Lead isotope signatures of mineralised rocks in the Caledonian fold belt of North-East Greenland

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Lead isotope analyses of samples with small accumulations of metals and incompatible elements from the Precambrian gneisses of North-East Greenland indicate that mineralisation mostly involved remobilisation of metals from local host rocks. Source ages of lead fall in three groups: (1) 1700–2400 Ma for Lower Proterozoic skarns, Caledonian sulphide-bearing pegmatites and quartz veins, and post-Jurassic pyrite-mineralised fault breccias; (2) 900–1000 Ma for Caledonian shear zones and Caledonian(?) skarns in Middle–Late Proterozoic rocks; and (3) ~400 Ma for Caledonian thrust zones with associated relative uranium enrichment along thrust planes.

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In the Caledonian fold belt of North-East Greenland (76°–78°N) only brief reconnaissance for indications of economic mineralisation has been carried out. Showings of mineralised rocks include skarn, shear and thrust zones with disseminated pyrite or hematite, and pyrite-mineralised fault breccias (Jensen & Stendal, 1994). None of the showings have dimensions or element concentrations of economic significance, but the study of their lead isotope systematics contributes to a characterisation of crustal source rocks of lead in this segment of the Caledonian fold belt. The lead isotope patterns also form a basis for comparison with lead isotope data for economic mineralisation in central East Greenland (Jensen, 1993). The area of study in North-East Greenland (Fig. 1) is dominated by Precambrian crystalline rocks which have been reworked during the Caledonian orogeny. The studied showings of mineralised rocks may be grouped by age and genetic association: (1) Lower Proterozoic skarns developed along contacts between paragneisses and orthogneisses; (2) Caledonian thrust and shear zones in the Precambrian metamorphic basement; (3) post-Jurassic normal faults with associated pyrite-mineralised breccias. The geology and geochemical characteristics of the mineralised localities are described by Jensen & Stendal (1994); in the present paper lead isotope data are presented and discussed.

Analytical procedure and precision

The isotopic compositions of lead in sixty mineral samples from mineralised rocks have been determined. Samples of sulphide minerals and uraninite were dissolved in nitric acid, iron oxides in hydrochloric acid, and other minerals and a few whole rock samples in hydrofluoric acid. Lead was then extracted in ion exchange columns from a hydrobromic acid solution and eluted with hydrochloric acid. The samples were loaded with silica gel in dilute phosphoric acid on single rhenium filaments and ionised at 1230°C in a Finnigan MAT-261 multiple-collector mass spectrometer. The NBS SRM 981 lead standard was measured frequently and average isotope ratios of 50 measurements were compared to the 'true' values of Todt *et al.* (1984). The determined mass fractionation factors for the ratios $^{206}Pb/^{204}Pb$, $^{207}Pb/^{204}Pb$ and $^{208}Pb/^{204}Pb$ are 1.0025, 1.0037 and 1.0050, respectively. The total errors for the measured lead isotope ratios are judged to be well below 0.10%. All confidence intervals stated in this paper are 2σ.

Isochrons were calculated using the York (1969) procedure for straight line fitting of bivariate data with correlated errors. The minimised quantity MSWD (mean square of weighted deviates) provides a measure of the fit. The present-day $^{238}U/^{235}U$ ratio and the decay constants for ^{232}Th, ^{235}U and ^{238}U from Steiger & Jäger (1977), together with the primordial terrestrial lead composition and the age of the Earth from Tatsumoto *et al.* (1973), were used in calculation of $^{207}Pb/^{206}Pb$ ages and model first-stage μ ($^{238}Pb/^{204}Pb$) values.

Secondary isochrons

Some principles of geochronological interpretation of

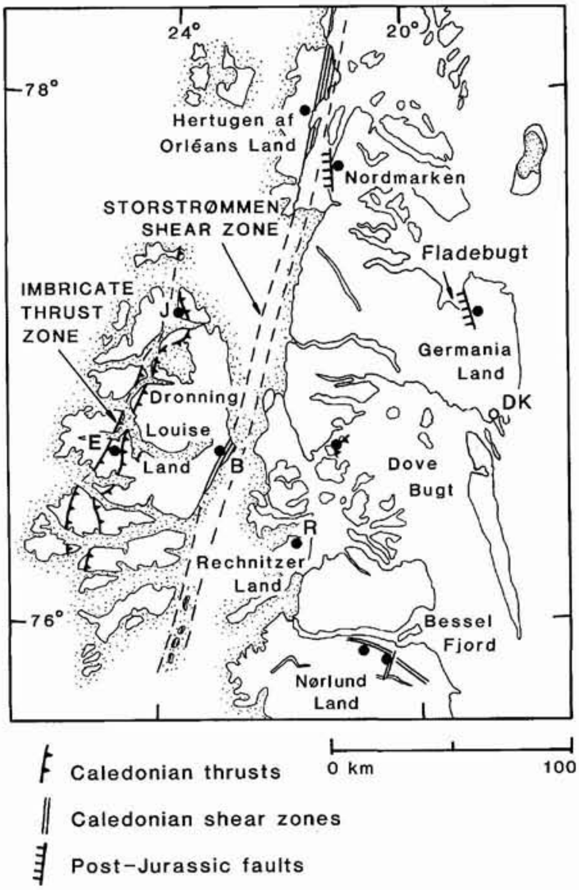

Fig. 1. Map of North-East Greenland (76°–78°N). *Filled circles*, sample localities for new lead isotope analyses; *open circle* (DK), locality of Danmarkshavn gneiss sample analysed by Steiger *et al.* (1976). R = Ravnedalen; B = Borgjøkel; E = Eigil Sø; J = H. A. Jensen Bjerg.

lead isotope data from mineralised rock suites are discussed below. For an extensive review of the decay systematics of the uranium-lead and thorium-lead systems and their geological significance the reader is referred to Kanasewich (1968) and Faure (1986).

Consider that, T years ago, some geological process reworked a segment of the Earth's crust to produce a system that then remained closed to gains or losses of uranium, thorium and lead until a time t years ago; consider further that a geological sample was collected from the system and its new lead isotope composition determined. The continually evolving isotopic ratios of the lead in the system would follow a *growth curve* in the $^{207}Pb/^{204}Pb$-$^{206}Pb/^{204}Pb$ diagram (curved path from I to A; Fig. 2). For a system with a higher μ ($^{238}U/^{204}Pb$) value the growth curve would be displaced towards the upper right-hand corner of the diagram (e.g. curved path from I to B; Fig. 2). The lead in cogenetic rocks or minerals with varying μ values would evolve along a series of growth curves ending at later times t, with compositions lying on straight lines that pass through the initial common composition (*I-d-c-a-b* for $0 < t < T$, or *I-D-C-A-B* for $t = 0$; Fig. 2). Such lines are termed secondary isochrons. The slope R of a secondary isochron is:

$$R = \frac{1}{137.88}\left[\frac{e^{\lambda_2 T}-e^{\lambda_2 t}}{e^{\lambda_1 T}-e^{\lambda_1 t}}\right], \qquad \text{[Equation 1]}$$

where λ_1 and λ_2 are the decay constants for ^{238}U and ^{235}U, respectively (e.g. Kanasewich, 1968; Faure, 1986). The slope depends on the times T and t only, and interpretation of the isochron requires no knowledge of the history of the lead prior to T.

Galena and pyrite, the sulphide minerals most commonly used in lead isotope studies, normally have such low contents of uranium and thorium that radiogenic lead evolution in them is considered to have essentially stopped at the time of mineralisation. Sulphide minerals thus serve as fossil indicators of the evolution of the contained lead prior to mineralisation. When applying Equation 1 to an isochron defined by lead isotope ratios for a sulphide mineral deposit, T is the age of the source rocks for the lead (typically an age of sedimentation, metamorphism or magmatism when lead in the rocks concerned was homogenised), and t is the age of mineralisation when lead was mobilised from the source and sequestered in sulphide minerals. If one of the ages t or T is known from other geological evidence the corresponding age, T or t, may be found from Equation 1.

Lead isotope signatures

Pre-Caledonian skarns

Lead isotope data for pre-Caledonian mineralised skarns in Lower to Middle Proterozoic gneisses in Rechnitzer Land and on two small islands in Dove Bugt (Fig. 1) are presented in Table 1. In a $^{207}Pb/^{204}Pb$–$^{206}Pb/^{204}Pb$ diagram (Fig. 3) the data points for sulphide samples from Rechnitzer Land define rather poorly a secondary isochron with a slope of 0.11984 ± 0.02711 (n = 4, MSWD = 8.78). Interpretation of the isochron is ambiguous because the nature and degree of Caledonian deformation and metamorphism in the area are not well known. In the most simple model it is assumed that the sulphide minerals in the skarn remained closed systems from the Lower Proterozoic to the present day ($t = 0$). The source age thus obtained from Equation 1 is 1950^{+360}_{-470} Ma and a corresponding first-stage μ value is 7.84. This interpretation, however, is not very probable: it requires significant radiogenic evolution of the lead while bound in the sulphide minerals, and it does not accommodate

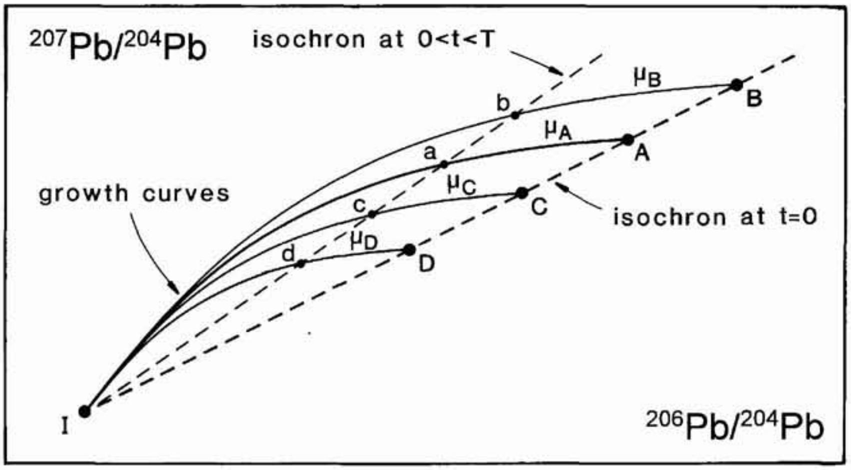

Fig. 2. Schematic $^{207}Pb/^{204}Pb$–$^{206}Pb/^{204}Pb$ diagram illustrating the concept of secondary isochrons. *I*, initial common lead isotope composition at the time *T* of homogenisation of the system. This lead evolved along a growth curve to the present composition *A*. Lead in samples from a cogenetic suite of rocks with varying μ ($^{238}U/^{204}Pb$) values evolved along a series of growth curves ending in points that lie on a straight line: a secondary isochron. For example, the lead in four rocks with the $^{238}U/^{204}Pb$ ratios μ_A, μ_B, μ_C and μ_D had evolved to *a*, *b*, *c* and *d* at a time $0 < t < T$, and to *A*, *B*, *C* and *D* at $t = 0$.

Fig. 3. Lead isotope diagrams for pre-Caledonian skarns. *Filled squares*, Rechnitzer Land samples define $^{207}Pb/^{206}Pb$ isochron for formation of Lower Proterozoic skarn; *circles*, moderately radiogenic samples from the islands in Dove Bugt scatter around the Rechnitzer Land isochron; *triangles*, mineral separates of sample 365156 from islands in Dove Bugt (of which 5 extremely radiogenic samples are not shown) define isochron for Caledonian deformation of the Lower Proterozoic skarn. Note the lack of correlation in the $^{208}Pb/^{204}Pb$–$^{206}Pb/^{204}Pb$ diagram.

possible Caledonian metamorphism and deformation of the skarn. In a perhaps more realistic model the lead in sulphide minerals in the Lower Proterozoic skarn did not evolve further until the skarn was affected by Caledonian metamorphism and deformation. The sulphide minerals

Table 1. Lead isotope analyses for mineralised pre-Caledonian skarns

Sample*	mineral	$^{206}Pb/^{204}Pb$	$^{207}Pb/^{204}Pb$	$^{208}Pb/^{204}Pb$
Ravnedalen, Rechnitzer Land				
139 skarn	py	21.268	15.780	41.283
140 skarn	py	22.662	16.010	40.726
141 pegmatite	py	19.842	15.685	39.286
143 amphibolite	py	18.589	15.494	42.677
Islands in Dove Bugt				
145 hbl skarn	py	23.221	15.841	57.961
147 hbl-gt-mt skarn	py	19.655	15.706	38.589
153 marble skarn	py	22.526	16.103	37.834
158 mt-hbl skarn	py	23.355	16.089	40.727
156 calc-sil skarn	mug	25.228	16.027	38.031
156 calc-sil skarn	nor	32.626	16.433	38.149
156 calc-sil skarn	apy/ura	134.99	22.048	53.347
156 calc-sil skarn	apy/ura	135.36	22.050	39.693
156 calc-sil skarn	apy/ura	1853.2	115.94	67.935
156 calc-sil skarn	ura	76923	4217.2	1307.8
156 calc-sil skarn	ura	64516	3532.1	1176.2

*GGU sample numbers prefixed 365.

apy: arsenopyrite; calc-sil: calc-silicate; hbl: hornblende; nor: norbergite; gt: garnet; mt: magnetite; mug: musgravite; py: pyrite; ura: uraninite.

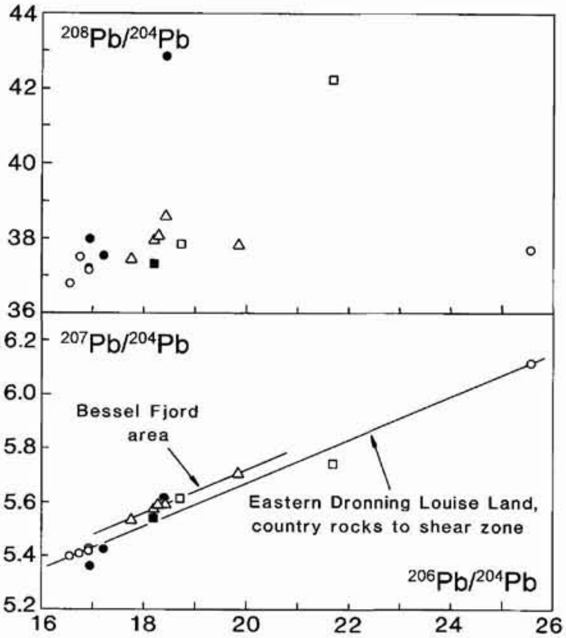

Fig. 4. Lead isotope diagrams for Caledonian shear zones and skarn. *Bessel Fjord area*: *triangles*, shear zones and skarn define $^{207}Pb/^{206}Pb$ isochron for Middle Proterozoic host rocks (Smallefjord sequence). *Storstrømmen shear zone*: *open circles*, data points for sulphides in country rocks to the shear zone define $^{207}Pb/^{206}Pb$ isochron for Middle Proterozoic cover sequence (eastern Dronning Louise Land); *open squares*, country rocks (Hertugen af Orléans Land); *filled symbols*, mylonitised rocks outline steep array suggesting addition of lead from deeper crustal sources.

may then have recrystallised and equilibrated isotopically with the host rocks, adopting their evolved lead isotope signatures. The lead in the sulphides did not evolve further after the Caledonian orogeny. If an age for Caledonian metamorphism and deformation of t = 400 Ma is assumed, the corresponding source (skarn mineralisation) age T is 1740^{+385}_{-515} Ma (μ = 7.78).

Samples from a skarn on the islands in Dove Bugt follow two contrasting linear trends in the $^{207}Pb/^{204}Pb$–$^{206}Pb/^{204}Pb$ diagram (Fig. 3): moderately radiogenic pyrite samples (365145, 365147, 365153, 365158) scatter around the Rechnitzer Land isochron, whereas seven highly radiogenic mineral separates from sample 365156 define a well-fitted isochron with a distinctly lower slope (0.05461 ± 0.00007, MSWD = 0.59) that corresponds to a mineralisation age of 396 ± 3 Ma. The radiogenic mineral separates (arsenopyrite, musgravite, norbergite and uraninite) have $^{206}Pb/^{204}Pb$ ratios ranging from 25.2 to *c.* 77 000. Musgravite, a rare beryllium-bearing oxide mineral (Chadwick *et al.*, 1990, 1993) is practically insoluble; leaching in hot (150°C) hydrofluoric acid for one week produced a slight colouring of the acid but hardly any corrosion of the grains. The lead isotope ratios for musgravite thus apply to a uraniferous surface coating on the grains, and the radiogenic nature of the norbergite and arsenopyrite samples is thought to be caused by similar grain surface coatings.

Neither of the two linear trends outlined above can be distinguished in the $^{208}Pb/^{204}Pb$–$^{206}Pb/^{204}Pb$ diagram (Fig. 3). For the Precambrian skarns the lack of correlation between uranogenic and thorogenic lead isotope ratios reflects derivation of the lead in the iron and copper sulphides from local host rock lithologies (paragneiss, amphibolite, pegmatite and calc-silicate skarn) that had different thorium-lead and thorium-uranium ratios. For the extremely radiogenic lead in mineral separates from the islands in Dove Bugt a primarily uranogenic origin is indicated, i.e., the skarn was locally enriched in uranium, but not in thorium. Low Th/U ratios are also suggested by two whole-rock chemical analyses of the musgravite-bearing skarn (3.3 ppm Th / 79.5 ppm U, and 3.5 ppm Th / 47 ppm U, respectively). In contrast, the moderately radiogenic samples from the islands in Dove Bugt and Rechnitzer Land have whole-rock Th/U abundance ratios

Table 2. Lead isotope analyses for sulphide occurrences in Caledonian shear zones

Sample*	mineral	$^{206}Pb/^{204}Pb$	$^{207}Pb/^{204}Pb$	$^{208}Pb/^{204}Pb$
Bessel Fjord region				
122 diopside skarn	py	18.228	15.578	37.944
124 diopside skarn	py	18.431	15.592	38.565
127 mylz; qz-gt amph	py	19.850	15.706	37.795
130 mylz; pegm in amph	py	18.297	15.590	38.051
131 mylz; vein in amph	py	17.760	15.534	37.431
Storstrømmen shear zone				
Borgjøkel, eastern Dronning Louise Land				
014 c-r; gt amph	py	16.558	15.399	36.790
015 c-r; amph	py	16.932	15.425	37.169
015 c-r; amph	py	16.931	15.418	37.150
016 c-r; amph	py	16.749	15.408	37.505
023 c-r; qz-gt-hbl skarn	po	25.554	16.117	37.694
017 mylz; amph	wr	17.224	15.427	37.533
018 mylz; amph	wr	18.430	15.599	42.850
020 mylz; amph/gneiss	po	16.946	15.362	37.981
Hertugen af Orléans Land				
065 c-r; qz vein in amph	py	18.723	15.616	37.849
070 c-r; amph	py	21.685	15.742	42.255
068 c-r; amph	py	18.203	15.546	37.304

*GGU sample numbers prefixed 365.

amph: amphibolite; c-r: country rocks to Storstrømmen shear zone; gt: garnet; hbl: hornblende; mylz: mylonite zone; pegm: pegmatite; po: pyrrhotite; py: pyrite; qz: quartz; wr: whole-rock.

between 0.7 and 10 (8 ratios with a median value of 1.2). The high ratio of 10 applies to sample 365145 whose $^{208}Pb/^{204}Pb$ ratio in pyrite is abnormally high (57.961; not shown in Fig. 3).

The skarns appear to have formed when granitic magmas intruded the supracrustal rocks in the Early Proterozoic 1700–2000 Ma ago. During the Caledonian orogeny, about 400 Ma ago, the skarn on the islands in Dove Bugt was deformed and metamorphic fluids migrated along the shear planes and modified the skarn; uranium was incorporated in uraninite and in intergranular mineral coatings and uranogenic lead began to accumulate. The skarn in Rechnitzer Land may also have been affected by Caledonian metamorphism and deformation, whereby the sulphide minerals recrystallised and acquired the evolved lead isotope composition of the host rocks.

Caledonian shear zones

Isotopic analyses of lead in pyrite disseminations from the Storstrømmen shear zone and Caledonian shear zones and skarn in the Bessel Fjord region are listed in Table 2.

Five pyrite samples from Caledonian shear zones and Caledonian(?) skarns in the Middle Proterozoic Smallefjord supracrustal sequence south of Bessel Fjord (Fig. 1) form a well-defined secondary isochron with a slope of 0.08081 ± 0.00709 ($n = 5$, MSWD = 0.15) in the $^{207}Pb/^{204}Pb–^{206}Pb/^{204}Pb$ diagram (Fig. 4). Using a Caledonian (400 Ma) sulphide mineralisation age in Equation 1 gives a corresponding lead source age of 930^{+180}_{-205} Ma ($\mu = 8.08$), implying that the lead mobilised in both shear zones and skarns was derived from the local Middle Proterozoic host rocks.

Iron sulphide-mineralised rocks from areas around the Storstrømmen shear zone in eastern Dronning Louise Land and Hertugen af Orléans Land (Fig. 1) show a wide range of lead isotope ratios. In the $^{207}Pb/^{204}Pb–^{206}Pb/^{204}Pb$ diagram (Fig. 4) the data points lie on a broad linear trend parallel to the Bessel Fjord isochron, but with considerably more scatter. Samples of country rocks to the Storstrømmen shear zone in eastern Dronning Louise Land define a secondary isochron (0.08037 ± 0.00132, $n = 5$, MSWD = 1.28) that, when assuming a Caledonian sulphide mineralisation age of 400 Ma, corresponds to a lead source age of 915 ± 35 Ma ($\mu = 8.00$). The precision of this age is achieved because of the large spread in isotope ratios caused by the radiogenic lead in sample 365023. Two pyrite-mineralised samples from similar country rocks to the Storstrømmen shear zone in Hertugen af Orléans Land broadly follow the latter trend (Fig. 4). Four mylonitised samples from the Storstrømmen shear zone appear to outline a steeper array that projects to lower $^{207}Pb/^{204}Pb$ lead compositions and possibly an older and deeper crustal source.

In the $^{208}Pb/^{204}Pb–^{206}Pb/^{204}Pb$ diagram (Fig. 4), disregarding radiogenic samples with $^{206}Pb/^{204}Pb$ ratios over 19, samples from the Storstrømmen shear zone and the Bessel Fjord region outline separate compositional fields that point to different thorium-uranium ratios in the source rocks. The first-stage μ values for lead evolution in the two regions are also slightly different: 8.1 for the Bessel Fjord rocks and 8.0 for country rocks to the Storstrømmen shear zone in eastern Dronning Louise Land.

The imbricate thrust zone of Dronning Louise Land

Lead isotope data for mineral showings within the Caledonian imbricate thrust zone of Dronning Louise Land are listed in Table 3. Two linear arrays with distinctly different slopes are outlined in the $^{207}Pb/^{204}Pb–^{206}Pb/^{204}Pb$ diagram (Fig. 5). In coordinates of $^{208}Pb/^{204}Pb$ *versus* $^{206}Pb/^{204}Pb$ data points for pyrite-mineralised pegmatites and quartz veins lie on steep, thorogenic trends, and points for hematised fossil magnetite placers and hematised amphibolites show a more diffuse, uranogenic trend. The lead in the hematised rocks is radiogenic with $^{206}Pb/^{204}Pb$ ratios in the range 17.2–40.0, and defines a $^{207}Pb/^{206}Pb$ isochron roughly parallel to that determined for the Caledonian shear zone on the islands in Dove Bugt (Fig. 3); the isochron has a slope of 0.05554 ± 0.00192 ($n = 11$, MSWD = 3.03) corresponding to a mineralisation age of 435^{+75}_{-80} Ma ($\mu = 7.93$). If samples of hematised amphibolite are excluded from the isochron calculation, the slope of the line is reduced to 0.05484 ± 0.00260 ($n = 7$, MSWD = 3.53) and the age is 410^{+100}_{-110} Ma ($\mu = 7.95$). Lead in pegmatite- and quartz vein-hosted pyrite samples from northern Dronning Louise Land define a much steeper $^{207}Pb/^{206}Pb$ isochron (Fig. 5) with a slope of 0.14298 ± 0.00473 ($n = 7$, MSWD = 1.03). The corresponding lead source age, assuming a Caledonian mineralisation age of 400 Ma, is 2070 ± 60 Ma ($\mu = 7.91$).

Post-Jurassic fault breccias

In Nordmarken and at Fladebugt in Germania Land (Fig. 1) pyrite-mineralised fault breccias are developed along subvertical fault planes that separate Palaeozoic – Mesozoic sediments from the older gneisses. The exact age of mineralisation is not known, but Jurassic plant fossils in the down-faulted conglomeratic sandstones in Nordmarken give a maximum age of faulting here. Lead isotope data for the fault breccia-hosted pyrite mineral-

Table 3. Lead isotope analyses for mineralised localities in the imbricate thrust zone, Dronning Louise Land

Sample*	mineral	$^{206}Pb/^{204}Pb$	$^{207}Pb/^{204}Pb$	$^{208}Pb/^{204}Pb$
H. A. Jensen Bjerg, northern Dronning Louise Land				
035 hematised mt-qzte	py	39.973	16.619	46.013
036 hematised mt-qzte	py	19.745	15.550	38.226
036 hematised mt-qzte	py	21.477	15.643	38.273
027 mt-rich pegmatite	mt	25.412	16.342	88.313
031 qz-py-cp vein	cp	18.506	15.575	38.530
040 marble	py	18.660	15.624	37.620
047 massive qz vein	py	25.150	16.541	47.885
048 qz vein	py	18.019	15.526	38.889
050 qz vein	py	20.233	15.850	40.789
050 qz vein	py	21.322	16.007	42.067
052 mt-rich pegmatite	py	19.340	15.734	38.048
Eigil Sø area, western Dronning Louise Land				
001 hematised amph	hm	17.253	15.385	39.228
001 hematised amph	hm	17.358	15.400	39.327
001 hematised amph	wr	17.592	15.451	39.735
002 qz-hm vein in amph	hm	17.172	15.382	38.924
007 qz-hm vein in gneiss	hm	18.667	15.482	40.620
008 qz-hm vein in gneiss	hm	24.406	15.831	44.421
011 hematised pelite	hm	38.913	16.626	39.880
012 hematised mt-qzte	hm	32.329	16.278	40.504

*GGU sample numbers prefixed 365.
amph: amphibolite; cp: chalcopyrite; hm: hematite; mt: magnetite; py: pyrite; qz: quartz; qzte: quartzite; wr: whole-rock.

isation are listed in Table 4. Samples from Fladebugt and Nordmarken together define a $^{207}Pb/^{204}Pb$–$^{206}Pb/^{204}Pb$ linear array with a slope of 0.16184 ± 0.01487 ($n = 10$, MSWD = 1.33) (Fig. 6). Using $t = 0$ (recent mineralisation) in Equation 1 gives a maximum source age of 2475^{+150}_{-160} Ma ($\mu = 7.92$), i.e. Late Archaean to Early Proterozoic. Using a Tertiary mineralisation age (e.g. t = 50 Ma) only reduces T slightly to 2455^{+150}_{-165} Ma.

Discussion and conclusions

Secondary isochrons defined by data from sulphide and non-sulphide mineral occurrences describe evolution of lead during different intervals of time in the history of the rocks concerned. An isochron outlined by lead isotope ratios in sulphide minerals (where $^{238}U/^{204}Pb \approx 0$) describes the evolution of the lead prior to the sulphide mineralisation, and in Equation 1, T is therefore the age of the source of lead. An isochron defined by data for non-sulphide minerals (with high $^{238}U/^{204}Pb$ ratios) describes lead evolution from the time T of mineralisation until the present time. The indicated source or mineralisation ages are only approximations, because the interpretation of secondary isochrons is based on assumptions whose validity cannot always be fully assessed, e.g.: initial homogeneity of lead isotope compositions in the source rocks; closed-system behaviour of source rocks or minerals until the time of mineralisation; age of mineralisation; non-evolution of lead in sulphide minerals.

When using an age of 400 Ma for Caledonian sulphide mineralisation in Equation 1, assuming no further evolution of the lead since that time, the resulting lead source age is a minimum estimate. An estimate of the maximum age is obtained by using a mineralisation age of $t = 0$ (tantamount to postulating continued evolution of lead in the sulphide minerals after mineralisation). For the rocks reviewed here, such maximum ages are about 200–300 Ma higher than the minimum ages stated.

Archaean (~3000 Ma) rocks in North-East Greenland were reported by Steiger *et al.* (1976) from studies on banded gneisses from the Danmarkshavn area (Fig. 1). New Rb-Sr and U-Pb isotopic dating results and Sm-Nd model ages suggest that the rocks in large parts of the region are about 2000 Ma old, and that reworking of Archaean material is traceable in some areas (Kalsbeek *et*

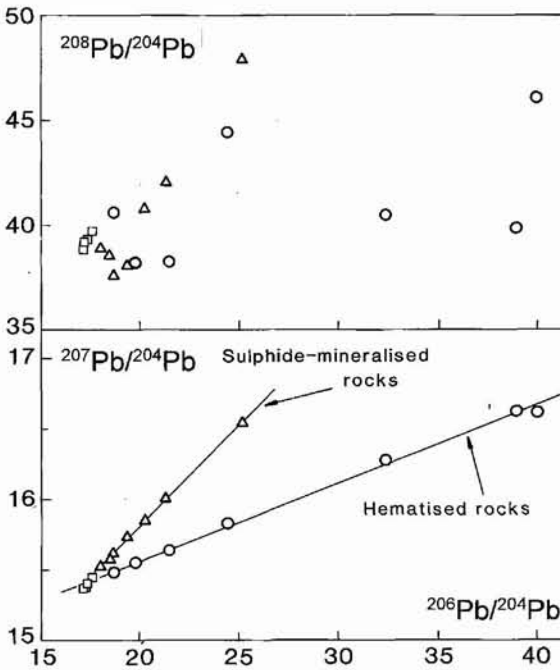

Fig. 5. Lead isotope diagrams for the imbricate thrust zone of Dronning Louise Land. *Squares* (hematised amphibolites) and *circles* (hematised magnetite placers) define $^{207}Pb/^{206}Pb$ isochron for Caledonian thrusts and hematisation; *triangles* (pyrite-mineralised pegmatites, quartz veins and marble) define $^{207}Pb/^{206}Pb$ isochron for source of lead in late Caledonian structures cutting the thrust sheets.

al., 1993). The present lead isotope survey shows that these rocks appear to be the source of lead in mineralisations ranging from Lower Proterozoic to post-Jurassic in age. Further south in East Greenland, between latitudes 70°–74°30'N, indicated lead source ages for Caledonian mineralisations are Middle Proterozoic (Jensen, 1993) or Lower Proterozoic (S. M. Jensen, unpublished data). In the Kangerlussuaq region (about 68°N) Archaean lead source ages are indicated for mineralisation associated with Tertiary magmatic activity (Jensen, 1993).

In North-East Greenland the highest apparent source ages for lead in mineralised rocks are found in pyrite in post-Jurassic fault breccias, and the lead appears to have been derived from the local basement gneisses.

Data points for highly radiogenic lead define isochrons for Caledonian deformation of rocks that contain lead with much higher source ages. The 'old' lead in the modified skarn on the islands in Dove Bugt is similar in composition to the lead in the Lower Proterozoic skarn in Rechnitzer Land. In the imbricate thrust zone in western Dronning Louise Land Caledonian metamorphic hematisation and influx of uranium was followed by intrusion of pegmatites and mobilisation of lead with a source age of about 2100 Ma. The source of the 'old' lead here is probably the gneisses that underlie the thrust sheets.

The shear zones and skarns in the Bessel Fjord region are Caledonian in age but have mobilised lead with a

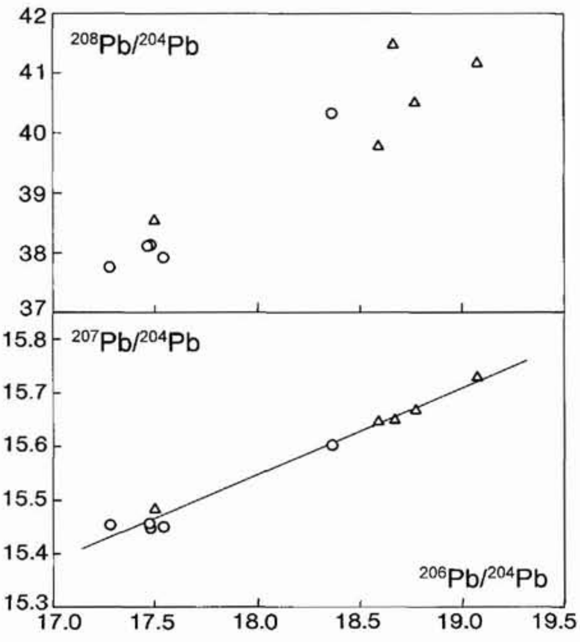

Fig. 6. Lead isotope diagrams for post-Jurassic fault breccias. *Triangles* (Nordmarken) and *circles* (Fladebugt) define $^{207}Pb/^{206}Pb$ isochron for source of mobilised lead, the local gneisses.

Table 4. Lead isotope analyses for pyrite-mineralised post-Jurassic fault breccias

Sample*	mineral	$^{206}Pb/^{204}Pb$	$^{207}Pb/^{204}Pb$	$^{208}Pb/^{204}Pb$
Nordmarken				
096 chd-cement. breccia	py	17.500	15.434	38.558
097 chd-cement. breccia	py	18.591	15.598	39.795
100 cc vein/massive py	py	18.769	15.619	40.509
114 chd-cement. breccia	py	19.076	15.682	41.177
115 chd-cement. breccia	py	18.668	15.600	41.477
Fladebugt, Germania Land				
077 pegmatite breccia	py	17.543	15.400	37.924
080 breccia	py	17.280	15.404	37.766
084 breccia/py veinlets	py	17.474	15.407	38.125
091 breccia	py	17.480	15.399	38.128
092 breccia	py	18.364	15.553	40.330

*GGU sample numbers prefixed 365.
cc: calcite; chd: chalcedony; py: pyrite.

source age of 900–1000 Ma. The most likely source of the lead is the local host rocks of the Middle Proterozoic Smallefjord supracrustal sequence. Lead in mineralised country rocks to the Caledonian Storstrømmen shear zone has a similar source age, and may also have been derived from Middle or Late Proterozoic cover rocks. A model that invokes mobilisation of metals at deep crustal levels and funnelling of the metamorphic fluids through shear zones could explain the lead isotope signature of mylonitised rocks from the Storstrømmen shear zone as well as scattered small gold anomalies in stream sediments in eastern Dronning Louise Land (see Jensen & Stendal, 1994).

Lead with source ages of 1700–2500 Ma (Rechnitzer Land, Nordmarken, Fladebugt and northern Dronning Louise Land) was mobilised from source rocks with uniform, relatively low μ values (7.9–8.0). For the lead sources with ages of about 900–1000 Ma, the μ values are slightly higher (8.0–8.1), and for Caledonian radiogenic lead the μ values are 8.1–8.3. Depletion of uranium relative to thorium in whole-rock systems is characteristic of high-grade metamorphism (e.g. Gray & Oversby, 1972) and could explain the relatively low first-stage μ values for the Lower Proterozoic gneisses. Several high-grade metamorphic terrains have been recognised in the region studied during GGU's geological mapping in 1989 and 1990 (e.g. Friderichsen *et al.*, 1991; Chadwick & Friend, 1991).

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