

Nd and Sr isotopic compositions of lower-crustal xenoliths from north Queensland, Australia: Implications for Nd model ages and crustal growth processes

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ABSTRACT

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Sr and Nd isotopic analyses of granulite-facies lower-crustal xenoliths from northern Queensland, Australia, fall on a mixing array on a $^{87}\text{Sr}/^{86}\text{Sr}$ vs. $^{143}\text{Nd}/^{144}\text{Nd}$ diagram at 300 Ma. This was a time of intense orogeny in northern Queensland, attended by granitic magmatism in the upper crust and granulite-facies metamorphism in the lower crust. Ion microprobe zircon dating indicates that most of the xenoliths formed at this time. The Sr and Nd isotopic compositions of these rocks are therefore interpreted to have resulted from large-scale mixing in the lower crust between mantle-derived basaltic melts and isotopically evolved, early Proterozoic continental crust. Both end-members are represented in the xenolith suite. Depleted-mantle Nd model age (t_{DM} ages) for meta-igneous granulite xenoliths having appropriate $^{147}\text{Sm}/^{144}\text{Nd}$ (i.e. between 0.12 and 0.15) range from 1.9 to 2.2 Ga for mafic melt-like xenoliths and 1.2 to 1.4 Ga for felsic melt-like xenoliths. However, zircon ages on these same samples show that their protoliths crystallized during the Permo-Triassic orogeny. Thus the old t_{DM} ages for the mafic xenoliths do not accurately reflect their crustal residence ages, possibly due to crustal assimilation or their derivation from an enriched mantle source. This is a common feature of mafic granulite xenoliths the world over and highlights the difficulty in determining the age of mafic underplates, hence the timing of crustal growth, from t_{DM} ages. Because the felsic melt-like xenoliths lie on the mixing array, their mid-Proterozoic t_{DM} ages are likely to have resulted from mixing and therefore represent an average crustal residence age. The combined data suggest that significant crustal growth and reworking occurs in the lower crust during Phanerozoic crustal orogenies.

1. Introduction

Study of granulite-facies xenoliths brought rapidly to the Earth's surface by mafic volcanics can help to define the age of the lowermost continental crust, its chemical and isotopic composition and important crustal growth processes. Generally such far-ranging topics can only be addressed through careful, integrated studies of xenoliths in which petro-

graphic, petrologic, geochemical and isotopic data are combined.

This paper presents new Sr and Nd isotopic data and some mineral trace-element data for a suite of lower-crustal xenoliths from the McBride volcanic province of north Queensland, Australia. Petrography, thermobarometry, mineral chemistry, major- and trace-element whole-rock chemistry and U-Pb zircon ion probe results for these xenoliths have previously been published by Rudnick and Taylor (1987) and Rudnick and Williams (1987). The new Sr and Nd isotopic measurements on samples for which protolith and metamorphic

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ages have previously been determined allow: (1) evaluation of the significance of Nd model ages for lower-crustal xenoliths; (2) evaluation of processes that form or modify the lower continental crust; and (3) characterization of the isotopic composition of the lower crust in a Phanerozoic continental margin.

2. Sample description and previous work

The xenoliths investigated here come from a young (< 3 Ma) basaltic vent (Hill 32) in the McBride volcanic province of northern Queensland, Australia. Earlier papers by Rudnick and Taylor (1987) and Rudnick and Williams (1987) report the geological setting, petrography, mineral chemistry, major- and trace-element chemistry and zircon ion microprobe

results for these rocks, and only the pertinent features will be reviewed here. Additional Sr and Nd isotopic results for another suite of granulite xenoliths from the same vent are reported in Stolz and Davies (1989).

The McBride volcanics erupted onto a chronologically diverse crust: the oldest exposed rocks are Proterozoic granites and amphibolite-facies metamorphics of the Georgetown Inlier (Black et al., 1979). 400 Ma ago granites intruded the southern margin of the inlier, 320–270 Ma ago extensive silicic ash flows erupted and high-level granites intruded the upper crust (Black, 1980; Black and McCulloch, 1990). No further magmatic activity occurred until the late Cenozoic, when the tholeiitic and alkalic basalts of the McBride province were erupted.

TABLE I

Age, *P*–*T* conditions, geochemical features and inferred petrogenesis of McBride xenoliths

Sample No.	<i>P</i> – <i>T</i> conditions		Zircon ages	Geochemical features
	<i>T</i> (°C)	<i>P</i> (GPa)		
<i>Pyroxene-rich cumulates:</i>				
83-158	900–1,000	1.1	no zircons observed	46% < SiO ₂ < 47%; LREE depleted
85-106	890–1,070		no zircons observed	
<i>Mafic melts:</i>				
85-100	960–1,000	0.8	250–400 Ma, Proterozoic xenocrysts	SiO ₂ < 52%; LREE enriched; negative or no Eu anomaly
85-108	81–860		no zircons observed	
85-120	860–910		200–340 Ma	
<i>Mafic restitutes/cumulates:</i>				
83-159	840–920		300 Ma, 1,570 Ma	41% < SiO ₂ < 53%; LREE enriched; positive Eu anomaly
85-107	680–760		220–320 Ma	
85-114	830–910		no zircons observed	
<i>Metasediment:</i>				
83-157	630–800	0.8– 1.0	220–270 Ma, 1,570 Ma	SiO ₂ = 55%; PAAS-like REE pattern; high Al ₂ O ₃ / (Na ₂ O + CaO)
<i>Felsic (melt-like) granulites:</i>				
83-160	740–900	0.9–	200–300 Ma	64% < SiO ₂ < 67%; LREE enriched; negative or no Eu anomaly
83-162		1.2	200–300 Ma	

LREE = light rare-earth elements; PAAS = post-Archean Australian shale (Taylor and McLennan, 1985).

The composition and inferred petrogenesis, P - T equilibration conditions and ages of the McBride granulite-facies xenoliths are summarized in Table I. The xenoliths range from felsic to mafic compositions and include metasedimentary types. As was shown by zircon ion probe ages (Rudnick and Williams, 1987), the xenoliths underwent high-grade metamorphism during the Permo-Triassic (300–200 Ma), broadly coincident with the eruption of the felsic volcanics. Most of the granulite protoliths are also Permo-Triassic in age. However, two samples (metasediment 83-157 and mafic restite 83-159) have Proterozoic crystallization ages and Permo-Triassic metamorphic ages. The Proterozoic age (~ 1570 Ma) corresponds to that of granite intrusion and metamorphism in the Georgetown Inlier. Several samples also contain older, xenocrystic (85-100) or inherited (83-160) zircons.

3. Analytical techniques

The general chemical procedure for separating Rb, Sr, Nd and Sm is slightly modified from that described by White and Patchett (1984). Totally spiked rock powders were dissolved in HF and HNO₃ in Teflon[®] bombs for a period of 4–11 days in order to assure total dissolution of accessory phases. After bomb dissolution samples were treated with HClO₄, then rare-earth elements (REE) and Sr were separated on cation-exchange columns and Sm was separated from Nd on HDEHP*-Teflon[®] powder columns.

Hand-picked mineral separates from 83-157 were analyzed for trace elements by spark-source mass spectrometry at the Australian National University. Analytical details are given in Rudnick and Taylor (1987).

4. Results

Sr and Nd analytical data are reported in Table II. The present-day Sr and Nd isotopic

compositions are widely variable and broadly correlate with major-element composition and inferred petrogenesis listed in Table I (Fig. 1). Thus the two mafic, pyroxene-rich cumulates have the most primitive isotopic compositions ($\epsilon_{Nd} = +4.8$ to $+6.4$ and $^{87}Sr/^{86}Sr = 0.7039$ – 0.7052) and the two Proterozoic rocks [metasediment (83-157) and mafic restite (83-159)] have the most evolved isotopic compositions ($\epsilon_{Nd} = -17.8$ and -14.6 and $^{87}Sr/^{86}Sr = 0.7236$ and 0.7130 , respectively). Lying isotopically between these two end-members are the Paleozoic mafic melts and restites/cumulates. The Paleozoic felsic melts plot at higher $^{87}Sr/^{86}Sr$ for a given ϵ_{Nd} than the Paleozoic mafic melts and restites/cumulates (Fig. 1).

Table III gives trace-element concentrations for plagioclase, biotite and garnet separates from metasedimentary xenolith 83-157; REE patterns for the minerals and whole rocks are plotted in Fig. 2. In general, the overall concentrations of REE and REE patterns are similar to those reported for minerals in granulite xenoliths measured by ion microprobe (Reid, 1990). Plagioclase is enriched in light REE (LREE) and Eu whereas the coexisting garnet is depleted in Eu and is heavy REE (HREE)-enriched. The slight LREE enrichment seen in the garnet may be due to the presence of LREE-enriched inclusions such as monazite, although no monazite has been observed in thin sections of this sample. High Th concentration in the garnet and high Th/U ratio also suggest the presence of a phase such as monazite. These mineral data suggest equilibrium partitioning of the REE between the garnet and plagioclase. Preliminary isotopic analyses of these same mineral separates yield a garnet-plagioclase-whole rock Sm–Nd internal isochron of 212 ± 50 Ma (R.L. Rudnick and W.F. McDonough, unpublished data, 1988) and a plagioclase-whole-rock $^{206}Pb/^{204}Pb$ age of ~ 240 Ma (Rudnick and Goldstein, 1990). Both of these ages overlap with the metamorphic zir-

*Hydrogen di-ethylhexyl phosphate.

TABLE II
Isotopic data for McBride province lower-crustal xenoliths

Sample No.	Rb (ppm)	Sr (ppm)	⁸⁷ Rb/ ⁸⁶ Sr	⁸⁷ Sr/ ⁸⁶ Sr ± 2σ _M	Sm	Nd	¹⁴⁷ Sm/ ¹⁴⁴ Nd	¹⁴³ Nd/ ¹⁴⁴ Nd ± 2σ _M	ε _{Nd(t)}	ε _{Nd(300)}	(⁸⁷ Sr/ ⁸⁶ Sr) ₃₀₀	t _{DM} (Ga)
<i>Mafic cumulates:</i>												
83-158	0.64	100	0.0184	0.705162 (8)	3.10	8.13	0.2304	0.512885 (11)	+4.8	+3.5	0.705083	
85-106	0.26	164	0.0046	0.703928 (10)	3.62	11.2	0.1954	0.512964 (7)	+6.4	+6.4	0.703908	
<i>Mafic melts:</i>												
85-100	1.48	160	0.0266	0.711934 (15)	4.28	20.32	0.1273	0.511956 (4)	-13.3	-10.6	0.711820	2.0
85-108	0.70	153	0.0085	0.712525 (13)	4.47	19.49	0.1383	0.512146 (4)	-9.6	-7.4	0.712489	1.9
85-120	1.16	350	0.0096	0.708043 (15)	3.95	15.61	0.1529	0.512196 (11)	-8.6	-6.9	0.708002	2.2
<i>Mafic restites/cumulates:</i>												
83-159	1.96	230	0.0246	0.712997 (14)	4.31	19.02	0.1370	0.511887 (5)	-14.6	-12.6	0.712892	2.3
85-107	1.48	334	0.0128	0.713249 (15)	5.73	21.49	0.1370	0.512011 (10)	-12.2	-9.9	0.713194	2.1
85-114	2.20	131	0.0484	0.707586 (22)	1.81	5.82	0.1880	0.512430 (25)	-4.1	-3.7	0.707379	3.5
<i>Metasediments/felsic melts:</i>												
83-157	2.91	258	0.0326	0.723648 (7)	6.00	27.5	0.1319	0.511724 (5)	-17.8	-15.4	0.723509	2.5 (1.9)*1
83-160	1.14	203	1.808	0.715103 (12)	5.11	24.4	0.1265	0.512280 (13)	-7.0	-4.3	0.707380	1.4
83-162	134*2	206	1.880	0.716347 (19)	5.86	18.8	0.1887	0.512285 (14)	-6.9	-6.6	0.708240	4.3 (1.2)*1

Uncertainties given as ±2σ_{mean} in 10⁻⁶. Isotopic measurements were made in static mode on a Finnigan[®] MAT 261 mass spectrometer; Nd measurements were normalized to ¹⁴⁶Nd/¹⁴⁴Nd = 0.7219. Measured value for La Jolla Nd standard is: 0.511844 ± 0.000019 (2σ, n=8). Measured value for NBS 987 is 0.710239 ± 0.000032 (2σ, n=8). Underlined samples are those with Proterozoic crystallization ages. t_{DM} ages calculated using:

$$t_{DM} = \frac{1}{\lambda} \ln \left[1 + \frac{({}^{143}\text{Nd}/{}^{144}\text{Nd})_{\text{meas}} - [\exp(\lambda t) - 1] \{ ({}^{147}\text{Sm}/{}^{144}\text{Nd})_{\text{meas}} - ({}^{147}\text{Sm}/{}^{144}\text{Nd})_{\text{CC}} - ({}^{143}\text{Nd}/{}^{144}\text{Nd})_{\text{DM}} \}}{({}^{147}\text{Sm}/{}^{144}\text{Nd})_{\text{CC}} - ({}^{147}\text{Sm}/{}^{144}\text{Nd})_{\text{DM}}} \right]$$

where (¹⁴³Nd/¹⁴⁴Nd)_{DM} = 0.513151; (¹⁴⁷Sm/¹⁴⁴Nd)_{DM} = 0.22; and (¹⁴⁷Sm/¹⁴⁴Nd)_{CC} = 0.120 (after Liew and Hofmann, 1988).

*1 t_{DM} age calculated assuming ¹⁴⁷Sm/¹⁴⁴Nd = 0.120 before 300 Ma.

*2 Measured by X-ray fluorescence spectrometry (XRF) (Rudnick and Taylor, 1987).

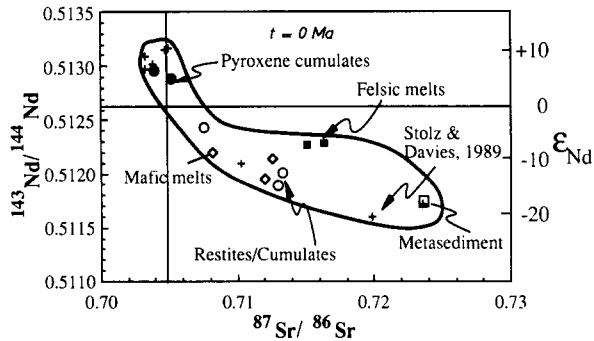


Fig. 1. Present-day Sr and Nd isotopic compositions of McBride province lower-crustal xenoliths, with different compositions designated. Also shown are data from Stolz and Davies (1989). Parameters for bulk Earth are: $^{87}\text{Sr}/^{86}\text{Sr}=0.7045$, $^{143}\text{Nd}/^{144}\text{Nd}=0.512638$.

TABLE III

Trace-element composition of minerals from 83-157

	Plagioclase	Garnet	Biotite	Whole rock
Rb	0.47	0.54	222	3.0
Sr	2,500	5.7	53	276
Y	0.41	132	3.4	35
Zr	33	204	65	381
Nb	0.55	0.82	3.4	6.6
Mo	0.04	0.22	9.6	1.5
Cs	0.09	0.41	2.2	-
Ba	900	24	-	445
La	56.2	5.0	50.2	33.2
Ce	91	10.6	104	66.1
Pr	5.83	1.43	13.6	7.25
Nd	14.2	10.5	53	29.7
Sm	1.46	12.3	17.0	6.46
Eu	3.7	0.87	8.5	1.61
Gd	0.74	18.1	12.9	6.20
Tb	0.06	3.40	1.51	-
Dy	0.27	22.6	4.95	6.74
Ho	0.04	5.56	0.46	1.40
Er	0.09	16.7	0.55	3.90
Yb	0.04	17.1	0.05	4.08
Hf	0.93	4.75	9.2	9.1
W	0.08	0.47	40.7	-
Pb	13.7	1.1	24.4	8.3
Th	0.05	1.79	1.12	1.14
U	0.02	0.16	0.68	0.37

con age of 250 ± 50 Ma (Rudnick and Williams, 1987). If these mineral data can be generalized to the whole xenolith suite, they suggest that minerals in the McBride samples

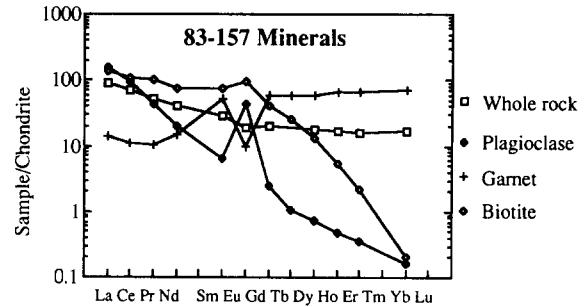


Fig. 2. REE patterns for plagioclase and garnet mineral separates from metasedimentary xenolith 83-157, compared with whole-rock pattern. Chondrite values from Taylor and McLennan (1985).

last equilibrated ~ 250 Ma then cooled slowly, passing below the Sm–Nd and U–Pb blocking temperatures in the early Mesozoic.

5. Sample heterogeneity

Both orthopyroxene-rich and garnet-rich layers are found in several of the McBride xenoliths (Rudnick and Taylor, 1987). This layering may or may not be a primary feature of the rock (e.g., Johannes and Gupta, 1982; Toriumi, 1986), nevertheless, it can have a profound effect on the whole-rock composition if the sample size is small in relation to the layering and preferential sampling of certain minerals occurs. This is a particularly important problem in studies of crustal xenoliths, where sample sizes are small but grain sizes are large and mineralogical banding common.

The effects of unrepresentative sampling on isotopic compositions and parent/daughter ratios will depend upon:

(1) How enriched a mineral phase is in the xenoliths sample relative to its modal abundance in a more representative whole rock.

(2) The partition coefficients of the parent and daughter elements in the enriched mineral relative to the other minerals.

(3) The degree of isotopic disequilibrium between mineral phases (i.e. how long the minerals have remained below their blocking temperatures for REE, Rb and Sr).

In the McBride suite, orthopyroxene enrichment is seen both petrographically and chemically in mafic xenolith 85-100 and garnet enrichment is observed in felsic xenolith 83-162 (Rudnick and Taylor, 1987). Because orthopyroxene contains very low abundances of both REE and Rb and Sr (e.g., Loock et al., 1990) orthopyroxene enrichment will simply dilute the concentrations of parent and daughter isotopes in the whole-rock analysis; it will not cause significant fractionation of parent/daughter isotope ratios and it should not significantly affect the whole-rock isotopic composition.

In contrast, garnets in granulite-facies rocks may contain significant amounts of REE, although Rb and Sr contents are low (Reid, 1989; Loock et al., 1990; see Table III). HREE are enriched in garnets relative to the whole rock, causing a garnet-enriched sample to have a higher $^{147}\text{Sm}/^{144}\text{Nd}$ ratio than the true whole rock. The effects of garnet enrichment on the $^{143}\text{Nd}/^{144}\text{Nd}$ ratio will depend heavily on the degree of isotopic disequilibrium between this mineral and the remainder of the rock. If the minerals are in isotopic equilibrium at the time of eruption, then the $^{143}\text{Nd}/^{144}\text{Nd}$ ratio will not be affected. If the minerals are in isotopic disequilibrium (due to radiogenic growth after the sample cooled below its blocking temperature), then the effects of garnet enrichment will be influenced by the time at which the sample passed below its blocking temperature.

Of the samples measured here, only 83-162 shows obvious garnet enrichment ($\sim 10\%$ based upon the degree of HREE enrichment and K_2O depletion; Rudnick and Taylor, 1987). If the minerals in this sample cooled to below their blocking temperature at ~ 250 Ma ago, as suggested by the mineral analyses for 83-157, then the present whole-rock $^{147}\text{Sm}/^{144}\text{Nd}$ and $^{143}\text{Nd}/^{144}\text{Nd}$ can be used to calculate a reliable $^{143}\text{Nd}/^{144}\text{Nd}$ ratio at 250 Ma. However, any extrapolation of data beyond that time is erroneous. This is reflected in the high $^{147}\text{Sm}/^{144}\text{Nd}$ and the consequently unrea-

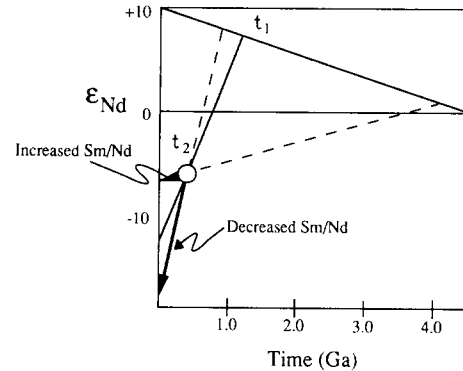


Fig. 3. Time (Ga) vs. ϵ_{Nd} showing effects of late fractionation of Sm/Nd ratio on depleted-mantle model ages. Rock with a depleted-mantle model age of ~ 1.2 Ga (t_1) evolves with a $^{147}\text{Sm}/^{144}\text{Nd}$ ratio of ~ 0.12 until time t_2 (~ 300 Ma). At this point the Sm/Nd ratio is either increased [due to concentration of garnets in layers (metamorphic differentiation), partial melt extraction or crystal accumulation from melt] or decreased (due to fractionation or garnet depletion caused by layer segregation). The resulting t_{DM} age is either too old (if Sm/Nd is increased) or too young (if Sm/Nd is decreased). Note the large effect on t_{DM} ages when the Sm/Nd ratio is relatively recently increased. Such a recent Sm/Nd fractionation explains the very old t_{DM} age for felsic xenolith 83-162.

sonably old t_{DM} age for this sample (4.3 Ga, Table II) and is schematically illustrated in Fig. 3. If, on the other hand, the model age is calculated assuming a $^{147}\text{Sm}/^{144}\text{Nd}$ whole-rock ratio of 0.120 before 300 Ma, similar to that of a variety of granites and sediments, the resulting t_{DM} (1.2 Ga) is similar to that of the other Paleozoic felsic granulite (83-160).

6. Discussion

6.1. Crust-mantle mixing

Based on the zircon ages given in Rudnick and Williams (1987), the protoliths of many of the McBride xenoliths formed between 300 and 200 Ma ago and all underwent granulite-facies metamorphism at this same time. The younger age represents the time at which the samples passed below the U-Pb zircon blocking temperature. The older range of ages overlaps the age of extensive calc-alkaline magma-

tism in this region (350–270 Ma). Therefore, the Sr and Nd isotopic composition of the xenoliths should be viewed at the time of this last orogenic event.

When the data are corrected for in situ decay of Rb and Sm since 300 Ma ago, the scatter in Fig. 1 disappears and the data define a narrow array on the $^{87}\text{Sr}/^{86}\text{Sr}$ vs. ϵ_{Nd} diagram (Fig. 4a). Three features are of interest on this diagram:

(1) The trend suggests that the isotopic compositions of the Paleozoic rocks are the result of mixing between a Paleozoic, mantle-derived component, represented by the pyroxene-rich cumulates, and a Proterozoic crustal end-member, represented by the Proterozoic metasediment (83-157) and restite (83-159)

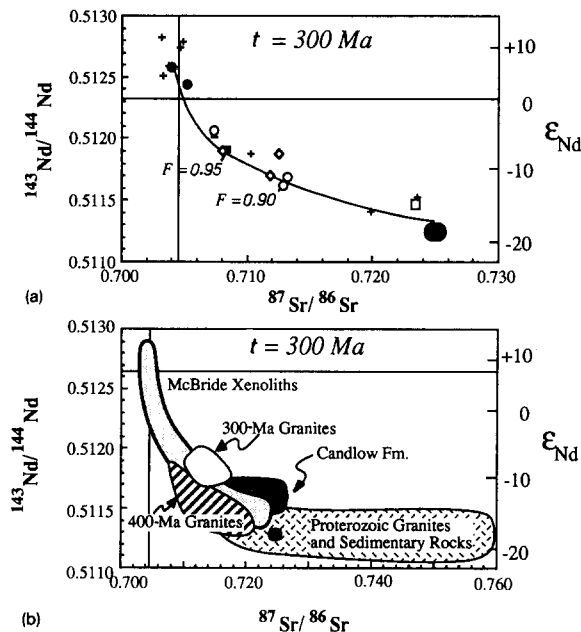


Fig. 4. a. Sr and Nd isotopic compositions of McBride province lower-crustal xenoliths at 300 Ma. Symbols as in Fig. 1. Curved line is AFC mixing trajectory between the most primitive granulite xenolith and a hypothetical crustal end-member (shown as shaded oval). See text for details of the calculation.

b. Sr and Nd isotopic compositions of surface rocks at 300 Ma compared with the field of the McBride xenoliths. The Proterozoic Candlow Formation (felsic ash flows) are distinguished from the remaining Proterozoic granites and metasediments (data from Black and McCulloch, 1984, 1989).

xenoliths. A similar mixing trend has been observed in granulite xenoliths from the nearby Chudleigh province (Rudnick et al., 1986). The fact that the trend in the McBride suite exists for a wide variety of rock types supports the suggestion that the age of some crustal xenolith suites may be derived by back-calculating isotopic ratios until a trend emerges on the ϵ_{Nd} vs. $^{87}\text{Sr}/^{86}\text{Sr}$ diagram (Rudnick et al., 1986). However, this is true only for suites which have evolved through large-scale mixing processes (e.g., Massif Central suite, France; Downes et al., 1990 in this special issue), and proving such a relationship on other than isotopic grounds may be difficult.

(2) The two Paleozoic felsic melt-like xenoliths have initial Nd isotopic compositions similar to the 300-Ma I-type granites in the Georgetown Inlier, but have lower $^{87}\text{Sr}/^{86}\text{Sr}$ (Fig. 4; Black and McCulloch, 1984, 1990). Since the felsic xenoliths lie on the mixing array, it is probable that their isotopic compositions resulted from mixing between mantle and crustal components at 300 Ma.

(3) The three mafic melt-like xenoliths had continental crust-like isotopic compositions at 300 Ma ($\epsilon_{\text{Nd}(300)} = -10.6$ to -7 , $^{87}\text{Sr}/^{86}\text{Sr} = 0.708$ – 0.7123), their presumed intrusion age. This evolved character may be the result of either: (1) derivation from an enriched mantle source, or (2) assimilation of an evolved crustal component by a more primitive mantle-derived basaltic magma.

The presence of an enriched mantle beneath northern Queensland is not supported by data from either primitive basalts (i.e. Mg-number ≥ 68 , Ni ≥ 300 ppm) or upper-mantle xenoliths. Primitive basalts from eastern Australia exhibit restricted isotopic compositions (with $^{87}\text{Sr}/^{86}\text{Sr} < 0.7050$ and $^{143}\text{Nd}/^{144}\text{Nd} > 0.51250$; Ewart et al., 1988). The basalts that are the most isotopically similar to these mafic McBride xenoliths are the Jurassic Tasmanian dolerites [$(^{87}\text{Sr}/^{86}\text{Sr})_0 = 0.7094$ – 0.7128 and $^{143}\text{Nd}/^{144}\text{Nd} = 0.51233$ – 0.51225], which have been interpreted to come from a

sediment-enriched, mid-ocean ridge basalt (MORB) source-like mantle reservoir (Hergt et al., 1989). However, these dolerites are evolved basalts and crop out over 2500 km to the south; no similarly enriched basalts have been reported within Queensland. In addition, mantle xenoliths from the McBride province have depleted isotopic characteristics (Stolz and Davies, 1989) and the most primitive (least contaminated) mafic granulite xenolith from the nearby Chudleigh volcanic province has isotopic characteristics of MORB (Rudnick et al., 1986), suggesting the presence of a depleted (rather than enriched) mantle source beneath this area.

If the evolved isotopic compositions of these xenoliths were produced by crustal contamination of mafic magmas, then it is probable that this occurred as they were intruded into the lower crust during the late Paleozoic. Proterozoic xenocrystic zircons in one of these samples (85-100) points to crustal assimilation. In addition, the samples have slightly fractionated compositions, with Mg-numbers between 55 and 63 and Ni contents between 79 and 84 ppm (excluding the orthopyroxene-enriched sample, 85-100). All are SiO₂ oversaturated (1–2% normative quartz), which may be the result of crustal assimilation. (However, it also may have resulted from early olivine fractionation.) Additional ferromagnesian phases which may have fractionated from these mafic melts include clinopyroxene and orthopyroxene, and negative Eu anomalies point to the fractionation of plagioclase feldspar (Rudnick and Taylor, 1987). Nevertheless, total REE contents are not extreme, and are similar to those of a variety of continental basalts (i.e. La_N = 30–40, cf. B.V.S.P., 1981). These features, plus the evolved isotopic characteristics of the xenoliths need to be reconciled in any model of crust–mantle mixing.

6.2. AFC calculations

The Sr and Nd isotopic compositions (at 300 Ma) and the Sr, Nd, Ni and V concentrations

of these three mafic xenoliths have been modelled by assimilation and fractional crystallization (AFC) (equations from DePaolo, 1981) and following the recommendations of Marsh (1989) of simultaneous evaluation of highly incompatible (Nd), moderately incompatible (V) and compatible (Ni) trace elements. Table IV lists the parameters chosen for the calculations. The starting isotopic composition for the basaltic melt is assumed to be that of the most isotopically primitive xenolith in the suite (85-106). A high *r*-value (mass of assimilated material to mass of fractionated crystals) of 0.9 is chosen as reasonable for the lower-crustal environment (James, 1981). High *r*-values cause the isotopic composition of the fractionating melt to change rapidly at small degrees of AFC, but they also cause incompatible-element concentrations to increase rapidly in the melt. Therefore, in order to shift the isotopic composition while at the same time maintain a reasonable concentration of incompatible elements in the melt, only small amounts of AFC can occur (i.e. $F=0.90-0.95$). The concentrations of Sr, Nd and Ni in the assimilate were chosen to approximate those of granites and sediments (Taylor and McLennan, 1985), whereas the initial Sr, Nd and Ni concentrations in the melt falls within the range of those observed in primitive basalts (the Sr/Nd ratio of 20–30 spans the range of values for intraplate and island arc basalts; McDonough and McCulloch, 1987). *D*-values were chosen to match the likely crystallizing assemblages listed above; the relatively high bulk *D* for Sr reflects the fact that plagioclase is a fractionating phase in these melts and a range of bulk *D*'s for V was used in order to accommodate possible magnetite fractionation.

Given the above parameters, the AFC equations can be solved for the isotopic and elemental composition of the differentiated melt. The results are listed in Table IV and plotted on an ϵ_{Nd} vs. $^{87}Sr/^{86}Sr$ diagram in Fig. 4a. Fig. 4b shows the range of isotopic compositions

TABLE IV

Parameters and results of AFC calculations [mass of assimilate to cumulate (r)=0.90; melt fraction (F)=0.90–0.95]

	Nd	Sr	Ni	V
Initial isotopic ratio of the melt, ϵ_m^0	0.51260	0.7040		
Initial concentration in the melt, C_m^0 (ppm)	10	300	300	230
Bulk partition coefficient, D	0.11	0.8	1.0	0.3–0.7
Concentration in assimilate, C_a (ppm)	25	150	10–30	50–100
Isotopic ratio of assimilate, ϵ_a	0.5112–0.5113	0.720–0.730		
<i>Results:</i>				
Concentration in the melt, C_m (ppm)	21–33	240–270	73–156	90–270
Observed concentrations* (ppm)	16–20	150–350	79–84	105–332
Isotopic ratio of melt, ϵ_m	0.5116–0.5119	0.7075–0.7147		

*Excluding Ni contents of orthopyroxene-rich sample 85-100.

observed in surface rocks of the Georgetown Inlier (from Black and McCulloch, 1984, 1990). The model assimilate has isotopic compositions which fall within the range of values observed for the surface rocks and are similar to those of the Proterozoic metasedimentary xenolith (83-157) (Fig. 4). The concentrations of Ni, Sr and V overlap with the observed concentrations but the model Nd concentrations are slightly high.

The above described AFC model effectively reproduces the isotopic and some of the trace-element characteristics of the mafic melts; however, it cannot explain the major-element compositions, a commonly overlooked feature in AFC modelling (Marsh, 1989). At the high r -values needed to shift the isotopic ratios so dramatically, the amount of crustal rock added to the remaining melt is so high that it is no longer basaltic in composition. For example, after 10% AFC [i.e. $F=(\text{residual melt})/(\text{original melt})=0.9$], the residual melt is composed of 37% of the original melt and 63% of the melted assimilate. Assuming for the time being that $D=1$ for the major elements, the major-element composition of the resulting melt can be modelled by simple mixing. If the initial melt and assimilate compositions are similar to those listed in Table V (a primitive basalt and an average shale, respectively), then

the residual melt would be intermediate in composition and would have significantly higher SiO_2 and K_2O contents than those observed in the mafic melt-like xenoliths (Table V). This calculation was performed assuming bulk mixing. The effects of crystal fractionation would only serve to drive the residual melt to even more evolved compositions.

The inability of the above AFC model to simultaneously account for the observed major-element, trace-element and isotopic data for the mafic melt-like xenoliths requires an alternative explanation for the origin of these rocks: either the isotopic compositions of the chosen

TABLE V

Major-element constraints on AFC model (elements in wt.%)

	Primitive basalt* ¹	Shale* ²	$F=0.95$	$F=0.90$	Observed* ³
SiO_2	50	62	55	58	49–52
Al_2O_3	13	18	15	16	15–16
FeO	9.4	7.0	8.4	7.9	9–13
MgO	14	3	9.6	7.1	8–9
CaO	12	4	8.8	7	9–13
K_2O	0	4	1.6	2.5	0.2
Mg-number* ⁴	72	43	67	61	55–63

*¹From Plank and Langmuir (1988).*²From Taylor and McLennan (1985).*³Excluding orthopyroxene-enriched sample 85-100.*⁴100 Mg/(Mg+Fe_{tot}).

end-members are incorrect or another contamination process was operative. In order to reproduce the isotopic ratios of the mafic melt-like xenoliths while at the same time retaining a basaltic composition of the evolving melt, smaller amounts of crust must be added to the melt. This means that either the mantle or the crustal end-members of the AFC model were substantially more isotopically evolved. Appealing to an enriched mantle source is one way out of the dilemma, although as noted previously, there is no evidence for such a mantle beneath northern Queensland. Alternatively, it is possible that the crustal end-member has a more evolved isotopic composition, possibly similar to the high- $^{87}\text{Sr}/^{86}\text{Sr}$ Proterozoic rocks cropping out at the surface (Fig. 4b). If this latter possibility is true, it would require either tectonic interleaving of similarly high- $^{87}\text{Sr}/^{86}\text{Sr}$ supracrustal rocks into the lower crust at 300 Ma or little to no Rb depletion in Proterozoic rocks within the lower crust.

Finally, recent experimental studies of diffusion across a chemical boundary layer separating felsic and mafic melts show that isotopic equilibration occurs well before chemical equilibration (Leshner, 1990). If this process can be applied to magma bodies within the deep crust, it may be one way to explain the data.

Despite the difficulties in quantitatively modelling the isotopic compositions, the curved array on the Sr–Nd diagram defined by the 300-Ma isotopic data is best explained by a model of crust–mantle mixing where primitive, mantle-derived basaltic magmas intrude into a warm lower crust consisting, at least in part, of evolved, Proterozoic rock types. The intrusion is attended by crustal melting and mixing between the mantle-derived magmas and crust. Both the mafic granulites and the felsic granulites are interpreted to be products of this mixing process. The mafic xenoliths are mostly new crustal additions, since little crust can be added to them before they are no longer basaltic. The amount of new crustal addition

represented by the felsic granulites can be modelled by simple mixing (following Patchett and Bridgwater, 1984) assuming, once again, that the mantle and crustal end-members are represented by the least and most isotopically evolved xenoliths in the suite, respectively. Thus if at 300 Ma ago a mantle component having $\epsilon_{\text{Nd}} = +6$ mixes with a crustal component having $\epsilon_{\text{Nd}} = -15$ the resulting granitic melt would contain between 50% and 70% new crustal additions (assuming the concentration of Nd in the mantle-derived component is 10–20 ppm and is 25–32 ppm in the crustal end-member).

6.3. Interpretation of the Nd model ages of lower-crustal xenoliths

Nd model ages for mafic granulite xenoliths have been interpreted in several ways:

(1) as the mantle extraction age, reflecting the time at which the protolith of the granulite xenolith formed (Halliday et al., 1985; Downes and Leyreloup, 1986; Stolz and Davies, 1989);

(2) as a mixed age, reflecting mixture between new Nd additions from the mantle and older crustal Nd (Rudnick et al., 1986; Ruiz et al., 1988; Kempton et al., 1990; Downes et al., 1990 in this special issue);

(3) as having no age significance if the xenoliths are cumulates with high $^{147}\text{Sm}/^{144}\text{Nd}$ and/or crystallized from an isotopically evolved parent magma (Cameron and Robinson, 1990).

In a sense, points (1) and (2) are similar, depending upon whether the evolved isotopic signature resulted from crustal contamination or an enriched mantle source. The closer the $^{147}\text{Sm}/^{144}\text{Nd}$ ratio of the xenolith is to the depleted mantle value (0.22), the less significance a model age holds. In addition, mafic cumulates will often have higher Sm/Nd ratios than their hosts [this can be considered as a “secondary process” (McCulloch and Wasserburg, 1978) that violates the basic assumptions behind Nd model age (see Fig. 3)].

Therefore, it is erroneous to discuss t_{DM} ages for mafic cumulate xenoliths having higher $^{147}\text{Sm}/^{144}\text{Nd}$ ratios than their parental melts (Cameron and Robinson, 1990; Ruiz et al., 1990).

The McBride xenoliths provide a unique opportunity to evaluate Nd model ages of crustal xenoliths since their crystallization ages are known (Rudnick and Williams, 1987). The only McBride samples for which t_{DM} calculations are appropriate are the xenoliths with melt-like compositions and the metasediment; both the mafic cumulates and restite/cumulate xenoliths have experienced Sm/Nd fractionation caused by cumulate and/or partial melting processes.

The three mafic melt-like xenoliths have relatively low $^{147}\text{Sm}/^{144}\text{Nd}$ ratios and exhibit a narrow range of early Proterozoic model ages (1.9–2.2 Ga, Table II). Their zircon age populations require Paleozoic intrusion ages for the mafic magmas that gave rise to these granulites (Rudnick and Williams, 1987). Therefore, these Proterozoic t_{DM} ages are the result of the parental magma having an evolved isotopic composition. As discussed in Section 6.4, this could reflect an enriched mantle source, or, more likely, crustal assimilation. If it is due to crustal assimilation, then the t_{DM} age reflects a mixed age, somewhere between that of the mantle-derived basalt (~300 Ma) and the crustal assimilate (earliest Proterozoic?); the specific model age depends upon the proportion of the Nd derived from the basalt vs. that derived from the pre-existing crust.

The metasedimentary xenolith, 83-157, has a slightly high $^{147}\text{Sm}/^{144}\text{Nd}$ ratio for a sediment (0.13). This may reflect a small amount of garnet enrichment, as discussed previously, or may be a true ratio. Nevertheless, the t_{DM} age for this sample is early Proterozoic irrespective of whether the measured $^{147}\text{Sm}/^{144}\text{Nd}$ ratio or a lower ratio of 0.120 is used (2.5 and 1.9 Ga, respectively). This sample contains 1570-Ma zircons and a single 2.1-Ga zircon, all of which suffered Pb loss at 250 Ma. These observations suggest that the old t_{DM} age reflects

the average crustal residence age of the source of the sediment.

The felsic granulite xenoliths exhibit middle Proterozoic Nd model ages, but their protoliths crystallized during the late Paleozoic. Old Nd model ages are relatively common features for many granitic rocks and are interpreted either as: (1) an age reflecting a mixture between mantle and crustal components and thus does not reflect a unique crust formation age (Farmer and DePaolo, 1983; Patchett and Bridgwater, 1984; Patchett and Arndt, 1986), or (2) the age of crust formation in the region (McCulloch and Chappell, 1982; Liew and McCulloch, 1985). Distinguishing which of these interpretations is correct for a given region requires independent criteria, e.g., zircon age data. The Nd and Sr isotopic compositions for the McBride felsic granulites lie directly on the 300-Ma mixing array defined by the entire xenolith suite, suggesting that the isotopic compositions of these felsic melts result from crust–mantle mixing and do not reflect a unique crustal source composition. If this is true, their model ages reflect a mixed age.

In summary, t_{DM} ages for granulite-facies xenoliths give meaningful age information only for non-cumulate, non-restitic rocks, which have not undergone multistage fractionation of their Sm/Nd ratio (McCulloch and Wasserburg, 1978; Arndt and Goldstein, 1987). Each sample must be evaluated separately to determine whether it fits these criteria. Even model ages for melt-like xenoliths may not necessarily be related to crust formation events if their initial ratios are affected by crustal assimilation or if the rocks are derived from an isotopically enriched mantle source. This is a particularly severe problem for mafic xenoliths which may have formed by basaltic intrusion into the lower continental crust, an environment conducive to contamination. The two studies of north Queensland xenoliths are unique in that the age of the basaltic underplating event has been constrained independently (through assessment of mixing trends and zircon dating) and is significantly younger than the t_{DM} age.

It appears likely that this is true for many other mafic xenolith suites (e.g., Eifel, F.R.G. – Rudnick and Goldstein, 1990; Massif Central, France – Downes et al., 1990 in this special issue; Geronimo Volcanic Field, Arizona, U.S.A. – Kempton et al., 1990).

6.4. *Implications for crustal growth*

This and other studies of lower-crustal xenoliths from around the world point to the importance of basaltic underplating in the growth of the lower continental crust (Wass and Hollis, 1983; Rudnick et al., 1986; Downes et al., 1990 in this special issue; Kempton et al., 1990). Isotopic data may allow time constraints to be placed on when the underplating occurred and, coupled with lithologic proportions of xenolith suites, the volumetric importance of such a crustal growth process.

In the northern Queensland xenolith suites two episodes of basaltic underplating are documented: at 300 Ma in the McBride province, and during the Tertiary in the Chudleigh province. The former event was manifested at the Earth's surface by extensive calc-alkaline felsic igneous activity and may have been related to subduction of oceanic crust beneath the Australian continent (Henderson and Stephenson, 1980). The latter event is manifested at the Earth's surface by extensive Tertiary basaltic volcanism that occurs throughout eastern Australia and is associated with crustal extension and/or hotspot activity (see Johnson et al., 1989). Therefore, the timing of basaltic underplating is intimately associated with magmatic activity at the Earth's surface and the regional tectonic setting.

Some limits on the amount of new crust created by basaltic underplating may be set from the xenolith data. Of the 12 xenoliths studied here from the McBride xenolith suite, 5 (42%) are interpreted as forming as basaltic underplates. When the 12 samples described by Stolz and Davies (1989) are included, the proportion of underplated material increases to 58%.

If these xenoliths are representative of the crust below ~26 km (the minimum equilibration pressure recorded in the xenoliths; Rudnick and Taylor, 1987; Stolz, 1987), and the crust is 40 km thick in this region, then up to 20% of the entire crust may consist of mafic compositions, underplated at 300 Ma. This would correspond to an 8-km-thick layer of underplated basaltic rocks, consistent with the volumetric estimates for basaltic underplating made by Furlong and Fountain (1986) based upon thermal models of basalt generation and emplacement.

However, not all mafic melts which intrude the crust remain mafic. The thermal perturbation created by basaltic underplating should cause crustal melting and these melts may mix with the mantle-derived basalts and their fractionated derivatives (cf. Patchett and Bridgewater, 1984; Hildreth and Moorbath, 1988). The two felsic granulites from the McBride suite are interpreted as products of just such crust–mantle mixing. Their isotopic compositions suggest that between 50% and 70% of these rocks may represent new crustal additions. If this is true, then the amount of crustal growth occurring during the Phanerozoic orogeny may be considerably greater than what would be estimated based upon study of the surface rocks alone (cf. Black and McCulloch, 1989).

7. Conclusions

The new Sr and Nd isotopic results reported here, in combination with previously published Th–U zircon ion probe ages and major- and trace-element compositions, suggest:

(1) The whole-rock isotopic composition of the McBride province lower-crustal xenoliths result mainly from mixing between a Paleozoic, mantle-derived basaltic component and an isotopically evolved Proterozoic lower-crustal component. Possible mixing end-members are found in the xenolith suite and in the outcropping surface rocks.

(2) Proterozoic t_{DM} ages for mafic melt-like xenoliths are much older than the basaltic underplating which gave rise to them. This is probably due to assimilation of small amounts of a Proterozoic crustal component by the basaltic melt. Thus it is difficult to infer the timing of lower-crustal underplating events from t_{DM} ages of mafic granulite xenoliths.

(3) Proterozoic t_{DM} ages for the felsic xenoliths also result from crust–mantle mixing and give an average crust formation age.

(4) The lower crust represents a geological environment in which large-scale mixing between new crustal additions (in the form of intruded basaltic melts) and pre-existing crust may occur (such as the MASH zone of Hildreth and Moorbath, 1988).

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References

- Arndt, N.T. and Goldstein, S.L., 1987. Use and abuse of crust-formation ages. *Geology*, 15: 893–895.
- Black, L.P., 1980. Rb–Sr systematics of the Claret Creek ring complex and their bearing on the origin of Upper Palaeozoic igneous rocks in northeast Queensland. *J. Geol. Soc. Aust.*, 27: 157–166.
- Black, L.P. and McCulloch, M.T., 1984. Sm–Nd ages of the Arunta, Tennant Creek, and Georgetown Inliers of northern Australia. *Aust. J. Earth Sci.*, 31: 49–60.
- Black, L.P. and McCulloch, M.T., 1990. The varied dependence of granite genesis on new crust formation, as illustrated by recurrent felsic magmatism in the Georgetown region of northeastern Australia. *Geochim. Cosmochim. Acta*, 54: 183–196.
- Black, L.P., Bell, T.H., Rubenach, M.J. and Withnall, I.W., 1979. Geochronology of discrete structural–metamorphic events in a multiply deformed Precambrian terrain. *Tectonophysics*, 54: 103–137.
- B.V.S.P. (Basaltic Volcanism on the Terrestrial Planets), 1981. Pergamon, New York, N.Y., 1286 pp.
- Cameron, K.L. and Robinson, J.V., 1990. Comments on “Nd–Sr isotopic compositions of lower crustal xenoliths — evidence for the origin of mid-Tertiary felsic volcanics in Mexico”, by J. Ruiz, P.J. Patchett and R.J. Arculus. *Contrib. Mineral. Petrol.* (in press).
- DePaolo, D.J., 1981. Trace element and isotopic effects of combined wallrock assimilation and fractional crystallization. *Earth Planet. Sci. Lett.*, 53: 189–202.
- Downes, H. and Leyreloup, A.F., 1986. Granulitic xenoliths from the French Massif Central — petrology, Sr and Nd isotope systematics and model age estimates. In: B. Dawson, D.A. Carswell, J. Hall and K.H. Wedepohl (Editors), *The Nature of the Lower Continental Crust*. *Geol. Soc. London, Spec. Publ. No. 24*, pp. 319–330.
- Downes, H., Dupuy, C. and Leyreloup, A.F., 1990. Crustal evolution of the Hercynian belt of Western Europe: Evidence from lower-crustal granulitic xenoliths (French Massif Central). In: B.K. Nelson and Ph. Vidal (Guest-Editors), *Development of Continental Crust through Geological Time*. *Chem. Geol.*, 83: 209–231 (this special issue).
- Esperança, S., Carlson, R.W. and Shirey, S.B., 1988. Lower crustal evolution under central Arizona: Sr, Nd and Pb isotopic and geochemical evidence from the mafic xenoliths of Camp Creek. *Earth Planet. Sci. Lett.*, 90: 26–40.
- Ewart, A.J., Chappell, B.W. and Menzies, M.A., 1988. An overview of the geochemical and isotopic characteristics of the eastern Australian Cainozoic volcanic provinces. *J. Petrol., Spec. Lithosphere Iss.*, pp. 225–273.
- Farmer, G.L. and DePaolo, D.J., 1983. Origin of Mesozoic and Tertiary granite in the western United States and implications for pre-Mesozoic crustal structure, 2. Nd and Sr isotopic studies of unmineralized and Cu- and Mo-mineralized granite in the Precambrian craton. *J. Geophys. Res.*, 89: 10141–10160.
- Furlong, K.P. and Fountain, D.M., 1986. Continental crustal underplating: thermal considerations and seismic–petrologic consequences. *J. Geophys. Res.*, 91: 8285–8294.
- Halliday, A.N., Stephens, W.E., Hunter, R.H., Menzies, M.A., Dickin, A.P. and Hamilton, P.J., 1985. Isotopic and chemical constraints on the building of the deep Scottish lithosphere. *Scott. J. Geol.*, 21: 465–491.
- Henderson, R.A. and Stephenson, P.J., 1980. *The Geology and Geophysics of Northeastern Australia*. *Geol. Soc. Aust., Brisbane, Qld.*, 468 pp.

- Hergt, J.M., Chappell, B.W., McCulloch, M.T., McDougall, I. and Chivas, A.R., 1989. Geochemical and isotopic constraints on the origin of the Jurassic dolerites of Tasmania. *J. Petrol.*, 30: 841–883.
- Hildreth, W. and Moorbath, S., 1988. Crustal contributions to arc magmatism in the Andes of central Chile. *Contrib. Mineral. Petrol.*, 98: 455–489.
- James, D.E., 1981. The combined use of oxygen and radiogenic isotopes as indicators of crustal contamination. *Annu. Rev. Earth Planet. Sci.*, 9: 311–344.
- Johannes, W. and Gupta, L.N., 1982. Origin and evolution of a migmatite. *Contrib. Mineral. Petrol.*, 79: 114–123.
- Johnson, R.W., Knutson, J. and Taylor, S.R., 1989. Intra-plate volcanism in eastern Australia and New Zealand. *Aust. Acad. Sci., Canberra. A.C.T.*, 408 pp.
- Kempton, P.D., Harmon, R.S., Hawkesworth, C.J. and Moorbath, S., 1990. Petrology and geochemistry of lower crustal granulites from the Geronimo volcanic field, southeastern Arizona. *Geochim. Cosmochim. Acta* (in press).
- Leshner, C.E., 1990. Decoupling of chemical and isotopic exchange during magma mixing. *Nature (London)*, 344: 235–237.
- Liew, T.C. and Hofmann, A.W., 1988. Precambrian crustal components, plutonic associations, plate environment of the Hercynian foldbelt of central Europe: indications from a Nd and Sr isotopic study. *Contrib. Mineral. Petrol.*, 98: 129–138.
- Liew, T.C. and McCulloch, M.T., 1985. Genesis of granitoid batholiths of Peninsular Malaysia and implications for models of crustal evolution: Evidence from a Nd–Sr isotopic and U–Pb zircon study. *Geochim. Cosmochim. Acta*, 49: 587–600.
- Loock, G., Seck, H.A. and Stosch, H.-G., 1990. Petrology and geochemistry of granulite facies lower crustal xenoliths from the Eifel, West Germany. *Contrib. Mineral. Petrol.* (in press).
- Marsh, J.S., 1989. Geochemical constraints on coupled assimilation and fractional crystallization involving upper crustal compositions and continental tholeiitic magma. *Earth Planet. Sci. Lett.*, 92: 70–80.
- McCulloch, M.T. and Chappell, B.W., 1982. Nd isotopic characteristics of S- and I-type granites. *Earth Planet. Sci. Lett.*, 58: 51–64.
- McCulloch, M.T. and Wasserburg, G.I., 1978. Sm–Nd and Rb–Sr chronology of continental crust formation. *Nature (London)*, 200: 1003–1011.
- McDonough, W.F. and McCulloch, M.T., 1987. The southeast Australian lithospheric mantle: isotopic and geochemical constraints on its growth and evolution. *Earth Planet. Sci. Lett.*, 86: 327–340.
- Patchett, P.J. and Arndt, N.T., 1986. Nd isotopes and tectonics of 1.9–1.7 Ga crustal genesis. *Earth Planet. Sci. Lett.*, 78: 329–328.
- Patchett, P.J. and Bridgwater, D., 1984. Origin of continental crust of 1.9–1.7 Ga age defined by Nd isotopes in the Ketilidian terrain of south Greenland. *Contrib. Mineral. Petrol.*, 87: 311–318.
- Plank, T. and Langmuir, C.H., 1988. An evaluation of the global variation in the major element chemistry of arc basalts. *Earth Planet. Sci. Lett.*, 90: 349–370.
- Reid, M.R., 1990. Rare earth element distributions and partial melting of metapelitic granulites. In: D. Vielzeuf and P. Vidal (Editors), *Granulites and Crustal Differentiation*. N.A.T.O. (North Atlantic Treaty Org.), A.S.I. (Adv. Stud. Inst.) Ser., Kluwer, Dordrecht (in press).
- Rudnick, R.L. and Goldstein, S.L., 1990. The Pb isotopic compositions of lower crustal xenoliths and the evolution of lower crustal Pb. *Earth Planet. Sci. Lett.* (in press).
- Rudnick, R.L. and Taylor, S.R., 1987. The composition and petrogenesis of the lower crust: a xenolith study. *J. Geophys. Res.*, 92: 13981–14005.
- Rudnick, R.L. and Williams, I.S., 1987. Dating the lower crust by ion microprobe. *Earth Planet. Sci. Lett.*, 85: 145–161.
- Rudnick, R.L., McDonough, W.F., McCulloch, M.T. and Taylor, S.R., 1986. Lower crustal xenoliths from Queensland, Australia: evidence for deep crustal assimilation and fractionation of continental basalts. *Geochim. Cosmochim. Acta*, 50: 1099–1115.
- Ruiz, J., Patchett, P.J. and Arculus, R.J., 1988. Nd–Sr isotope composition of lower crustal xenoliths — evidence for the origin of mid-Tertiary felsic volcanics in Mexico. *Contrib. Mineral. Petrol.*, 99: 36–43.
- Ruiz, J., Patchett, P.J. and Arculus, R.J., 1990. Reply to Comments on “Nd–Sr isotopic compositions of lower crustal xenoliths — evidence for the origin of mid-Tertiary felsic volcanics in Mexico”, by K.L. Cameron and J.V. Robinson. *Contrib. Mineral. Petrol.* (in press).
- Stolz, A.J., 1987. Fluid activity in the lower crust and upper mantle: mineralogical evidence bearing on the origin of amphibole and scapolite in ultramafic and mafic granulite xenoliths. *Mineral. Mag.*, 51: 719–732.
- Stolz, A.J. and Davies, G.R., 1989. Metasomatized lower crustal and upper mantle xenoliths from north Queensland: chemical and isotopic evidence bearing on the composition and source of the fluid phase. *Geochim. Cosmochim. Acta*, 53: 649–660.
- Taylor, S.R. and McLennan, S.M., 1985. *The Continental Crust: Its Composition and Evolution*. Blackwell, Oxford, 312 pp.
- Toriumi, M., 1986. Mechanical segregation of garnet in synmetamorphic flow of pelitic schists. *J. Petrol.*, 27: 1393–1408.
- Wass, S.Y. and Hollis, J.D., 1983. Crustal growth in southeastern Australia — evidence from lower crustal eclogitic and granulitic xenoliths. *J. Metam. Geol.*, 1: 25–45.
- White, W.M. and Patchett, P.J., 1984. Hf–Nd–Sr isotopes and incompatible element abundances in island arcs: implications for magma origins and crust–mantle evolution. *Earth Planet. Sci. Lett.*, 67: 167–185.