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Isotopic assessment of relative contributions from crust and mantle sources to the magma genesis of Precambrian granitoid rocks

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Rb–Sr, Sm–Nd and U–Th–Pb isotopic data for Precambrian granitoids (i.e. granites and intermediate calc-alkaline plutonic rocks) from Greenland, Scotland and Zimbabwe are used to assess the relative contributions to magma genesis of various source materials. Ancient continental crustal contributions are identified by negative ϵ_{Nd} values in the magmas at time of formation. Initial $^{87}Sr/^{86}Sr$ (Sr_I) values identify crustal contributions as derived from deep (low Rb/Sr) or upper (high Rb/Sr) crust. Pb isotopic data, expressed as model μ_1 ($^{238}U/^{204}Pb$) values, permit the distinction between deep (low U/Pb) and upper (high U/Pb) crustal contributions. However, it is not usually possible to distinguish between mantle (low Rb/Sr) and deep crustal sources using Sr_I values. In contrast, Nd and Pb isotopic data permit such a distinction to be made.

The granitoids isotopically analysed for the present study range from calc-alkaline types with mantle or mixed mantle–crust isotopic characteristics (for example, late Archaean orthogneisses from west Greenland) to true granites probably produced solely by anatexis of ancient sialic crust (for example, Badcall Quay red granite, northwest Scotland; Qôrqut granite, west Greenland; Mont d'Or granite, Zimbabwe)

1. Introduction

Much debate centres on the petrogenetic interpretation of initial Sr, Nd and Pb isotopic compositions of continental igneous rocks in different tectonic environments. Some of the principal processes and mechanisms proposed for modelling the intial istotope characteristics are (i) partial melting of either upper mantle materials or basic oceanic crust or both; (ii) crystal fractionation differentiation of magmas derived from either the upper mantle or basic oceanic crust or both; (iii) partial melting of continental crust; (iv) bulk assimilation of continental crust; (v) assimilation of easily fusible crustal components enriched in incompatible elements; (vi) contamination by mantle- or crust-derived fluids enriched in incompatible elements; or (vii) various combinations of these mechanisms.

The Rb–Sr decay scheme is widely used in petrogenetic studies, but in some cases it cannot provide unambiguous diagnostic criteria for or against crustal melting. Rb-depleted, lower continental crust in granulite facies typically has $Rb/Sr < ca. 0.04$, so that even very ancient crust of this type has $^{87}Sr/^{86}Sr$ ratios not significantly different from modern upper mantle values. For example, present-day $^{87}Sr/^{86}Sr$ ratios of late Archaean (*ca.* 2900–2700 Ma) basic-to-intermediate Lewisian granulites of northwest Scotland range from 0.7021 to 0.7034 (Chapman 1978), while Proterozoic (*ca.* 1800 Ma) granulites from Moskenesøy, Lofoten, north Norway range from 0.7033 to 0.7052 (Taylor, unpublished data). Melting in such gneisses today would produce magmas with low Sr_I values (*ca.* 0.703–0.705) not clearly distinguishable from mantle-derived rocks. However, U/Pb ratios in deep, high-grade sialic crust are typically much lower than in the mantle, so that Pb isotopic ratios in magmas may be used to distinguish between lower crust and mantle origins. If Lewisian granulites were partially melted today, Pb isotopic ratios of the resulting magmas would be *far* less radiogenic (mean $^{206}Pb/^{204}Pb \approx 14.0$ and $^{207}Pb/^{204}Pb \approx 14.7$; Chapman & Moorbath 1977) than modern sub-Lewisian mantle (mean $^{206}Pb/^{204}Pb \approx 18.2$ and $^{207}Pb/^{204}Pb \approx 15.5$; Dickin 1981). Amphibolite facies gneisses are more variable and may have a combination of average crustal Rb/Sr ≈ 0.2–0.4, with U/Pb ratios as low as granulite facies rocks. For example, if amphibolite facies Amîtsoq gneisses (*ca.* 3650 Ma) of the type exposed in west Greenland were melted today, the resulting magmas would have $^{87}Sr/^{86}Sr$ ratios of *ca.* 0.72–0.74, but extremely unradiogenic $^{206}Pb/^{204}Pb$ and $^{207}Pb/^{204}Pb$ ratios of *ca.* 11.5–13.0 and 13.1–13.6. Partial melting of, or contamination with, ancient U-depleted (low-U/Pb) sialic crust may be demonstrated from Pb isotopes in a wide variety of continental magmas. This has been used to characterize deeply buried continental crust (see, for example, Taylor *et al.* 1980; Dickin 1981; Moorbath & Taylor 1981). Conversely, partial melting of, or contamination with, ancient U-enriched (high-U/Pb) sialic crust may also be clearly recognized from Pb isotopic studies. The apparent $^{238}U/^{204}Pb$ (μ_1) values for the sources of crustally mobilized or contaminated granitic melts can be calculated assuming a single-stage model for Pb isotopic evolution from time of Earth formation to the measured isochron age. They may be significantly below or above the range *ca.* 7.5–8.0, regarded as typical for Archaean upper mantle sources (Moorbath & Taylor 1981).

The principal contrast between the Sm–Nd method and both Rb–Sr and U–Pb methods lies in the close geochemical coherence between Sm and Nd. These two elements are not significantly fractionated within the continental crust by metamorphic or sedimentary processes (see, for example, McCulloch & Wasserburg 1978). On the other hand, magmatic processes generate light rare-earth element (l.r.e.e.) enriched continental crustal material, so that the increase in $^{143}Nd/^{144}Nd$ is retarded in continental crust relative to the mantle. Although Sm–Nd studies of granitoid rocks are not numerous (see, for example, Hamilton *et al.* 1980; Allègre & Othman 1980; DePaolo 1981 *a*, *b*; McCulloch & Chappell 1982; Duyverman *et al.* 1982), the available data strongly support much earlier Sr and Pb isotopic evidence leading to classification of granitoid rocks into those of mantle origin, those of crustal origin, and those of mixed origins. The influence of old continental crust in the genesis of many true granites is clearly shown by Sm–Nd model ages greatly exceeding the age of intrusion, and by unradiogenic initial $^{143}Nd/^{144}Nd$ ratios compared with the Nd isotopic composition of contemporaneous mantle.

We stress that for most situations, resolution of crustal residence time before the closure of isotopic systems is not normally better than *ca.* 100–200 Ma, but for Archaean crust-forming events Pb isotopes can be particularly sensitive indicators of older crustal involvement.

The view of Allègre & Othman (1980) that 'granites' younger than *ca.* 2000 Ma contain some recycled crustal component but that older ones are juvenile mantle extracts makes no petrogenetic, tectonic or other distinction between true granites and the calc-alkaline magmatic rocks, while the limited sampling of the great variety of Precambrian and Phanerozoic environments cannot be regarded as adequate to justify their generalized global modelling. Published isotopic evidence demonstrates that true granites of *any* geological age may include large proportions of crustal components, while calc-alkaline granitoids (e.g. granodiorite, tonalite, diorite) of *any* geological age – but especially Precambrian orthogneisses in shield areas – may be predominantly derived from mantle-like sources, although there may be isotopic evidence for limited crustal contamination. Each geological province, of whatever age, must be investigated in detail before making global generalization of the type proposed by Allègre & Othman (1980). Isotopic data should not be discussed in isolation from geological, petrological and structural evidence in complex terrains. Granitoid petrogenesis bears no direct relation to age but must be considered primarily in terms of the regional geological setting. Both crust and mantle have contributed to crustal magma genesis throughout geological time, except that the earliest continental crust could only have had a mantle-type precursor.

Recent data from experimental petrology emphasizes the fundamental petrogenetic distinction between granites and calc-alkaline granitoids, with respective emphasis on sialic and simatic precursors (see, for example, Stern *et al.* 1975; Wyllie *et al.* 1976; Wyllie 1977, 1981).

In this paper, we investigate combined Rb–Sr, Pb/Pb and Sm–Nd systematics of several Precambrian granites and granitoids from northwest Scotland, west and east Greenland, and Zimbabwe. The aim is to compare and contrast results from these isotopic systems in order to obtain isotope-geochemical and petrogenetic constraints of general applicability to magma genesis and crustal evolution. Few studies using all three methods on individual rock units have been published to date (e.g. DePaolo *et al.* 1982). Rb–Sr and Pb/Pb data for the Nûk gneisses and the Qôrqut granite of west Greenland have been published previously (Taylor *et al.* 1980; Moorbath *et al.* 1981), as well as Rb–Sr data for the Mont d'Or granite of Zimbabwe (Moorbath *et al.* 1976). No Sm–Nd data are yet available for two of the rock units (Mont d'Or granite, Loch Stack White Granite Sheet).

2. ANALYTICAL METHODS

Rb/Sr ratios were determined on pressed powder pellets by X.R.F., by using a method similar to that of Pankhurst & O'Nions (1973). Sr was separated from rock powders by conventional cation exchange techniques, and isotopically analysed on a V.G. Micromass-30 mass spectrometer.

Pb samples for mass spectrometry were prepared by the double electro-deposition method of Arden & Gale (1974) and loaded on single rhenium filaments with H_3PO_4 and silica gel. Pb isotopic analyses were run either on a 30 cm radius, 90° sector, solid-source mass spectrometer designed by N. H. Gale, or on a fully automated V.G.-Isomass 54E mass spectrometer. The sample preparation blank was *ca.* 6–10 ng, which has a negligible effect on reported Pb isotopic analyses since several micrograms of Pb were extracted from each sample. Pb concentrations of a few samples were determined by mass-spectrometric isotopic dilution; these were then used as calibration standards for determining Pb concentrations on the other samples by an X.R.F. method.

Sm and Nd were extracted using a two-column chromatographic procedure similar to that of Jahn *et al.* (1980), but with smaller column dimensions to achieve low blank levels. Total procedural blanks for Sm and Nd were about 20 pg and 100 pg respectively, and are negligible. Both Sm and Nd were loaded on triple filaments (Ta side, Re centre) in H_3PO_4 and analysed as the M^+ species with the VG-Isomass 54E mass spectrometer. Nd data are normalized to $^{146}Nd/^{142}Nd = 0.63223$ and Sm data to $^{147}Sm/^{154}Sm = 0.66625$. The mean $^{143}Nd/^{144}Nd$ of seven analyses of BCR-1 during this work was 0.512636 ± 12 (2σ).

TABLE 1. Rb–Sr AND Pb/Pb ANALYTICAL DATA

sample	Rb (μg/g)	Sr (μg/g)	^{87}Rb/^{86}Sr	^{87}Sr/^{86}Sr	Pb (μg/g)	$\frac{^{206}\text{Pb}}{^{204}\text{Pb}}$	$\frac{^{207}\text{Pb}}{^{204}\text{Pb}}$	$\frac{^{208}\text{Pb}}{^{204}\text{Pb}}$
				Loch Laxford region, northwest Scotland				
Badcall Quay Red Granite								
NJ7	144	316	1.32	0.73771	54	14.754	14.763	35.644
NJ9	101	298	0.977	0.72927	30	14.551	14.744	36.824
NJ10	116	315	1.06	0.73167	30	14.993	14.820	38.068
NJ11	139	327	1.22	0.73482	31	14.571	14.754	34.411
NJ12	150	316	1.38	0.73821	30	14.317	14.721	34.578
NJ15	150	304	1.42	0.74047	38	14.497	14.749	34.517
NJ16	149	296	1.46	0.74152	31	14.105	14.712	34.401
NJ17	151	350	1.25	0.73582	45	14.745	14.780	37.277
NJ18	89	305	0.845	0.72658	29	14.247	14.717	34.783
NJ19	66	286	0.661	0.72056	21	14.892	14.778	35.976
NJ20	96	344	0.801	0.72466	37	17.741	15.094	37.906
NJ19pl	14	224	0.170	0.70946	—	—	—	—
NJ8	—	—	—	—	40	19.810	15.313	36.050
NJ13	—	—	—	—	32	14.280	14.729	35.091
NJ14	—	—	—	—	34	14.160	14.709	35.076
NJ16 ep	—	—	—	—	—	14.101	14.711	34.359
NJ19 Kf	—	—	—	—	68	13.946	14.690	34.294
Rubha Ruadh Granite Sheet								
NJ30	138	2674	0.145	0.70710	41	15.301	14.987	38.178
NJ31	101	1883	0.151	0.70712	37	15.865	14.997	37.329
NJ32	140	2417	0.164	0.70707	44	15.515	14.964	37.982
NJ33	121	2416	0.141	0.70687	38	15.518	15.001	39.069
NJ34	148	2242	0.189	0.70796	40	15.586	15.001	38.757
NJ35	115	2398	0.135	0.70675	43	15.379	14.974	37.723
NJ36	133	1510	0.251	0.70932	37	15.374	14.935	35.939
NJ37	116	2335	0.139	0.70679	39	15.446	14.975	38.109
NJ39	105	458	0.665	0.71923	16	15.190	14.891	36.300
NJ40	93	910	0.292	0.71077	30	14.927	14.873	34.918
NJ41	204	1770	0.332	0.71127	42	16.517	15.055	38.460
NJ42	46	1064	0.119	0.70655	26	15.807	14.998	34.750
NJ43	142	1986	0.203	0.70837	40	15.512	14.975	37.152
NJ35 l	70	2242	0.086	0.70544	33	14.754	14.906	34.899
NJ35 m	118	2353	0.142	0.70689	46	15.495	15.004	37.657
NJ38	—	—	—	—	40	15.529	15.012	38.510
NJ35 lKf	—	—	—	—	—	14.381	14.862	34.417
NJ40 Kf	—	—	—	—	—	14.687	14.864	34.545
Loch Stack White Granite Sheet								
NJ22	45	576	0.218	0.70888	66	36.045	17.156	34.986
NJ24	144	502	0.828	0.72315	92	28.403	16.327	34.917
NJ25	30	586	0.144	0.70710	56	29.467	16.452	35.658
NJ26	60	587	0.297	0.71090	64	29.842	16.490	34.794
NJ27	157	417	1.09	0.70328	98	16.184	15.000	34.618
NJ28	126	603	0.603	0.71799	81	23.711	15.824	34.817
NJ29	82	515	0.456	0.71459	71	23.900	15.871	34.516
NJ21	—	—	—	—	50	33.798	16.865	34.857
NJ23	—	—	—	—	52	37.632	17.308	35.483
NJ24 Kf	—	—	—	—	—	15.004	14.894	34.294
NJ25 Kf	—	—	—	—	—	14.407	14.812	35.282
				East Greenland				
Angmagssalik Granite								
229555	93	198	1.32	0.73433	17	15.450	14.908	38.426
229556	96	199	1.37	0.73522	16	15.319	14.886	38.519
229557	91	199	1.29	0.73392	15	15.416	14.885	37.928
229558	92	201	1.31	0.73368	17	15.492	14.900	38.988
229559	111	107	2.98	0.77162	17	15.473	14.903	37.632
229560	143	123	3.32	0.77791	17	17.809	15.134	40.522
229561	121	53	6.60	0.85378	19	14.953	14.871	36.311
229562	117	46	7.30	0.86840	17	14.843	14.858	36.620

Table 1 (*cont.*)

229563	123	98	3.58	0.78529	20	15.473	14.892	36.979
229564	166	122	3.88	0.79282	18	16.146	14.963	39.973
229565	149	130	3.25	0.77746	17	15.724	14.932	41.038
229566	103	106	2.75	0.76738	18	15.446	14.915	38.005
				West Greenland				
Nûk-type gneisses								
273697	—	—	—	—	18	13.653	14.423	70.504
69151	98	2060	0.128	0.70672	18.0 (i.d.)	14.096	14.555	40.632
171887	58	437	0.369	0.71720	10	14.232	14.497	35.695
273656	—	—	—	—	7	14.891	14.696	33.398
171848	56	249	0.630	0.72794	9.7 (i.d.)	13.361	13.933	33.609
171849	121	227	1.51	0.76430	23.1 (i.d.)	13.560	13.983	45.501
171850	17	348	0.135	0.70686	7	12.882	13.998	32.793
171852	14	319	0.119	0.70660	7	13.365	14.136	32.939
175731	82	234	1.02	0.74382	23	12.753	13.751	42.260
175766	64	277	0.673	0.73142	13	13.499	13.885	42.505
131588	41	570	0.194	0.71070	15	12.891	14.181	32.981
86523	146	192	2.15	0.79226	47.3 (i.d.)	15.025	14.244	37.490
86550	144	205	1.99	0.78965	42	15.270	14.337	32.582
131502	180	192	2.68	0.81431	35	13.563	13.969	37.096
131503	179	149	3.43	0.84070	46	13.146	13.812	34.303
Ivisârtoq Granite								
235002	205	15	45.9	2.3290	—	16.831	14.685	32.823
235018	226	81	8.35	1.0178	—	17.211	14.751	35.562
235019	215	85	7.49	0.98132	—	18.000	14.856	34.824
235021	229	90	7.61	0.98802	—	16.626	14.662	34.355
235022	178	47	11.4	1.1281	—	25.867	16.275	35.189
235023	172	65	7.83	1.0047	—	19.335	15.124	33.737
				Zimbabwe				
Mont d'Or Granite								
1167	—	—	1.97	0.8083	19	41.327	22.276	43.505
1204	—	—	1.94	0.8010	11	38.731	21.521	49.013
1223	—	—	1.49	0.7873	14	27.504	18.632	42.890
1249	—	—	2.79	0.8514	14	24.766	17.893	45.519
1263	—	—	1.80	0.7982	18	31.323	19.848	47.427
2123	—	—	2.20	0.8218	29	31.430	20.045	40.364
2974	—	—	3.54	0.8949	22	30.561	19.519	43.478
3692	—	—	0.633	0.7431	11	40.399	22.282	54.782
3724	—	—	0.921	0.7561	12	54.817	26.299	70.351

Notes: All 5- and 6- digit sample numbers are those of the Geological Survey of Greenland; pl = plagioclase; ep = epidote; Kf = potash feldspar; l = leucocratic; m = melanocratic. Precision on X.R.F.-determined ^{87}Rb/^{86}Sr ± 1 %. Rb and Sr contents computed with mass absorption coefficients obtained from Compton scatter peak intensities with precision better than ± 5 %. Average 2σ error on individual ^{87}Sr/^{86}Sr ratios (normalized to ^{86}Sr/^{88}Sr = 0.1194) = 0.01 %. Pb isotope ratios include mass fractionation correction assessed from standards N.B.S. 981 and 982. Average precision for ^{206}Pb/^{204}Pb, ^{207}Pb/^{204}Pb and ^{208}Pb/^{204}Pb ± 0.15 %. Pb contents determined by X.R.F. with average precision ± 1 µg/g in range 5–70 µg/g. Pb isotope dilution analyses are marked i.d. For main body of Rb–Sr and Pb/Pb data on Nûk gneisses and on Qôrqut granite, see Moorbath & Pankhurst (1976), Taylor *et al.* (1980), Moorbath *et al.* (1981).

3. RESULTS

New Rb–Sr and Pb/Pb analytical data are presented in table 1. All essential Rb–Sr line-fitting parameters for analysed rock units are given in table 2. Pb/Pb plots are shown in figure 1, and Pb/Pb line fitting parameters are summarized in table 2. Methods of graphical representation and interpretation of Pb/Pb data, as well as calculation of model parameters, exactly follow Taylor *et al.* (1980). Sm–Nd isotopic data are listed in table 3. Initial ^{143}Nd/^{144}Nd is reported in the ϵ_{Nd} notation (DePaolo & Wasserburg 1976) as deviations in parts per 10^4 from the chondritic uniform reservoir (CHUR) as determined by Jacobsen & Wasserburg (1980) with adjustments for the different normalization used here. Table 3 also gives Sm–Nd model ages in the T_{CHUR} notation of McCulloch & Wasserburg (1978). All errors on ages and isotopic ratios are quoted at the 2σ level. The threshold for distinguishing between 'isochrons' and 'errorchrons' in this work is taken at an m.s.w.d. value of 2.5, following the method of Brooks *et al.* (1972). This represents a 95% confidence level that regressions with relatively few points exhibit greater-than-analytical (i.e. geological) scatter.

Isotopic data are discussed in regional groupings. Full details of regional geology will be found in the quoted references.

4. Discussion of results

(*a*) *Granitic rocks from the Lewisian Complex of northwest Scotland and from the Precambrian basement of east Greenland*

The analysed rocks come from the area of the Laxford Front, near the hamlet of Laxford Bridge, *ca.* 8 km east-northeast of Scourie village. The Laxford Front is a zone of complex deformation and alkali metasomatism separating intensely deformed Proterozoic (*ca.* 1800–1600 Ma) Laxfordian migmatites to the north from heterogeneously deformed Scourian (*ca.* 2900–2700 Ma) amphibolite facies gneisses (between Laxford Bridge and Scourie) and pyroxene granulite facies gneisses, south of Scourie (Sutton & Watson 1951, 1962; Lambert & Holland 1972; Pidgeon & Bowes 1972; Beach *et al.* 1974; Hamilton *et al.* 1979). A major problem concerning the development of the Lewisian Complex is the age and origin of the voluminous granitic sheets, dykes and pegmatites found in the Laxfordian gneiss around Laxford Bridge. Three different types of these Laxfordian granitic intrusives were sampled.

(i) *Badcall Quay Red Granite* (B.Q.R.G.)

Samples were collected over a distance of 200 m at Badcall Quay, northwest of Laxford Bridge (grid reference NC 228475). The rocks consist of coarse-grained or pegmatitic granite devoid of foliation or mineral lineation. Contacts with country rock grey gneisses are irregular and indistinct. Mineralogy comprises quartz, microcline, orthoclase, plagioclase; subordinate muscovite, biotite, perthite, epidote; accessory opaques, zircon.

Eleven whole-rock samples, plus one plagioclase separate, yield an Rb–Sr errorchron (m.s.w.d. = 3.9) age of 1706 ± 38 Ma, with $Sr_i = 0.7052 \pm 0.0004$ (table 2). This Sr_i is significantly higher than a plausible *ca.* 1700 Ma-old upper mantle source (*ca.* 0.702–0.703), or than the highly Rb-depleted *ca.* 2900–2700 Ma-old Scourian granulite facies rocks, which even today fall in the range 0.7021–0.7034 (Chapman 1978). To attain an Sr_i of 0.7052 would require a source region between *ca.* 2700–1700 Ma with Rb–Sr $\approx$ 0.09, which is much greater than the analysed granulites (*ca.* 0.003–0.01) and about three times greater than upper mantle.

Fourteen whole-rock samples, one K-feldspar and one epidote give a Pb/Pb isochron (m.s.w.d. = 0.36) age of 1740 ± 80 Ma (table 2), in agreement with the Rb–Sr age. All but two points cluster near the unradiogenic end of the isochron, the least radiogenic being the feldspar Pb. An apparent μ_1 value of 7.27 is obtained on the assumption of a single-stage model of Pb isotopic evolution until 1740 Ma. This is significantly below the range (*ca.* 7.5–8.0) expected for a valid single-stage model for a mantle-type source region (Moorbath & Taylor

TABLE 2. SUMMARY OF Rb–Sr AND Pb/Pb REGRESSION DATA

sample suite	Rb–Sr age/Ma	Sr_i	number of data points	m.s.w.d.	Pb–Pb age/Ma	apparent μ_1	number of data points	m.s.w.d.
Badcall Quay Red Granite NW Scotland	1706 ± 38	0.7052 ± 0.0004	12	3.9	1740 ± 80	7.27	16	0.36
Rubha Ruadh Granite Sheet, NW Scotland	1650 ± 55	0.7035 ± 0.0002	15	2.6	1710^{+400}_{-560}	7.49	18	3.5
Loch Stack White Granite Sheet, NW Scotland	1665 ± 30	0.7037 ± 0.0002	7	1.5	1754 ± 18	7.44	11	1.6
Angmagssalik Granite, E Greenland	1570 ± 20	0.7045 ± 0.0005	12	0.9	1520^{+210}_{-240}	7.35	12	0.6
Nûk-type gneisses, W Greenland (table 1)	2900 ± 35	0.7014 ± 0.0002	9	1.1	variably Pb-contaminated; see table 3 and Taylor *et al.* (1980)			
Qôrqut Granite, W Greenland	2530 ± 30	0.7081 ± 0.0008	23	3.2	2580 ± 80	6.23	23	3.2
Ivisârtoq Granite, W Greenland	2430 ± 60	0.723 ± 0.007	6	1.6	2615 ± 35	6.59	6	1.7
Mont d'Or Granite, Zimbabwe	3430 ± 160	0.711 ± 0.003	9	3.6	3320 ± 80	9.42	9	105
	3420 ± 120	0.711 ± 0.002	7	2.2	3340 ± 50	9.25	7	49

Notes: Decay constants and model parameters: $\lambda_{87} = 1.42 \times 10^{-11} a^{-1}$; $\lambda_{238} = 0.155125 \times 10^{-9} a^{-1}$; $\lambda_{235} = 0.98485 \times 10^{-9} a^{-1}$; $^{238}U/^{235}U = 137.88$; age of Earth = 4570 Ma; for primordial Pb, $^{206}Pb/^{204}Pb = 9.307$, $^{207}Pb/^{204}Pb = 10.294$. All errors given at 2σ level. For detailed discussion of isotopic data on Nûk gneisses and Qôrqut Granite, see Taylor *et al.* (1980) and Moorbath *et al.* (1981). For discussion of Rb–Sr data on Mont d'Or Granite, see Moorbath *et al.* (1976).

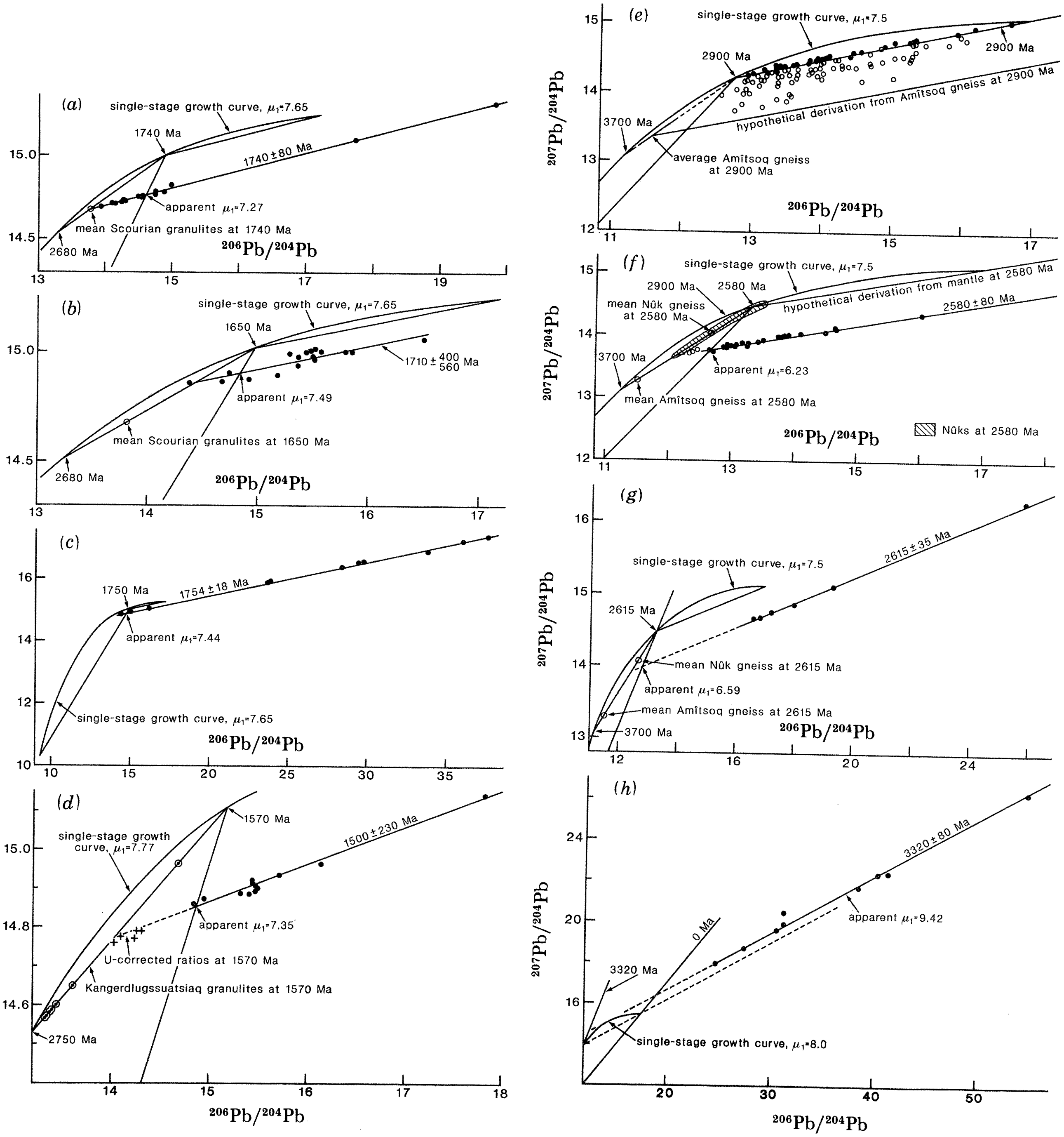

FIGURE 1. Pb/Pb plots for all rock suites discussed in the text. (*a*) Badcall Quay Red Granite. (*b*) Rubha Ruadh Granite Sheet. (*c*) Loch Stack White Granite Sheet. (*d*) Angmagssalik Granites. (*e*) ●, Nûk-type gneisses outside Godthaabsfjord region; ○, Nûk gneisses in Godthaabsfjord region. (*f*) Qôrqut Granite Complex. (*g*) Ivisârtoq Granite. (*h*) Mont d'Or Granite.
Method of presentation follows Taylor *et al.* (1980). For data on Nûk gneisses (*e*) and on Qôrqut granite (*f*) see Taylor *et al.* (1980) and Moorbath *et al.* (1981) respectively.

1981) and thus casts doubt on the assumed model. Ten of the samples have such unradiogenic present-day Pb that they plot to the left of the first-stage isochron at 1740 Ma (figure 1*a*). This invalidates interpretation of present-day Pb isotopic ratios of B.Q.R.G. in terms of two-stage evolution (i.e. from 4570 to 1740 Ma, and from 1740 Ma until now). The most plausible three-stage model involves derivation of B.Q.R.G. at *ca.* 1740 Ma ago from a Scourian basement with an age of 2680 ± 80 Ma and a μ_1 value of 7.65, similar to the U-depleted Scourian granulites analysed by Chapman & Moorbath (1977). These granulites require an average μ_2 value of 2.64 to attain their present-day average Pb isotopic composition. Their average Pb isotopic composition at 1740 Ma is shown by the open circle on figure 1*a*. Deriving the B.Q.R.G. at 1740 Ma from the same granulite basement requires an average μ_2 of 2.48 in the basement. This close agreement between proposed and required sources strongly suggests that the B.Q.R.G was derived solely by crustal anatexis of Scourian basement gneisses, with U/Pb ratios similar to U-depleted Scourian granulites, at *ca.* 1740 Ma. However, the agreement between U/Pb characteristics of the B.Q.R.G. source region and the Scourian granulites contrasts with their mismatched Rb/Sr characteristics, described above. The frequently observed combination of low U/Pb ratios in U-depleted amphibolite facies rocks with normal crustal Rb/Sr ratios was already mentioned earlier.

The computed average μ_3 value for the B.Q.R.G. (omitting the two very radiogenic samples which may have experienced selective U-enrichment, figure 1*a*) between 1740 Ma and today is 2.43, compared to the μ_2 value of 2.48 for the source region during the second stage of evolution between 2680 and 1740 Ma. The close agreement between μ_2 and μ_3 renders it unlikely that significant amounts of U- or Pb-bearing mineral phases remained in the residuum after the melting event that produced the B.Q.R.G. In this connection, a plot of $^{208}Pb/^{204}Pb$ against $^{206}Pb/^{204}Pb$ (not shown here) produces a good linear correlation for all except the two samples with high uranogenic Pb ratios. The computed Th/U value of 18 ± 4 is much higher than the value of 3.1 quoted by Chapman & Moorbath (1977) for Scourian granulites. Amphibolite facies gneisses commonly have higher and more variable Th/U ratios than granulite facies gneisses (e.g. Rybach 1976), and this certainly applies to the Lewisian (Chapman 1978). Thus the Th/U evidence indirectly supports Sr isotopic evidence for deriving the B.Q.R.G. by melting of amphibolite- rather than granulite-facies gneisses, and further suggests that little or no Th may have remained behind in the anatectic residuum. The B.Q.R.G. is the only rock unit analysed in the present work which shows a clear-cut correlation between $^{208}Pb/^{204}Pb$ against $^{206}Pb/^{204}Pb$.

Two samples of B.Q.R.G. yield ϵ_{Nd} values of −11.9 and −9.9 (table 3) at time of emplacement *ca.* 1740 Ma ago. A Scourian-type $T_{\overline{CHUR}}$ model age of *ca.* 2750 Ma suggests that the granite was derived solely by anatexis of Scourian gneisses with essentially no change in Sm/Nd ratio on melting. This result parallels the Pb isotopic evidence in that no residual mineral phases enriched in light or heavy r.e.e. separated from the melt. Figure 2 illustrates Nd isotopic evolution of the Lewisian, based on the eleven samples (eight granitoid gneisses, three basic gneisses) analysed by Hamilton *et al.* (1979). Line A represents Nd isotopic evolution for 'mean Lewisian gneiss' and line B for 'mean Lewisian tonalitic–granodioritic gneiss', in both cases weighted according to the abundance of ^{144}Nd in individual samples. It is evident that at an assumed mean age of 1720 Ma both B.Q.R.G. samples had $^{143}Nd/^{144}Nd$ ratios very similar to those of the granitoid gneisses.

Petrogenesis of the B.Q.R.G. may be analogous to that of some much older concordant

Table 3. Sm–Nd analytical data and source parameters, and Pb-contamination parameter

sample	Sm (μg/g)	Nd (μg/g)	$^{147}Sm/^{144}Nd$	$^{143}Nd/^{144}Nd$	ϵ^{T}_{Nd}	model T^{Nd}_{chur}/Ma	emplacement age/Ma	$^{204}Pb_c/^{204}Pb_t$
Badcall Quay Red Granite								
NJ16	0.453	2.54	0.1081	0.511004	−11.9	2780	≈1720	—
NJ19	3.46	17.48	0.1203	0.511249	− 9.9	2720	≈1720	—
Rubha Ruadh Granite Sheet								
NJ30	20.39	152.1	0.0814	0.510964	− 8.1	2190	≈1650	—
NJ35L	1.83	10.85	0.1027	0.511210	− 7.8	2280	≈1650	—
NJ39	2.43	21.78	0.0677	0.510685	−10.6	2280	≈1650	—
Angmagssalik Granite								
229556	20.55	150.8	0.0827	0.510908	−10.6	2280	≈1570	—
229561	10.96	74.2	0.0898	0.511042	− 9.4	2240	≈1570	—
229565	13.59	93.3	0.0884	0.510957	−10.8	2330	≈1570	—
Nûk-type gneisses, Pb-*uncontaminated*								
273697 Sukkertoppen	21.75	223.4	0.0591	0.509995	+ 2.0	< true age	≈3000	0
69151 Fiskenaesset	25.05	241.4	0.0630	0.510285	+ 3.6	< true age	≈2850	0
171887 Sermilik	4.30	27.64	0.0944	0.510765	+ 3.4	< true age	≈3000	0
273656 Nordland	2.57	10.86	0.1438	0.511566	− 0.1	3040	≈3000	0
Nûk gneisses, Pb-*contaminated*								
171848 Buksefjord	3.43	19.02	0.1095	0.511028	+ 1.0	< true age	≈2850	0.63
171849 Buksefjord	9.76	52.84	0.1122	0.510981	− 1.0	2950	≈2850	0.61
171850 Buksefjord	3.07	24.89	0.0750	0.510346	+ 0.3	< true age	≈2850	0.40
171852 Buksefjord	1.96	12.29	0.0968	0.510854	+ 2.2	< true age	≈2850	0.35
175731 Buksefjord	2.33	17.13	0.0825	0.510243	− 4.5	3160	≈2850	0.71
175766 Buksefjord	5.49	46.07	0.0724	0.510220	− 1.2	2930	≈2850	0.73
131588 Godthaab	0.944	7.15	0.0802	0.510371	− 1.9	2930	≈2800	0.18
86523 Bjørneøen	3.50	22.27	0.0955	0.510484	− 3.9	3200	≈2900	0.68
86550 Bjørneøen	1.03	5.62	0.1114	0.510583	− 7.9	3660	≈2900	0.62
131502 N Godthaabsfjord	1.90	12.38	0.0932	0.510326	− 6.8	3360	≈2850	0.64
131503 N Godthaabsfjord	2.14	13.26	0.0979	0.510440	− 6.3	3340	≈2850	0.74
Qôrqut Granite								
171701	2.24	13.06	0.1041	0.510718	− 6.8	3120	≈2550	Amitsoq-type Pb/ Nûk-type Pb ≈0.6/0.4
171703	4.30	32.52	0.0802	0.510322	− 6.7	3000	≈2550	
273614	6.95	58.70	0.0719	0.510136	− 7.6	3020	≈2550	
273615	5.33	52.81	0.0613	0.509933	− 8.1	3010	≈2550	

Notes:
$$\lambda_{147} = 6.54\times10^{-12}\,\mathrm{a}^{-1};\quad \epsilon_{Nd} = \left[\frac{(^{143}Nd/^{144}Nd)\ T_{init}}{(^{143}Nd/^{144}Nd)\ T_{CHUR}} - 1\right]\times10^{4},$$

and

$$(^{143}Nd/^{144}Nd)^{T}_{CHUR} = (^{143}Nd/^{144}Nd)^{0}_{CHUR} - (^{147}Sm/^{144}Nd)^{0}_{CHUR}\ (e^{\lambda T}-1);$$

$$(^{143}Nd/^{144}Nd)^{0}_{CHUR} = 0.512637;\ (^{147}Sm/^{144}Nd)^{0}_{CHUR} = 0.1976;$$

$(^{143}Nd/^{144}Nd)^{T}_{init}$, is the measured ratio in the rock corrected for decay since time of crystallization, T, measured independently by Rb–Sr or Pb/Pb methods.

$$T^{Nd}_{CHUR} = \frac{1}{\lambda}\ln\left[1+\frac{(^{143}Nd/^{144}Nd)_{now}-(^{143}Nd/^{144}Nd)^{0}_{CHUR}}{(^{147}Sr/^{144}Nd)_{now}-(^{147}Sm/^{144}Nd)^{0}_{CHUR}}\right].$$

For detailed discussion of the Pb-contamination parameter $^{204}Pb_c/^{204}Pb_t$ see text, and Taylor *et al.* 1980 and Moorbath *et al.* 1981. Estimated accuracy for isotope dilution measurements of Sm and Nd is *ca.* 0.2 %. Accuracy of $^{147}Sm/^{144}Nd$ is better than 0.1 %. Within-run precision of $^{143}Nd/^{144}Nd$ is ±0.000020 (2σ).

granitic sheets in the granulite facies Scourian Complex. From trace element data, rare earth patterns and Sr isotopic data, Pride & Muecke (1982) proposed that these Scourian granite sheets 'originated by anatexis of gneisses undergoing granulite facies metamorphism that were already essentially dry and depleted in incompatible elements'.

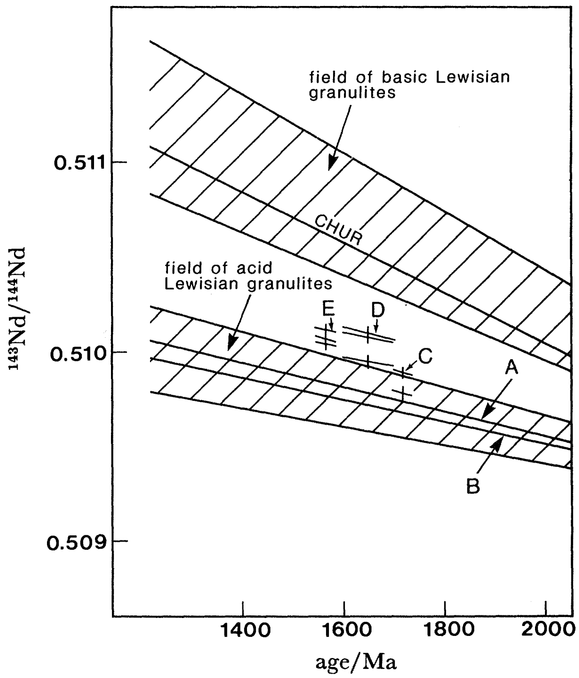

FIGURE 2. Nd isotopic evolution diagram for Lewisian gneisses (shaded) in relation to initial Nd ratios (crosses) for three rock units. CHUR is the growth line for a chondritic mantle. Line A represents the Nd isotopic evolution of 'mean Lewisian gneiss', line B of 'mean Lewisian tonalitic–granodioritic gneiss'; C, Badcall Quay granite; D, Rubha Ruadh granite; E, Angmagssalik granite.

(ii) *Rubha Ruadh granite sheet* (R.R.G.S.)

This is the largest granite intrusion in the Laxford Bridge area. It is polyphase, with several distinct facies. Its outcrop extends along the southern shore of Loch Laxford parallel to the regional NW–SE trending structures. Its southern limit defines the course of the so-called Ben Stack Line (Lambert & Holland 1972). It is *ca.* 100–150 m wide and can be traced for *ca.* 17 km. The granite sheet and its pronounced foliation dip steeply to the south-west, and geophysical evidence indicates that the associated zone of granite sheets extends obliquely under the granulites to a depth of at least 3 km (Bott *et al.* 1972). Samples were collected over an oblique traverse of 200 m across the sheet at Badnabay (grid reference NC 220473). Two samples (40 and 42) are pegmatites from within the sheet. One granite samples has alternating hornblende-rich and -poor bands *ca.* 2 cm thick, which were analysed separately (35L and 35M). Mineralogy comprises quartz, microcline, orthoclase, hornblende; subordinate perthite, epidote; accessory apatite, sphene, allanite, opaques, zircon.

Fifteen whole-rock samples yield an Rb–Sr errorchron (m.s.w.d. $= 2.6$) age of 1650 ± 50 Ma, with $\mathrm{Sr_i} = 0.7035 \pm 0.0002$ (table 2). This $\mathrm{Sr_i}$ is ambiguous in that it virtually overlaps with plausible ranges for contemporaneous mantle and Rb-depleted basement granulites.

Pb isotopic data for sixteen whole rocks and two K-feldspars yield a scatter on a Pb/Pb plot (figure 1*b*), reminiscent of the Nûk gneisses of west Greenland (Taylor *et al.* 1980). The best-fit line (m.s.w.d. = 3.5) yields a poorly defined 'age' of 1710^{+400}_{-560} Ma (table 2). Note that three points lie to the left of the first-stage isochron at 1650 Ma (the Rb–Sr age). Assuming derivation of the various components of the R.R.G.S. from sources in *ca.* 2680 Ma-old Lewisian crust, enables a range of μ_2 values from *ca.* 4.2 to 6.3 to be computed that all exceed the average μ_2 of 2.64 for Lewisian granulites. Because of the low Sr_i, it is unlikely that derivation of R.R.G.S from higher crustal levels than the granulites can account for the relatively radiogenic character of the initial Pb isotopic compositions of the R.R.G.S. These can be modelled by mixing varying proportions of material derived from ancient U-depleted crust and from the mantle. Relative proportions of ^{204}Pb derived from the two sources can be estimated for each sample, with the method of Taylor *et al.* (1980) for the Nûk gneisses. The choice of a single-stage model for mantle Pb isotopic evolution with $\mu_1 \approx 7.7$ provides a *minimum* plausible estimate of the ancient crustal ^{204}Pb contribution in each sample. The proportions range from 27% (sample 38) to 68% (sample 39). Relative mass contributions of the two sources are not determinable in the absence of information on the Pb content and isotopic composition of the juvenile component.

Three R.R.G.S. samples yield crustal ϵ_{Nd} values of -8.1, -7.8, -10.6 (table 3) at 1650 Ma. T_{CHUR} model ages of *ca.* 2200–2300 Ma suggest minimum values for the age of the crustal component. On the Nd isotope evolution diagram (figure 2) the three samples have somewhat more radiogenic Nd isotopic compositions than acid Lewisian granulites at 1650 Ma. The radiogenic Nd contribution may have originated either in contemporaneous mantle, close to the CHUR line of figure 2, or in basic components of the Lewisian gneisses, but such basic components might be too refractory to melt. Thus it is more likely that the heterogeneous components of the R.R.G.S. were derived by mixing of materials derived in part from ancient Scourian granitoid crust and in part from the mantle, as was also deduced from Pb isotopic data. However, a heterogeneous acid-basic crustal source for the R.R.G.S. cannot be excluded from the combined isotopic evidence.

(iii) *Loch Stack White Granite Sheet* (L.S.W.G.S.)

This approximately 1 m-thick, steeply dipping sheet is very close to the Ben Stack Line south of Loch Stack. Samples were collected over a distance of *ca.* 30 m (grid reference NC 292417) and include some fallen blocks. The rock is medium-to-coarse grained, occasionally pegmatitic and lacks penetrative foliation. Mineralogy is quartz, microcline, plagioclase, orthoclase; subordinate perthite, biotite, muscovite, epidote; accessory pyrite, zircon, molybdenite.

Seven whole-rock samples yield an Rb–Sr isochron (m.s.w.d. = 1.5) age of 1665 ± 30 Ma, with $Sr_i = 0.7037 \pm 0.0002$ (table 2). As with the R.R.G.S., this Sr_i value is close to contemporaneous mantle and to Rb-depleted lower crust.

Nine whole-rock samples and two K-feldspars give a Pb/Pb isochron (m.s.w.d. = 1.6) age of 1754 ± 18 Ma (table 2). The high precision of the age results from the wide spread of Pb isotopic compositions to very radiogenic values (table 1, figure 1*c*). An apparent μ_1 value of 7.44 is obtained on the assumption of single-stage Pb isotopic evolution until 1750 Ma, but since one feldspar Pb plots to the left of the first stage isochron at 1750 Ma, this assumption is invalidated. In order to derive the L.S.W.G.S. from *ca.* 2680 Ma-old Scourian crust with $\mu_1 = 7.65$ (Chapman & Moorbath 1977), a model μ_2 of 4.79 would be required between 2680 and 1750 Ma. This is much higher than the average μ_2 of 2.64 in analysed Scourian granulites

(Chapman & Moorbath 1977). In view of the low Sr_i of 0.7037, the L.S.W.G.S. is unlikely to be derived from a higher crustal level than the granulites, but certainly from a lower crustal level than the B.Q.R.G. ($Sr_i = 0.7052$). As with the R.R.G.S., we favour a mixed source consisting of lower crust and upper mantle materials. Assuming a μ_1 value of 7.65 for mantle evolution prior to 2680 Ma, and identifying high-grade Scourian gneisses as the only other source of Pb, it is computed that not less than *ca.* 57% of the total ^{204}Pb in the L.S.W.G.S. is of crustal origin. This is not necessarily representative of the relative mass contributions of crust and mantle, which requires a knowledge of the Pb content of the mantle-derived component.

The very radiogenic Pb isotopic ratios show that most samples of L.S.W.G.S. (table 1, figure 1*c*) had very high U/Pb ratios during the past 1750 Ma. Computed μ_3 values range from *ca.* 1 to 75, while the *mean* enrichment factor from the second ($\mu_2 = 4.79$) to the third stage (μ_3/μ_2) for all whole rock samples is *ca.* 10. From Pb isotopic ratios and Pb contents, computed model U contents range from 11 to 60 μg/g, with a mean of 42 μg/g. However, U-enrichment during L.S.W.G.S. genesis was *not* accompanied by Th-enrichment, as shown by the low and homogeneous $^{208}Pb/^{204}Pb$ ratios (table 1). It is probable, therefore, that during emplacement the L.S.W.G.S. was contaminated by crustally derived fluids selectively enriched in U and probably in Rb, as shown by the higher Rb/Sr values for the L.S.W.G.S. compared to the R.R.G.S.

A striking result for the L.S.W.G.S. is that the Rb–Sr age (1665 ± 30 Ma) and Pb/Pb age (1754 ± 18 Ma) are discordant, although both isochrons are well defined. This particular type of discordance, which may be strongly linked to mineral composition of the dated rock, has been reported by several workers (for example, Beckinsale *et al.* 1980; Taylor *et al.* 1980). We favour a model for the L.S.W.G.S., and for some other cases where the age discordance does not exceed *ca.* 200–300 Ma, in which whole-rock blocking temperatures for Rb–Sr systems are lower than for U–Pb (Pb/Pb) systems so that the Pb/Pb > Rb–Sr age discordance reflects a lengthy cooling interval for the environment of the dated rocks. The Pb/Pb age may more closely approximate to the time of crystallization. Details of the model will be published elsewhere.

(iv) *Angmagssalik Granites* (A.G.), *southeast Greenland*

These are undeformed, post-tectonic, high-K granites of batholitic proportions which represent the last major rock-forming event in the Precambrian of southeast Greenland (65° 45′N, 37° 15′W). The country rock comprises an Archaean gneiss terrain modified by a Proterozoic shear belt and an intrusive charnockite-norite complex. The immediate country rocks have not yet been investigated isotopically.

Twelve whole-rock samples yield an Rb–Sr isochron (m.s.w.d. = 0.9) age of 1570 ± 20 Ma, with $Sr_i = 0.7045 \pm 0.0005$ (table 2), indicating the possibility of some crustal involvement in genesis of A.G.

The same twelve whole-rock samples give a well-fitted Pb/Pb isochron (m.s.w.d. = 0.6) which, however, yields a poorly-defined age of 1520^{+210}_{-240} Ma, with an apparent μ_1 value of 7.35 (table 2, figure 1*d*), indicating at least partial derivation from an ancient U-depleted crustal source. Poor definition of the age results from the narrow spread of isotopic ratios for most samples. Unlike the situation for the Laxford granites, possible crustal sources for the A.G. are not adequately characterized isotopically. A small suite of Archaean granulites from Kangerdlugssuatsiaq, around 110 km northeast of the A.G., provides a possible data set for modelling Pb isotopic evolution of A.G. These granulites were formed at about 2750 Ma from a source with an apparent μ_1 value of 7.77 (Taylor, unpublished data). They have an average model μ_2 value of 1.61, indicating severe U-depletion.

When some A.G. samples, for which U and Pb contents are known, are corrected for U decay over 1570 Ma (the Rb–Sr age), the least radiogenic compositions (crosses on figure 1*d*) coincide with the isochron for the Kangerdlugssuatsiaq granulites as developed up to 1570 Ma. However, the initial Pb of the A.G. is more radiogenic than almost all the granulites at that time (figure 1*d*), as with the L.S.W.G.S. discussed earlier. Derivation from a mixed source consisting of ancient crust and juvenile mantle ($\mu_1 \approx 7.7$) is once more indicated. This is particularly plausible on account of intimate association of A.G. with more basic intrusions. A minimum of 74% of crustally derived ^{204}Pb component can be calculated for the A.G., but is subject to uncertainty because of inadequate characterisation of the crustal source material.

Sm–Nd analyses on three A.G. samples (table 3) yield characteristically negative crustal ϵ_{Nd} values between −9.4 and −10.8 at 1570 Ma. T_{CHUR} model ages are between 2240 and 2330 Ma, which can be viewed as a minimum age for the old crustal component on the assumption of a straightforward crust-mantle mixing model. On the assumption of a tentative correlation between the Scourian granulites of northwest Scotland and the Kangerdlugssuatsiaq granulites, the Nd isotopic evolution diagram (figure 2) indicates similar mixed-source characteristics for the A.G. to those already discussed from Pb isotopes.

(*b*) *Late Archaean Nûk gneisses and their equivalents, southern West Greenland*

Much age and isotope work, using Rb–Sr, U–Pb and Pb/Pb methods, has been published on the type-Nûk gneisses of the Godthaabsfjord region, and broadly time-equivalent gneisses in adjacent regions (see, for example, Moorbath & Pankhurst 1976; Taylor *et al.* 1980; Baadsgaard & McGregor 1981). Geological descriptions of the rocks and the regional setting may be found in McGregor (1973, 1979) and in Bridgwater *et al.* (1976). Here we supplement published Rb–Sr and Pb/Pb data with new Sm–Nd analyses on a selection of the same samples.

Nûk gneisses and their time-equivalents have mostly yielded Rb–Sr whole-rock isochron, and U–Pb zircon, ages in the range 3000–2750 Ma, and Sr_i values in the range *ca.* 0.7015–0.7025. Moorbath & Pankhurst (1976) concluded that the magmatic precursors of these gneisses were derived from a source region with mantle-type Rb/Sr ratios not more than 200–300 Ma before the measured isochron ages. Any significant contribution to the late Archaean magmas from *ca.* 3700 Ma-old Amîtsoq gneisses of the type exposed in the Godthaabsfjord region was regarded as unlikely, on account of their relatively high Rb/Sr ratios (Moorbath *et al.* 1972). It was further shown that Pb/Pb whole-rock systematics of late Archaean gneisses *outside* the Godthaabsfjord region indicated derivation of their magmatic precursors from a source region with a mantle-type μ_1 value (*ca.* 7.5) at, or shortly before, *ca.* 2900 Ma ago (Black *et al.* 1973; Taylor *et al.* 1980). These are the solid circles in figure 1*e*. However, in the Godthaabsfjord region itself, where Nûk and Amîtsoq gneisses are both exposed, most Nûk gneisses contain variable proportions of two isotopically quite distinct types of Pb which started their respective crustal developments at *ca.* 3700 and 2900 Ma ago. These are the open circles in figure 1*e*. Taylor *et al.* (1980) proposed a model in which the mantle-derived magmatic precursors of the Nûk gneisses were contaminated with ancient, unradiogenic Pb derived from *ca.* 3700 Ma-old Amîtsoq gneiss-type continental crust invaded by the Nûk magmas. The contamination parameter $^{204}\text{Pb}_\text{c}/^{204}\text{Pb}_\text{t}$ (where c refers to contaminant, and t to total Pb) calculated from the Pb isotopic data provided a measure of the proportion of contaminant Amîtsoq-type Pb in the Nûk gneisses and gave values in the range 0–0.74. A positive correlation was observed between degree of Pb contamination and Rb, U and K contents of the rocks. The contaminant of the Nûk magmas was considered to be a trace-element-enriched fluid phase released from dehydrating older continental crust during progressive burial and heating resulting from emplacement of calc-alkaline magmas and crustal thickening (Wells 1979, 1980). This was followed by mixing of the released fluids with younger Nûk magmas.

Sm–Nd data for Pb-uncontaminated late Archaean gneisses from north (Sukkertoppen) and south (Sermilik, Fiskenaesset) of the Godthaabsfjord region (for locality map, as well as Rb–Sr and Pb/Pb ages, see Taylor *et al.* 1980) yield initial ϵ_{Nd} values of $+2.0$, $+3.6$ and $+3.4$ (table 3). These values indicate derivation from late Archaean Nd-depleted mantle. Analogous values, ranging from $+1$ to $+3$, have been obtained by Hamilton *et al.* (1983), and by the present authors (unpublished work), from the early Archaean Isua and late Archaean Malene supracrustal sequences of southern West Greenland. Model Sm–Nd ages for these formations are only compatible with their measured age if their sources were *ca.* 2ϵ higher relative to CHUR of those times. A granulite sample from Nordland (no. 273656), only 4 km west of Godthaab, on the other side of a major fault, yields $\epsilon_{Nd} = -0.1$, suggesting slight contamination by older crust.

ϵ_{Nd} values of time of emplacement for Pb-contaminated Nûk gneisses from various parts of the Godthaabsfjord region exhibit a wide range from $+2.2$ to -7.9 (table 3), indicating a contribution from low-Sm/Nd crustal sources to some samples. Model T_{CHUR} ages for crustally contaminated samples with negative ϵ_{Nd} values range from 2830–3660 Ma, and technically yield a minimum age for the early Archaean (Amîtsoq-like) crustal component. Figure 3 shows that ϵ_{Nd} is positively correlated with ^{204}Pb μg/g and Rb μg/g (and with K and U contents, not plotted here, but see Taylor *et al.* 1980), but not with the contamination parameter $^{204}Pb_c/^{204}Pb_t$, also listed in table 3. Evidently, severe Pb contamination ($^{204}Pb_c/^{204}Pb_t \approx 0.6$) can occur for *any* values of the other parameters, and shows that Pb isotopic contamination of Nûk gneisses may have occurred by different mechanisms. On the one hand, anatectic generation of partial melts would not effect decoupling of Pb and Nd, but provides a means for enriching an initially uncontaminated magma in mobile elements. Thus, partial melting of Amîtsoq gneisses in the lower crust is regarded as the probable mechanism for generating the contaminant in those Nûk gneisses in which combined Pb and Nd isotopic contamination are coupled with mobile element enrichment. On the other hand, in those Nûk gneisses where Pb isotopic data provide the sole evidence for contamination, selective extraction of Pb from Amîtsoq gneisses in an aqueous fluid phase may be the most plausible mechanism for decoupling Pb from Nd (Taylor *et al.* 1980; Thompson *et al.* 1982). On this reasoning, we postulate that those Pb-contaminated Nûk gneisses which also show major Nd contamination (e.g. 175731, 86523, 86550, 131502, 131503, table 3) contain a substantial component of partial melt of *lower* crustal Amîtsoq gneisses. Indeed, sample 86550 (with $\epsilon_{Nd} = -7.9$ at 2900 Ma, $T_{CHUR} = 3660$ Ma) may be derived solely from deep Amîtsoq gneiss, with little or no additional component.

Computed Sr_i values for individual Pb- and Nd-contaminated Nûk gneisses are in the range 0.701–0.703 (except for sample 86550, which is *ca.* 0.707). In the absence of other isotopic evidence, such Sr_i values are conventionally interpreted as mantle-derived, but in the present case they are compatible with contamination by lower crustal Amîtsoq gneisses with Rb/Sr ratios significantly lower than those exposed at the surface (Moorbath *et al.* 1972). As mentioned earlier, Sr isotopes cannot normally distinguish between mantle and lower crust source regions.

Out of the eleven Nd- or Pb-contaminated Nûk gneisses, seven (86523, 131502, 171848, 171849, 171850, 171852, 175731, tables 1 and 3) yield a whole-rock Rb–Sr isochron (m.s.w.d. = 1.25) age of 2895 ± 35 Ma, with Sr_i = 0.7014 ± 0.0002. Incorporation of two uncontaminated gneisses for which Rb–Sr data are available (69151, 171887, table 1) produces no significant change (2900 ± 35 Ma, 0.7014 ± 0.0002, table 2). If additional contaminated Nûk samples (86550, 131588, 175766, tables 1 and 3) are included, the m.s.w.d. and errors increase accordingly, but with no significant overall change in age or Sr_i.

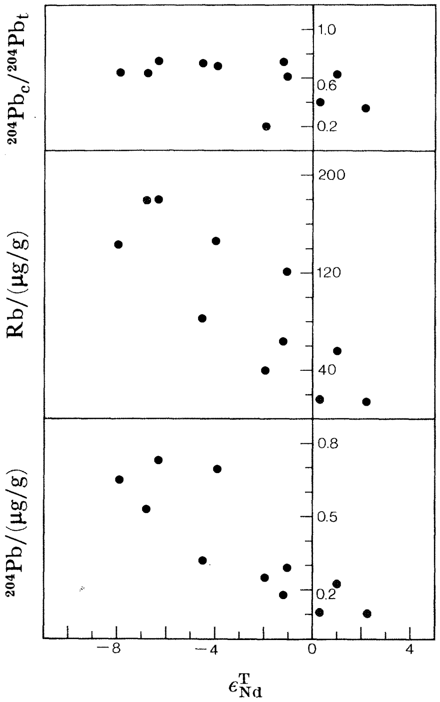

FIGURE 3. Correlation diagrams for eleven samples of contaminated Nûk gneisses (table 3).

This demonstration that low-Sr_i rocks can show severe Nd or Pb (or both) contamination suggests that caution is necessary in the petrogenetic interpretation of low Sr_i values. However, a combination of low Sr_i with typical depleted-mantle-type ϵ_{Nd} values (i.e. +1 to +3) could be regarded as strong evidence for mantle derivation.

(c) *The Qôrqut Granite Complex* (Q.G.C.), *southern west Greenland*

The Q.G.C. represents the last major rock-forming event in the Archaean history of the Godthaabsfjord region. Brown *et al.* (1981) have given a detailed geological description, while Moorbath *et al.* (1981) have reported Rb–Sr and Pb/Pb age and isotope data. Twenty-three whole rock samples yielded an Rb–Sr errorchron (m.s.w.d. = 3.2) age of 2530 ± 30 Ma, with a high Sr_i value of 0.7081 ± 0.0008. The same samples gave a Pb/Pb errorchron (m.s.w.d. = 3.2) age of 2580 ± 80 Ma, with an apparent μ_1 value of 6.2. This, together with the observation that three K-feldspar samples plotted to the left of the 2580 Ma geochron (open circles, figure 1*f*), demonstrated that the Q.G.C. magma was *not* produced from a source region with a μ_1 value of *ca.* 7.5, characteristic of the postulated mantle source of the Amîtsoq and Nûk gneisses at *ca.* 3700 and 2900 Ma respectively. Pb isotope modelling based on intersection of the Pb/Pb isochron with a mixing line relating computed Pb isotopic fields occupied by Amîtsoq and Nûk gneisses at *ca.* 2580 Ma ago, as well as on Pb contents of the gneisses, showed that the Q.G.C. magma could have been generated by anatexis of *ca.* 40 % Amîtsoq gneisses and *ca.* 60 % of Nûk gneisses. An analogous calculation based on Sr_i and Sr contents of the three rock units suggested a *ca.* 50 % contribution from both Amîtsoq and Nûk gneisses to the Q.G.C. magma.

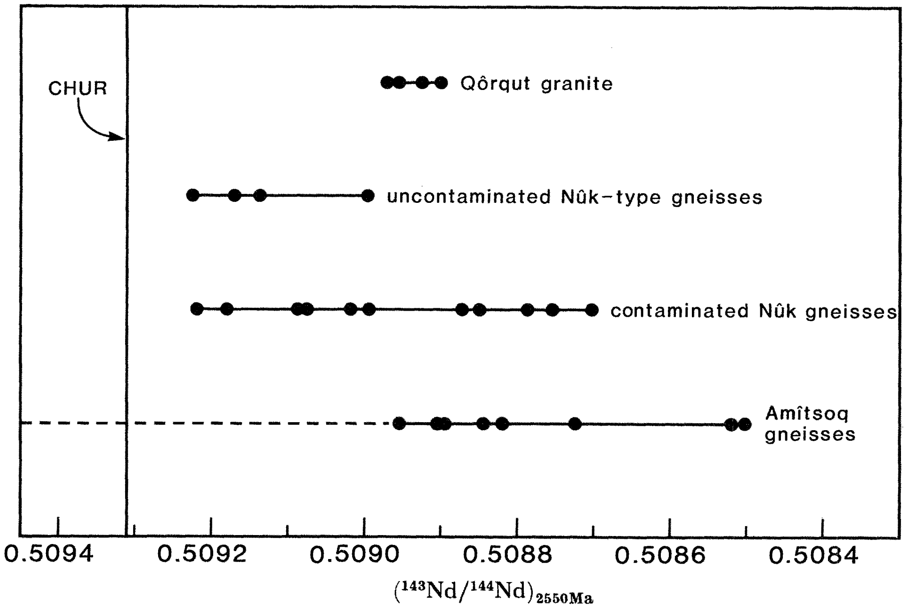

FIGURE 4. Comparison of Qôrqut granite with West Greenland basement gneisses. Computed $(^{143}Nd/^{144}Nd)_{2550\ Ma}$ values for Qôrqut granite and Nûk gneisses are based on data in table 3, and for Amîtsoq gneisses on unpublished Sm-Nd isotopic data by N. W. Jones. Dashed line is based on Sm and Nd concentration data by O'Nions & Pankhurst (1974).

For an assumed mean emplacement age of 2550 Ma, four samples of Q.G.C. yield ϵ_{Nd} values in the range -6.7 to -8.1, with T_{CHUR} model ages of *ca.* 3000–3100 Ma (table 3), demonstrating major crustal involvement in Q.G.C. petrogenesis. Figure 4 shows computed $^{143}Nd/^{144}Nd$ ratios at 2550 Ma for Q.G.C., Amîtsoq gneisses (Jones, unpublished data), Nd- and/or Pb-contaminated Nûk gneisses from the Godthaabsfjord region, and uncontaminated late Archaean gneisses in neighbouring regions. Sm and Nd concentration data for additional Amîtsoq gneiss samples (O'Nions & Pankhurst 1974) indicate that their range of $^{143}Nd/^{144}Nd$ ratios at 2550 Ma may extend to much more radiogenic compositions (dashed line on figure 4). Because of the large overlap in $^{143}Nd/^{144}Nd$ ranges in Amîtsoq and Nûk gneisses, an estimate of relative contributions of these two possible sources of Q.G.C. magma is not possible from Nd isotopic data. From figure 4, as well as the regional geological setting, the most plausible combination of sources consists of either Amîtsoq gneisses or contaminated Nûk gneisses (such as form the country rocks to the Q.G.C.) or both, although some contribution from contemporaneous mantle-derived material cannot be ruled out. The recognition of ancient crustal sources in the genesis of the Q.G.C. magma from Sm–Nd data thus accords well with previous conclusions from Rb–Sr and Pb/Pb data (Moorbath *et al.* 1981). The high Sr_i of 0.7081 for the Q.G.C.

demonstrates that its crustal contribution was derived from a much higher crustal level, with higher Rb/Sr, than the crustal contribution to the contaminated Nûk gneisses in the immediately surrounding region.

Rb–Sr and Pb/Pb analyses are also reported here for a post-tectonic granite sheet from Ivisârtoq, in the inner Godthaabsfjord area some 80–120 km east-northeast of the analysed samples of the main Q.G.C. The Ivisârtoq granite sheet (I.G.S.) has been provisionally correlated with the Q.G.C. from field evidence (Hall & Friend 1979; Coe & Robertson 1982). Six whole-rock samples yield a Rb–Sr errorchron (m.s.w.d. = 2.7) age of 2430 ± 60 Ma, with $Sr_i = 0.723 \pm 0.007$ (table 2), contrasting with corresponding Q.G.C. values of 2530 ± 30 Ma and 0.7081 ± 0.0008. The same six samples yield a Pb/Pb isochron (m.s.w.d. = 1.7) age of 2615 ± 35 Ma, with an apparent μ_1 value of 6.59 (table 2), comparing with the Q.G.C. values of 2580 ± 80 Ma and 6.23. Thus at *ca.* 2600 Ma, the source of the crustal component of the I.G.S. was slightly less U-depleted (higher U/Pb) than that of the Q.G.C., indicating possible derivation from a higher crustal level within the regional Amîtsoq or Nûk gneisses. No Sm–Nd data are yet available.

The discordance between Pb/Pb and Rb–Sr ages of the I.G.S. is analogous to that described earlier for the L.S.W.G.S., and may reflect a crustal cooling interval of some 170 Ma. If an Sr_i of 0.708 (similar to that of the Q.G.C.) is assumed for the I.G.S. at *ca.* 2600 Ma ago, the Rb/Sr ratio required to generate the observed Sr_i of 0.723 at *ca.* 2430 Ma is 2.2, which is quite close to an averaged value of *ca.* 2.6 for four of the six analysed I.G.S. samples and indicates no major disturbance of Rb/Sr ratios at *ca.* 2430 Ma.

(*d*) *The Mont d'Or Granite* (M.D.G.), *Zimbabwe*

This granite occurs in the northeastern sector of the Mont d'Or formation in the central parts of the Zimbabwe Archaean craton, and intrudes a major nappe structure in the Sebakwian greenstone belt in the Selukwe area (Stowe 1968, 1974). Moorbath *et al.* (1976) published a nine-point Rb–Sr whole-rock errorchron age of 3350 ± 120 Ma (adjusted for revised decay constants and 2σ error), with $Sr_i = 0.711 \pm 0.002$. This still remains the highest Sr_i reported for such an old granite. Moorbath *et al.* (1976, 1977) suggested that the M.D.G. originated by partial melting of older sialic crust with high Rb/Sr ratios similar to those of nearby *ca.* 3500 Ma-old Shabani gneisses, and speculated on the possibility that the Selukwe area is underlain by similar crust. Recent re-analysis of Rb/Sr ratios for the same nine M.D.G. samples by a modified X.R.F. method produced a Rb–Sr whole-rock errorchron (m.s.w.d. = 3.6) of 3430 ± 160 Ma, with $Sr_i = 0.711 \pm 0.003$. Omission of two samples yielded a better-defined errorchron (m.s.w.d. = 2.2) age of 3420 ± 120 Ma and $Sr_i = 0.711 \pm 0.002$ (table 2).

The same nine M.D.G. whole-rock samples define a linear Pb/Pb array, which yields a slope age of 3320 ± 80 Ma, with $\mu_1 = 9.4$ (figure 1*h*, table 2). Despite the high m.s.w.d. (105), the age is reasonably well defined because of the wide range of (highly radiogenic) Pb isotopic ratios. Omission of two samples improves the fit of the best line (m.s.w.d. = 49) and yields an age of 3345 ± 55 Ma, with $\mu_1 = 9.25$ (table 2). In contrast to all other granites reported here, the apparent μ_1 value for the source at *ca.* 3340 Ma is much higher than for normal mantle (*ca.* 7.5–8.0), and demonstrates a relatively high-U/Pb source, presumable in the upper crust. No evidence for a Rb- or U-depleted lower crustal source is provided by the Rb–Sr or Pb/Pb data. This accords with the much more radiogenic overall character, especially as regards U/Pb, of the exposed Zimbabwean craton as compared with the exposed North Atlantic craton

(Oxford data, unpublished). The Zimbabwean craton, with its well preserved low- to medium-grade supracrustal rocks represents a relatively high level in the Archaean continental crust. In the much higher grade gneisses and supracrustal rocks of the North Atlantic craton, much deeper, U-depleted levels of Archaean crust are exposed. By the time of granite formation, quite different crustal levels were probably already being tapped, i.e. a high-Rb/Sr, high-U/Pb level in Zimbabwe, and a variable-Rb/Sr and low-U/Pb level in the North Atlantic craton.

No Sm–Nd data are yet available for the M.D.G. A major contribution from *ca.* 200 Ma-older continental crust, such as is indicated by the Rb–Sr and Pb/Pb data, should be resolvable from Nd isotopic data.

5. Conclusions

The following generalizations are based in part on the present results, and in part on a survey of recent isotopic literature on granitoid rocks cited in the text.

(i) Whole-rock isochrons sometimes yield significantly older Pb/Pb ages than Rb–Sr ages. Where the difference does not exceed *ca.* 100–200 Ma, and where the rocks are not obviously affected by subsequent metamorphism, deformation or metasomatism, the age discordance may reflect different whole rock blocking temperatures for the respective decay schemes being reached at different times during a lengthy cooling period.

(ii) Sr_i for a magmatic rock is likely to be equivocal in deciding between an origin from Rb-depleted, low-Rb/Sr, lower crust or from contemporaneous upper mantle.

(iii) Low Sr_i, combined with other isotopic evidence for lower crustal contamination (e.g. negative ϵ_{Nd}, and low apparent μ_1 as compared with the mantle), suggests a significant or dominant contribution from Rb- and U-depleted granulites. High Sr_i, combined with negative ϵ_{Nd} and low apparent μ_1 demonstrates the involvement of high-Rb/Sr, low-U/Pb upper-amphibolite facies crust. High Sr_i, combined with negative ϵ_{Nd} and high apparent μ_1 indicates partial or complete derivation from high-Rb/Sr, high-U/Pb upper crustal levels, at medium-to-low metamorphic grade. A smooth, rather than stepwise, gradation is envisaged between all possible combinations. In contrast, combination of low Sr_i, with typical mantle type ϵ_{Nd} and μ_1 values (i.e. no isotopic evidence for any crustal contamination) provides the strongest possible evidence for a mantle origin (but see (iv) below).

(iv) Pb may be coupled or decoupled from either Sr or Nd or both. Coupling may be expected during production of, and contamination with, partial melts. Decoupling is more likely during production of, and subsequent contamination with, fluids selectively enriched in Pb and other incompatible elements.

(v) The extreme sensitivity of Pb isotopes to crustal contamination provides a valuable constraint on incompatible-element-based models, because if there is no indication from Pb isotopes that a particular magma batch interacted with a distintive crustal unit, then it is extremely unlikely that significant amounts of other elements or isotopes in magmas were derived from a crustal source (see also Thompson *et al.* 1982).

(vi) U and Th are not normally closely coupled in heterogeneous granitic bodies derived from more than one source (e.g. crust–crust, mantle–crust). However, they may be closely coupled in granites derived by partial melting of a single source in which essentially all U, Th and Pb is extracted from the source into the magma.

(vii) Granitoid rocks may contain radiogenic isotopic components derived from a single or multiple crustal source, or from a combination of crustal and mantle sources, or from a mantle-derived source with or without crustal contamination by either melts or fluids or both. The proportion of isotopic contaminants from different sources may be estimated when the isotopic characteristics of all the possible source materials are established. In most cases, however, additional geochemical evidence will be needed to determine unequivocally whether the proportion of different isotopic components reflects the true proportion of bulk components derived from different sources. In some cases this is demonstrably not so.

(viii) All the granitoid rocks investigated here (except for the Pb-uncontaminated late Archaean gneisses of west Greenland), ranging in age from *ca.* 3400 to 1600 Ma, contain a significant component derived from older continental crust. The initial Sr, Nd and Pb isotopic character of granitoid rocks is not directly related to their age (see, for example, Allègre & Othman 1980) but to their petrogenesis, which is itself closely dependent on the presence or absence of available continental crust.

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