The tectonic framework of the Precambrian shield of Greenland.
A review of new isotopic evidence

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Abstract

There is now reliable isotopic evidence that most of the crystalline basement of Greenland consists of Archaean (>2500 Ma) rocks: only in the Ketilidian mobile belt of southernmost Greenland no Archaean rocks have yet been found. Proterozoic orogenic activity was widespread in the Nagssugtoqidian and Rinkian mobile belts of central and northern West Greenland, and peaked at *c.* 1850 Ma. There is some evidence that the Nagssugtoqidian mobile belt may define the boundary between two once separate Archaean continental plates and it is possible that comparable plate boundaries also exist elsewhere in Greenland.

Introduction

The Archaean craton of southern Greenland is bordered to the north and south by Proterozoic mobile belts (fig. 1). These main divisions within the Greenland shield were first established on the basis of field investigations: the Nagssugtoqidian mobile belt to the north was differentiated from the craton by Ramberg (1948), and the Ketilidian mobile belt south of the craton (Wegmann, 1938) was shown to be younger than the bordering Archaean rocks during field work in the early sixties (Bondesen, 1970). Later isotope evidence has confirmed this subdivision and not only provided information on the age of the various rocks but also on their mutual relations.

The Archaean age (i.e. >2500 Ma; 1 Ma = 10^6 years) of most of the rocks in the craton has been demonstrated in a large number of papers, reviewed, among others, by Bridgwater *et al.* (1976). On the basis of field work by McGregor (1973), Black *et al.* (1971) found that in the Godthåbsfjord area both early Archaean (3800–3600 Ma) and late Archaean (3000–2600 Ma) rocks could be distinguished. For the Ketilidian mobile belt to the south of the craton Proterozoic ages were first determined by van Breemen *et al.* (1974) and by Gulson & Krogh (1975).

Field work had suggested that Archaean rocks continued into areas north of the Archaean craton, and the Nagssugtoqidian mobile belt was thought to consist mainly of Archaean rocks deformed and metamorphosed during the Nagssugtoqidian orogeny (Escher & Watt, 1976; Escher *et al.*, 1976). Farther north, preliminary isotope data suggested the presence of Archaean rocks far into the northern part of West Greenland (Kalsbeek, 1981). This region belongs to the Rinkian mobile belt which is differentiated from the Nagssugtoqidian mobile belt by its distinctive tectonic style (Escher & Pulvertaft, 1976). Because of strong Proterozoic deformation and metamorphism of the rocks, the Archaean isotope relations are here often disturbed, and reliable age determinations by the Rb-Sr method can in general not be obtained.

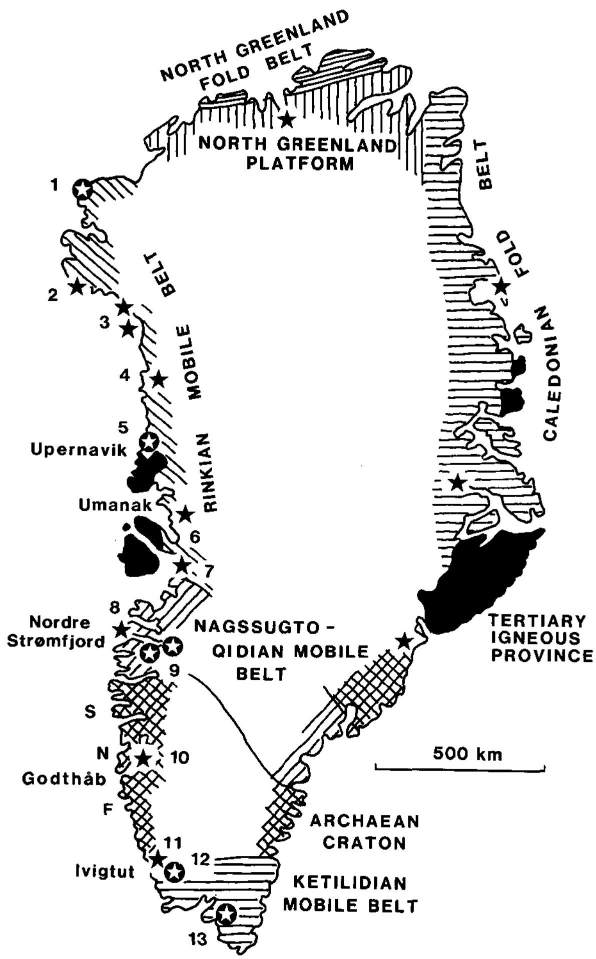

Fig. 1. Sketch of the main geological divisions in Greenland with localities mentioned in the text numbered. S: Sukkertoppen; N: Nordlandet; F: Fiskenæsset. Filled stars indicate the presence of proven Archaean rocks; open stars indicate Proterozoic rocks – see the text. For a discussion of the occurrence of Archaean rocks in East Greenland, see Kalsbeek (1981).

The regional geochronological investigation of Greenland has now been expanded to include isotope systems that are less readily upset by later metamorphism, and this paper summarises our present knowledge of the regional distribution of Archaean and Proterozoic rocks in the western half of Greenland. It is largely based on data from three sources: Rb-Sr isotope data obtained at the isotope laboratory of the Institute of Petrology, University of Copenhagen, in cooperation with GGU geologists and O. Larsen (Copenhagen University); Pb-Pb and Rb-Sr isotope work carried out at the University of Oxford in cooperation with S. Moorbath and P. N. Taylor; and zircon U-Pb age determinations carried out by R. T. Pidgeon (Western Australian Institute of Technology) for the Geological Survey of Greenland.

The Rinkian mobile belt

Fig. 1 and Table 1 give a synopsis of reliable evidence for the presence of Archaean and Proterozoic rocks north of the Archaean craton. In the Rinkian mobile belt a crystalline

Table 1. Recent isotopic age determinations on gneisses and granitic rocks from West Greenland

Locality/Rock type		*Method*		*Result*		*Source*
1 Etah meta-igneous complex, granite/charnockite, 78°40'N–72°50'W		Rb-Sr (WR)	errorchron	Age *c.* 1850 Ma	Sr_i *c.* 0.7030	1
2 Kap York meta-igneous complex, norite – granite, A: 75°57'N–66°40'W B: 76°00'N–67°10'W	A	"	"	*c.* 2650 Ma	*c.* 0.7028	1
	B	"	"	*c.* 2700 Ma	*c.* 0.7035	2
3 Melville Bugt, basement gneisses, A: 76°09'N–61°30'W	A	Zircon U–Pb	combined discordia (A, B)	2620 Ma		3
B: 75°30'N–60°10'W	B	"				
C: 75°52'N–59°50'W	C	Rb-Sr (WR)	errorchron	*c.* 2600 Ma	*c.* 0.7025	1
4 170 km N of Upernavik, basement gneiss, 74°30'N–56°30'W		Zircon U–Pb	discordia	2710 Ma		3
5 Upernavik district, Prøven granite/charnockite, 72°47'N–55°37'W		Rb–Sr (WR)	isochron	1860±25 Ma	0.7067±5	4
6 Umanak district, A: granodiorite, 71°05'N–51°24'W	A	"	"	2570±90 Ma	0.7049±11	4
B: tonalite, 71°06'N–51°26'W	B	"	"	3090±140 Ma	0.7008±3	5
7 Disko Bugt, Atâ intrusion, 69°45'N–50°52'W		Pb–Pb (WR)	"	*c.* 2750 Ma	μ_1 7.48	6
		Zircon U–Pb	discordia	2730 Ma		3
8 Rifkol, granite/charnockite, 67°58'N–53°47'W		Pb–Pb (WR)	isochron	2650±110 Ma	μ_1 7.42	7
9 Nordre Strømfjord, gneisses, A: 67°01'N–53°27'W B: 67°59'N–51°04'W C: 67°53'N–52°08'W	A	Rb–Sr (WR)	'site-mean' isochron	1933±60 Ma	Sr_i 0.7031±8	8
	B	Pb–Pb (WR)	errorchron	1930±170 Ma	μ_1 7.96	7
		Zircon U–Pb	discordia	1850 Ma		3
	C	Pb–Pb (WR)	isochron	2210±160 Ma	μ_1 8.10	7
10 Godthåbsfjord area, various methods; ages fall in two ranges: 3600–3800 Ma and 2600–3000 Ma, numerous references – see Bridgwater *et al.* (1976)						
11 Frederikshåb – Ivigtut, gneisses, A: 61°43'N–49°24'W B: 61°32'N–49°12'W	A	Pb–Pb (WR)	isochron	2780±55 Ma	μ_1 7.21	6 (A–C)
C: 61°20'N–48°20'W	B	"	"	2770±110 Ma	7.25	
	C	"	errorchron	3090±75 Ma	7.19	
12 Ivigtut district, Ketilidian granites, A: 61°05'N–47°59'W	A	Rb–Sr (WR)	isochron	1835±145 Ma	Sr_i 0.704±4	9 (A–C)
		Pb–Pb (WR)	"	1705±350 Ma	μ_1 7.58	
B: 61°06'N–48°12'W	B	Rb–Sr (WR)	"	1675±45 Ma	Sr_i 0.7044±18	
C: 61°04'N–48°32'W		Pb–Pb (WR)	"	1560±350 Ma	μ_1 7.30	
	C	Rb–Sr (WR)	"	1775±25 Ma	Sr_i 0.7110±28	
		Pb–Pb (WR)	"	1720±95 Ma	μ_1 7.19	
13 Ketilidian mobile belt, granites, see van Breemen *et al.* (1974)		Rb–Sr (WR)	isochrons	1855–1745 Ma	Sr_i 0.7022–0.7032	10 (with Zircon U–Pb)
		Zircon U–Pb	discordias	1805–1740 Ma		
		Pb–Pb (WR)	isochrons	1895–1715 Ma	μ_1 7.87–8.03	9

Locality: numbers as in fig. 1. In most cases the samples come from a larger area and the geographical coordinates are therefore approximate. *Method:* WR = whole-rock. *Result:* 'isochron' is used where the samples in the isochron diagram fit within analytical precision on a line; otherwise the term 'errorchron' is used. All precisions are given at the 95% level of confidence, and modern decay constants (Stieger & Jäger, 1977) were used throughout. Sr_i is the initial $^{87}Sr/^{86}Sr$ ratio; the uncertainties refer to the last digit(s) of the Sr_i value shown. For an explanation of the model μ_1 value see the text. Sources: 1. P. R. Dawes, O. Larsen & F. Kalsbeek, unpublished data; 2. Kalsbeek & Dawes (1980); 3. R. T. Pidgeon, personal communications, 1983, 1984, 1985; 4. Kalsbeek (1981); 5. Andersen (1981); 6. P. N. Taylor & F. Kalsbeek, unpublished data; 7. Kalsbeek *et al.* (1984). 8. Hickman & Glassley (1984); 9. Kalsbeek & Taylor (1985a); 10. Van Breemen *et al.* (1974).

basement is overlain by a thick sequence of metamorphosed supracrustal rocks. For the basement rocks Archaean zircon U-Pb ages have been obtained from two localities in Melville Bugt and from the area north of Upernavik (localities 3 and 4, fig. 1; R. T. Pidgeon, personal communications, 1983 and 1984), and even in northernmost Greenland Archaean ages have recently been determined for granitic rocks in the basement underlying the North Greenland platform (B. T. Hansen, personal communication, 1985). New Rb-Sr isotope data for the intrusive rocks of the Kap York complex (2, fig. 1), obtained by O. Larsen in cooperation with P. R. Dawes (GGU) and the writer, have confirmed the Archaean age of this complex suggested by Kalsbeek & Dawes (1980), and rocks from the Umanak district (6, fig. 1) have also given undoubted Archaean ages (Kalsbeek, 1981; Andersen, 1981). The Archaean age of the crystalline basement in the Rinkian mobile belt is thus now well established.

The Atâ intrusion in the northeastern part of Disko Bugt (loc. 7 in fig. 1) has also yielded an Archaean age (*c.* 2750 Ma, Pb-Pb and U-Pb zircon data; Taylor & Kalsbeek, unpublished; R. T. Pidgeon, personal communication, 1985). Unlike most other Archaean rocks in the Rinkian mobile belt, the rocks of the Atâ intrusion are at many localities undisturbed by later deformation and metamorphism, and it appears therefore that Proterozoic orogenic activity was not significant here.

The age of the supracrustal rocks in the Rinkian mobile belt is not well known. They rest unconformably on late Archaean rocks in the Umanak district (Garde & Pulvertaft, 1976) and are cut by *c.* 1850 Ma intrusive rocks in the area around Upernavik (Kalsbeek, 1981). An early Proterozoic age of deposition seems therefore likely.

At several localities the Rinkian mobile belt contains Proterozoic intrusive rocks. The Prøven granite/charnockite near Upernavik (5, fig. 1) and rocks from the Etah meta-igneous complex in northernmost West Greenland (1, fig. 1) have given Rb-Sr isochron ages of *c.* 1850 Ma (Kalsbeek, 1981; O. Larsen, personal communication, 1984), and were apparently formed in connection with the metamorphic maximum at that time. Most of the Rinkian mobile belt has not yet been mapped in detail and the number of isotopic age determinations is so far very restricted. It is therefore uncertain how common Proterozoic intrusive rocks are and how they relate to the surrounding Archaean rocks.

Metamorphic ages of *c.* 1700 to 1850 Ma have been obtained for the supracrustal rocks by the Rb-Sr and Pb-Pb isochron methods (Kalsbeek, 1981; Kalsbeek *et al.*, 1984). The peak of metamorphism was probably at *c.* 1850 Ma (Kalsbeek *et al.*, 1984). K-Ar biotite ages in the Rinkian mobile belt are in the order of 1700–1750 Ma (Larsen & Møller, 1968) and date the waning phases of metamorphism. An undeformed and very fresh basic dyke in the Rinkian mobile belt with well-preserved olivine has yielded a Rb-Sr isochron age of 1645 ± 35 Ma (Kalsbeek & Taylor, unpublished). Apparently, by that time deformation and metamorphism had ceased completely.

The Nagssugtoqidian mobile belt

The Nagssugtoqidian mobile belt was differentiated from the Archaean craton on the basis of the 'Kangâmiut dykes', which form well preserved dolerite dykes in the craton, but become strongly attenuated and boudinaged amphibolite layers in the Nagssugtoqidian gneisses to the north (Ramberg, 1948; Escher *et al.*, 1976). The Kangâmiut dykes have been dated at *c.* 1950 Ma (Kalsbeek *et al.*, 1978), and the main phase of Nagssugtoqidian metamorphism and deformation took place, as in the Rinkian mobile belt, at *c.* 1850 Ma.

Since Ramberg's (1948) first description of the Nagssugtoqidian mobile belt it has been assumed that most of the area consists of deformed Archaean gneisses, and recent isotope studies have confirmed this (Hickman & Glassley, 1984; Kalsbeek & Taylor, unpublished data). A granite body on the island of Rifkol (8, fig. 1), for example, has given a Pb-Pb isochron age of *c.* 2650 Ma (Kalsbeek *et al.*, 1984). However, it was also found that part of the gneisses that make up the mobile belt give Proterozoic ages (two localities in Nordre Strømfjord, 9 in fig. 1), and zircon U-Pb data obtained by R. T. Pidgeon (personal communication, 1983) confirm the Proterozoic age (*c.* 1850 Ma) of these rocks. Hickman & Glasley (1984) obtained good Rb-Sr isochrons on gneisses from Tiggait, slightly farther to the west in Nordre Strømfjord, which yielded Proterozoic ages ('site-mean' age 1933 ± 60 Ma, see Table 1). However, they interpreted this result as due to thorough resetting of the Sr-isotopic composition of original Archaean rocks.

In the Nagssugtoqidian mobile belt distinct 'linear belts' – in which there is a strong parallelism for all structural elements – alternate with areas of more open folding. It was thought that the latter were areas that had largely escaped the Nagssugtoqidian deformation, and that Archaean structures were here preserved (Escher *et al.*, 1976). However, one of the gneiss localities that have given Proterozoic Pb-Pb isochron and zircon U-Pb ages lies within one of these areas and forms part of the 'pre-Nagssugtoqidian' structures. These structures cannot, therefore, be of Archaean age, but must have formed during the Proterozoic Nagssugtoqidian orogeny, before the formation of the neighbouring linear belts, which, as a consequence, must also be Proterozoic. Rb-Sr isotope evidence has shown, however, that some of the shear zones near the southern border of the Nagssugtoqidian mobile belt date back to the late Archaean (*c.* 2600 Ma; Kalsbeek & Zeck, 1978, in press; Hickman, 1979; Kalsbeek, 1979). Apparently, the tectonic development of the Nagssugtoqidian mobile belt was complicated, and many details are as yet not well known.

Supracrustal rocks in the Nagssugtoqidian mobile belt have yielded Proterozoic Pb-Pb whole-rock isochron ages of *c.* 1850 Ma (Kalsbeek *et al.*, 1984). These date the metamorphism of the rocks and the age of deposition is uncertain. Circumstantial lithological and field evidence, however, suggests that these supracrustal rocks correlate with those in the Rinkian mobile belt and, like those, were deposited during the early Proterozoic (Kalsbeek *et al.*, 1984). Pb-isotope data obtained from marbles in the Rinkian and Nagssugtoqidian mobile belts support this view. The rocks yield ages of *c.* 1850 Ma, dating the time of metamorphism, but the data also strongly suggest that deposition of the sediments cannot have taken place more than at most a few hundred million years earlier than the metamorphism at 1850 Ma (P. N. Taylor, personal communication, 1984).

The Archaean craton and the Ketilidian mobile belt

Whereas much isotopic information is available for the central part of the Archaean craton, very little has been published for the northern and southern parts of the craton. Likewise, isotopic data from the Ketilidian mobile belt are as yet limited. During the mapping in the fifties it was thought that the Ketilidian mobile belt contained an Archaean basement. For example, in the legend of the 1:100 000 map sheet 60 V.1 Syd (Nanortalik), some gneissose granites are stated to represent 'predominantly reactivated Archaean basement'. However, zircon U-Pb and whole-rock Rb-Sr isochron ages obtained by van Breemen *et al.* (1974) did not support this contention. The age of the supposed basement was *c.* 1850 Ma and the isotopic results did not give any indication of the presence in the investigated rocks of components derived from much older crustal material. Van Breemen *et al.* (1974) concluded therefore that most of the Ketilidian mobile belt consists of new Proterozoic crust.

Kalsbeek & Taylor (1985a) have carried out Pb-isotopic measurements to test this view. Lead isotopes are particularly useful in this respect because contamination of igneous rocks with lead derived from deep, older, continental crust is often clearly reflected in the Pb-Pb isochron diagram. Deep crustal rocks are often markedly depleted in U relative to Pb, and as a consequence the increase in $^{207}Pb/^{204}Pb$ and $^{206}Pb/^{204}Pb$ by the decay of uranium is here much slower than in the mantle or in the upper crust. Rocks contaminated with such 'retarded' lead derived from deep older crust will have low initial Pb-isotopic ratios compared to pristine mantle-derived magma of the same age, and this is particularly reflected in a displacement of the Pb-Pb isochrons towards lower $^{207}Pb/^{204}Pb$ ratios in the isochron diagram. This conception is formally expressed with the help of the 'model μ_1' value, which can be read off on the 'geochron' line (fig. 2). For non-contaminated, mantle-derived rocks, the model μ_1 value is a measure of the U/Pb ratio of the mantle source. For contaminated mantle-derived magmas, or granitic rocks formed from crustally derived magmas, this is not the case. The observed model μ_1 values for such rocks, read off on the geochron line, are the result of mixing of lead derived from the mantle with older crustal lead, and give no direct information on the U/Pb ratio of the mantle (or crustal) source of the rocks. For non-contaminated Archaean rocks, mantle-type μ_1 values in the order of 7.5–8.0 are most commonly found, for Proterozoic rocks they increase to *c.* 8 (Moorbath & Taylor, 1981; Oversby, 1974). Values significantly lower than this are strong evidence for crustal contamination of the rocks in question (e.g. Taylor *et al.*, 1980).

A comparison of the isochrons obtained for granites in the central part of the Ketilidian mobile belt (13 in fig. 1) with Ketilidian granites in the border zone of the Archaean craton (12, fig. 1) examplifies this: The three granites from the border zone have much lower model μ_1 values (7.2–7.6, fig. 2A, Table 1) than those from the central part of the mobile belt (μ_1 *c.* 8.0, which is normal for uncontaminated Proterozoic rocks). The former apparently contain large proportions of lead derived from the surrounding Archaean rocks whereas this is not the case for the Ketilidian granites farther south. This supports the contention of van Breemen *et al.* (1974) that probably no Archaean basement is present underneath most of the Ketilidian mobile belt. Recent Sm-Nd data of Patchett & Bridgwater (1984) further confirm this view. These authors conclude that the Ketilidian granites they studied may contain up to *c.* 10–15 per cent of material derived from the Archaean craton, but that this material was incorporated into the granites via the sedimentary/volcanic rocks from which the granites were formed by partial melting.

During the investigation mentioned above, Pb-Pb isochrons were also obtained for the gneisses of the southern part of the Archaean craton (11, fig. 1) and ages between *c.* 3100 Ma and 2800 Ma were found. These isochrons, however, also define lower model μ_1 values (7.20–7.25) than would be expected for more or less pristine late Archaean rocks (fig. 2B). The same phenomenon has been described from the Godthåbsfjord region (10, fig. 1). In this area early Archaean *(c.* 3600 Ma) and late Archaean *(c.* 3000–2600 Ma) gneisses occur side by side, and the late Archaean rocks often have low model μ_1 values because of contamination at depth with lead from early Archaean rocks (Taylor *et al.*, 1980). Gneisses from areas where no early Archaean rocks have been found (Sukkertoppen, Nordlandet and Fiskenæsset, S, N and F in fig. 1) have model μ_1 values of *c.* 7.5 (fig. 2B), which is normal for

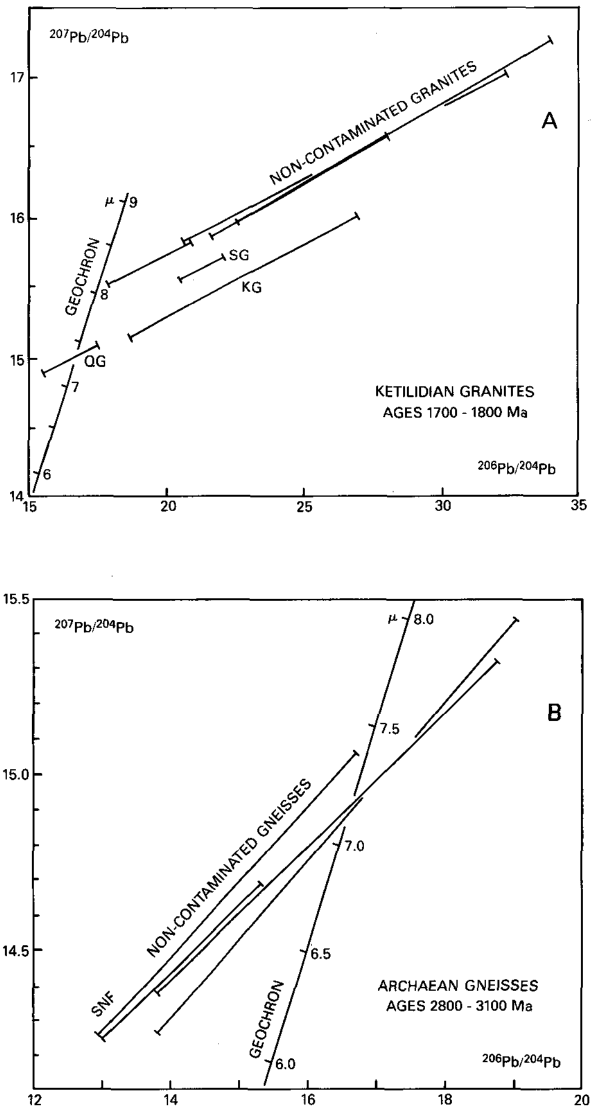

Fig. 2. Synopsis of Pb-Pb isochrons (individual samples not shown) obtained for Ketilidian granites (A) and Archaean gneisses (B) in South Greenland. Igneous rocks contaminated at depth with lead from older rocks are characterised by a displacement of their isochrons to lower $^{207}Pb/^{204}Pb$ ratios compared to non-contaminated rocks. Such isochrons intersect the 'geochron' at lower model μ_1 values than comparable non-contaminated rocks.

A. Ketilidian granites: SG, QG and KG are the Storø, Quiartorfik and Kærne granites from the border zone of the Archaean craton (12, fig. 1). The other isochrons represent granites from the central part of the Ketilidian mobile belt (13, fig. 1) which are not contaminated with lead from an Archaean basement. Figure based on data of Kalsbeek & Taylor (1985a).

B. Archaean gneisses: SNF is the isochron obtained by Taylor *et al.* (1980) for gneisses from Sukkertoppen, Nordlandet and Fiskenæsset (S, N and F in fig. 1) which are considered not to have been contaminated with older lead. The other three isochrons represent gneisses from the southern part of the Archaean craton (11, fig. 1). The low model μ_1 values defined by these isochrons suggest the presence of older Archaean rocks at depth – see the text. Figure based on information from Taylor & Kalsbeek (1985).

non-contaminated igneous rocks of that age. Early Archaean rocks have not been found in the southern part of the craton, but the low model μ_1 values found for the late Archaean gneisses suggest their presence at depth (Taylor & Kalsbeek, 1985). This suggestion is supported by Pb-isotope data obtained for a *c.* 2150 Ma 'MD' (dolerite) dyke in the southern part of the Archaean craton. The Pb-isotopic composition of this dyke indicates such a low model μ_1, that derivation of a large proportion of the lead from early Archaean rocks at depth is an almost inevitable conclusion (Kalsbeek & Taylor, 1985b).

At first sight it may appear strange that the isotopic composition of the lead in *Proterozoic* intrusions may be used to deduce the age of the *Archaean* rocks in the deep crust underlying these intrusions. Nevertheless, one of the first pieces of evidence for the presence of Archaean rocks in Greenland was derived from Pb-isotopic analyses of galena – not from the Archaean rocks themselves, but from the *c.* 1250 Ma cryolite body at Ivigtut (Slawson *et al.*, 1963).

Relations between Archaean and Proterozoic tectonic units in the Greenland shield

Archaean rocks have now been recognised over most of Greenland (fig. 1) and this leads to the question whether these, together with similar Archaean rocks in Canada, Scotland and Norway, once formed a continuous continental unit, or whether they represent a number of originally dispersed 'micro continents' (cf. detailed discussions on Archaean and Proterozoic crustal evolution in Windley, 1977 and Kröner, 1981).

Orogenic activity was widespread over most of Greenland during the Proterozoic, and such activity is most commonly related to plate margins rather than within-plate settings. Still, apart from the northern border of the Ketilidian mobile belt where the Archaean craton ends, no independent evidence of the presence of plate margins has yet been described. However, the Pb-Pb isochrons obtained for the Proterozoic gneisses from Nordre Strømfjord in the Nagssugtoqidian mobile belt (9 in fig. 1) give no evidence that these rocks contain lead derived from Archaean rocks (Kalsbeek *et al.*, 1984; see also Table 1). The isochrons define model μ_1 values of *c.* 8.0 which is normal for non-contaminated Proterozoic rocks. This suggests that no Archaean rocks were present near the place where these rocks were formed and it is possible that the Nordre Strømfjord area contains a suture between two originally separated Archaean miniplates. A geochemical study of the supracrustal rocks in the Nordre Strømfjord area (Rehkopff, 1984) shows that parts of these rocks are of volcanic origin and have a distinct calc-alkaline chemical signature. At present such rocks are found at 'destructive' plate boundaries, and if this was also the case during the Proterozoic it would support the presence of an ancient plate margin in this area. Much more field and isotope work will be required to substantiate this suggestion and to see whether comparable evidence for other possible plate margins can be found elsewhere within the Greenland shield.

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