Age determination of Precambrian rocks from Greenland: past and present

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Age determination is an essential part of many geological investigations. The ages of Phanerozoic sedimentary rocks are typically determined by palaeontological studies (often with high precision), but for Precambrian rocks as well as for younger igneous intrusions, precise ages can only be obtained by isotopic analysis of minerals or rocks. Isotopic (radiometric) age determination of Greenland rocks began in the early 1960s and has continued since with gradually improving methods. In this contribution, the development of geochronological knowledge of the Precambrian of Greenland is described in historical perspective, and an outline of new results is given.

The history of geochronology can be roughly divided into three periods:

1) a period of single-sample K-Ar and Rb-Sr mineral or whole-rock age determinations;
2) a time when most ages were determined with the help of Rb-Sr and Pb-Pb whole-rock isochrons and multi-grain zircon U-Pb isotope data;
3) the present, where 'single' zircon U-Pb data are the preferred method to obtain rock ages.

These stages in the development of radiometric dating methods partly overlap in time, and each has yielded very significant contributions to the knowledge of Precambrian evolution in Greenland.

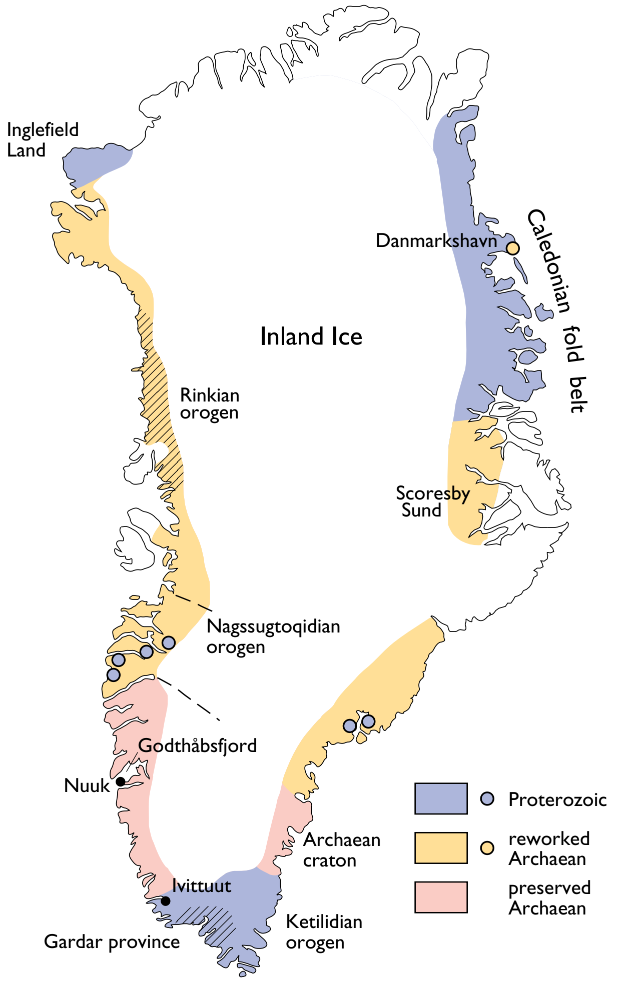

Fig. 1. Map showing Precambrian provinces referred to in the article.

The early years

The first results of K-Ar and Rb-Sr single-sample dating for Greenland rocks were published around 1960. Moorbath *et al.* (1960) presented Rb-Sr and K-Ar data for micas from two intrusions belonging to the Gardar igneous province of South Greenland (Fig. 1), from which they calculated ages between *c.* 1100 and 1250 Ma (Ma = million years). Until then it was believed these intrusions could be of Palaeozoic age (Ussing, 1912; Moorbath *et al.*, 1958). Moorbath *et al.* (1960) also obtained a minimum age of *c.* 1600 Ma for the Julianehåb granite, the country rock to the Gardar intrusions. Subsequent isotopic data have demonstrated that the age of the Julianehåb granitoids is about 1800 Ma (see p. 56-57). Shortly after, the first evidence was found

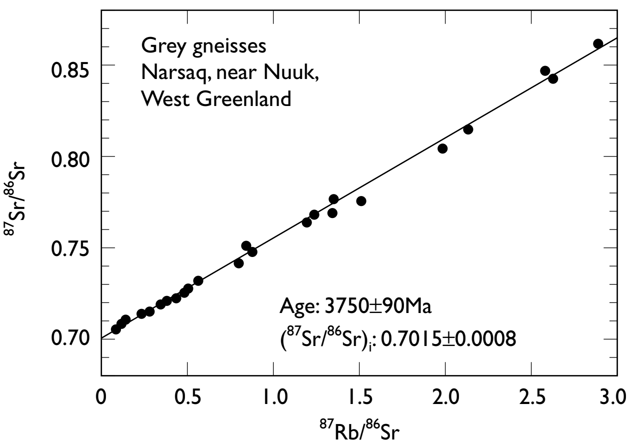

Fig. 2. Rb-Sr isochron diagram for early Archaean orthogneisses from Narsaq, 20 km south of Nuuk, West Greenland; data from Moorbath *et al.* (1972). Each point represents one sample analysed for Rb-Sr isotopic ratios. Since ^{87}Rb is radioactive and decays to ^{87}Sr, the $^{87}Sr/^{86}Sr$ ratio of the samples increases with time, dependent on the $^{87}Rb/^{86}Sr$ ratios. The slope of the line-of-best-fit is a measure of the age of the rocks, and the initial Sr-isotopic composition $(^{87}Sr/^{86}Sr)_i$ (i.e. the $^{87}Sr/^{86}Sr$ ratio of the samples 3750 million years ago) gives information on the origin of the parent granitoid magmas.

for the presence of much older rocks in Greenland; Armstrong (1963) obtained a K-Ar date of *c.* 2700 Ma for biotite from a granitoid rock from the Godthåbsfjord region (Fig. 1). Indirect evidence for the presence of very old rocks (> 3000 Ma) in South-West Greenland was seen in the abnormal isotopic composition of Pb in galena from the *c.* 1200 Ma Ivittuut (Ivigtut) cryolite body (Slawson *et al.*, 1963). The presence of such old rocks at depth has recently been confirmed by finds of very old (*c.* 3600 Ma) Archaean zircons in younger metavolcanic rocks of the Tartoq Group, north-west of Ivittuut (V. R. McGregor & A. P. Nutman, personal communication, 1996). An overview of the first results of 'absolute' age determinations for South Greenland was presented by Bridgwater (1965), and it is remarkable how, in a period of very few years, an essentially correct chronological framework was established for the rocks in that region.

In East Greenland, Kulp *et al.* (1962) reported K-Ar biotite dates for rocks from the Caledonian fold belt of East Greenland (Fig. 1) and demonstrated the presence of older rocks, not affected by Caledonian metamorphism, in the Scoresby Sund area, west of the fold belt. Wager & Hamilton (1964), working further south, obtained Archaean and Early Proterozoic ages from South-East Greenland and were able to demonstrate a direct correlation of the East Greenland Caledonian fold belt with that of Scotland.

Larsen & Møller (1968) reported on a survey of K-Ar biotite ages obtained for rocks scattered along the west coast of Greenland, and were the first to differentiate areas where Proterozoic (1600–1800 Ma) ages prevail from areas where Archaean ages are locally preserved.

The most serious draw-back for both Rb-Sr and K-Ar mineral ages is that (at best) they date the last period of heating, and not the age of formation of the rocks. In some cases K-Ar ages on whole-rock samples were found to be totally unreliable. Moreover, to calculate an age from Rb-Sr data an 'initial' Sr-isotopic composition had to be assumed with the possibility of significant error. Introduction of the Rb-Sr isochron diagram (Nicolaysen, 1961) permitted calculation of both the age and initial Sr-isotopic composition of rocks by analysing different samples from the same rock unit; since then Rb-Sr (and Pb-Pb) isochron dating has played a major role in geochronology.

Rb-Sr and Pb-Pb whole-rock isochrons and multi-grain zircon U-Pb ages

By the beginning of the 1970s, dating of whole rocks with the help of Rb-Sr isochrons had come into general use. In Greenland this method has been used very extensively, and with many important results. In 1971 the very old age (3600–3900 Ma) of rocks in the Godthåbsfjord region was documented by Rb-Sr and Pb-Pb whole rock data (Fig. 2) acquired at the Age and Isotope Laboratory, Oxford University (Black *et al.*, 1971; Moorbath *et al.*, 1972), confirming field evidence that such old rocks might be present (McGregor, 1968). At that time they were the oldest rocks known on earth. These first results were followed by numerous other isotope studies of the Godthåbsfjord region, making it one of the most intensely studied Precambrian areas in the world.

Simultaneously with the development of improved methods for Rb-Sr and Pb-Pb whole-rock dating, major advances had been made in the U-Pb dating of zircon. Among the first to report modern U-Pb zircon data for Greenland rocks was Baadsgaard (1973), who obtained a 3650±50 Ma age for the Early Archaean Amitsoq gneisses at Godthåbsfjord.

The geochronology of the Ketilidian orogen of South Greenland (Fig. 1) was further investigated by van Breemen *et al.* (1974). They obtained Rb-Sr whole-rock isochron dates of 1890±90 Ma and 1780±20 Ma for early and late Ketilidian 'Julianehåb' granites, respectively, and corresponding U-Pb zircon dates of 1840±25 Ma and 1780±20 Ma. Furthermore, they calculated initial Sr-isotope ratios of 0.7022 and 0.7032 for early and late Ketilidian granites, respectively, and argued that such low initial ratios were inconsistent with the then current interpretation of field observations that the Ketilidian granites could have formed by remelting of Archaean basement gneisses.

Knowledge of the chronology of the Gardar province was significantly improved by Rb-Sr whole-rock dating (e.g. van Breemen & Upton, 1972; Blaxland *et al.*, 1978). Many independent intrusions have been dated and an age range from 1300 to 1120 Ma obtained.

The first Rb-Sr whole-rock and U-Pb zircon age determinations from the pre-Caledonian basement of North-East Greenland yielded an age of *c.* 3000 Ma for a banded gneiss sequence near Danmarkshavn (Fig. 1; Steiger *et al.*, 1976). This result has recently been confirmed by new U-Pb zircon dating (Nutman & Kalsbeek, 1994a); however, all other samples from the pre-Caledonian basement studied in this region have yielded Early Proterozoic dates (e.g. Kalsbeek *et al.*, 1993).

Although a major improvement compared to K-Ar and Rb-Sr single sample data, Rb-Sr and Pb-Pb whole-rock isochron dating also had its serious problems. First, the method was very time-consuming: a large number of samples had to be collected from the rock to be dated, and up to perhaps 10 samples or more had to be analysed to obtain a useful result (cf. Fig. 2). Moreover, metamorphic events post-dating original rock formation commonly disturbed Rb-Sr and Pb-Pb isotope relationships, resulting in significant scatter in the isochron diagram; this often made it impossible to obtain precise information on the age of the rocks. In view of the large investment of time, this was unfortunate. Since large parts of Greenland consist of Archaean rocks (typically 2600–3000 Ma old) which underwent high grade metamorphism during the Early Proterozoic (Fig. 1), this was a major problem.

Modern zircon U-Pb age determination

Experience has shown that U-Pb isotope systematics in the mineral zircon are among the most difficult to disturb by later metamorphism. Even after high grade metamorphism, at least some zircon crystals retain evidence of the original age of the rock. However, new zircons may be formed during metamorphism, and old zircon may lose some of its radiogenic lead. In multi-grain zircon concentrates, zircons of different ages were commonly present, which could result in erroneous age determinations. Modern methods concentrate on the analysis of single, carefully selected crystals, or of a few grains for which there is morphological evidence that they belong to the same generation. Analysis can, in principle, be carried out in two ways: either by classical methods, i.e. by dissolution of the zircon followed by mass-spectrometrical analysis, or with the help of an ion microprobe. Both methods have recently been employed on Greenland rocks with considerable success.

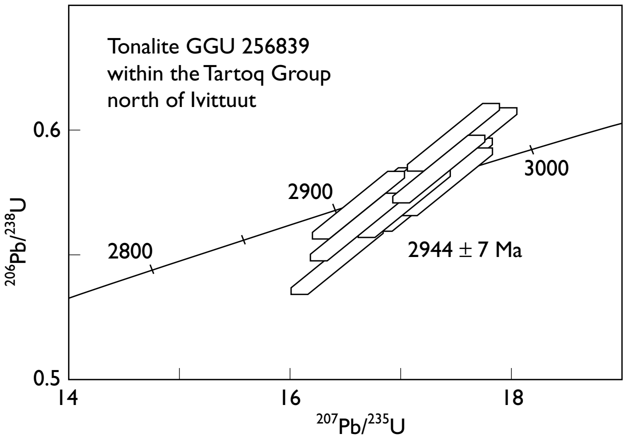

Fig. 3. Concordia diagram with U-Pb isotope data for zircons from granitoid sheets cutting metavolcanic rocks of the Tartoq Group in South Greenland (Nutman & Kalsbeek, 1994b). Age determinations are based on the decay of two isotopes of uranium, ^{235}U and ^{238}U, which yield ^{207}Pb and ^{206}Pb, respectively. The ratios $^{207}Pb/^{235}U$ and $^{206}Pb/^{238}U$ are independent measures of the age of the zircons. If these two ages are in agreement the analyses fit on the 'concordia line', suggesting minimal later disturbance of the U-Pb isotope systems.

High-precision dates have been obtained by classical mass spectrometry for zircons from granitic rocks and sediments in the Ketilidian orogen of South Greenland by Hamilton *et al.* (1996). Here it could be shown that, from the time of final granite emplacement, subsequent deformation, erosion of the granites, and high-grade metamorphism of the resulting sediments took place within the very short time span of perhaps ten million years. This required individual rock samples to be dated with a precision of 1–2 Ma, about 1 *per mil* of the age itself! Unfortunately this method is very time-consuming.

Zircon U-Pb dating by ion microprobe was pioneered by W. Compston at the Australian National University (ANU; Compston *et al.*, 1984). A number of comparisons have documented that dating with SHRIMP

(SHRIMP = Sensitive High Resolution Ion Micro-Probe) yields reliable results (e.g. Roddick & van Breemen, 1994), albeit of generally lower precision than can be obtained by conventional mass spectrometry. Analysis by SHRIMP permits ages to be determined on areas of about 30 μm in diameter on polished sections of zircon crystals. One analysis requires about 20 minutes, and 10–20 spots are usually analysed to obtain a precision of about 10 Ma on an 1800 Ma old rock. For older zircons, higher precisions can often be obtained (Fig. 3) because more radiogenic Pb has accumulated, giving rise to better counting statistics during measurement. Numerous samples from different areas in Greenland have been analysed with SHRIMP over the past decade in cooperation with ANU. A few examples follow.

Detailed study of numerous samples from the Early Archaean gneiss complex in the Godthåbsfjord region has shown that these can be subdivided into different age groups in the range of 3900–3700 Ma, together with 3650–3625 Ma granites (Nutman *et al.*, 1993). These authors suggest that the Early Archaean complex may consist of several independent microcontinents that were welded together around 3650 Ma ago.

Ninety samples from the Nagssugtoqidian orogen, north of the Archaean craton, have recently been studied by SHRIMP in a reconnaissance manner to gain an impression of the distribution of Archaean and Early Proterozoic rocks, which could not easily be differentiated in the field (Kalsbeek & Nutman, 1996). This work proved that by analysing only three or four zircon grains per sample, an age with an estimated error of less than about 50 Ma could be made for most samples. About 90 minutes of instrument time were used per sample.

During 1996, cooperation with the Australian National University was continued. New age information was obtained for rocks from eastern North Greenland, from Inglefield Land in North-West Greenland, and from the Rinkian and Nagssugtoqidian orogens of West Greenland. In coming years it is hoped that a reliable geochronological map of all of Greenland will become available.

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