Noritic dykes which are orientated north-south are early members of the Proterozoic dyke swarms which cut the Archaean craton of West Greenland. A diffuse-margined felsic patch within a >100 m wide dyke at Isukasia is interpreted to have crystallised at the same time as the rest of the dyke. Three zircons were separated from a 500 g sample of the felsic patch. Two of the grains are prismatic, euhedral, metamict with very high U contents, and are interpreted to have crystallised at the same time as the felsic patch. The most concordant analyses from the first two grains yield a weighted mean \(^{206}\)Pb/\(^{207}\)Pb age of 2214 ± 10 Ma (2F). The third grain is somewhat rounded, non-metamict with a low U content, and four spots yield \(^{206}\)Pb/\(^{207}\)Pb ages between 3390 and 3310 Ma. This is within error of whole-rock Rb-Sr and Sm-Nd isochron ages (with large uncertainties) for pegmatites forming part of the country rocks to the dyke. 2214 ± 10 Ma is interpreted as the time of emplacement and crystallisation of the dyke, during which it assimilated blocks of country rocks, giving rise to the felsic patches and inherited zircons such as the >3300 Ma grain.

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modelling of the whole rock isotopic data. The presence of any zircons inherited from dyke’s country rocks would suggest that contamination by country rocks played a part in giving these dykes their distinct geochemical and isotopic signatures.

Isukasia dyke

A north-south trending noritic dyke cuts the Isua supracrustal rocks and the Amtsoq gneisses of the Isukasia area. It is locally offset by en echelon relationships, but can be traced for at least 20 km close to the Inland Ice. This dyke was sampled where it cuts the Isua supracrustal belt (Fig. 1). The country rocks are predominantly mafic in composition, with some units of banded iron formation and also some veins of pegmatite and granitoid. The dyke has steep, sharp contacts with chilled marginal facies of fine-grained norite, partly altered to chlorite + actinolite + epidote + albite rock. The dyke may be classified as being dominated by augite norite with lesser amounts of augite granophyre. Weathered surfaces are brownish, and it is traversed by various-sized diffuse-marginated white patches and veins which do not extend into the country rocks. This dyke is slightly enriched in SiO₂ compared with typical noritic dykes in southern West Greenland reported by Hall & Hughes (1987). Medium-grained (1-4 mm) orthopyroxene and clinopyroxene (partly altered to amphiboles) and plagioclase form a mosaic of grains surrounded by a finer-grained matrix of quartz, plagioclase (oligoclase-albite), K-feldspar, biotite, Fe-Ti oxide, hornblende and apatite. Orthopyroxene is absent from the most felsic samples of the dyke. Orthopyroxenes are concentrically zoned from bronzite cores (e.g. En_95 Fs_0 Wo_5) to hypersthenic rims (e.g. En_65 Fs_30 Wo_10). The clinopyroxene is augite (e.g. En_55 Fs_10 Wo_35). Medium-grained plagioclase varies from An_65 to An_45 with normal zoning.

Sample DY62 was collected from the (irregular) margin of a large (2 by 3 m) white K-feldspathic granophyre patch. The rim of this patch is dark coloured and relatively fine-grained (0.5 to 2 mm), whilst its core is white and contains coarse-grained (2 to 5 mm) euhedral orthoclase. Both core and rim display the same granophyric texture. Fine-grained biotite, hornblende and epidote appear as aggregates up to 2 mm diameter, which also include apatite and zircon. The latter phase was confirmed by EDS analysis. Zircon separation of two splits of DY62 consisting of both the dark rim and white interior parts of the patch was undertaken by standard heavy liquid techniques. No zircons were recovered from one sample, whilst the other yielded three zircons from approximately 500 g of rock.

SHRIMP U-Pb zircon geochronology

Analytical method

U-Th-Pb isotopic ratios and absolute abundances in ca. 30 μm diameter areas of zircons were analysed using the ion microprobe SHRIMP, and were referenced to the Australian National University standard zircon SL13 (ε⁹⁰⁰ Pb/²³⁵U = 0.0928; 572 Ma). Repeated analyses of the standard during the analytical session was
used to calculate the uncertainty in the interelement isotopic ratios of unknowns. Further details of the general analytical procedure are given by Compston et al. (1984) and Williams & Claesson (1987). Ages have been calculated using the values for decay constants and present day $^{238}\text{U}/^{235}\text{U}$ recommended by the IUGS Subcommission on Geochronology (Steiger and Jäger, 1978).

Previously, counting statistics alone has been used as an estimate of error on the measured ratios. This has always been understood to be a minimum estimate of error, and in low U, non metamict, low common Pb zircon is a reasonable approximation. However, in either high Th-U or metamict damaged zircon sites ion count rates in successive mass-scans commonly vary well beyond the scatter expected from counting statistics alone (the ratio between the observed and expected variance, $F$, exceeds about 2.5). This is due to target heterogeneity on the sub-micron scale. Modification to the SHRIMP data processing programs by Trevor Ireland that augments the counting error by $\sqrt{F}$ has been applied to the data presented here.

We have taken Cumming & Richards (1975) linear model III 2200 Ma Pb as the common Pb composition. However, as most analysed sites have very low proportions of common Pb, the calculated ages are insensitive to the choice of common Pb composition.

**Prismatic, metamict grains**

Grains 2 and 3 are euhedral, with extremely high U contents (2200-4900 ppm). Grain 2 is prismatic, yellow in colour and approximately 200 μm long and grain 3 is opaque and is approximately 100 μm long. These characteristics (including high U content) are typical of zircons found in low abundance in noritic dykes and felsic patches and veins within them (Black et al., 1991; Lanyon et al., 1993). Both grains 2 and 3 from sample DY62 contain extensive metamict domains which could not be avoided totally during analysis. Seven analyses on grain 2 and 3 analyses on grain 3 were done. All these analyses show low proportions of common Pb. All the corrected $^{207}\text{Pb}/^{206}\text{Pb}$ ages lie between 1800-2220 Ma (Table 1). Analyses of grain 2 range from almost concordant to strongly normal discordant, and analyses of grain 3 are all reverse discordant (Fig. 3).

The observed reverse discordance could be due to several causes:

1) Because the ion-sputtering process gives differential yields of Pb and U species from the target zircon, U-Pb isotopic ratios are calibrated using a relationship between measured $^{206}\text{Pb}/^{238}\text{U}$ and UO/

![Fig. 2. U-pb concordia plot for zircons in dyke samples DY62.](image)

![Fig. 3. A: Discordance (${^{206}\text{Pb}^{208}\text{U}}/^{207}\text{Pb}^{206}\text{Pb}}$)×100 versus UO/U and B: Discordance versus $^{207}\text{Pb}^{206}\text{Pb}$ age for DY62 zircons.](image)

Nutman et al.: SHRIMP U-Pb zircon geochronology
Table 1. SHRIMP U-Pb zircon data for Isukasia dyke sample DY62. Isotopic ratios are after removal of small amounts of common lead, using the 206Pb correction method. The common Pb composition used is Cumming & Richards (1975) linear model III 2200 Ma Pb. Uncertainties are given at the 1F level. Disc % is discordance (1-206Pb/238U age/206Pb/206Pb age) x 100.

<table>
<thead>
<tr>
<th>Site</th>
<th>U (ppm)</th>
<th>Th (ppm)</th>
<th>Th/U</th>
<th>206Pb (ppb)</th>
<th>206Pb/238U</th>
<th>207Pb/235U</th>
<th>207Pb/206Pb</th>
<th>Age (Ma)</th>
<th>disc.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-1</td>
<td>248</td>
<td>61</td>
<td>0.25</td>
<td>&lt;1</td>
<td>&lt;0.01</td>
<td>0.603±11</td>
<td>23.38±0.47</td>
<td>0.2814±17</td>
<td>3370±9</td>
</tr>
<tr>
<td>1-2</td>
<td>59</td>
<td>19</td>
<td>0.32</td>
<td>11</td>
<td>0.47</td>
<td>0.659±08</td>
<td>25.34±0.50</td>
<td>0.279±17</td>
<td>3358±21</td>
</tr>
<tr>
<td>1-3</td>
<td>158</td>
<td>55</td>
<td>0.35</td>
<td>3</td>
<td>0.05</td>
<td>0.618±07</td>
<td>24.22±0.35</td>
<td>0.2844±21</td>
<td>3387±12</td>
</tr>
<tr>
<td>1-4</td>
<td>129</td>
<td>52</td>
<td>0.41</td>
<td>2</td>
<td>0.04</td>
<td>0.613±08</td>
<td>22.94±0.42</td>
<td>0.271±21</td>
<td>3315±18</td>
</tr>
<tr>
<td>2-1</td>
<td>3505</td>
<td>4722</td>
<td>1.35</td>
<td>2</td>
<td>0.28</td>
<td>0.216±03</td>
<td>3.83±0.06</td>
<td>0.1288±10</td>
<td>2082±13</td>
</tr>
<tr>
<td>2-2</td>
<td>2306</td>
<td>2288</td>
<td>0.99</td>
<td>73</td>
<td>0.28</td>
<td>0.228±11</td>
<td>4.02±0.26</td>
<td>0.1281±8</td>
<td>2072±65</td>
</tr>
<tr>
<td>2-3</td>
<td>3182</td>
<td>3249</td>
<td>1.02</td>
<td>140</td>
<td>0.30</td>
<td>0.255±03</td>
<td>4.62±0.06</td>
<td>0.1314±08</td>
<td>2117±11</td>
</tr>
<tr>
<td>2-4</td>
<td>4863</td>
<td>7781</td>
<td>1.60</td>
<td>32</td>
<td>0.06</td>
<td>0.200±04</td>
<td>3.64±0.10</td>
<td>0.1316±18</td>
<td>2120±24</td>
</tr>
<tr>
<td>2-5</td>
<td>3447</td>
<td>3241</td>
<td>0.94</td>
<td>185</td>
<td>0.24</td>
<td>0.386±05</td>
<td>7.40±0.11</td>
<td>0.1392±06</td>
<td>2217±08</td>
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<tr>
<td>2-6</td>
<td>3550</td>
<td>3313</td>
<td>0.93</td>
<td>210</td>
<td>0.26</td>
<td>0.385±04</td>
<td>7.38±0.09</td>
<td>0.1388±05</td>
<td>2213±06</td>
</tr>
<tr>
<td>2-7</td>
<td>4692</td>
<td>7506</td>
<td>1.60</td>
<td>1526</td>
<td>3.42</td>
<td>0.158±04</td>
<td>2.51±0.15</td>
<td>0.1156±06</td>
<td>0889±89</td>
</tr>
<tr>
<td>3-1</td>
<td>4235</td>
<td>6172</td>
<td>1.46</td>
<td>219</td>
<td>0.17</td>
<td>0.511±54</td>
<td>9.47±1.10</td>
<td>0.1346±47</td>
<td>2157±62</td>
</tr>
<tr>
<td>3-2</td>
<td>4364</td>
<td>6937</td>
<td>1.59</td>
<td>296</td>
<td>0.27</td>
<td>0.423±14</td>
<td>7.99±0.35</td>
<td>0.1370±32</td>
<td>2190±40</td>
</tr>
<tr>
<td>3-3</td>
<td>4037</td>
<td>1134</td>
<td>0.28</td>
<td>339</td>
<td>0.31</td>
<td>0.462±19</td>
<td>8.80±0.41</td>
<td>0.1384±26</td>
<td>2207±33</td>
</tr>
</tbody>
</table>

U, using the standard zircon SL13 analyses (Williams and Claesson, 1987). In the case of the Isukasia dyke data, both apparently reverse and normal discordant analyses of grains 2 and 3 have considerably higher UO/U values than the standard (Fig. 3a). The extrapolation of the calibration curve to these high UO/U values reduces our confidence in the accuracy of the calculated U-Pb ratios for these analyses.

2) Perhaps in damaged, metamict, high U domains, sputtering of 206Pb relative to 238U ions is more efficient than in undamaged zircon, giving rise to reverse discordance. This possibility was first suggested on the basis of a reconnaissance SHRIMP and TEM microstructural study of high-U zircon (McClaren et al., 1990). Both these factors can be regarded as site-specific matrix effects on damaged, metamict, high-U zircon.

3) Assessment should also be made whether the reverse discordance could be genuine, due to unsupported radiogenic Pb. An example of this has been documented in an early Archaean gneiss from Mount Sones, Antarctica (Williams et al., 1984), where domains within early Archaean zircons gained their excess radiogenic Pb from neighbouring areas in an Archaean event (in this case at ca. 2500 Ma), giving rise to reverse discordant points which also show the highest 207Pb/206Pb ages. For the Isukasia dyke analyses sites which show apparent normal discordance have somewhat lower 207Pb/206Pb ages than the least discordant analyses, indicating ancient Pb-loss (Fig. 3b). On the other hand, the reverse discordant analyses have indistinguishable 207Pb/206Pb ages to the most concordant analyses (Table 1 and Fig. 3b). Thus reverse discordance is not due to unsupported radiogenic Pb, obtained in an ancient event. Instead, we conclude that the reverse discordance problem is due to site-specific matrix affects during analysis of high-U metamict zircon, leading to inaccurate determination of U-Pb ratios. It is stressed that this problem is restricted to types of zircons which, if others are available, would definitely not be analysed. Furthermore, this problem does not affect 207Pb/206Pb ratios, where both species are measured directly using SHRIMP without the need for calibration against a standard.

Further discussion of these grains is restricted to analyses 2.5, 2.6 and 3.2, which show UO/U values closest to those obtained on the standard SL13, the lowest degrees of apparent discordance and comparatively small uncertainties due to the variance ratio between observed and expected errors in ion counting of each measured mass being low. These analyses have mutually indistinguishable 207Pb/206Pb values and yield a weighted mean 207Pb/206Pb age of 2214 ± 10 Ma (2F). Combined with the petrologic evidence given above, this age is interpreted as the best estimate of the time of crystallisation of the dyke.

Rounded, non-metamict grain
Grain 1 (ca 150 μ long) is half of a distinctly rounded, red-brown zircon, with low to moderate U content (between 50 and 250 ppm). The four analyses of this grain range from concordant to slightly discordant, with low common Pb content and 206Pb/206Pb (2a) ages between 3315 ± 36 Ma and 3387 ± 24 Ma (Fig. 2, Table 1). This grain, with its rounded morphology and...
spread in $^{207}\text{Pb}/^{206}\text{Pb}$ ages, is interpreted as an inherited grain with a minimum age of $3387 \pm 24\text{ Ma}$ which has suffered variable degrees of ancient Pb-loss, perhaps at $2214\text{ Ma}$ when it was incorporated into the dyke.

Discussion

Given the low yield of zircon from the sample, some thought should be given to the possibility that all three grains are laboratory contaminants. Laboratory contaminants are likely to have been derived from granitic rocks or sediments, normally with lower (<1000 p.p.m) Th and U contents and less likely to be metamict. On the other hand, the chemistry and habit of grains 2 and 3 are like those extracted from other noritic dykes (Black et al., 1991; Lanyon et al., 1993). Although the U-Th contents and morphology of grain 1 are more "normal", its age ($3315-3387\text{ Ma}$) matches that of some of the country rocks of the dyke, and it is therefore best interpreted as belonging to the dyke sample rather than being a laboratory contaminant.

The field and petrographic observations combined with the zircon geochronology suggest that the dyke is ca. $2214\text{ Ma}$ old. The $^{207}\text{Pb}/^{206}\text{Pb}$ ages obtained from grain 1 of between $3310$ and $3390\text{ Ma}$ (Table 1) agree with Sm-Nd and Rb-Sr whole rock isochron ages of $3362 \pm 62\text{ Ma}$ and $3382 \pm 81\text{ Ma}$ respectively (Baadsgaard et al., 1986), of pegmatitic dykes which cut the Isua supracrustal belt. Furthermore, the sampled dyke contains diffuse-margined blocks of foliated, granitic pegmatite. Assimilation and partial melting of these felsic inclusions did not proceed to completion, leaving some inclusions of country rocks intact, plus felsic patches such as DY62 which did not completely mix with the mafic magma. We suggest that $>3300\text{ Ma}$ zircons such as grain 1 became incorporated into the dyke magma by such a mechanism. All the Proterozoic noritic dykes are enriched in the LIL elements and LREE compared with tholeiitic dykes (e.g., Hall & Hughes, 1987; Bridgwater et al., 1985). They also show anomalously old (Archaean) DM model Nd ages, high initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratios and radiogenic, low $^{207}\text{Pb}/^{206}\text{Pb}$ values (Bridgwater et al., 1991).

The Isukasia dyke which cuts early Archaean rocks shows an older DM Nd model age ($>3100\text{ Ma}$), the highest initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratio and the lower $^{207}\text{Pb}/^{206}\text{Pb}$ values, compared with the Pakitsooq and Aornit dykes (e.g. DM model Nd age of $2700\text{ Ma}$ for Pakitsooq dyke) which cut a middle to late Archaean terrane in the west (Fig. 1; Bridgwater et al., 1991). Thus there may be a correlation between the isotopic signature of the dykes and the age of their country rocks. Combined with finding a $>3300\text{ Ma}$ inherited zircon in the Isukasia dyke, we conclude that the noritic magma did assimilate country rocks during its passage through the crust. However, this conclusion does not rule out the possibility that prior to interaction with contin-

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