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Contributions to Mineralogy and Petrology

Multi-chronometric ages and origin of Archaean tonalitic gneisses in Finnish Lapland: a case for long crustal residence time

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Abstract. The Tojottamanselkä gneisses of the Koitelainen region, northern Finland, have been dated by the Sm–Nd and the common Pb methods. The Sm–Nd data of seven samples from a small area (100 m × 100 m) define an isochron of $T = 3.06 \pm 0.12$ (2σ) Ga, with corresponding $I_{Nd} = 0.50848 \pm 9$ (2σ), or $\varepsilon_{Nd}(T) = -3.7 \pm 1.8$. This age is in good agreement with the zircon U–Pb discordia age (3.1 Ga) reported by Kröner et al. (1981) and is interpreted as the time of magmatic emplacement. The distinctly negative $\varepsilon_{Nd}(T)$ value is found for the first time for Archean tonalitic gneisses and implies derivation of these magmas by remelting of continental material with a long (200–500 Ma) crustal residence time. A few samples, on the other hand, possess $\varepsilon_{Nd}(T)$ values close to zero, hence they are thought to be derived by partial melting of basaltic sources with near-chondritic REE distribution patterns.

Common Pb isotopic data yield an isochron age of 2.64 ± 0.24 (2σ) Ga which is in agreement, within error limit, with the published Rb–Sr isochron age of 2.73 ± 0.24 Ga (Kröner et al. 1981). The age of ca. 2.7 Ga is interpreted as the time of regional metamorphism during which both Pb and Sr isotopes were rehomogenised.

The tonalitic gneisses have highly fractionated REE patterns with $(La/Yb)_N$ ratios varying from 9 to 43. Like most Archean gneisses of TTG composition (tonalite-trondhjemite-granodiorite), they could be derived by partial melting of crustal sources of basaltic to granodioritic compositions. Direct derivation by melting of mantle peridotites is excluded.

The present geochemical study indicates that the Tojottamanselkä gneisses have had a very complex history that involved multi-stage development. Together with the published age data for the basement gneisses and greenstone belts of eastern central Finland (Vidal et al. 1980; Martin et al. 1983a), we conclude that the Archean crustal development in Finland started at least 3.5 Ga ago and passed through a series of magmatic and metamorphic events at 3.1, 2.85, 2.65 and 2.5 Ga before the final intrusions of K-rich granites about 2.4 Ga ago.

Introduction

The Archean terrain of Finland is part of the Baltic or Fennoscandian Shield and consists mainly of granitoid batholiths, greenstone belts and their high-grade metamorphic equivalents. The bulk of the shield rocks has long been recognized as Precambrian, but modern geochemical and isotopic studies on the Finnish Archean rocks have been rather limited as compared to those on the Archean terrains elsewhere. Since 1975 work by the research group of Rennes has focussed on various Archean rocks of Finland (e.g. greenstone belts: Blais et al. 1978; Jahn et al. 1980; Auvray et al. 1982; basement gneisses: Martin et al. 1983a, b; Martin and Querré 1984; geochronology: Vidal et al. 1980; granulites and anorthosites of Lapland: Barbey 1982; Barbey et al. 1980; Moreau 1980; Convert 1981; Bernard-Griffiths et al. 1984). In addition, Kröner et al. (1981) reported a Rb–Sr whole-rock isochron age and a zircon U–Pb age for a tonalitic gneiss dome (Tojottamanselkä) in northern Finland. The zircon age of 3.1 Ga was found to be the oldest reliable age so far recognised for Archean rocks of the Baltic Shield.

In this article we present new isotopic (Sm–Nd, Pb–Pb) and REE geochemical data for the Tojottamanselkä tonalitic gneisses. The specific purposes are:

(1) to confirm or to deny the ancient age (3.1 Ga) recorded in the zircon U–Pb system by the Sm–Nd and the common Pb methods,

(2) to characterise the tonalitic gneisses using major and trace (particularly REE) element data,

(3) to discuss the petrogenesis of these gneisses and to decipher the processes of crustal evolution of the Finnish Archean sialic crust using the available initial Nd and Sr isotopic compositions and REE data.

General geology and geochronology

Granitoid basement of Finland

The Archean rocks of the eastern Baltic Shield occur in east-central (Karelia) and northern parts (Lapland) of Finland, and extend into Soviet Karelia and the Kola Peninsula. As in all Archean terrains of the world, the Finnish rocks consist predominantly of basement gneisses of TTG composition (tonalite-trondhjemite-granodiorite) with subordinate greenstone belts. The majority of the supracrustal rocks has until recently been regarded as Proterozoic (Svecokarelian, e.g., Eskola 1963). However, radiometric dating by Kouvo and his collaborators at the Geological Survey of Finland (Kouvo and Tilton 1966; and many unpublished data quoted in the Annual Reports of Geological Survey

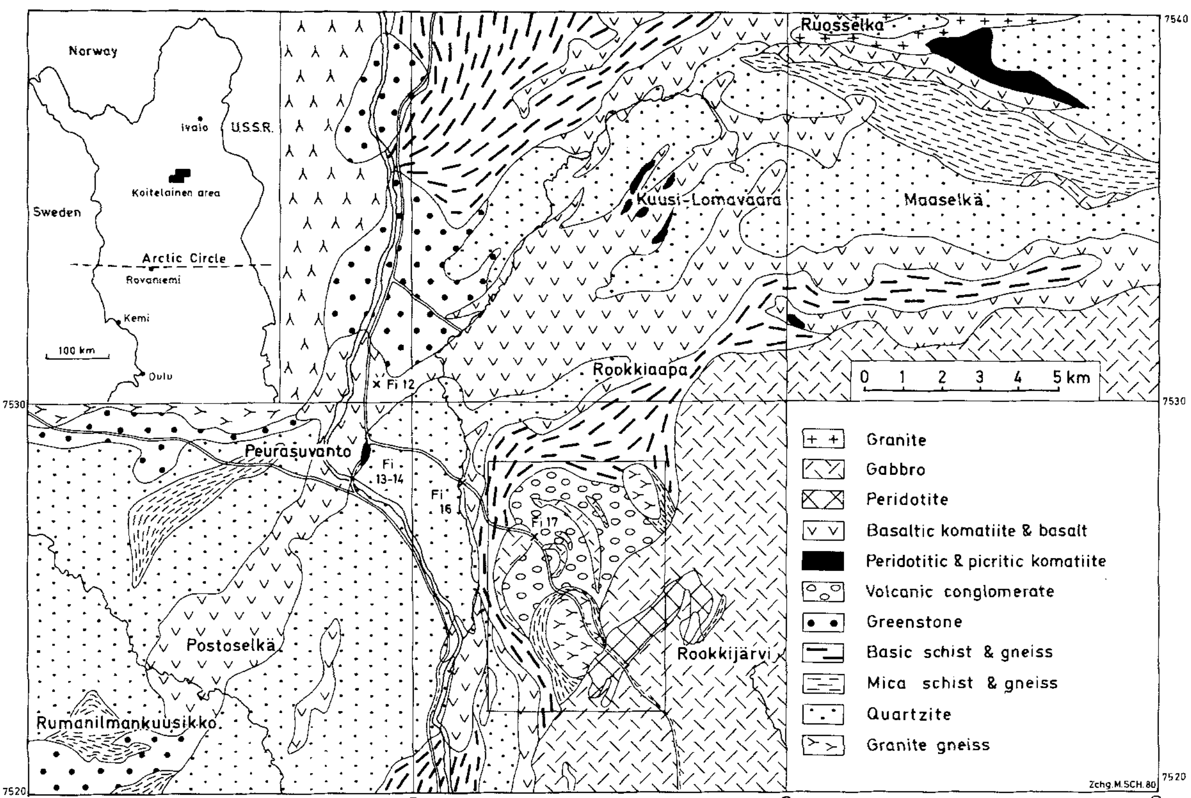

Fig. 1. Geological map of the Koitelainen area of central Lapland (after Puustinen 1977). The Tojottamanselkä gneiss dome is located to the left of Rookkijärvi (lower central)

of Finland) and recent contributions by Vidal et al. (1980), Martin et al. (1983a) and Martin and Querré (1984) have proved that the greenstone belts are of Archean age.

According to Gaál et al. (1978) the Finnish Archean, like other Archean terrains of the world, may be divided into a granitoid association and a greenstone belt association. The granitoid association is thought to form to basement infrastructure and the greenstone belt association forms the suprastructure located in synforms between granitoid diapirs. Gaál et al. (1978) have divided the granitoid association into three generations (from oldest to youngest):

(1) migmatitic granitic gneisses, generally of TTG composition, comprising about 2/3 of all Archean rocks. The ubiquitous grey gneisses belong to this category.

(2) batholiths of leucogranodiorite or trondhjemite: these are thought to be palingenetic products of the ultrametamorphism of the TTG suites. Included in this category are the granodiorite intrusions surrounding the Suomussalmi greenstone belt of Karelia.

(3) late- or post-kinematic potassic granites: these also include red pegmatites or aplitic veins.

In addition to this granitoid association, a narrow transition zone between the granitoid rocks and the greenstone belts shows intense shearing and cataclastic deformation. The granitoid rocks within this zone have frequently been changed to tectonized augen gneisses which, in turn, grade into strongly schistose and cataclastic basal schists (Gaál et al. 1978).

Although the general scheme proposed by Gaál et al. (1978) appears to be valid, field work and recent geochronological data show that not all rocks of the TTG suite belong to the same generation (Martin et al. 1983a). In eastern central Finland, Martin et al. (1983a) have recognised at least four distinct episodes of granitoid intrusion: (1) emplacement of the first generation of grey gneiss (Kivijärvi type) at $T=2.86$ Ga, (2) emplacement of the second generation of grey gneiss (Naavala type) at $T=2.65$ Ga, (3) intrusion of the augen gneiss (Suomussalmi and Arola types) at $T=2.51$ Ga, and (4) late intrusion of pinkish and greyish granites at $T=2.41$ Ga (Martin and Querré 1984). With the 3.1 Ga zircon age reported by Kröner et al. (1981) it is clear that the Archean basement of Finland was built by multi-episodic granitic intrusions that began at least 3.1 Ga ago. Incidentally, greenstone deposition in the Suomussalmi-Kuhmo belt took place about 2.65 Ga ago (Vidal et al. 1980).

The Koitelainen region (Central Lapland)

The regional geology of the Koitelainen region (Fig. 1) has been described by Mikkola (1941) and Puustinen (1977). According to Puustinen the oldest rock unit is made up of granitoid basement gneisses to the north of Peurasuvanto and of granite gneiss domes around Rookkijärvi. These gneisses are generally of tonalite or TTG composition. The basement gneisses are overlain by a supracrustal sequence of metasediments and metavolcanic rocks, which together make up a greenstone assemblage that may belong to the Kittilä greenstone belt of central Lapland (Gaál et al. 1978). The Tojottamanselkä gneiss dome (Figs. 1, 2) has been recently dated by the zircon U–Pb and Rb–Sr methods. The zircon age of 3.1 Ga was interpreted as the time of tonalitic magma emplacement; the Rb–Sr results yielded

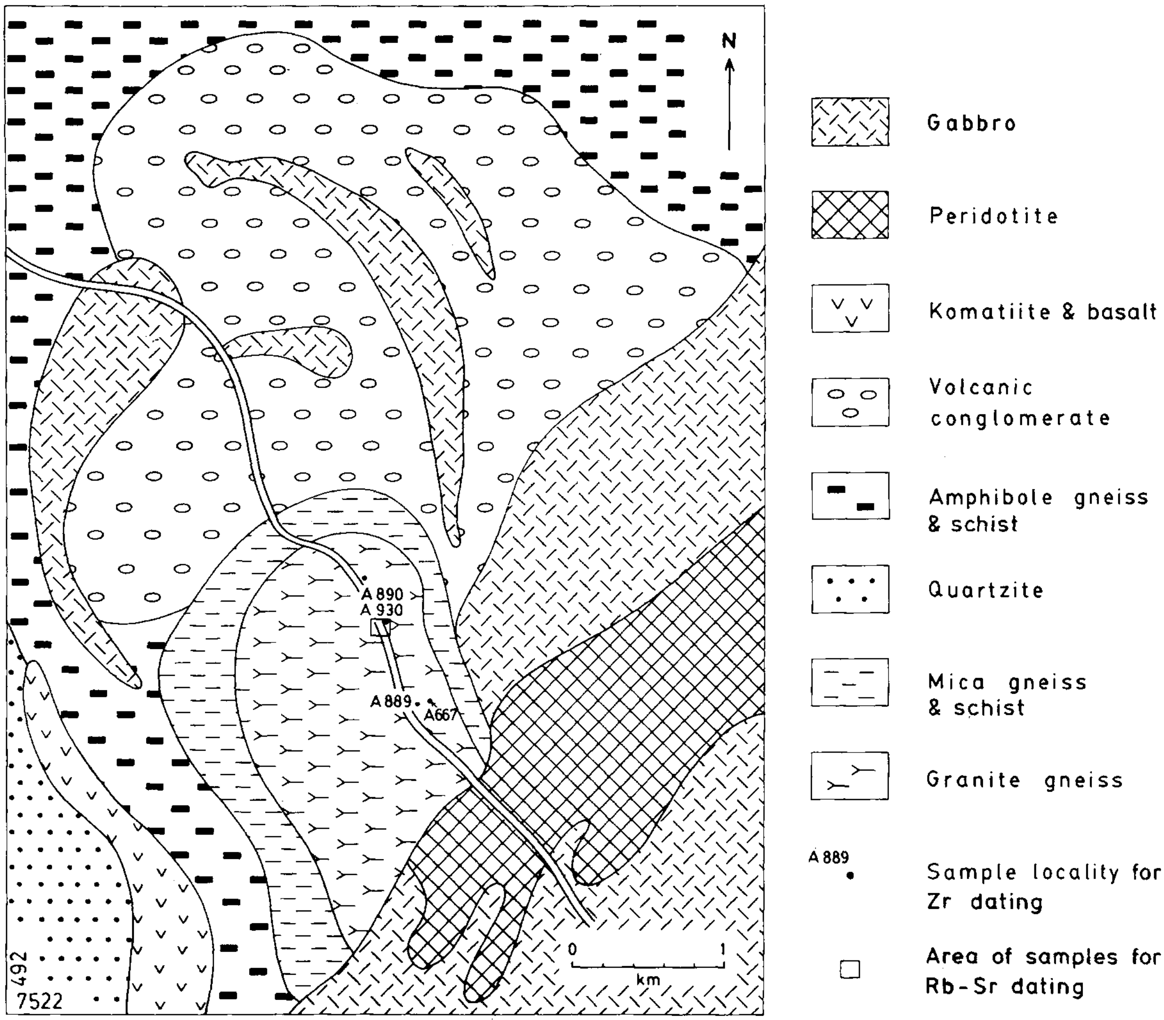

Fig. 2. More detailed map of the Tojottamanselkä gneiss dome and its environment. F-series samples and A-930 were collected from the small square. Other sampling localities are also indicated

a much younger and less precise age of about 2.7 Ga, which was thought to record the time of metamorphism (Kröner et al. 1981). The present geochemical study was conducted on splits of the same samples used by these authors.

Some metasediments underlie the metavolcanic rocks (Puustinen 1977), and consist of quartzites, mica schists and graphite phyllites. Some mica schists are characterized by the presence of magnetite, chlorite, staurolite and andalusite or kyanite. In certain cases, the schists may contain abundant amphibole and consequently grade into amphibolites or amphibole gneisses.

Mafic volcanism took place during and after deposition of the above metasediments and produced basaltic and komatiitic lavas and tuffs that are found intercalated with the quartzites near Petkula, about 15 km south of the map limit of Fig. 1. The greenstone materials also include intercalated bands of volcanogenic chert and jasper. At Rookkijärvi the volcanic sequence includes a polymict conglomerate at its base in which the clasts consist of granitic gneiss, granite, mica schist, volcanic fragments and quartzite. The occurrence of this granite-bearing conglomerate within the greenstone belt has been regarded as evidence for that the basement gneisses are older than the Kittilä greenstone belt (Kröner et al. 1981).

The above greenstone sequence, a mixture of metasediments and metavolcanics is in turn overlain by a later generation of greenstone volcanic rocks including extrusive basalts and peridotites of komatiitic affinity (Mutanen 1976; Kröner et al. 1981). Deposition of these two sequences was then followed by the intrusion of the Koitelainen layered gabbroic complex which forms a near circular area of about 20 km in diameter. The layered intrusion consists, from bottom to top, of periodotite, olivine gabbro, pyroxene gabbro, norite, hornblende gabbro and granophyre as a late differentiate. Zircon $^{207}Pb/^{206}Pb$ minimum ages of 2.44 Ga and 2.39 Ga have been reported for pegmatitic segregations from the gabbroic body and the granophyre, respectively (Puustinen 1977). No other radiometric age data are available for the rocks from the Koitelainen region.

Sample localities and analytical procedures

All samples were collected from a small area (about 100 m × 100 m) in the Tojottamanselkä gneiss dome (Fig. 2). In addition, Sm–Nd isotopic data for 5 samples were provided by Jon Patchett (Max-Planck-Institut, Mainz). These five samples come from the same general area, but only A930 was collected from precisely the same square as those analyzed in this work (F-series samples, Table 1). It should be noted here that although the samples may belong

Table 1. Sm – Nd isotopic results of the Tojottamanselkä gneisses, Northern Finland

Sample no.	$^{147}Sm/^{144}Nd$ [a]	$^{143}Nd/^{144}Nd$	$\pm 2\sigma_m$	$\varepsilon^{CHUR}(O)$ [b]	T_m (AE) [c]	
					(A)	(B)
F-19						
I	0.1145	0.511024	40	−31.5	3.09	2.98
II	0.1163	0.511153	40	−29.0	2.91	2.80
F-20						
I	0.0903	0.510285	35	−45.9	3.45	3.35
II	0.0909	0.510297	31	−45.7	3.45	3.35
F-21						
I	0.1363	0.511229	38	−27.5	3.72	3.53
II	0.1381	0.511296	52	−26.2	3.66	3.47
F-22	0.1218	0.510930	35	−33.4	3.60	3.45
F-23	0.1205	0.510930	40	−33.4	3.55	3.39
F-25						
I	0.1110	0.510700	40	−37.8	3.55	3.42
II	0.1069	0.510651	29	−38.8	3.47	3.35
F-26	0.0935	0.510405	40	−43.6	3.38	3.28
A930	0.1301	0.511087	17	−30.3	3.70	3.53
A890	0.0863	0.510395	12	−43.8	3.17	3.08
A889	0.0985	0.510404	64	−43.6	3.56	3.44
A667	0.0820	0.510300	27	−45.6	3.17	3.09
IKP-80	0.0914	0.510389	10	−43.9	3.33	3.23

Note: F-series samples were analysed in Rennes; Data of A-series and IKP samples were analysed by Jon Patchett of the Max-Planck-Institut, Mainz

[a] 1% error

[b] $\varepsilon^{CHUR}(O) = \left[\frac{(^{143}Nd/^{144}Nd)_{meas}}{0.51264} - 1\right] \times 10^4$

[c] Model age $T_m = \frac{1}{\lambda} \ln\left[1 + \frac{(^{143}Nd/^{144}Nd)_{meas} - 0.51264}{(^{147}Sm/^{144}Nd)_{meas} - (^{147}Sm/^{144}Nd)_{CHUR}}\right]$,

where $\lambda = 0.00654\ Ga^{-1}$ and $(^{147}Sm/^{144}Nd)_{CHUR} = 0.1936$ for column A, and 0.1967 for column B

to a single tonalitic dome, the poor outcrop exposure makes it difficult to clearly establish the field relations. It is also possible that, except for pegmatitic dikes and aplitic veins, the dome consists of several granitoid units derived from distinct protoliths.

Major element data were determined at the University of Mainz using the conventional wet chemistry method. All isotopic and rare earth element (REE) analyses were performed at the University of Rennes. Brief analytical procedures can be found in Jahn et al. (1980a) for REE isotopic dilution, in Jahn et al. (1980b) for Nd isotopes, and in Vidal et al. (1980) for Pb isotopic compositions. The errors for REE concentration determinations are estimated at 3% for La, Lu and Gd; and 1 to 2% for the rest of REE. The overall uncertainty in $^{147}Sm/^{144}Nd$ isotopic ratios is about 1%. All measured $^{143}Nd/^{144}Nd$ isotopic ratios have been normalized against the value of 0.7219 for $^{146}Nd/^{144}Nd$. The $^{143}Nd/^{144}Nd$ ratio measurements for the Johnson Matthey Nd_2O_3 standard salt (Catalogue No. JMC 321) yielded 0.511132 ± 12 ($2\sigma_m$) on 24 separate runs during the period 1978 to 1983. Errors for Pb isotopic analyses are 0.1% for $^{206}Pb/^{204}Pb$ and 0.15% for $^{207}Pb/^{204}Pb$. The decay constants used are: $0.00654\ Ga^{-1}$ for ^{147}Sm, $0.155125\ Ga^{-1}$ for ^{238}U and $0.98485\ Ga^{-1}$ for ^{235}U. Line-fitting and age computation were done using the method of York (1966) and all regression errors reported herein are quoted at 2σ level.

Results

Sm – Nd isotopic data

The results of Sm – Nd isotopic analyses are presented in Table 1. Individual data points are further displayed in the isochron diagram of Fig. 3. Except for F-19, all samples from the small square (i.e., F-series plus A930) define an isochron (MSWD = 1.13) of $T = 3.06 \pm 0.12$ (2σ) Ga, with corresponding $I_{Nd} = 0.50848 \pm 9$ (2σ) or $\varepsilon_{Nd}(T) = -3.7 \pm 1.8$ (2σ). Model ages (T_{CHUR}, assuming $^{147}Sm/^{144}Nd = 0.1967$ for CHUR) range from 3.3 to 3.5 Ga for all samples but F-19 which yields a younger model age of 3.0 Ga (Table 1). The Sm – Nd isochron age is in good agreement with the zircon U – Pb discordia age of about 3.1 Ga (Kröner et al. 1981), and hence confirms the *oldest reliable age* reported so far for the Baltic Shield. Like the zircon age, the Sm – Nd whole-rock isochron age of about 3.1 Ga is interpreted as the time of protolith emplacement or the time of tonalitic magma genesis.

In Fig. 3 it is seen that duplicate analyses do not always produce identical results, suggesting that the powder samples were not homogeneous in all cases. Nevertheless, the isotopic data of sample F-19 deviate conspicuously from the defined isochron of 3.1 Ga. Among four samples collected outside of the small area, two (A889, IKP-80) lie near the 3.1 Ga isochron, whereas the others (A667, A890), together with F-19, fall near the chrondritic reference isochron of the same age. This may suggest that the gneisses belong to more than one generation and their protoliths were probably derived from at least two distinct sources in terms of their Nd isotopic compositions.

With regard to the F-series rocks, the very low I_{Nd} hence the negative $\varepsilon_{Nd}(T)$ value (-3.7 ± 1.8) presents an unexpected yet very significant constraint on the genetic history

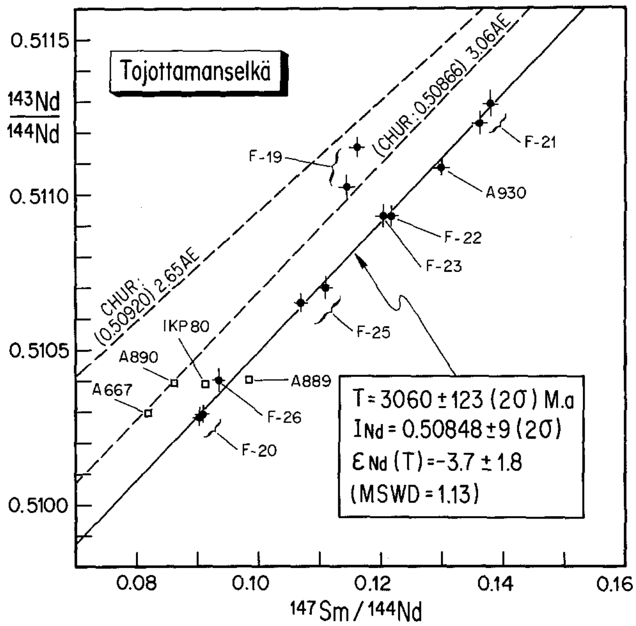

Fig. 3. Whole-rock Sm – Nd isochron diagram for Tojottamanselkä gneiss samples

of these rocks. This will be further addressed in a later section. We recall that until present the published Sm – Nd isotopic data on Archean granitoids have not revealed any ε_{Nd} (T) value as low as this one. Consequently, the model ages calculated (T_m) for these rocks are invariably greater than 3.3 Ga, and as high as 3.5 Ga (see Table 1). This clearly indicates that Archean granitoid rocks might have had complex histories and so cannot always be accurately dated by the model age method. As in this case the use of model ages will lead to an erroneous conclusion.

Common Pb isotopic data

The analytical results of common Pb isotopic compositions are listed in Table 2. The seven data points define an isochron (MSWD = 0.82, Fig. 4) of $T = 2.64 \pm 0.24$ (2σ) Ga. This age, however imprecise, is much lower than the 3.1 Ga age obtained by both the zircon U – Pb and the Sm – Nd methods, but is compatible with the Rb – Sr whole-rock isochron age of ca. 2.7 Ga (Kröner et al. 1981). This age probably reflects the time of Pb isotopic rehomogenisation (but incomplete) during the metamorphism about 2.65 Ga ago. Incidentally, the period of ca. 2.65 Ga represents perhaps the most important thermal event in the Fennoscandian Shield, including greenstone deposition and granitoid intrusion (Vidal et al. 1980; Martin et al. 1983 a).

Major and rare earth element abundances

Major and REE data are presented in Table 3. The Tojottamanselkä samples have a rather uniform composition and are located within the typical Archean TTG field (Fig. 5) according to the classification scheme of O'Connor (1965) using normative feldspar variations. For comparison, grey gneisses of the Suomussalmi region ($T = 2.86 - 2.65$ Ga) also have TTG compositions (Martin et al. 1983 b). Thus, the Archean basement gneisses of Finland, regardless of their age, have a general composition of the Na-rich TTG suite, a feature true for almost all Archean basement gneisses and their volcanic equivalents (Arth and Hanson 1975; Glikson 1976, 1979; Drury 1978; Compton 1978; Barker 1979; Tarney et al. 1979; Jahn et al. 1981; and papers in Barker 1979).

Table 2. Common Pb isotopic compositions of the Tojottamanselkä gneisses, Northern Finland

Sample no.	$^{206}Pb/^{204}Pb$	$^{207}Pb/^{204}Pb$	$^{208}Pb/^{204}Pb$
F-19	17.880	15.479	38.459
F-20	19.660	15.829	40.828
F-21	17.324	15.413	38.296
F-22	18.289	15.569	38.484
F-23	19.974	15.846	39.077
F-25	17.667	15.465	43.177
F-26	17.127	15.329	38.615

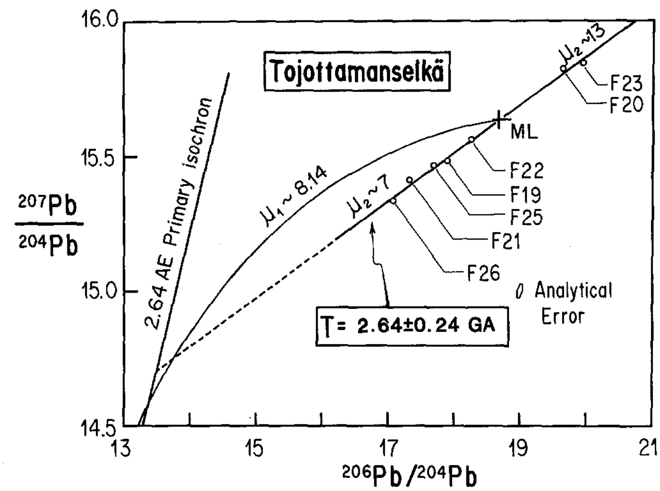

Fig. 4. Common Pb isochron diagram for Tojottamanselkä gneiss samples

The chondrite normalised REE patterns are shown in Fig. 6. The normalisation values used here are from Masuda et al. (1973) divided by 1.2. All gneiss samples from the Tojottamanselkä dome have fractionated REE patterns with $La_N = 30–100$ X, Yb_N or $Lu_N = 2–4$ X and $(La/Yb)_N$ ratios ranging from 8.5 to 43. In all but one cases, positive Eu anomalies are observed; and except for F-25 and F-26, the samples have nearly uniform Eu concentrations (0.55–0.58 ppm). The similar REE patterns, together with their uniform major element chemistry and isotopic systematics (U – Pb, Rb – Sr, Sm – Nd, Pb – Pb) suggest that most F-series rocks are probably cogenetic. The variation in REE abundances is likely to have been produced by crystal fractionation during magmatic emplacement. In the following discussion, detailed modelling for the petrogenesis of individual rock samples will not be pursued. Rather, we shall use the isotopic and REE data do address more general problems regarding the genesis and evolution of Archean basement gneisses of Finland.

Discussion

Petrogenesis of Archean basement gneisses: general consideration

Archean basement gneisses are generally dominated by rocks of TTG composition. High-K adamellite and true

Table 3. Major and rare earth element data for the Tojottamanselkä gneisses, Northern Finland

Sample no.	F-19	F-20	F-21	F-22	F-23	F-25	F-26
Analysis no.	4973	4974	4975	4976	4977	4978	
SiO_2 (%)	68.21	70.01	68.15	68.50	68.33	67.99	70.34
Al_2O_3	15.35	15.02	15.61	15.50	15.46	16.20	14.57
Fe_2O_3	2.22	1.84	1.65	1.65	1.85	2.19	1.31
FeO	1.38	1.32	1.70	1.63	1.44	0.88	1.50
MnO	0.04	0.03	0.04	0.04	0.05	0.03	0.03
MgO	0.91	0.74	0.95	0.83	0.86	0.83	0.82
CaO	3.72	2.43	4.04	3.70	3.44	3.19	1.47
Na_2O	4.63	4.66	4.57	4.74	5.01	5.10	4.87
K_2O	1.78	2.34	1.84	1.77	2.02	2.09	2.83
TiO_2	0.58	0.45	0.46	0.46	0.44	0.54	0.40
P_2O_5	0.11	0.10	0.12	0.11	0.12	0.12	0.13
LOI	1.00	0.99	0.97	1.08	0.92	1.01	1.14
Total	99.93	99.93	100.10	100.01	99.94	100.17	99.43
An } 100%	24.15	17.74	25.12	23.77	20.15	21.40	9.91
Ab } 100%	59.77	60.87	58.42	60.44	62.28	61.08	64.21
Or } 100%	16.08	21.39	16.46	15.79	17.57	17.52	25.88
La (ppm)	12.07	18.29	8.98	9.43	10.53	18.00	32.3
Ce	20.64	–	16.74	18.79	–	–	65.1
Nd	8.26	10.75	6.234	7.044	7.52	14.30	19.54
Sm	1.554	1.595	1.396	1.409	1.489	2.609	3.00
Eu	0.583	0.565	0.584	0.579	0.554	0.792	0.751
Gd	1.284	1.165	1.260	1.269	1.288	1.932	2.004
Dy	1.08	1.238	1.020	1.089	1.235	1.406	1.340
Er	0.573	–	0.485	0.606	0.753	0.704	0.614
Yb	0.571	0.802	0.418	0.611	0.825	0.637	0.491
Lu	0.095	0.130	0.071	0.099	0.127	0.102	0.076
$(La/Yb)_N$	14.0	15.1	14.2	10.2	8.4	18.7	43.4

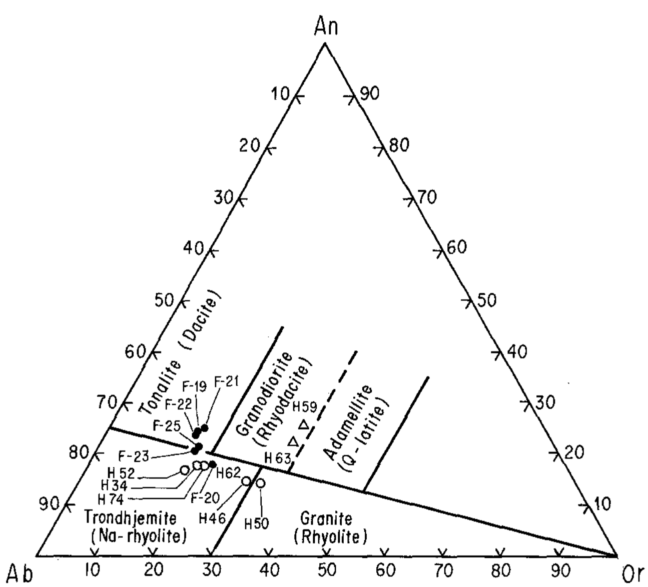

Fig. 5. Classification of granitoid rocks based on normative feldspar ratio (O'Connor 1965). Solid dots: Tojottamanselkä gneisses; open circles and triangles: Archean TTG grey gneisses of the Suomussalmi region (Martin et al. 1983b)

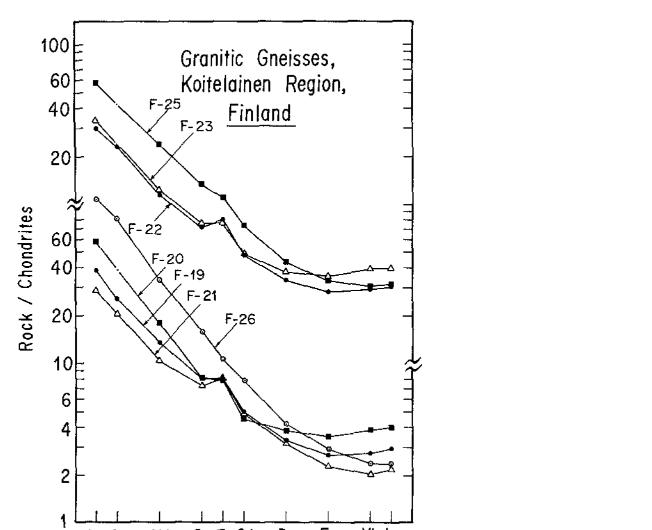

Fig. 6. REE distribution patterns for the Tojottamanselkä gneisses

granite (s.s.) often form post- or late-tectonic phases, as exemplified in Finland, in the Kaapvaal Craton of southern Africa and in the Pilbara Block of Australia (e.g., Glikson 1979; Jahn et al. 1981; Martin et al. 1983a, b; Martin and Querré 1984). The Na-rich TTG plutonic suites are generally characterized by highly fractionated REE patterns, often accompanied by depleted heavy REE. Their $(La/Yb)_N$ ratios commonly range from 15 to 50, occasionally reaching values greater than 200 (Fig. 7). Since the genesis of these rocks is vital to the understanding of early continental development, it is appropriate to examine carefully all geochemical constraints placed on the genetic models.

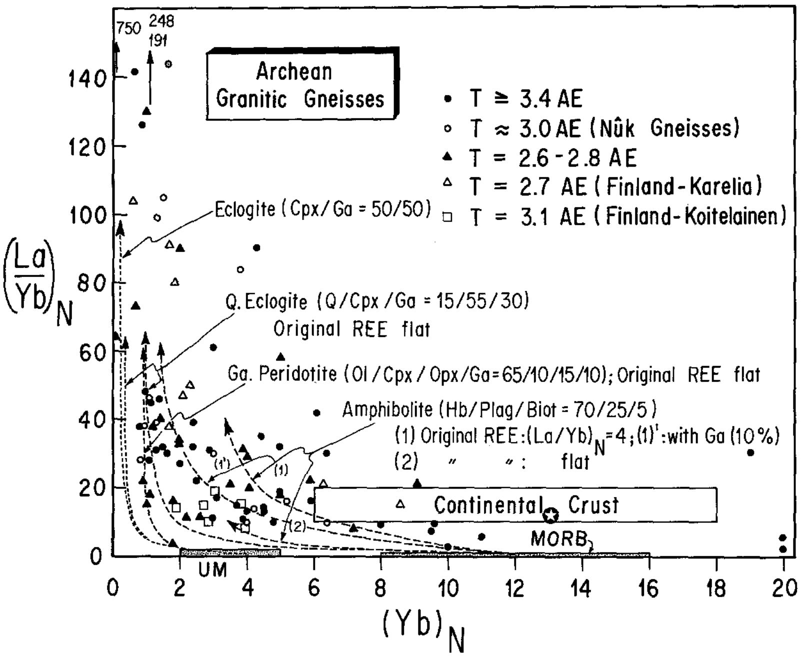

Fig. 7. $(La/Yb)_N$ vs $(Yb)_N$ diagram showing Archean granitic gneisses and Tojottamanselkä gneisses (open squares). See text for explanation

Relevant genetic hypotheses can be classified in terms of three categories: (1) partial melting of eclogitic or mafic garnet granulite source materials (Arth and Hanson 1972, 1975; O'Nions and Pankhurst 1974; Condie and Hunter 1976; Glikson 1976, 1979; Compton 1978; Jahn et al. 1981). (2) Partial melting of amphibolite, with or without garnet (Barker and Arth 1976; Hunter et al. 1978; Jahn et al. 1981), and (3) Fractional crystallization of basaltic magma (Arth et al. 1978). Direct melting of mantle peridotite has not generally been regarded as a plausible mechanism for the generation of Archean TTG magmas, despite the fact that they often possess mantle-like I_{Sr} values (Moorbath 1977).

Figure 7 shows a simplified representation of REE data for Archean Na-rich granitic gneisses (TTG suite). Most of these rocks do not have significant Eu anomalies (Tojottamanselkä rocks are among the exceptions). Rocks of different ages show the same degree of scatter and no obvious separation or secular variation is discerned. This may imply that fractionation processes were essentially similar in early and late Archean times. Superimposed on Fig. 7 are the fields of upper mantle peridotites (UM), mid-ocean ridge basalts and common Archean tholeiites (represented by MORB), and the average continental crust. Note that the positions of data points for TTG gneisses which form the bulk of the Archean upper crust fall distinctly outside the field of average continental upper crust. This suggests that (1) the geodynamic processes in the development of Archean and post-Archean granitic rocks and average crust may have been different, and (2) the average crust is heavily influenced by the composition of post-Archean and more K-rich granites of crustal origin (Nance and Taylor 1976, 1977).

Also shown in Fig. 7 are partial melting trends assuming different source materials and various initial REE concentrations. All arrow heads represent limiting values (zero degree of melting) of enrichment or depletion in terms of $(La/Yb)_N$ and $(Yb)_N$. Starting from a source with flat REE distribution, partial melting of eclogitic or any appropriate source material will produce a maximum value of $(La/Yb)_N \simeq 100$. For this reason, rocks with high $(La/Yb)_N$ ratios (≥ 60) are likely to have had a multi-stage development. Partial melts of eclogites with flat initial REE distribution of 10–15X chondritic abundances would have extremely depleted HREE, namely, $(Yb)_N$ values less than 2. As shown in Fig. 7 this mechanism can produce REE profiles as observed in some Na-rich granites, but the majority of such rocks seems to lie to the right of the eclogite trend. Garnet peridotite or mantle eclogite with 2 to 5 X chondritic REE abundances will not be able to produce the TTG melts, thus it renders improbable their derivation by direct melting of a primary upper mantle source. Partial melting of an amphibolite source (without garnet) with about 12 X flat REE will produce liquids with a maximum $(La/Yb)_N$ ratio of 10, and so is not capable of generating the observed REE patterns. Partial melting of amphibolite with initial $(La/Yb)_N = 4$, a composition similar to continental basalts, a mixture of MORB and alkali basalt, a mixture of depleted and enriched Archean tholeiites (DAT and EAT of Condie 1981), or some Archean greywackes (Arth and Hanson 1975), will produce melts with up to 40 for $(La/Yb)_N$ and no less than 3.5 for $(Yb)_N$. If the amphibolite residues contain up to 10% garnet, the $(La/Yb)_N$ ratios could be raised to about 60.

The above model calculations suggest that the probable sources for TTG magmas are largely basaltic in composition (in the form of amphibolite or eclogite) and the initial REE distribution in the sources is likely to be somewhat fractionated with LREE enrichment. A profound implication of this conclusion is that the Archean TTG rocks are not direct partial melts of the upper mantle as might be implied in some cases by their Sr isotopic data; rather, they were probably derived from basaltic materials which had been transformed to amphibolites or eclogites not too long after their initial separation from a mantle source. Note that although this conclusion is generally true to a first approximation, the possible effect of fractional crystallisation can not be discounted, as observed in Pilbara silicic rocks (Jahn et al. 1981) and in the present case of the Tojottamanselkä gneisses. At any rate, the existence of a basaltic

Table 4. Summary of geochronological results for Archean Tonalitic gneisses (Tojottamanselkä Gneiss Dome) from the Koitelainen region, N. Finland

Method	T (Ma)	I_{Sr} or I_{Nd}	Reference	Comments
Rb–Sr (WR)	2729 ± 244 (2σ)	0.7029 ± 22	Kröner et al. (1981)	T = age of regional metamorphism
U–Pb (Zircon)	3110 ± 34 (2σ)		Kröner et al. (1981)	T = age of primary emplacement
Sm–Nd (WR)	3060 ± 123 (2σ)	0.50848 ± 9 $\varepsilon_{Nd}(T) = -3.7 \pm 1.8$[a]	This work	T = age of primary emplacement
Pb–Pb (WR)	2640 ± 240 (2σ)		This work	T = time of Pb isotope rehomogenisation due to intense metamorphism

[a] Calculated with $^{143}Nd/^{144}Nd$ (CHUR, O) = 0.51264, and $^{147}Sm/^{144}Nd$ (CHUR) = 0.1967

protolith appears to be necessary from which the Na-rich TTG rocks and their volcanic equivalents formed. This protolith could have been part of an early, pre-basement basaltic crust which might have been totally transformed and partially melted, or which might be partly preserved as mafic enclaves within the granitoid batholiths (Glikson 1976, 1979).

Archean crustal development in Finland

Since Archean TTG rocks cannot be derived directly by melting of upper mantle material but may be produced by remelting of crustal basalts or their sedimentary equivalents such as volcanogenic greywackes, a question to be addressed is how long was the crustal residence time for the basaltic protoliths? Furthermore, there is good evidence that throughout geologic time increasing volumes of granitic rocks were produced by remelting of continental crust material (e.g., Vidal 1976; Vidal et al. 1981; Allègre and Ben Othman 1980; Moorbath 1978; O'Nions et al. 1979). Certainly, some Archean granitic gneisses, particularly the high-K type, have been produced in such a manner (for example, the Qôrqut granite of W. Greenland, Moorbath et al. 1981; the Arola pink granite and the Luoma acid volcanics of Finland, Martin and Querré 1984). However, the tonalitic gneisses of Lapland probably provide the first definite example that indicates an origin of Archean Na-rich TTG rocks by recycling of much older continental crust.

A summary of ages obtained by four different radiochronometers for the Tojottamanselkä gneisses is given in Table 4. The time of magmatic emplacement for the domed gneisses is well established at 3.1 Ga. The negative ε_{Nd} (T) value of -3.7 ± 1.8 clearly indicates that the protolith(s) of these gneisses had a time-integrated $^{147}Sm/^{144}Nd$ ratio lower than that of the average chondrite (0.1967). That is, the REE patterns for the protoliths must be characterised by an enrichment in LREE. A further inference is that these protoliths are likely to have been part of pre-existing continental crust, probably also of TTG composition. Assuming a probable range of $^{147}Sm/^{144}Nd$ ratios (0.08–0.14) for the pre-existing granitoid protoliths, the crustal residence time (ΔT) is calculated to be 250–500 Ma. This period is considered long and is almost equal to the entire Paleozoic era. If the protoliths are of tholeiitic nature with only slight LREE enrichment, then their crustal residence time could have been greater than 800 or even 1000 Ma. This latter model is considered less likely because of the implausibly long residence time in early Archean times when most crustal rocks would probably have been reworked or destroyed

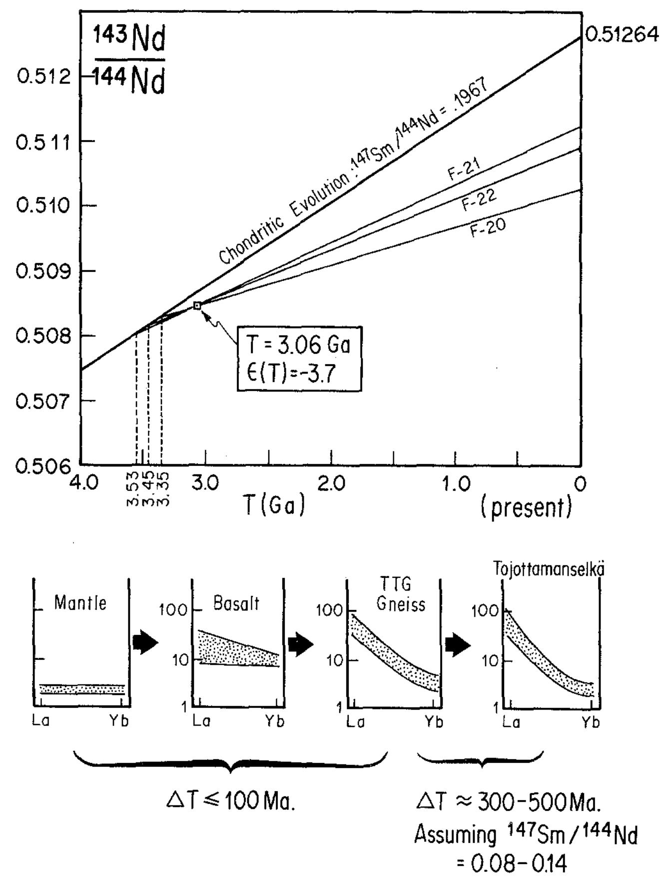

Fig. 8. Interpretation of mulit-stage development of the Tojottamanselkä gneisses using the Nd isotopic and REE geochemical constraints

in short periods due to presumably very active tectonic and magmatic processes.

The REE geochemical constraints require that almost all grey gneisses of the TTG suite be derived from remelting of basaltic materials or their sedimentary equivalents. With this rationale, we conclude that generation of the gneisses in the Koitelainen region (Tojottamanselkä) has involved at least three stages of development. A schematic representation is shown in Fig. 8. Initially, basaltic magmas were produced by partial melting of primitive mantle peridotites, and these basaltic rocks were soon transformed to amphibolites (or eclogites when P, T conditions allowed) and partially remelted to produce the early TTG rocks. The initial separation of this "crustal" material from the mantle probably took place about 3.5–3.6 Ga ago, and all these processes could have been accomplished within a relatively short time span of less than 100 Ma. The early TTG rocks were remelted 3.1 Ga ago to produce the Tojottamanselkä tonalitic magmas. In this scenario, the initial 3.5–3.6 Ga event could be compared with the 3.6–3.7 Ga superevent registered in the Amitsôq gneisses of West Greenland (Moorbath 1977). In Finland, however, these early TTG rocks have not survived through later thermal events. Nevertheless, the Sm – Nd isotopic data convincingly demonstrate that a very ancient (3.5–3.6 Ga) continental crust had existed in the Baltic Shield.

Regarding the few gneiss samples showing ε_{Nd} (T) values close to zero (F-19, A667, A890, Table 1), their genetic history is probably simpler. They could have been produced by partial melting of basaltic sources which may or may not have had a long crustal residence time (>300 Ma) if their sources were characterized by relatively unfractionated REE patterns.

Interpretation of the common Pb age

The relatively young common Pb isochron age obtained (Fig. 4) is something of a surprise. Because the isochron passes through the modern Pb field (ML of Fig. 4), it in principle defines a secondary isochron age. That is, the age of 2.64 Ga should normally represent the time of magmatism including a continuous event of mantle melting, igneous differentiation and final emplacement. However, the age of magmatic intrusion has been firmly established by the U – Pb and Sm – Nd methods at 3.1 Ga ago. Moreover, the negative ε_{Nd} (T) value requires a multi-stage development before 3.1 Ga ago (see Fig. 8). As a consequence the interpretation of the Pb – Pb age is not straightforward.

Our model interpretation is presented in Fig. 9. The common Pb isochron age is here viewed as representing an intense metamorphism about 2.7 Ga ago during which Pb isotopic compositions were subject to rehomogenization. Consequently the present data array as shown in Fig. 4 should imply a tertiary isochron. The relatively large error in the Pb – Pb isochron age (2.64±0.24 Ga) might be explained by incomplete isotopic homogenization during the ca. 2.7 Ga thermal event. As a matter of fact, a linear relationship can often be acquired through an aging effect even though the analysed samples do not posses the same initial isotopic ratios. Furthermore, the fact that the present data array or the tertiary isochron passes through the ML point (Fig. 9) suggests that the average μ (or $^{238}U/^{20}Pb$) value of about 8 was maintained through metamorphism – perhaps merely by chance. Equally because of this fact, the common Pb data have failed completely to register the crustal history prior to the 2.7 Ga metamorphism.

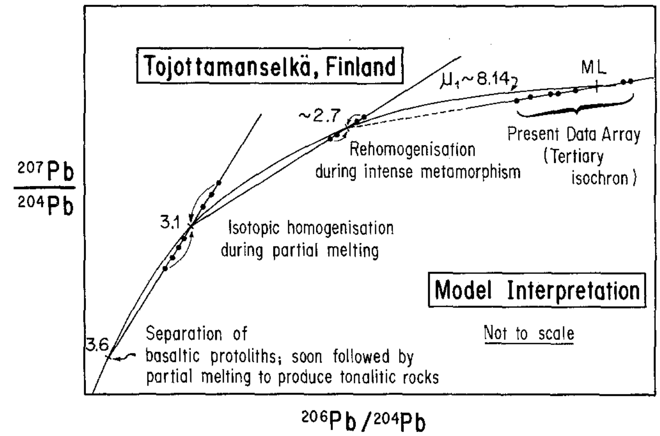

Fig. 9. Model interpretation for the common Pb isotopic evolution in the Tojottamanselkä gneiss samples. It is emphasized here that the last Pb isotopic rehomogenisation about 2.7 AE ago produced, by chance, a mean μ value of about 8, thus the present day data array passes through the modern Pb (ML) field of Stacey and Kramers (1975)

Conclusions

The present isotopic and REE geochemical study, together with the age data already reported by Kröner et al. (1981), clearly indicate that the Tojottamanselkä gneisses have had a very complex history that involved multi-stage development. A model interpretation of major events recorded in these rocks by four different chronometers (U – Pb, Sm – Nd, Rb – Sr, Common Pb) and trace element abundance patterns is given in Table 5.

We believe that multi-stage development is probably also true for other Archean terrains of the world. The Na-rich rocks of the TTG suite are usually the oldest unit preserved and they form the dominant part of the Archean basement. It has been demonstrated in Minnesota, in the Pilbara Block and in Finland (Arth and Hanson 1975; Jahn et al. 1981; Martin et al. 1983a, b) that most Archean TTG rocks and their volcanic equivalents are likely to be derived from basaltic sources or pre-existing continental crust, but not directly by melting of upper mantle material as has frequently been implied on the basis of Sr isotopic arguments. If the assumed basaltic protoliths had near-chondritic REE patterns and low Rb/Sr ratios, as found in many Archean greenstones (see Jahn and Sun 1979, for review), and if basaltic rocks formed an essential part of the Archean crust, especially the very early crust, then the protoliths would show little deviation in radiogenic isotope (Nd, Sr) growth from the mantle over a long period of time. In other words, the TTG magmas produced by partial melting

Table 5. Model interpretation of major events recorded in the Tojottamanselkä gneisses

T (Ga ago)	Event
2.7	Intense regional metamorphism; Rb – Sr and common Pb isotopic systems reset; Present tectonic fabric produced. At the same time, the second generation of TTG magmas was emplaced at $T=2.65$ Ga in Karelia (the first generation being at $T=2.85$ Ga). Meanwhile, the greenstone belts (Suomussalmi, Kuhmo and Tipasjärvi) were formed as a result of continental rifting.
3.1	After a long crustal residence time, the crust was remelted to produce tonalitic magmas. Fractional crystallisation has played a role in magma differentiation.
3.5–3.6	Separation of basaltic magma from chondritic type upper mantle; soon ($\Delta T<100$ Ma) followed by partial melting of basaltic sources to produce TTG-type continental crust in which LREE are highly enriched.

of these crustal sources of very long crustal residence time could still possess I_{Nd} or I_{Sr} close to mantle values. Therefore, isotopic data should be used with great care in the discussion of petrogenesis and crustal evolution.

At present, a matter of considerable debate concerns the present location of these remnant basaltic fragments. The Suomussalmi-Kuhmo greenstone belts (2.65 Ga) may be explained by a continental rifting model on the basis of structural analyses (Blais et al. 1977); the surrounding basement gneisses have already been shown to be older or at least contemporaneous with the greenstone belts (Vidal et al. 1980; Martin et al. 1983a). Thus, the present greenstone belt material is not likely to have been the principal source for the grey gneisses. It appears, therefore, that the pre-existing basaltic crust was totally "subducted" or destroyed by melting processes in which the partial melts produced directly or indirectly the basement gneisses and their volcanic equivalents of TTG composition and the residues were permanently buried at depths or returned to the upper mantle, or the remnants of basalt are now represented by the mafic-ultramafic enclaves within the TTG batholiths.

Finally, some important questions still remain unanswered. First, the published I_{Sr} value of 0.703 ± 0.002 (Kröner et al. 1981, see Table 4) is unexpectedly low in view of the long crustal residence time inferred for the tonalitic gneisses. Second, the U−Pb zircon data (Kröner et al. 1981) do not seem to have recorded any trace of the important 2.7 Ga thermal event which would normally be expected to cause some episodic Pb loss. Third, a particular sample (A889) has an inexplicable discrepancy between the ε_{Nd} (3.1 Ga) value of -4.4 ± 1.2 and the ε_{Hf} (3.1 Ga) value of $+1.0 \pm 0.7$ (Patchett et al. 1981). At present, we have not found satisfactory explanations for these questions. We hope that more future research using the similar multichronometric approach on complex Archean terrains may help clarify this apparent contradiction.

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