XRF using wavelength dispersive techniques modified from Norrish and Chappell (1977). Rb-Sr isotopic ratios were determined on a modified 35 cm radius, 90° degree sector, Avco spectrometer at Virginia Polytechnic Institute and State University (VPI and SU). Samples were loaded on single Re filaments with H_3PO_4. All isotopic data are normalized to the Eimer and Amend $SrCO_3$ standard value of 0.70800 from an average value of 0.70813($n = 23$, standard error

Table 3—*Continued*

BW84-25A fg encl	BW84-25 gdiorite	BW84-27 cg encl	CA84-113 fg encl	CA84-173 fg encl	CA85-118 cg encl	CA84-114 cg encl	CA84-65A m dike
52.02	64.96	52.59	51.27	50.32	54.79	54.75	51.40
1.10	0.53	1.17	0.98	1.16	1.26	0.58	1.27
18.60	16.56	15.35	18.70	18.19	15.03	12.20	17.26
8.52	4.41	8.69	9.20	10.21	7.93	9.01	9.93
0.25	0.10	0.19	0.20	0.28	0.16	0.30	0.26
6.71	1.95	7.62	4.84	4.51	6.61	9.96	5.52
8.90	5.22	10.64	8.41	9.44	10.01	9.17	9.14
2.02	2.85	1.87	2.61	3.33	1.90	1.32	2.44
1.86	2.19	0.87	1.61	1.21	2.01	1.85	1.71
0.45	0.23	0.20	0.44	0.41	0.26	0.26	0.40
1.13	0.51	1.14	0.85	0.48	1.17	1.38	1.30
101.56	99.51	100.33	99.11	99.54	101.13	100.78	100.63
296	784	163	186	—	—	—	495
58	53	21	66	28	46	64	55
503	547	376	524	507	412	234	613
			C.I.P.W. norms				
67.92	50.29	66.15	61.01	52.48	62.28	66.23	60.10
0.00	23.18	2.68	0.00	0.00	4.28	3.61	0.00
10.99	12.94	5.14	9.51	7.15	11.88	10.93	10.11
17.09	24.12	15.82	22.09	28.18	16.08	11.17	20.65
36.19	24.39	30.92	34.56	31.11	26.55	21.90	31.09
0.00	0.56	0.00	0.00	0.00	0.00	0.00	0.00
4.13	0.00	16.85	3.58	10.95	17.57	17.87	9.69
28.68	12.27	25.08	24.88	5.24	20.61	32.23	21.39
0.21	0.00	0.00	0.77	13.27	0.00	0.00	3.07
2.09	1.01	2.22	1.86	2.20	2.39	1.10	2.41
1.04	0.53	0.46	1.02	0.95	0.60	0.60	0.93
			Isotopic data				
0.33	0.28	0.16	0.36	0.16	0.32	0.79	0.26
0.70772	0.70698	0.70630	0.70737	0.70672	0.70555	0.70702	0.70600
0.7071	0.7065	0.7060	0.7067	0.7064	0.7050	0.7056	0.7055
0.1283	0.1205	0.1484	—	0.1428	—	—	0.1329
0.512512	0.512440	0.512605	—	0.512518	—	—	0.512489
−2.46	−3.86	−0.64	—	−2.34	—	—	−2.91
0.51240	0.51234	0.51248	—	0.51240	—	—	0.51238
−1.33	−2.60	0.16	—	−1.45	—	—	−1.85

of mean = 0.00001). Total blanks for Rb and Sr were less than 0.2 ng. Nd-Sm isotopic ratios and elemental concentrations were determined on a Finnigan-Matt 262 at the U.S. Geological Survey, Menlo Park, California and no bias corrections are necessary. Isotopic analyses were determined on samples loaded with HNO_3 and H_3PO_4 onto Re in a double Re filament configuration and obtained in a dynamic switching mode (143, 144, 145-144, 145, 146). Multiple analyses of BCR-1 yield $^{143}Nd/^{144}Nd = 0.512633 \pm 10$ (95% confidence level). $^{143}Nd/^{144}Nd$ was normalized to $^{146}Nd/^{144}Nd$. Present day chondritic values used are $^{143}Nd/^{144}Nd = 0.512635$ and $^{147}Sm/^{144}Nd = 0.1967$. A mixed $^{149}Sm/^{150}Nd$ spike was used and mass ratios were obtained in a static mode. Total blanks for Nd and Sm are less than 0.1 ng. Analytical errors are listed in Table 3.

The Turtle pluton grades in composition across the rim sequence and schlieren zone, and into the core facies. The ranges of composition for this reversely zoned granitic (rim) to granodioritic (core) pluton are 73.32–61.68 wt% SiO_2, 102–56 ppm Rb, 275–600 ppm Sr, $^{87}Sr/^{86}Sr$ at 130 Ma (hitherto SRI) of 0.7083 to 0.7065, and $\epsilon_{Nd}(t)$ (where $t = 130$ Ma) of -6.00 to -2.60 (Table 3, Figs. 7 and 8). There is a strong linear correlation among time-corrected isotopic ratios (Fig. 8) and of isotopic ratios and most major element abundances of these granitoids. These data have been modeled as magma mixing and concomitant fractional crystallization (Allen, 1989, and in preparation). The facies exposed in the Four Deuce Hills does not fall on trend with other facies on Rb-Sr isotopic plot, but similarity of SRI of the rocks of the Four Deuce Hills and the core facies suggests the former is likely to be a fractionate of the latter (Fig. 8a).

The chemical contribution of mafic enclaves and dikes to granitoids of the Turtle pluton will be evaluated with reference to linear arrays (bulk mixing lines) on isotopic plots.

Fine-grained enclaves are olivine normative, medium- to high-K_2O basalt (SiO_2 = 50.32–52.02 wt%) with the exception of one high K_2O andesite (53.35 wt%; terminology from Gill, 1981). Coarse-grained enclaves are quartz normative, medium- to high-K_2O basalt to andesite that contain more SiO_2 (52.59–54.79 wt%) than the fine-grained variety. Mafic dikes are high-K_2O, olivine normative basalt (SiO_2 = 51.40–52.09 wt%). Based on major and trace element data and SRI, the three mafic rock types fall into three chemical groupings. Fine-grained enclaves and mafic dikes overlap in major and trace element composition, but dikes have significantly lower SRI ratios and higher TiO_2 than enclaves (Fig. 8a and Table 3).

In view of the field relationships that suggest fine-grained enclaves result from dike disaggregation (Fig. 4), the fact that the enclaves have the more radiogenic SRI points to interaction with host granitoids. This interaction is supported by the correlations of SRI and by the K_2O and Rb contents of enclaves and nearby host granitoids (Table 3, Fig. 8a). In particular, the similarity of Rb contents of enclave and host is striking (<10% difference; Fig. 7). On the other hand, nonoverlapping $\epsilon_{Nd}(t)$ (Fig. 8b) suggest discrete origins of enclaves and granitoids of the Turtle pluton. The complications caused by pluton-enclave interaction in assessing whether enclaves are restite, magmas that contributed to evolution of the pluton, or accidental magmas is discussed below.

Coarse-grained enclaves contain more SiO_2, CaO, and MgO, and less Al_2O_3, than the other mafic rock types; they have SRI less than that of fine-grained enclaves and granitoids, but SRI similar to those of the dikes. The chemical dissimilarity of the two enclave types suggests distinct histories. These mafic rocks have very different Rb concentrations than those of host granitoids, unlike those of the fine-grained enclaves. The low SRI (<0.7060) and high $\epsilon_{Nd}(t)$ (+0.16) of the coarse-grained type and lack of overlap with Turtle pluton granitoid isotopic values indicate (1) less crustal interaction in formation of this type than in the formation of fine-grained enclaves and (2) perhaps little or no interaction with the surrounding pluton. No model of assimilation and fractional crystallization relating fine-grained enclaves, granitoids, and coarse-grained enclaves can be derived from the available geochemical data.

The following generalizations can be made about mafic rocks and adjacent host rocks (field groupings given in Table 1 and Figs. 7 and 8). Of the fine-grained enclaves, the ones in the more evolved host granitoids contain more K_2O and Rb, less Sr, and variable concentrations of other major elements and Ba (Table 3). The SRI and Rb contents of most of these fine-grained enclaves are similar to those of their hosts (Table 3), and in one case the SRI of the enclave is significantly greater (BW84-25A). Data for one coarse-grained enclave and its host granodiorite, and one mafic dike and its host, indicate that these mafic rock types have a much lower SRI than their hosts. The $\epsilon_{Nd}(t)$ for both mafic enclave types and a mafic dike are all greater than the range observed for granitoids.

Mineral chemistry

Biotite, hornblende, plagioclase, and apatite from mafic rocks and host granitoids were analyzed with an au-

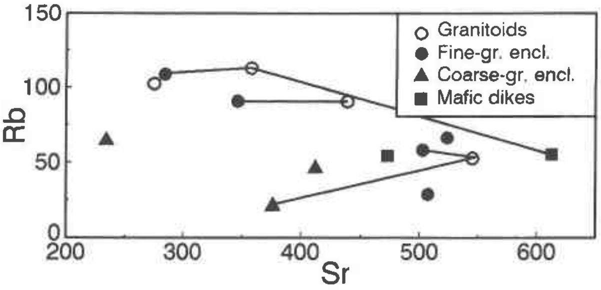


Fig. 7. Plot of Rb vs. Sr in ppm. Lines connect paired mafic rock-host granitoid samples.

TABLE 4. Kakanui hornblende standard analyses

	Mean	Standard deviation		Mean	Standard deviation	%2STD/ mean	Wet chemistry
SiO_2	40.84	0.66	Si	5.972	0.050	1.68	5.900
Al_2O_3	14.20	0.30	Al^{tet}	2.447	0.050	4.09	2.570
TiO_2	4.83	0.15	Ti	0.532	0.019	6.96	0.520
FeO	10.51	0.14	Fe	1.286	0.020	3.17	1.340
MnO	0.10	0.03	Mn	0.012	0.003	52.17	0.010
MgO	13.05	0.24	Mg	2.846	0.057	3.99	2.780
CaO	10.11	0.18	Ca	1.583	0.025	3.16	1.610
Na_2O	2.50	0.20	Na	0.709	0.056	15.88	0.800
K_2O	2.06	0.05	K	0.385	0.011	5.49	0.380
F	0.19	0.05	F	0.085	0.022	51.56	
H_2O*	1.96	0.02	OH	1.915	0.022		
−O = F	0.13		O	24.000			
SUM	100.23	0.85	Fe no.	0.311	0.006		

Note: $n = 40$.
* Calculated, assuming F + OH = 2, molecular.

tomated, nine-spectrometer, ARAL-SEMQ electron microprobe at VPI and SU using silicates and oxides as standards in an analytical scheme called QALL (Solberg and Speer, 1982). Analytical errors are based on multiple analyses of a Kakanui hornblende standard, one not used in calibration (Table 4). Representative and average analyses of minerals appear in Tables 5 through 8.

Biotite

Biotite is the only ferromagnesian silicate that occurs in all facies of the Turtle pluton and in all mafic rocks. As can be seen from representative plots of biotite compositions (Table 5 and Fig. 9), biotite from granite and fine-grained enclaves that contain ilmenite (outer portion of the pluton) are distinct in composition from biotite in magnetite-bearing samples, but in all cases, compositions of biotite from fine-grained enclaves overlap the compositions of biotite from their host granitoid. A mafic dike (CA84-65A) contains biotite with a composition similar to those of fine-grained enclaves but with Fe/(Fe + Mg) at the high end and F at the low end of the ranges observed for the enclaves. In contrast, data from one coarse-grained enclave are different with Fe/(Fe + Mg) of 0.377–0.381 (not shown).

These data suggest biotite in fine-grained enclaves attained equilibrium with the surrounding granitoid. Because enclaves contain a significant proportion of biotite (10–20 modal %), equilibration of biotite can profoundly affect the whole rock composition, especially those elements strongly partitioned into biotite, namely K, Rb, Cs, Ba, Sc, and LREE.

Amphibole

Amphibole from mafic enclaves and dikes and hosts is calcic magnesio-hornblende, with the exception of some amphibole samples from a mafic dike (CA84-65A) that are edenite (Na + K > 0.50; classification scheme of Hawthorne, 1981; Table 6; Fig. 10). No consistent optical or chemical zonation of amphibole is apparent except for five analyses of amphibole immediately adjacent to biotite inclusions in an enclave (BW84-29). These amphi-

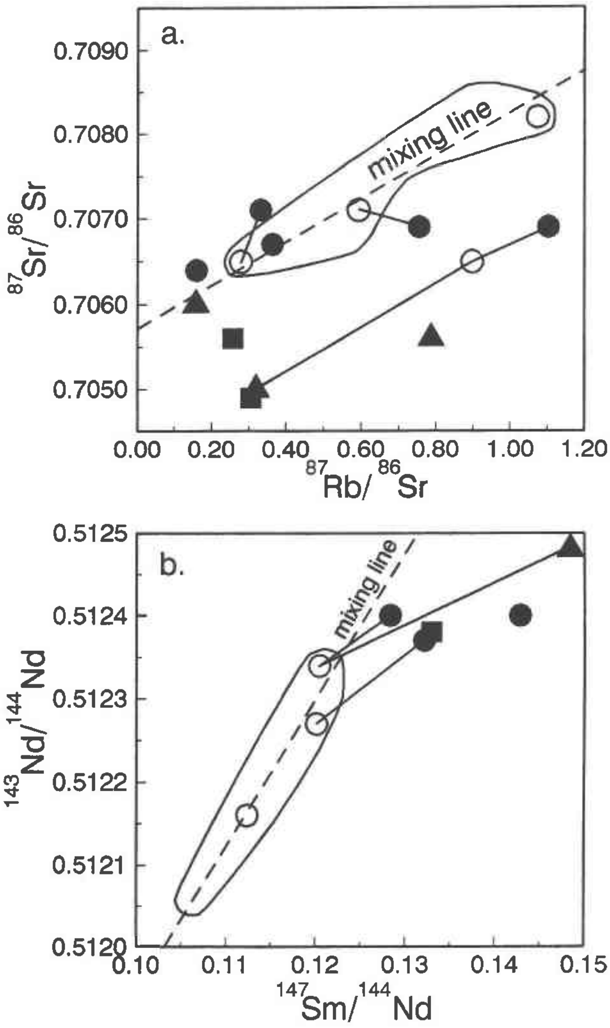
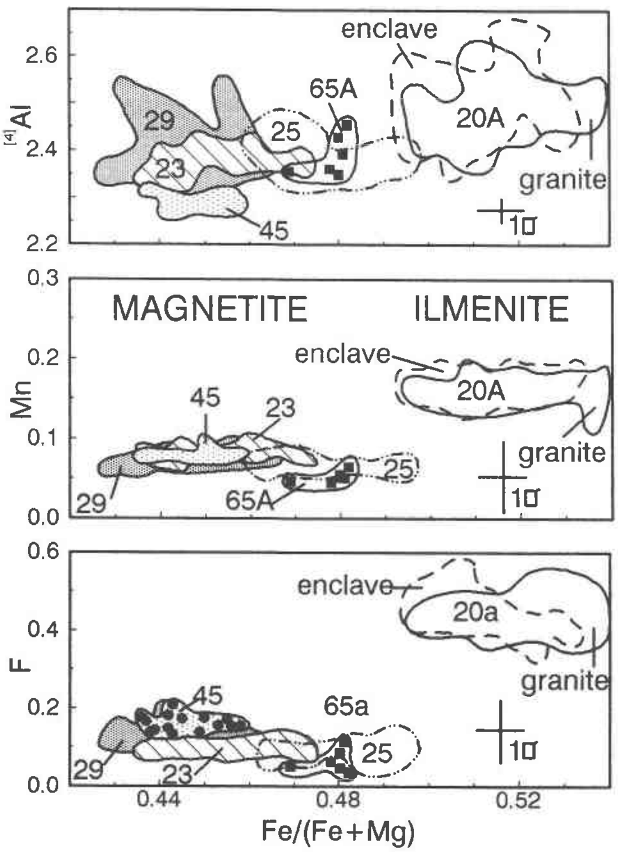


Fig. 8. Time-corrected isotopic plots of Rb-Sr and Nd-Sm systems. Symbols as in Figure 7. Mixing lines are linear regressions of available data for Turtle pluton granitoids (fields) except for anomalous granitoids from the Four Deuce Hills (CA85-4). Most enclave data do not lie along mixing lines. See text for discussion.

TABLE 5. Biotite compositions

	BW84-20A Bt granite		BW84-20A f.g. enclave		BW84-23 granodiorite		BW84-25 granodiorite	
	Avg $n = 40$	Std	Avg $n = 77$	Std	Avg $n = 22$	Std	Avg $n = 25$	Std
			Compositions in wt%					
SiO_2	36.22	0.82	35.94	0.70	37.33	0.45	37.05	0.46
Al_2O_3	16.05	0.68	16.27	0.56	15.53	0.50	15.31	0.31
TiO_2	2.66	0.49	2.69	0.39	3.22	0.46	2.91	0.47
FeO	19.20	0.60	18.29	0.53	17.39	0.79	18.77	0.42
MnO	1.24	0.10	1.26	0.10	0.63	0.06	0.53	0.05
MgO	9.42	0.48	9.84	0.37	11.94	0.43	11.61	0.43
CaO	0.04	0.02	0.02	0.01	0.02	0.05	0.06	0.06
Na_2O	0.06	0.08	0.21	0.09	0.08	0.02	0.13	0.05
K_2O	9.63	0.36	9.34	0.35	9.37	0.70	9.20	0.34
F	0.89	0.08	0.92	0.09	0.20	0.03	0.22	0.16
H_2O	3.50	0.10	3.82	0.08	3.87	0.06	3.82	0.09
$-O = F$	0.46		1.05		0.11		0.07	
Total	98.45	1.00	97.55	1.24	99.50	1.97	99.54	0.87
			Cations per 24 O atoms					
Si	5.471	0.192	5.510	0.067	5.627	0.040	5.616	0.049
$^{[4]}Al$	2.529	0.192	2.490	0.067	2.373	0.040	2.384	0.049
$^{[6]}Al$	0.498	0.265	0.449	0.087	0.385	0.082	0.349	0.064
Ti	0.347	0.103	0.310	0.044	0.364	0.049	0.331	0.052
Fe	2.306	0.167	2.346	0.061	2.191	0.083	2.380	0.056
Mn	0.162	0.022	0.164	0.013	0.080	0.008	0.067	0.007
Mg	2.179	0.190	2.249	0.078	2.683	0.131	2.624	0.105
Ca	0.011	0.044	0.003	0.002	0.003	0.008	0.010	0.010
Na	0.062	0.047	0.062	0.027	0.024	0.007	0.038	0.014
K	1.793	0.123	1.827	0.061	1.799	0.118	1.778	0.059
F	0.418	0.101	0.443	0.041	0.097	0.015	0.108	0.075
Fe/(Fe + Mg)	0.515	0.015	0.511	0.010	0.450	0.017	0.476	0.013



bole grains contain anomalously high Al contents, and these analyses have been excluded from further discussion and calculation of average composition. Figure 10 shows a general overlap in composition of analyses from fine-grained enclaves and host granitoid. The only notable difference between fine-grained enclaves and host granitoid is the greater Na content of hornblende in the enclaves. Amphibole from the mafic dike (CA84-65A) contains more total Al and alkalis and less Si than amphibole in most fine-grained enclaves. The hornblende samples from coarse-grained enclaves (BW84-27 and CA84-114) have significantly lower Fe/(Fe + Mg), and they have lower contents of Al, Mn, Na, and K, and greater contents of Si and Ca. These data suggest equilibration of amphibole in fine-grained enclaves and host and little (if any) equilibration of coarse-grained enclaves with their surroundings.

←

Fig. 9. Biotite microprobe data. Numbers correspond to abbreviations of sample numbers given in Table 3 and rock types in legend for Figure 10. Density of data within envelopes is represented by two samples, filled circles (CA84-45) and filled squares (CA84-65A). Compositions of biotite in fine-grained enclaves from ilmenite-bearing granites (labeled ilmenite on right) are distinct from those found in magnetite-bearing granodiorites (magnetite on left). In general, compositions of biotite are very similar for grains in fine-grained enclaves and corresponding host granitoids (see Table 1); those in a mafic dike have a similar composition. Biotites from a coarse-grained dike have lower Fe/(Fe + Mg) and are not shown.

Table 5—*Continued*

BW84-29 fg enclave		CA84-45 fg enclave		CA84-65A mafic dike		CA84-114 cg enclave	
Avg $n = 47$	Std	Avg $n = 15$	Std	Avg $n = 6$	Std	Avg $n = 3$	Std
			Compositions in wt%				
37.43	0.75	37.74	0.75	37.37	0.67	36.87	0.65
15.75	0.90	15.23	1.02	15.36	0.23	16.48	0.56
3.32	0.30	3.11	0.23	3.39	0.15	3.49	0.12
17.71	0.43	17.31	0.47	18.91	0.21	14.89	0.22
0.60	0.06	0.63	0.05	0.41	0.05	0.18	0.01
12.34	0.41	12.08	0.42	11.58	0.12	13.64	0.23
0.03	0.04	0.10	0.07	0.08	0.04	0.06	0.01
0.26	0.18	0.26	0.08	0.14	0.04	0.34	0.04
9.08	0.46	8.62	0.50	9.15	0.32	8.75	0.13
0.26	0.05	0.34	0.04	0.14	0.05	0.16	0.07
3.88	0.05	3.80	0.06	3.92	0.04	3.93	0.05
0.21		0.20		0.09		0.13	
100.46	1.22	99.00	1.57	100.34	0.95	98.66	0.87
			Cations per 24 O atoms				
5.582	0.077	5.687	0.091	5.610	0.039	5.502	0.064
2.418	0.077	2.313	0.091	2.390	0.039	2.498	0.064
0.350	0.086	0.390	0.095	0.327	0.048	0.420	0.072
0.372	0.032	0.352	0.027	0.382	0.017	0.387	0.006
2.210	0.066	2.181	0.058	2.374	0.049	1.874	0.024
0.076	0.008	0.080	0.006	0.052	0.007	0.023	0.001
2.744	0.075	2.713	0.084	2.590	0.042	3.041	0.039
0.005	0.006	0.016	0.011	0.012	0.007	0.011	0.002
0.076	0.051	0.076	0.022	0.040	0.011	0.107	0.004
1.728	0.084	1.656	0.079	1.751	0.045	1.665	0.006
0.123	0.022	0.160	0.020	0.067	0.025	0.069	0.041
0.446	0.010	0.446	0.007	0.478	0.004	0.380	0.002

Plagioclase

The zonation patterns and anorthite contents of plagioclase from granitoids and mafic rocks are oscillatory and variable in chemical trend (Fig. 11). Except for a small volume enclave (approximately 25 cm^3) in biotite-ilmenite granite (BW84-20A), mafic rocks have zonation patterns that differ from their host granitoid. The zona-

Table 6. Amphibole compositions

	BW84-23 granodiorite		BW84-25 granodiorite		BW84-29 fg enclave		CA84-45 fg enclave		CA84-65A mafic dike		CA84-114 cg enclave		CA84-27 cg enclave	
	Avg $n = 28$	Std	Avg $n = 41$	Std	Avg $n = 14$	Std	Avg $n = 27$	Std	Avg $n = 10$	Std	Avg $n = 5$	Std	Avg $n = 5$	Std
							Compositions in wt%							
SiO_2	46.42	0.73	45.42	0.94	46.49	0.62	47.66	0.77	46.07	0.67	48.69	0.17	47.32	1.35
Al_2O_3	8.09	0.48	8.60	0.68	8.43	0.25	7.57	0.95	9.18	0.40	6.40	0.13	8.44	1.43
TiO_2	1.01	0.17	1.21	0.18	0.96	0.10	0.81	0.10	1.39	0.11	0.97	0.05	1.02	0.25
FeO	16.14	0.35	16.90	0.56	16.49	0.24	15.55	0.55	16.78	0.36	11.91	0.26	14.42	0.34
MnO	0.98	0.07	0.73	0.07	0.95	0.04	0.99	0.06	0.54	0.03	0.27	0.03	0.33	0.04
MgO	11.95	0.38	11.29	0.51	11.97	0.28	12.26	0.40	11.61	0.37	14.44	0.53	12.81	0.75
CaO	11.80	0.19	11.47	0.49	11.75	0.32	11.57	0.36	11.90	0.12	12.22	0.07	12.11	0.24
Na_2O	0.86	0.09	0.86	0.12	1.02	0.11	0.98	0.10	1.07	0.15	0.99	0.33	0.66	0.09
K_2O	0.77	0.06	0.99	0.28	0.84	0.05	0.69	0.08	0.97	0.05	0.58	0.01	0.73	0.12
F	0.07	0.06	0.13	0.03	0.11	0.11	0.24	0.08	0.09	0.05	0.10	0.09	0.04	0.03
H_2O	1.95	0.03	1.91	0.04	1.95	0.05	1.91	0.05	1.98	0.03	1.99	0.05	2.02	0.03
$-O = F$	0.03		0.02		0.01		0.15		0.06		0.08		0.05	
Total	99.98	0.63	99.56	1.03	101.06	0.82	100.39	1.25	101.52	0.52	98.52	0.79	99.90	0.83
							Cations per 24 O atoms							
Si	6.896	0.068	6.816	0.093	6.859	0.044	7.019	0.068	6.765	0.064	7.172	0.035	6.949	0.147
$^{[4]}Al$	1.104	0.068	1.184	0.093	1.141	0.044	0.981	0.068	1.235	0.064	0.828	0.035	1.051	0.147
$^{[6]}Al$	0.313	0.061	0.338	0.083	0.325	0.022	0.362	0.103	0.353	0.019	0.283	0.034	0.412	0.114
Ti	0.113	0.018	0.137	0.020	0.106	0.011	0.090	0.011	0.153	0.013	0.108	0.006	0.113	0.028
Fe	2.006	0.053	2.121	0.079	2.034	0.031	1.916	0.077	2.061	0.054	1.467	0.036	1.771	0.046
Mn	0.123	0.009	0.093	0.008	0.118	0.005	0.124	0.007	0.067	0.004	0.034	0.004	0.041	0.005
Mg	2.646	0.074	2.526	0.097	2.632	0.054	2.691	0.076	2.540	0.068	3.170	0.098	2.803	0.145
Ca	1.878	0.034	1.844	0.069	1.857	0.049	1.825	0.043	1.872	0.020	1.929	0.007	1.906	0.035
Na	0.249	0.025	0.252	0.035	0.295	0.029	0.279	0.026	0.298	0.046	0.233	0.012	0.179	0.014
K	0.145	0.011	0.189	0.055	0.158	0.010	0.130	0.015	0.182	0.011	0.110	0.003	0.138	0.023
F	0.065	0.028	0.064	0.026	0.069	0.048	0.113	0.038	0.046	0.029	0.048	0.041	0.017	0.014
Fe/(Fe + Mg)	0.431	0.011	0.457	0.017	0.436	0.008	0.416	0.013	0.448	0.013	0.316	0.011	0.388	0.016
Na + K	0.395	0.028	0.441	0.061	0.453	0.030	0.408	0.028	0.480	0.047	0.343	0.014	0.316	0.032

TABLE 7. Representative plagioclase analyses

Sample	BW84-20A granite	BW84-20A fg encl	BW84-23 granodiorite	BW84-29 fg encl	BW84-25 granodiorite	BW84-27 cg encl	CA84-114 cg encl	CA84-65A mafic dike
				Compositions in wt%				
Analysis no.	5057	4205	1348	1492	1294	1381	1469	1400
SiO_2	62.64	63.42	60.20	60.51	59.63	57.66	59.61	57.46
Al_2O_3	23.96	22.29	25.87	25.28	25.91	27.88	25.95	27.95
FeO	0.02	0.08	0.08	0.01	0.09	0.10	0.05	0.06
CaO	5.35	3.76	6.94	6.55	7.24	9.50	7.25	9.02
Na_2O	8.11	9.51	6.00	7.92	6.20	4.91	7.35	5.41
K_2O	0.26	0.18	0.20	0.11	0.23	0.23	0.20	0.12
Total	100.34	99.24	99.29	100.38	99.30	100.28	100.41	100.02
				Cations per 8 O atoms				
Si	2.762	2.824	2.681	2.682	2.664	2.565	2.647	2.562
Al	1.245	1.169	1.358	1.320	1.364	1.462	1.358	1.469
Fe	0.001	0.003	0.003	0.000	0.003	0.004	0.002	0.002
Ca	0.253	0.179	0.331	0.311	0.347	0.453	0.345	0.431
Na	0.693	0.821	0.518	0.680	0.537	0.424	0.633	0.468
K	0.015	0.010	0.011	0.006	0.013	0.013	0.011	0.007
Total	4.969	5.006	4.902	4.999	4.928	4.921	4.996	4.939
An	26.3	17.7	38.5	31.2	38.7	50.9	34.9	47.6
Ab	72.1	81.3	60.2	68.2	59.9	47.6	64.0	51.7
Or	1.6	1.0	1.6	0.6	1.4	1.5	1.1	0.8

tion pattern of plagioclase (phenocrysts and ground mass) in all enclaves is normal in contrast to a reversed trend for plagioclase in granodiorites. The maintenance of this different zonation pattern in mafic rocks, and some differences in the range of anorthite contents (Fig. 11) indicates that plagioclase in mafic rocks has not fully equilibrated with surrounding granitoids. A possible exception is plagioclase in the small enclave in granite.

Apatite

Apatite was analyzed in order to test for chemical differences between apatite with acicular and prismatic habits, and chemical differences between apatite from mafic rocks (excluding coarse-grained enclaves) and apatite from granitoids. Representative and average analyses appear in Table 8. Differences of concentration occur for Ca, Mn, and F. A plot of MnO and F in wt% (Fig. 12) shows that acicular and prismatic apatite in biotite granite (BW84-20A) and biotite-hornblende granodiorite (BW84-23) contain more MnO and F than acicular apatite in a fine-grained enclave (BW84-29) and mafic dike (CA84-65A). Figure 12 also shows that acicular apatite from a small enclave in granite (BW-20A) is intermediate in composition and does overlap the compositions of acicular apatite from its host granite. A survey of apatite compositions from the literature indicates that apatite from mafic rocks commonly contains less MnO and F than apatite from granitoids (see Wyborn, 1983; Lee et al., 1973; Nash, 1972). Thus, apatite compositions from mafic rocks appear to record growth in a magma more mafic than those in granitoids, and both acicular and prismatic apatite in granite are chemically indigenous to granite. It is possible that apatite from the small enclave in granite (BW84-20A) partially equilibrated with its surroundings.

TABLE 8. Apatite analyses, representative and average

Sample	Prismatic in granite BW84-20A			Prismatic in granodiorite BW84-23			Acicular in granite BW84-20A		
Analysis no.	7042	Avg $n = 25$	Std	7146	Avg $n = 3$	Std	7179	Avg $n = 14$	Std
				Composition in wt%					
SiO_2	0.22	0.24	0.10	0.26	0.23	0.02	0.40	0.27	0.08
P_2O_5	40.71	39.82	0.77	43.59	43.65	0.48	40.47	40.92	0.98
FeO	0.17	0.24	0.18	0.05	0.06	0.01	0.10	0.33	0.16
MnO	0.50	0.46	0.07	0.47	0.49	0.01	0.58	0.41	0.11
CaO	55.13	54.42	0.81	51.73	51.43	0.42	53.05	53.35	0.99
F	2.90	3.48	0.44	3.23	3.27	0.03	3.48	3.07	0.46
$-O=F$	1.22	1.47		1.36	1.38		1.47	1.29	
Total	98.41	97.19	0.99	97.97	97.75	0.97	96.61	97.04	2.79
				Cations per 13 O atoms					
Si	0.02	0.02	0.01	0.02	0.02	0.00	0.03	0.02	0.01
P	2.85	2.82	0.03	2.99	3.00	0.01	2.86	2.89	0.04
Fe	0.01	0.02	0.01	0.00	0.00	0.00	0.01	0.02	0.01
Mn	0.04	0.03	0.01	0.03	0.03	0.00	0.04	0.03	0.01
Ca	4.88	4.87	0.08	4.50	4.47	0.02	4.74	4.77	0.09
F	0.76	0.92	0.12	0.83	0.84	0.01	0.92	0.81	0.12
Total	7.79	7.76		7.55	7.53		7.68	7.73	

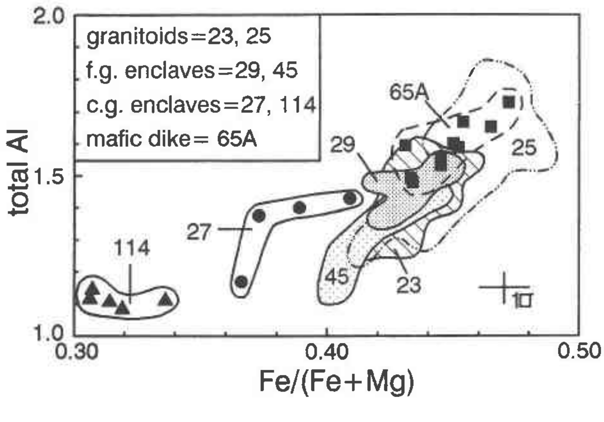


Fig. 10. Amphibole microprobe data. Numbers and filled squares as in Figure 9. All analyses are of calcic magnesio-hornblende except some from CA84-65A (mafic dike) which are edenite. The label f.g. = fine-grained; c.g. = coarse-grained.

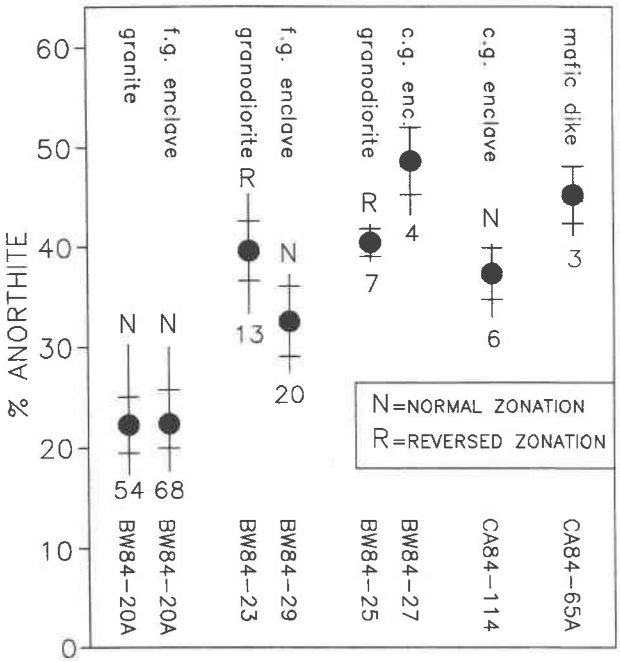


Fig. 11. Plagioclase compositions. Range is given by vertical line, 1 standard deviation by cross bars, and mean by dot. Number of analyses is given below the line. Host granitoid-mafic rock pairs are given together.

Apatite Rb-Sr isotopic data

The presence of some chemical contrasts in apatite from mafic and felsic rocks suggests isotopic contrasts might also exist. Apatite was chosen for analysis because its textures suggested early crystallization, perhaps prior to partial homogenization through magma mixing, assimilation, diffusion, etc. The two apatite habits from granite are in isotopic equilibrium with each other and the whole rock (Table 9; SRI = 0.7084 ± 1). Acicular apatite from an enclave (BW84-29), however, is more radiogenic than the bulk enclave (SRI = 0.7074 ± 1 and 0.7069 ± 1, respectively). The surrounding granodiorite (BW84-23) is in isotopic equilibrium with the bulk enclave (SRI = 0.7071 ± 1).

An apparent age of 67 Ma can be calculated from data from apatite and the whole enclave. This age is not significant in the history of the Turtle pluton (Allen, 1989). This result suggests that apatite gained radiogenic Sr or lost Rb relative to the whole enclave. Diffusion across these narrow grains in a geologically reasonable time can account for the more radiogenic apatite (Watson et al., 1985).

Discussion

The chemistry and mineral content of mafic rocks within the Turtle pluton suggest that three mafic rock types have equilibrated with their local environment to different degrees. Fine-grained enclaves have been affect-

Table 8—*Continued*

Acicular in enclave BW84-20A			Acicular in enclave BW84-29			Acicular in mafic dike CA84-65A		
7148	Avg $n = 14$	Std	7115	Avg $n = 14$	Std	7192	Avg $n = 5$	Std
				Composition in wt%				
0.40	0.46	0.21	0.23	0.66	0.37	0.30	0.47	0.26
42.67	42.11	3.51	43.67	42.82	0.80	42.20	41.48	0.72
0.49	0.29	0.24	0.06	0.17	0.17	0.03	0.06	0.08
0.45	0.29	0.12	0.04	0.09	0.02	0.06	0.08	0.03
52.19	53.06	1.63	54.78	54.41	0.51	54.81	54.01	0.50
2.42	2.74	0.56	2.06	1.86	0.24	2.01	1.79	0.16
1.02	1.16		0.87	0.79		0.85	0.76	
97.60	97.78	1.59	99.97	99.23	2.12	98.56	97.13	1.74
				Cations per 13 O atoms				
0.03	0.04	0.02	0.02	0.05	0.03	0.03	0.04	0.02
2.97	2.92	0.16	2.98	2.95	0.04	2.94	2.93	0.03
0.03	0.02	0.02	0.00	0.01	0.01	0.00	0.00	0.01
0.03	0.02	0.01	0.00	0.01	0.00	0.00	0.01	0.00
4.60	4.68	0.30	4.73	4.74	0.04	4.83	4.83	0.03
0.63	0.72	0.17	0.53	0.48	0.06	0.52	0.47	0.04
7.66	7.68		7.74	7.77		7.80	7.81	

ed the most, and coarse-grained enclaves and mafic dikes, less so. The degree of equilibration through mixing, mingling, or diffusion and reaction depends on several factors: proportion of mafic to felsic magma (Sparks and Marshall, 1986), transport properties (Lesher, 1990), enclaves size, average grain size, and residence time in the pluton (Frost and Mahood, 1987).

Coarse-grained enclaves are relatively large bodies that are chemically and isotopically distinct from host granodiorites and other mafic rocks, hence they are not cumulates or restites related to the Turtle pluton. However, the Al contents of amphibole rims from one enclave suggest equilibration at pressures similar to that of the pluton (Table 10). Most probably these coarse-grained enclaves represent accidental inclusions of a mafic rock type in the granitoid magma.

Some isotopic and mineral chemical differences remain between mafic dikes and surrounding granodiorites, perhaps resulting from the relatively late introduction of the dikes into the plutonic environment, compared to fine-grained enclaves. The greater alkali content of biotite and amphibole (edenite) in dikes, as compared to fine-grained enclaves, may reflect a distinct source. A lower SRI and a higher $\epsilon_{Nd}(t)$ in the dikes as compared with the granitoids suggest less crustal involvement in the dikes.

Fine-grained enclaves have thoroughly interacted with the surrounding granitoids. This is reflected in whole rock compositions, mineral abundances, and mineral chemistry. Different minerals have equilibrated with their surroundings to different degrees; biotite has most fully equilibrated, amphibole and apatite less so, and plagioclase maintains distinct compositions and zoning patterns.

The modal abundance of biotite in fine-grained enclaves (10–20%), igneous textures of biotite, and the medium- to high-K_2O composition of these enclaves suggest that components (particularly K_2O) from host granitoids were added to the enclaves at temperatures above the solidus. Overlap of compositions of biotite from enclaves and host rocks, and similar Rb contents of whole rock enclave and host granitoid, suggest continued equilibration of biotite (the Rb-controlling phase in enclaves). Equilibration of biotite is to be expected given its reported behavior in igneous and metamorphic rocks under hydrous conditions (Brimhall et al., 1983; Moore and Czamanske, 1973).

Amphibole compositions from enclave and host partially overlap, and the total Al contents of the two rock types are similar. For selected analyses near rims, and in biotite-free amphibole grains, pressures calculated from Al contents of most fine-grained enclaves and granitoids are indistinguishable (Table 10) and, consequently, suggest equilibration at similar pressures. Note that the appropriate assemblage for use of hornblende geothermometry is available, except where the absence of potassium feldspar is noted.

The low anorthite content of plagioclase (An = 28–38) from a fine-grained enclave of basaltic composition (BW84-29) indicates lack of equilibration and a possible xenocrystic origin.

No bulk mixing model of dike and granitoid can account for the range of observed fine-grained enclave compositions in the Turtle pluton. In particular, no bulk model of mafic dike plus mineral components from granitoids can account (1) for SRI of some enclaves exceeding that of their hosts or (2) for the dispersion of enclave isotopic compositions away from the mixing line defined by granitoids on isotopic plots (Fig. 8).

Assimilation of granitoids by dikes followed by fractional crystallization can account for the range of enclave geochemical data (including Rb-Sr isotopic ratios), but the assimilant cannot be the local host rock in all cases because some enclaves are more radiogenic than their hosts. Addition of radiogenic Sr through weathering or alteration of biotite to produce SRI higher in enclaves than in host granitoids is unlikely given the similar modal abundances of biotite in both rock types. The higher SRI of the enclaves probably indicates interaction with a more radiogenic source than their present hosts in the Turtle pluton.

The dispersion of enclave data from the mixing line on isotope plots defined by the granitoids (Fig. 8) could represent assimilation and fractionation or a multiplicity of sources, or it could be the result of partial equilibration of enclaves with granitoids through diffusion. Results from a recent experimental study of elemental and isotopic diffusion of Sr and Nd near an interface of felsic and mafic magma suggest complicated diffusion paths, more rapid equilibration of isotopic ratios than elemental concentrations, and equilibration rates of $^{87}Sr/^{86}Sr$ twice as fast as $^{143}Nd/^{144}Nd$ (Lesher, 1990). Thus in natural settings, enclaves modified by interaction with granitoid magmas

TABLE 9. Apatite and whole rock Rb-Sr isotopic data

Mineral	$^{87}Sr/^{86}Sr$	Rb (ppm)	Sr (ppm)	$^{87}Rb/^{86}Sr$	$^{87}Sr/^{86}Sr_i^*$
		Granite (CA85-5)			
Whole rock	0.70985	97.1	338.1	0.83	0.7083
ac. apatite	0.70881	17.5	271.7	0.19	0.7085
pr. apatite	0.70858	2.3	112.7	0.06	0.7085
		Fine-grained enclave (BW84-29)			
Whole rock	0.70833	90.5	346.4	0.76	0.7069
ac. apatite	0.70778	5.0	81.7	0.18	0.7074

Note: Abbreviations: ac. = acicular, pr. = prismatic.
* Assumes a crystallization age of 130 Ma (Allen, 1989).

TABLE 10. Hornblende geobarometry

Sample number	No. of analyses	Avg. Al_{tot}	Standard deviation	Calculated *P* (kbar) A	B	C
BW84-23	20	1.51	0.13	3.7	3.8	2.9
BW84-29	10	1.45	0.04	3.4	3.4	2.7
BW84-25	17	1.50	0.13	3.6	3.7	2.9
BW84-27	4	1.34	0.10	2.8	2.8	2.2
CA84-45	9	1.27	0.09	2.5	2.4	1.9
CA84-65A*	6	1.56	0.07	3.9	4.0	3.1

Note: A = Hammarstrom and Zen (1986), ±3 kbar; B = Hollister et al. (1987), ±1 kbar; C = Johnson and Rutherford (1989), ±0.5 kbar.
* Lacks potassium feldspar.

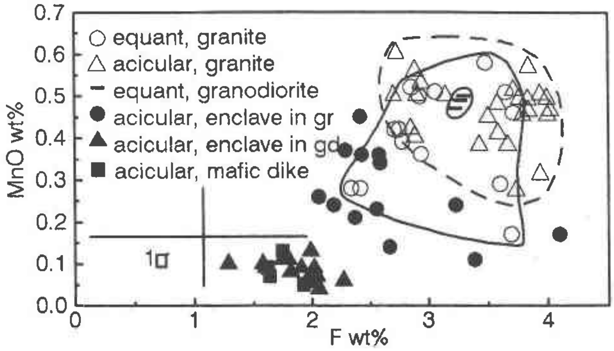


Fig. 12. Apatite compositions as represented by wt% MnO and F. Apatite of both morphologies in granite (BW84-20A) and granodiorite have similar compositions, and the small enclave in the granite has a similar F range but contains less MnO. Acicular apatite from another fine-grained enclave (BW84-29) and mafic dike (CA84-65A) have similar MnO and F concentrations but distinctly lower than those of other samples.

through diffusion may not have the compositions of simple mixtures of granitoid and basalt or even lie along assimilation-fractionation paths. If so, determination of a enclave source based on isotopic ratios and, perhaps, concentrations of other elements would be very difficult; nonetheless, these experiments do suggest that Nd isotopic data are more likely to retain source information than Sr isotopic data.

Although overlapping mineral compositions, K_2O and Rb contents, and SRI have been interpreted as signs of local interaction of fine-grained enclaves and Turtle pluton granitoids, these data could also be interpreted to indicate a genetic relationship of the enclaves to the enclosing pluton. However, that enclaves have higher $\epsilon_{Nd}(t)$ than their host granitoids indicates distinct and more primitive sources for the enclaves.

Rb-Sr isotopic and geochemical relationships similar to those described in this study have been reported for fine-grained enclaves and granitoids of the Criffell and Strontian plutons of Scotland (Halliday et al., 1980; Holden et al., 1987). Relative to host granodiorites, fine-grained enclaves have greater or equal SRI (within 0.0004, except one pair), greater or equal concentrations of Rb, and lesser or equal concentrations of Sr. Though no Sr isotopic signature of mantle derivation remains in these enclaves, Nd-Sm isotopic data suggest a mantle source for enclaves [$\epsilon_{Nd}(t)$ of enclaves is $+0.4 >$ hosts]. They attributed maintenance of Nd isotopic composition in enclaves to behavior of this relatively immobile element in apatite.

Conclusions

Determination of sources of mafic enclaves has been hampered by the interaction of enclaves and surrounding granitoids. Evidence of local interaction presented in this study includes similar mineral assemblages, similar mineral compositions of amphibole and biotite, whole rock Rb contents, and similar SRI of enclaves and granitoids. Equilibration of modally significant biotite and hornblende probably affects whole rock major and trace element compositions and Sr isotopic ratios. Partial equilibration of an unrelated mafic magma in a granitoid pluton can account for the similar geochemical characteristics of enclave and host that have been attributed to mixing of distinct batches of mafic magmas with a felsic magma to generate a range of intermediate compositions (Cocirta et al., 1989), and to incomplete removal of restite (Chen et al., 1989). Petrogenetic indicators that equilibrate relatively rapidly at high temperatures, such as many major and trace elements and Sr isotopes, cannot be used to establish enclave sources. Instead petrogenetic indicators that equilibrate more slowly, such as Nd isotopes, are more reliable.

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