Ice sheet development in Central Greenland: implications from the Nd, Sr and Pb isotopic compositions of basal material

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Abstract

The Nd, Sr and Pb isotopic compositions of silt particles from the basal silty ice of the two deep ice cores in Central Greenland, GISP 2 and GRIP, are compared to those of the subglacial rock material at GISP 2 (dolerite boulder, till and granitic bedrock). The silt particles embedded in the GRIP basal ice result from the reworking of the subglacial till unit overlying granitic bedrock at GISP 2, 28 km to the east. This implies that the till unit is continuous in Central Greenland. The silt particles embedded in the GISP 2 basal ice result from local erosion of the granitic bedrock. An erratic dolerite boulder in the subglacial till at GISP 2 is from a mafic dyke that can be related to the Carolinian mid-Proterozoic fold belt exposed in East Greenland. This study supports the hypothesis that the Greenland Ice Sheet in the Summit area did not result from in situ growth from local snowbanks. The composition of the dolerite boulder points to East Greenland as the most probable source region for the ice sheet. © 1997 Elsevier Science B.V.

Keywords: Greenland ice sheet; isotope ratios; provenance

1. Introduction and scientific context

To document the source area for the Greenland Ice Sheet, which is not fully established, we present results of a Nd, Sr and Pb isotopic study conducted on different parts of the GISP 2 rock core: an erratic dolerite boulder, subglacial till and granitic bedrock, and on silt particles embedded in the basal silty ice of both the GISP 2 and GRIP ice cores. The American GISP 2 ice core and the European GRIP ice core (Fig. 1) were recently retrieved from Central Greenland and constitute unique records of the past climate over at least 100,000 years. The GISP 2 site is located near the summit of the Greenland Ice Sheet (72°58'N, 38°48'W) at 3208 m above sea level and reached the bedrock at a depth of 3053.44 m on July 1, 1993. The bottom 13.11 m of the ice core consists of banded, brown silty ice, with silt particles and rock inclusions. A 1.55 m long till and bedrock core was recovered from beneath the ice, making this a unique geological sample in Greenland and providing the opportunity to study the relationships between the particles embedded in the ice sheet and local bedrock (Fig. 1). The GRIP site is located at
the present ice divide (72°34'N, 37°37'W), 28 km to the east of the GISP 2 site. In July 1992, after having penetrated 6 m of silty ice, drilling was stopped close to bedrock at a depth of 3028.8 m (Fig. 1).

The $\delta^{18}$O profiles of the two ice cores [1,2] are remarkably similar from the surface to about 2700 m depth. At this depth, ice from the beginning of the Last Glacial period is present. Ice from the Eemian and earlier periods exists below 2790 m at GRIP and in somewhat deeper levels at GISP 2. Due to ice

![Sketch map of Greenland](image)

Fig. 1. Sketch map of Greenland with features relevant to this paper and sketches of the cores (not to scale). A = Archean; $P =$ Proterozoic mobile belts (K = Ketilidian, $N =$ Nagssugtoqidian, $R =$ Rinkian); the Gardar (G) Proterozoic igneous province is restricted to the small box area in the southern tip of Greenland; $C =$ Caledonian fold belt.
deformation adjacent to the bedrock, the preserved isotopic record of the deeper ice levels is different in the two cores [2]. The δ18O isotopic compositions, however, leave little doubt that the Greenland Ice Sheet was already present in the Summit area during the Eemian interglacial period and earlier, well before the Last Glaciation [2]. The climate during earlier interglacial periods was less warm than that of the Eemian [3].

At GISP 2, a sharp transition from glacier ice to silty ice occurs at approximately 13 m above the ice–bedrock interface (Fig. 1). The temperature of this basal silty ice is −9°C and the ice is currently frozen to its bed. The upper 3 m of the silty ice consist of till containing erratic boulders (Fig. 1). A single boulder, previously described as a ‘schistose’ rock, is doleritic in texture. The contact between the GISP 2 silty ice and the underlying till is sharp. Beneath the boulders, the drill penetrated a layer of frozen till 0.08 m thick, overlying granitic bedrock.

The maximum elevation of the Greenland Ice Sheet is currently in the Summit area (Fig. 1). As a consequence, the ice is flowing towards the western coast of Greenland to the west of the GRIP and GISP 2 sites, while it is flowing towards the mountainous region of eastern Greenland to the east of the GRIP site. This divergent ice flow could indicate that the ice sheet originated in situ. The extent of the ice sheet during different climatic epochs is an important constraint for determining the relative role of the cryosphere during global changes in the Northern Hemisphere during the Pleistocene. Gas and stable isotope compositions of the silty ice from the GRIP core drilled in the Summit area, together with mineralogical compositions of the particles [6], support the hypothesis of ‘highland origin and windward growth’ for ice sheet development as first proposed by Flint [7]. Local ice, formed at or close to the ground surface prior to the development of the existing Greenland Ice Sheet, is preserved at the base of the GRIP core [8–10]. This ice was mixed with glacier ice from the growing ice sheet, with the proportion of the latter increasing upward in the silty ice sequence. This documented mixing is evidence against in situ growth of the ice sheet, which could not have developed from local snowbanks in Central Greenland.

2. Sample preparation and analysis

Eight samples from the GISP 2 site were analyzed for Nd, Sr and Pb isotopic compositions and for Rb, Sr, Sm, Nd, U and Pb concentrations by isotope dilution: the dolerite, one till sample, four samples from the granitic bedrock and two samples of particles from the GISP 2 basal silty ice. These results are compared with those of two samples of silt particles from the GRIP core (F. Grousset, pers. comm. ) (Table 1).

The samples were carefully selected to analyze
Table 1
Rb, Sr, Sm, Nd, U and Pb concentrations measured by isotope dilution and Sr, Nd and Pb isotopic compositions of GISP 2 and GRIP basal material

<table>
<thead>
<tr>
<th>Sample Type</th>
<th>Sample Type</th>
<th>Rb (ppm)</th>
<th>Sr (ppm)</th>
<th>$^{87}$Sr/$^{86}$Sr</th>
<th>Sm (ppm)</th>
<th>Nd (ppm)</th>
<th>$^{143}$Nd/$^{144}$Nd</th>
<th>Nd $^{143}$Nd</th>
<th>T$_{DM}$ (10$^9$ yr)</th>
<th>U (ppm)</th>
<th>Pb $^{206}$Pb/ $^{204}$Pb</th>
<th>Pb $^{207}$Pb/ $^{204}$Pb</th>
<th>Pb $^{208}$Pb/ $^{204}$Pb</th>
</tr>
</thead>
<tbody>
<tr>
<td>granitic bedrock 0.63 m depth</td>
<td>1</td>
<td>66</td>
<td>323</td>
<td>0.72594</td>
<td>8</td>
<td>1.00</td>
<td>5.40</td>
<td>0.511125</td>
<td>15</td>
<td>-29.5</td>
<td>3.01</td>
<td>3.70</td>
<td>26.7</td>
</tr>
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<td>granitic bedrock 0.8 m depth</td>
<td>2</td>
<td>53</td>
<td>310</td>
<td>0.72343</td>
<td>8</td>
<td>0.48</td>
<td>2.45</td>
<td>0.511159</td>
<td>6</td>
<td>-28.9</td>
<td>3.16</td>
<td>2.10</td>
<td>24.4</td>
</tr>
<tr>
<td>granitic bedrock 1.1 m depth</td>
<td>3</td>
<td>71</td>
<td>302</td>
<td>0.72884</td>
<td>5</td>
<td>0.72</td>
<td>3.65</td>
<td>0.511038</td>
<td>7</td>
<td>-31.2</td>
<td>3.38</td>
<td>5.50</td>
<td>27.0</td>
</tr>
<tr>
<td>granitic bedrock 1.38 m depth</td>
<td>4</td>
<td>67</td>
<td>300</td>
<td>0.72830</td>
<td>6</td>
<td>1.00</td>
<td>4.79</td>
<td>0.511068</td>
<td>11</td>
<td>-30.6</td>
<td>3.59</td>
<td>5.40</td>
<td>28.5</td>
</tr>
<tr>
<td>dolerite boulder</td>
<td>5</td>
<td>15</td>
<td>185</td>
<td>0.71211</td>
<td>8</td>
<td>2.43</td>
<td>7.38</td>
<td>0.512672</td>
<td>8</td>
<td>0.7</td>
<td>1.94</td>
<td>0.21</td>
<td>4.7</td>
</tr>
<tr>
<td>GISP2, particles in basal ice</td>
<td>A</td>
<td>67</td>
<td>259</td>
<td>0.72752</td>
<td>7</td>
<td>5.42</td>
<td>35.2</td>
<td>0.511191</td>
<td>8</td>
<td>-28.2</td>
<td>2.46</td>
<td>3.00</td>
<td>34.5</td>
</tr>
<tr>
<td>GISP2, particles in basal ice</td>
<td>A'</td>
<td>82</td>
<td>239</td>
<td>0.72852</td>
<td>6</td>
<td>5.60</td>
<td>37.1</td>
<td>0.511211</td>
<td>9</td>
<td>-27.8</td>
<td>2.40</td>
<td>5.90</td>
<td>22.4</td>
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<tr>
<td>GRIP, particles in basal ice</td>
<td>B</td>
<td>51</td>
<td>182</td>
<td>0.72879</td>
<td>11</td>
<td>2.04</td>
<td>13.7</td>
<td>0.510403</td>
<td>20</td>
<td>-43.6</td>
<td>3.35</td>
<td></td>
<td></td>
</tr>
<tr>
<td>GRIP, particles in basal ice</td>
<td>B'</td>
<td>13</td>
<td>388</td>
<td>0.73167</td>
<td>7</td>
<td>3.51</td>
<td>25.2</td>
<td>0.510739</td>
<td>12</td>
<td>-37.0</td>
<td>2.82</td>
<td></td>
<td></td>
</tr>
<tr>
<td>GISP2, subglacial till</td>
<td>C</td>
<td>59</td>
<td>215</td>
<td>0.73078</td>
<td>7</td>
<td>2.88</td>
<td>17.9</td>
<td>0.510695</td>
<td>10</td>
<td>-37.9</td>
<td>3.20</td>
<td>2.10</td>
<td>15.8</td>
</tr>
</tbody>
</table>

*a* Analyses provided by F. Grousset.
the freshest material possible. The chemical and mass spectrometric procedures are similar to those described in Weis and Frey [11] and in Weis et al. [12], except that the samples have not been leached. The column blanks were below 1 ng Sr and the total blanks for the whole procedure were below 2 ng Sr and 1 ng Nd. Total Pb blank values for the entire chemical procedure were typically below 1 ng. Such values are negligible in comparison to the elemental concentrations in the samples. Sr isotopic compositions were measured on single Ta filaments in the dynamic mode on a VG Sector 54 multicollector mass spectrometer with an internal precision better than $1 \times 10^{-5}$ and normalized to $^{88}\text{Sr}/^{86}\text{Sr} = 0.1194$. The average $^{87}\text{Sr}/^{86}\text{Sr}$ value of the NBS 987 Sr standard was $0.710232 \pm 8 (2\sigma_m$ on 18 samples). Nd isotopic compositions were measured on triple Ta–Re filaments with the VG Sector 54 multicollector mass spectrometer (analyses of the Merck Nd standard yielded $^{143}\text{Nd}/^{144}\text{Nd} = 0.51173 \pm 1$ and $^{145}\text{Nd}/^{144}\text{Nd} = 0.52429 \pm 1 (2\sigma_m$ on 12 samples)). For each analytical run the Nd isotopes 146, 145, 144 and 143 were measured with all values normalized to $^{146}\text{Nd}/^{144}\text{Nd} = 0.7219$.

Pb isotopic compositions and Pb and U concentrations prepared by the isotope dilution (ID) technique were measured on single Re filaments with a Finnigan MAT 260 mass spectrometer, using the $\text{H}_3\text{PO}_4$–silica gel technique [13]. All the results were corrected for mass fractionation ($0.13\% \pm 0.04\%$ per a.m.u.) on the basis of 72 analyses of the NBS 981 Pb standard [14] for a temperature range of 1090–1200°C. Between-run precision was better than $\approx 0.1\%$ for $^{206}\text{Pb}/^{204}\text{Pb}$ and $^{207}\text{Pb}/^{204}\text{Pb}$ and $\approx 0.15\%$ for $^{208}\text{Pb}/^{204}\text{Pb}$. All the elemental concentrations measured on the Finnigan MAT 260 mass spectrometer had better than 2% precision.

3. Results

3.1. Granitic bedrock

The basement beneath the Greenland Ice Sheet consists of east-trending Precambrian mobile belts [15]. At GISP 2, the basement probably belongs to the Proterozoic Rinkian (= Hudsonian) mobile belt. The southern part of the Rinkian belt is composed of gneiss and a metasedimentary cover with a large granitoid sheet along the gneiss/cover contact [16,17]. The granitic material originated, at least partly, by remelting and homogenization of the adjacent Archean gneisses [18]. Few geochronological data are available for rocks of the Rinkian belt: K–Ar biotite ages are in the range 1.87–1.68 Ga [18]. Local bedrock at the GISP 2 site is an undeformed, medium-grained, greyish-white leucocratic granite. The four samples are similar, containing
subhedral, weakly zoned plagioclase grains (commonly retrogressed to muscovite and epidote), two types of K-feldspar (orthoclase and microcline) and quartz.

The four granite samples have similar elemental concentrations and Sr and Pb isotopic compositions (Table 1), suggesting that they were derived from the same source, that is, a granitic intrusion. The isotopic data plot as a linear array (MSWD = 0.8) (Fig. 2), which, if considered as a Rb–Sr isochron, corresponds to an age of 2.10 Ga, with an initial $^{87}$Sr/$^{86}$Sr value of 0.7083. The Pb isotopic data also define a linear array with a slope corresponding to an age of 2.96 Ga (Fig. 3). The four samples have Sr and Nd isotopic compositions consistent with that of Archean gneiss [19] (Fig. 4). The Nd model ages relative to CHUR (Chondritic Uniform Reservoir) [20] are between 2.9 and 3.4 Ga, and the model ages relative to depleted mantle are about 200 my older than these values ($T_{DM}$ in Table 1). The protolith to the granitic basement probably formed during the Archean (> 2.9 Ga), with a subsequent ‘remelting’ event occurring during Rinkian metamorphism yielding the Rb–Sr isochron. The K–Ar biotite ages [18] are evidently ‘cooling ages’ related to uplift following the Rinkian event.

3.2. Dolerite boulder

The fine-grained greenish boulder provisionally identified as ‘schistose’ [5] is a weakly deformed and recrystallized dolerite with euhedral plagioclase laths enclosed in a fine-grained mesostasis of quartz with minor amounts of K-feldspar, apatite, biotite and Fe–Ti oxides. A secondary, low-grade metamorphic assemblage is also present, consisting of chlorite, epidote, titanite and calcite. This later feature, together with the Nd isotopic composition of the dolerite boulder (Table 1), precludes an origin from the undeformed and unmetamorphosed Mesozoic and
Tertiary dykes and sills in Greenland. In addition, the giant unmetamorphosed mafic dyke swarms forming the mid-Proterozoic alkaline Gardar province of southernmost Greenland [21], which intrude the Ketilidian mobile belt and the tip of the southwestern part of the Archean block, are also an unsuitable source. The general motion of the Greenland Ice Sheet away from the Summit area makes the northward transport of Gardar material from the southern part of Greenland to the Summit area highly improbable (Fig. 1).

Mafic dykes, dolerites and quartz dolerites, up to 400 m thick and with K–Ar ages between 0.98 and 0.58 Ga, occur in numerous tectonic windows (from lat. 70°N to lat. 81°N) [22] containing remnants of the Carolinidian mid-Proterozoic fold belt in the Caledonian fold belt of East Greenland (Fig. 1). These dykes are thus good candidates for the source of the erratic dolerite boulder. It is also possible that the source of the dolerite is now buried beneath the ice sheet. Carolinidian doleritic dykes occur to the west of the Caledonian fold belt, intruding the Proterozoic basement in the northern tip of Greenland. The apparent provenance of the dolerite boulder indicates that it has probably been transported in a western direction along the base of an ice sheet that subsequently developed an ice dome in Central Greenland.

3.3. Subglacial till and particles embedded in basal silty ice

The isotopic compositions of the subglacial till at the GISP 2 site and of the silt particles from the basal silty ice at GRIP and GISP 2 were analyzed from the following samples:

1. silt particles from the basal ice of the GISP 2 core between 3042.90 and 3042.94 m depth (A in Fig. 4) and between 3053.05 and 3053.09 m depth (A');
2. silt particles from the basal ice of the GRIP core between 3026.42 and 3026.46 m depth (B) and between 3027.30 and 3027.34 m depth (B');
3. silt particles from the subglacial till in the GISP 2 rock core (C).

The measured Sr and Nd isotopic compositions of the silt particles are compared with measured isotopic compositions of the granitic bedrock samples and the dolerite boulder in Fig. 4. This is an effective approach for tracing the origin of particles and has been used for unravelling the provenance of dust in the Pacific Ocean [23]. The dolerite boulder is clearly distinct from the other samples; it has slightly depleted Nd characteristics with \( \varepsilon_{\text{Nd}} = +0.7 \) (\( \varepsilon_{\text{Nd}} \) is defined as \( \frac{[(^{143}\text{Nd} / ^{144}\text{Nd})_{\text{sample}} - (^{143}\text{Nd} / ^{144}\text{Nd})_{\text{CHUR}}]}{1} \times 1000 \) [20]). The rather high \(^{87}\text{Sr} / ^{86}\text{Sr} \) compared to the depleted Nd isotopic composition probably reflects the effect of metamorphism and/or minor secondary alteration. The granitic bedrock samples are clustered, with \(^{87}\text{Sr} / ^{86}\text{Sr} \) between 0.7234 and 0.7288 and \( \varepsilon_{\text{Nd}} \) between –28.9 and –31.2, values that are compatible with those of other Archean granitic rocks from the Greenland Shield [18,19]. The most important features in Fig. 4 are: (1) the similar Sr and Nd isotopic compositions of the silt particles embedded in the GRIP basal ice and of the subglacial till of the GISP 2 rock core; (2) the similarity of the silt particles embedded in the GISP 2 basal ice to the granitic bedrock; and (3) the clear differences between the isotopic compositions of the silt particles embedded in the GISP 2 basal ice and the compositions of the underlying till.

4. Glaciological implications

The till unit present in the GISP 2 rock core just above the granitic bedrock is the source of the silt particles embedded in the GRIP basal ice, as reflected by similar Sr and Nd isotopic compositions. The presence of the till unit near GRIP, 28 km up-glacier, can be inferred from analyses of the particles embedded in the silty ice, which result from reworking of the till. This unit, containing erratic boulders, must have a significant areal extent in Central Greenland. Conversely, the silt particles embedded in the GISP 2 basal ice have Sr and Nd isotopic compositions similar to those of the local granitic bedrock. This suggests that subglacial bedrock erosion occurred locally, perhaps on topographically high knobs, where the till sheet was not present. This is supported by the observation that reworked till material is absent in the GISP 2 silty ice. Although bedrock was not reached at GRIP, local ice generated before the development of the
existing ice sheet is present in the bottom of this core [8-10]. The abundance of local ice decreases upwards through mixing with overlying glacial ice.

The age of formation of the silty ice at both drill sites is not known. We suggest that the till layer overlying bedrock at GISP 2 and the mixing of glacier ice with local ice formed in the absence of the Greenland Ice Sheet at GRIP date back from the build-up of the present ice sheet, well before the age of the oldest glacier ice present in the cores. Comparison of Nd, Sr and Pb isotopic compositions of the basal material from the GISP 2 and the GRIP ice cores, together with those of the different components in the GISP 2 rock core, support the hypothesis that the Greenland Ice Sheet, in the Summit area, did not result from in situ growth from local snowbanks. The probable origin of the erratic boulder from East Greenland indicates progression of the ice sheet from the east.

Acknowledgements

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[20] D.J. Depaolo, G.J. Wasserburg, Inferences about magma


