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# The Egersund dykes (SW Norway): a robust Early Ediacaran (Vendian) palaeomagnetic pole from Baltica

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## SUMMARY

Palaeomagnetic data for Baltica in the Late Precambrian are highly ambiguous, and have therefore, given rise to different interpretations concerning the need to explain Varangerian glaciations through snowball Earth conditions. We present new palaeomagnetic data from the 616 ± 3 Ma (U-Pb) Egersund dykes in SW Norway, which yield a palaeolatitude of $53^\circ +16^\circ/-13^\circ$ for the studied location. This would indicate that the Baltica plate spanned latitudes between 50° and 75° S in the Early Ediacaran. The pole position (31°N, 44°E, $dp/dm = 15/17$) confirms earlier studies, but the primary nature of the remanence is now supported by two positive contact tests. A new $^{40}Ar/^{39}Ar$ biotite age of 600 ± 10 Ma from one of the dykes suggests that remanence acquisition in the dykes took place between 600 and 616 Ma. The Egersund palaeomagnetic data demonstrate that Baltica was located at relatively high latitudes at the time of the Varangerian glaciations.

Additional palaeomagnetic sites in the Rogaland Igneous Complex yield a pole position (46°S, 238°E, $dp/dm = 17/19$) that confirms previous studies. The age of this remanence has traditionally been quoted as c. 930 Ma based on U-Pb ages from the complex. However, previous $^{40}Ar/^{39}Ar$ hornblende ages of around 870 Ma are now supported by a new $^{40}Ar/^{39}Ar$ biotite age of 869 ± 14 Ma obtained from a noritic dyke, and we argue that this represents an uplift/cooling age which better represents the age of the remanence in SW Norway.

**Key words:** Baltica, Ediacaran, Egersund dykes, geochronology, neoproterozoic glaciations, palaeomagnetism.

## INTRODUCTION

The Late Precambrian was a pivotal time in Earth history, with the breakup of the supercontinent Rodinia and possible 'snowball Earth' conditions (Kirschvink 1992) setting the scene for the Cambrian animal diversification. In this context, reliable palaeomagnetic data are crucial to determining whether the numerous Late Precambrian glacial deposits recorded on different continents represent glaciations which were truly global in nature, or may, at least in some cases, simply be explained by the (latitudinal) positions of individual continents.

The termination of the Precambrian has conventionally been termed the Vendian Period (*ca*. 650–543 Ma), but recently the latest Precambrian has been named Ediacaran (Knoll *et al.* 2004). The lower boundary (in Australia) is defined as the contact between Marinoan glacial rocks and overlying Ediacaran cap carbonates, thus defining the boundary between a global ice age ending at around 635 Ma (Hoffman *et al.* 2004; Condon *et al.* 2005) and the diversification of soft-bodied life. Two further epochs of global glaciation are also believed to have occurred at around 730 Ma. ('Sturtian') and 580 Ma ('Gaskiers') respectively, although the exact dates remain somewhat uncertain (Halverson *et al.* 2005).

Specifically for Baltica, a key question is whether the poorly dated Varangerian tillites (traditionally linked to either the Marinoan or the Gaskiers glaciations; see Bingen *et al.* 2005) were deposited at low or high latitudes. Unfortunately, the existing palaeomagnetic data for Baltica are ambiguous. In their widely cited data compilation, Torsvik *et al.* (1996) argued for a high latitude position of Baltica during the Vendian, based on palaeomagnetic data from Fen (Oslo region), Sredny (North Russia) and Egersund (SW Norway), but they pointed out that there is a general lack of reliable palaeomagnetic data for Baltica prior to the Early Ordovician. In contrast, recent palaeomagnetic contributions from the 608 ± 1 Ma (U-Pb) Sarek dyke swarm in Northern Sweden (Eneroth 2002; Eneroth & Svenningsen 2004) suggested an equatorial palaeolatitude. This result has subsequently been referred to as a 'robust palaeolatitude

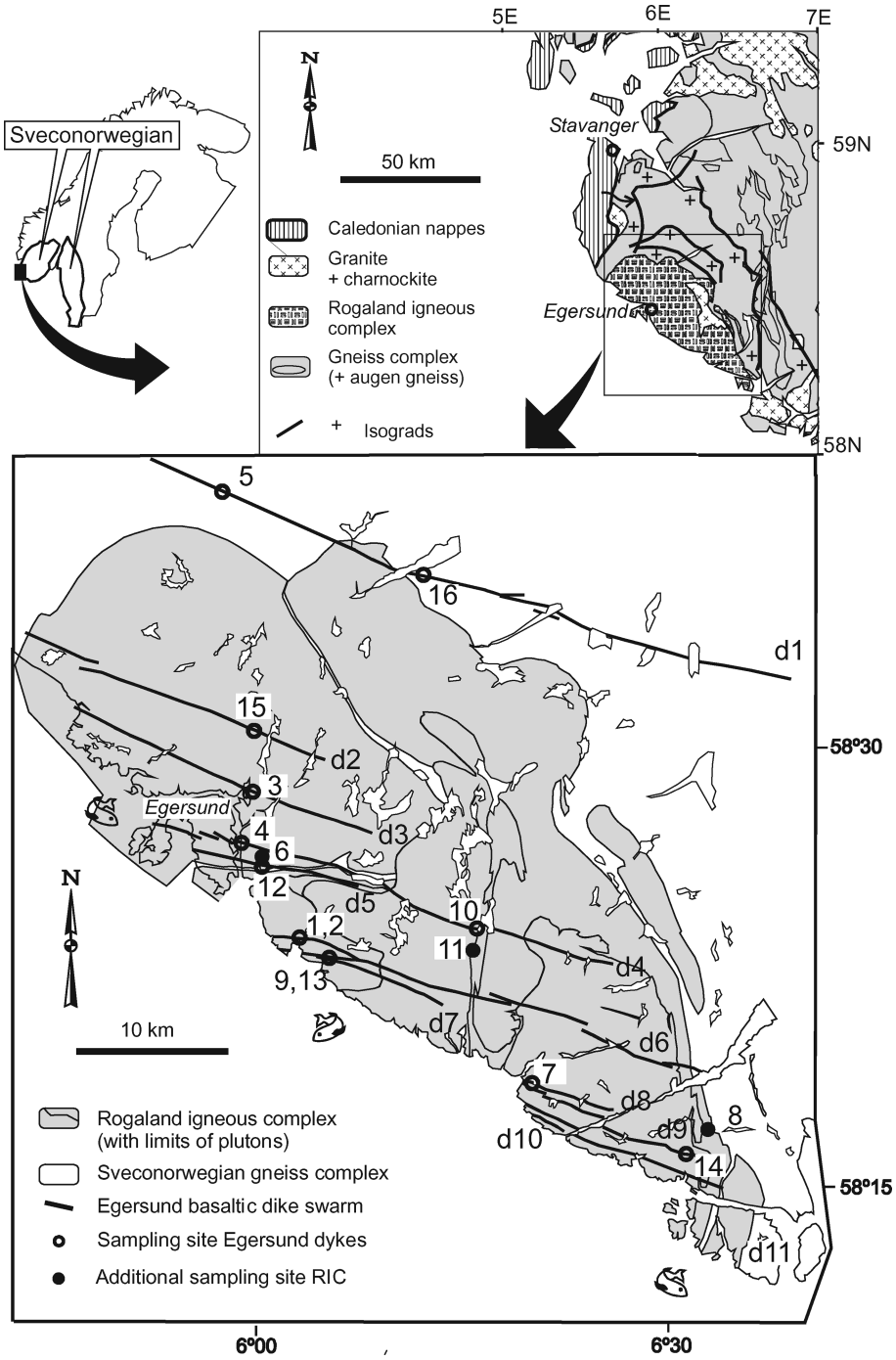


**Figure 1.** Map giving the location of the Egersund dykes within the Sweconorwegian province of SW Norway (top left), regional setting (top right), and location of the individual dykes within the RIC and Sveconorwegian gneiss complex (bottom) following Antun (1955). Individual palaeomagnetic sampling sites in the dykes are indicated by open circles, with three additional sampling sites in norites from of the RIC indicated by solid circles.

for Baltica' by Macouin *et al.* (2004, p. 396) and used as evidence for a global Neoproterozoic glaciation event spanning low to high latitudes. However, the palaeomagnetic data and interpretations reported in Eneroth (2002) and Eneroth & Svenningsen (2004) are flawed due to a mistake in the measurement orientation convention, and the authors have subsequently withdrawn both papers (Eneroth 2006a,b). Thus, the Sarek palaeomagnetic results should not be used to establish the position of Baltica during the Neoproterozoic.

The most widely used palaeomagnetic results which seem to argue for an intermediate to high latitude position for Baltica at this time (Storetvedt 1966; Poorter 1972), originate from the now well dated 616 ± 3 Egersund dyke system (Bingen *et al.* 1998) in southwestern Norway. However, the existing palaeomagnetic data have been called into question (e.g. Eneroth & Svenningsen 2004) due to the limited amount of data, seemingly unstable remanence with a direction close to the present day field, and the absence of field tests to constrain the age and stability of magnetization. The aim of the present study is to resolve the latitudinal ambiguity in the Vendian data for Baltica by reexamining the palaeomagnetic signature of the Egersund dykes and the host rocks of the surrounding Rogaland Igneous Complex

**Table 1.** $^{40}Ar/^{39}Ar$ biotite furnace step heating of samples e-12d (Noritic dyke) and E16D (Egersund dyke) (weight = 5 mg).

| Temp | $^{40}Ar/^{39}Ar$ | $^{38}Ar/^{39}Ar$ | $^{37}Ar/^{39}Ar$ | $^{36}Ar/^{39}Ar$ | $^{39}Ar$ | $^{39}Ar$ (per cent) | $^{40}Ar^{*a}$ (per cent) | $^{40}Ar^{*}/^{39}K$ | Age (Ma) | $\pm\sigma$ |
|---|---|---|---|---|---|---|---|---|---|---|
| **Sample = e-12d** | | | | | | | | | | |
| **J = .0060870** | | | | | | | | | | |
| 500 | 84.172 | 0.024 | 0 | 105.225 | 1.787 | 0.63 | 63 | 53.06 | 505.18 | 7.24 |
| 540 | 113.395 | 0.024 | 0 | 70.225 | 1.865 | 1.29 | 81.7 | 92.62 | 807.06 | 5.71 |
| 600 | 120.108 | 0.027 | 0 | 92.993 | 5.183 | 3.12 | 77.1 | 92.61 | 806.95 | 2.93 |
| 60 | 140.319 | 0.022 | 0 | 131.373 | 15.985 | 8.76 | 72.3 | 101.48 | 868.23 | 1.88 |
| 690 | 102.872 | 0.011 | 0 | 3.498 | 44.31 | 24.4 | 99 | 101.82 | 870.54 | 0.65 |
| 730 | 102.813 | 0.012 | 0 | 5.047 | 76.083 | 51.26 | 98.5 | 101.3 | 867.02 | 0.48 |
| 750 | 102.559 | 0.013 | 0 | 4.82 | 49.789 | 68.83 | 98.6 | 101.11 | 865.76 | 0.75 |
| 770 | 110.706 | 0.013 | 0 | 28.546 | 26.939 | 78.34 | 92.4 | 102.25 | 873.47 | 0.93 |
| 790 | 120.77 | 0.021 | 0.283 | 59.181 | 10.899 | 82.19 | 85.6 | 103.32 | 880.72 | 3.1 |
| 820 | 121.204 | 0.015 | 0 | 64.62 | 4.782 | 83.88 | 84.2 | 102.09 | 872.37 | 6.29 |
| 850 | 115.086 | 0.016 | 0 | 48.888 | 3.395 | 85.08 | 87.4 | 100.62 | 862.39 | 5.09 |
| 890 | 107.569 | 0.019 | 0 | 31.212 | 4.934 | 86.82 | 91.4 | 98.32 | 846.69 | 3.8 |
| 940 | 102.518 | 0.017 | 0 | 18.507 | 10.699 | 90.6 | 94.6 | 97.03 | 837.75 | 1.43 |
| 990 | 105.72 | 0.015 | 0 | 13.634 | 10.195 | 94.2 | 96.2 | 101.67 | 869.54 | 2.82 |
| 1040 | 110.768 | 0.01 | 0 | 23.84 | 11.326 | 98.19 | 93.6 | 103.7 | 883.27 | 1.93 |
| 1090 | 107.839 | 0.015 | 0 | 14.849 | 5.118 | 100 | 95.9 | 103.43 | 881.44 | 3.35 |
| **Sample = E16D** | | | | | | | | | | |
| **J = .0058540** | | | | | | | | | | |
| 550 | 175.715 | 0.242 | 0 | 301.119 | 0.418 | 0.65 | 49.3 | 86.7 | 740.96 | 46.01 |
| 600 | 253.791 | 0.228 | 0 | 593.105 | 0.676 | 1.69 | 30.9 | 78.5 | 682.51 | 23.66 |
| 650 | 635.971 | 0.2 | 0.08 | 1755.251 | 1.129 | 3.44 | 18.4 | 117.28 | 943.49 | 89.66 |
| 700 | 106.862 | 0.124 | 0.198 | 92.714 | 1.823 | 6.26 | 74.4 | 79.47 | 689.53 | 6.17 |
| 735 | 93.873 | 0.133 | 0.126 | 56.478 | 2.39 | 9.96 | 82.2 | 77.18 | 672.91 | 5.72 |
| 770 | 169.774 | 0.102 | 0.145 | 305.084 | 3.173 | 14.88 | 46.9 | 79.62 | 690.59 | 13.08 |
| 810 | 131.515 | 0.081 | 0.203 | 162.435 | 3.361 | 20.08 | 63.5 | 83.52 | 718.52 | 4.35 |
| 850 | 76.108 | 0.06 | 0.078 | 11.981 | 3.839 | 26.02 | 95.3 | 72.55 | 638.93 | 3.65 |
| 890 | 77.201 | 0.104 | 0.191 | 24.507 | 4.407 | 32.84 | 90.6 | 69.96 | 619.62 | 3.2 |
| 940 | 77.438 | 0.105 | 0.099 | 18.156 | 6.114 | 42.31 | 93.1 | 72.06 | 635.28 | 2.82 |
| 1000 | 71.88 | 0.052 | 0.04 | 13.266 | 10.177 | 58.06 | 94.5 | 67.94 | 604.38 | 0.89 |
| 1050 | 72.758 | 0.059 | 0.058 | 13.136 | 9.668 | 73.03 | 94.6 | 68.86 | 611.32 | 2.18 |
| 1100 | 68.685 | 0.079 | 0.113 | 6.045 | 9.098 | 87.11 | 97.4 | 66.89 | 596.43 | 0.94 |
| 1150 | 71.562 | 0.066 | 0.217 | 15.375 | 8.325 | 100 | 93.7 | 67.02 | 597.47 | 0.93 |

Individual temperature steps are listed with $1\sigma$ errors (excluding $J$). Uncertainty in J-values for monitors ranged from 0.1 to 0.8 per cent without including error in monitor age; we incorporated a conservative 1 per cent error in J-value for all unknowns.[a] $^{40}Ar^{*}$ = radiogenic $^{40}Ar$.

(RIC), with emphasis on field tests and a more extensive sampling scheme. In addition we present the first $^{40}Ar/^{39}Ar$ age for one of the dykes as well as a noritic dyke from the RIC.

## REGIONAL SETTING

The Egersund dyke system is located within the The Rogaland and Vest-Agder Gneiss Complex (RVGC) in SW Norway (Fig. 1). This complex was highly deformed during the Sveconorwegian orogeny and subsequently intruded by massif-type anorthosites, the RIC, between 932 ± 3 and 929 ± 2 Ma (U-Pb zircon ages; Schärer *et al.* 1996). RVGC augen gneisses yield U-Pb titanite cooling ages between 917 ± 2 and 920 ± 4 Ma, whilst $^{40}Ar/^{39}Ar$ hornblende yields ages of 875 ± 20 and 867 ± 2 Ma (Bingen & van Breemen 1998; Bingen *et al.* 1998). The latter probably reflect cooling through 500 ± 25°C (Harrison 1981).

Two major dyke systems are recognized in SW Norway. The NE-SW trending Hunnedalen dykes intrude the RVGC and are dated to 848 ± 27 Ma ( $^{40}Ar/^{39}Ar$ biotite; Walderhaug *et al.* 1999). The second dyke swarm, the WNW-ESE trending Egersund dyke system (olivine dolerites, dolerites and trachydolerites), mainly intrudes the RIC but also the RVGC (site 5 and 16 in Fig. 1). The Egersund dykes are typically vertical, can be traced for tens of kilometres, and vary in width between 0.3 and 30 m. They often show glassy chilled margins and skeletal crystals suggesting rapid cooling. A precise U-Pb baddeleyite age of 616 ± 3 Ma has been reported by Bingen *et al.* (1998).

## EXPERIMENTAL DATA

Thirteen sites in the Egersund dykes were examined for palaeomagnetic analysis (Fig. 1), including contacts and the host rock at three sites [site 5 (migmatitic gneisses from RVGC) and sites 9 and 16 (Anorthosite from the RIC)]. One dyke was selected for $^{40}Ar/^{39}Ar$ geochronology (site 10, Fig. 1). In addition, three noritic dykes belonging to RIC were palaeomagnetically tested, and one of these dykes was also dated by $^{40}Ar/^{39}Ar$.

### $^{40}Ar/^{39}Ar$ data

The $^{40}Ar/^{39}Ar$ incremental heating experiments on biotites were performed at the Geological Survey of Norway argon laboratory.

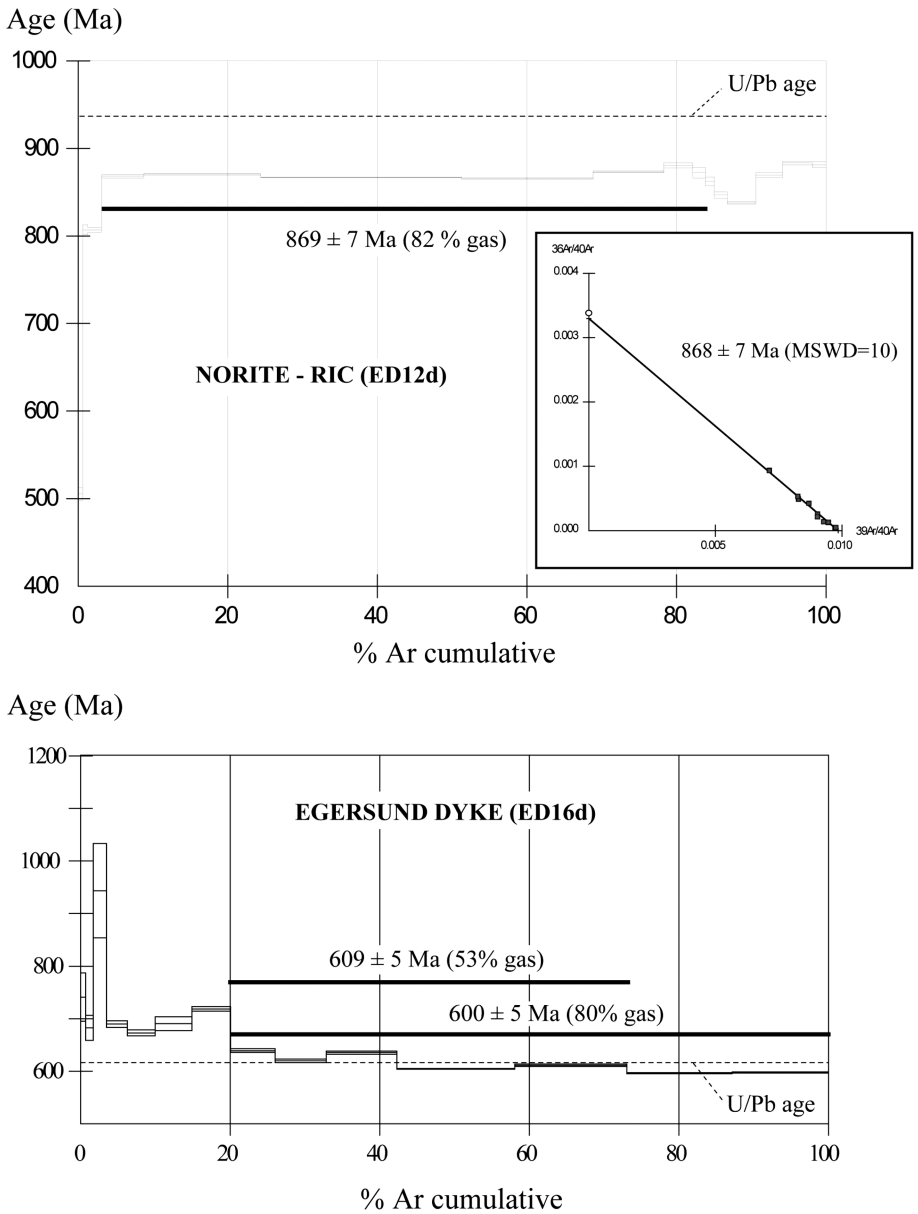


**Figure 2.** $^{40}Ar/^{39}Ar$ biotite spectrum for a norite (top) and Egersund dyke sample (Table 1) that shows apparent age as a function of the cumulative fraction of $^{39}Ar$ released. Height of boxes indicates analytical error ($\pm 1\sigma$) about each step. We cite uncertainties at the $2\sigma$ level and include uncertainties in $J$-value. Inset diagram: inverse isochron for the norite sample after removing the three first low temperature steps and temperature steps 890 and 940°C ($^{40}Ar/^{36}Ar$ intercept = 303.5 ± 8). See text for age discussion.

Gas from irradiated samples was released in a step-wise fashion from a resistance furnace, and the purified gas was analyzed on a MAP 215–50 mass spectrometer with general analytical protocol and irradiation parameters similar to Eide *et al.* (2002). The ages we cite in the text (either final plateau or isochron ages) are at $2\sigma$ and including error in $J$-value.

A noritic dyke (Site 6—Sample e-12D in Table 1) yielded a $^{40}Ar/^{39}Ar$ biotite weighted mean near-plateau age (WMPA—weighted on both gas length and individual errors at each temperature step) of 869 ± 14 Ma for steps 8–11 (82 per cent gas; Fig. 2a). An inverse isochron (removing the three first low temperature steps) yields an identical age (867 ± 14 Ma) but with high MSWD (31)($^{40}Ar/^{36}Ar$ intercept = 303.1 ± 14). Further removal of temperature steps 890, 940 °C maintains the same age (868 ± 14 Ma) but with improved MSWD (10)($^{40}Ar/^{36}Ar$ intercept = 303.5 ± 8). These ages are statistically younger than U-Pb zircon ages for the RIC (∼60 Ma) but are concordant at the 95 per cent confidence level with $^{40}Ar/^{39}Ar$ hornblende cooling ages (867 and 875 Ma; Fig. 1) from the surrounding RVGC (Bingen *et al.* 1998).

The Egersund dyke (Site 10; Sample E16D in Table 1; Fig. 2b) yielded a near WMPA $^{40}Ar/^{39}Ar$ biotite age of 600 ± 5 Ma for the seven last high temperature steps (80 per cent gas). This age estimate is statistically younger than the U-Pb baddeleyite age for the same dyke location (616 ± 3 Ma; Bingen *et al.* 1998) but overlaps with a simple mean age (615 ± 36 Ma) for the same temperature interval. The biotite age is to a large extent weighted on the last two steps, and calculating an age over five intermediate to high temperature steps yields a WMPA of 609 ± 10 (53 per cent gas) that is statistically concordant with the U/Pb baddeleyite age. In the subsequent discussion we refer to the Egersund dykes as 616 Ma

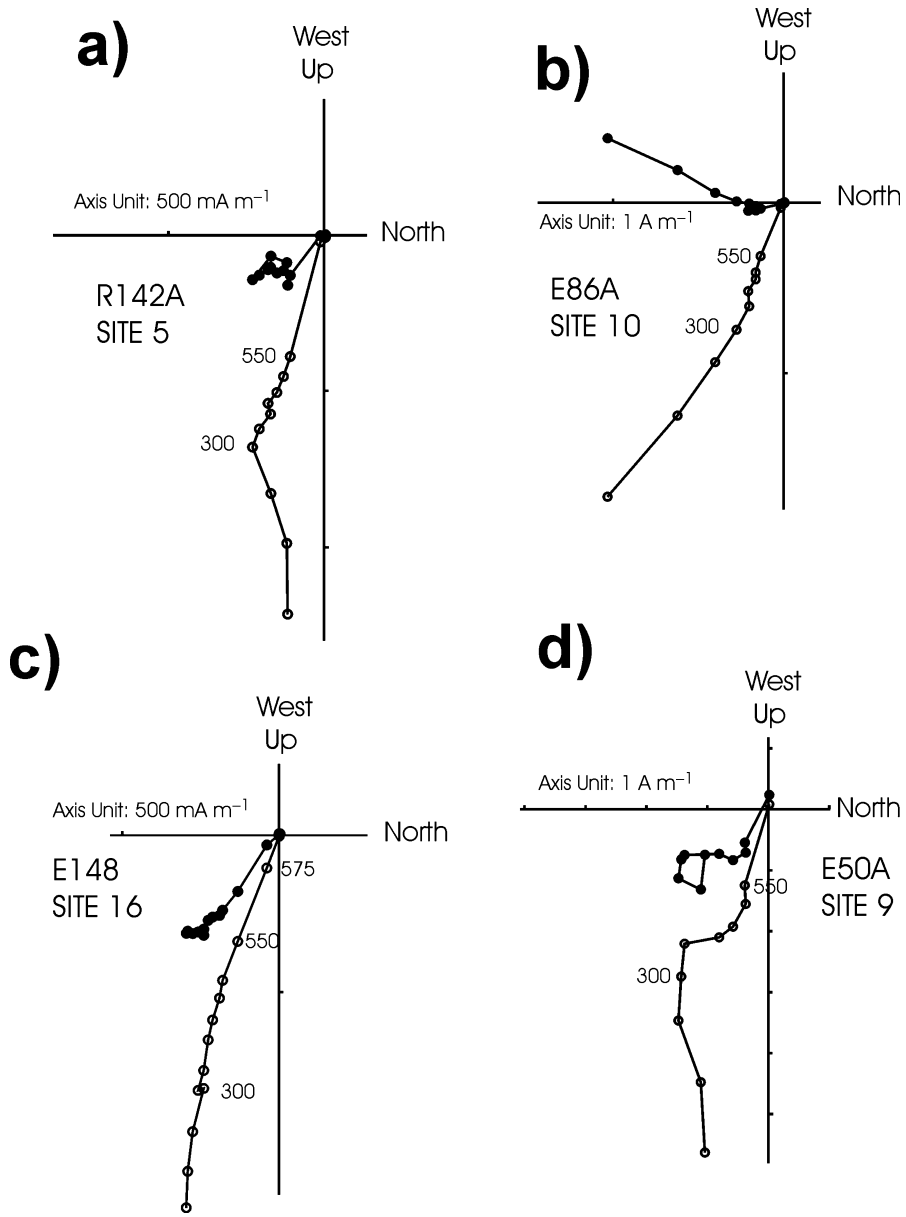


**Figure 3.** Examples of thermal demagnetisation results from the Egersund dykes shown in orthogonal vector plots. Open (solid) symbols represent projections onto the vertical (horizontal) planes, respectively.

but acknowledge remanence acquisition may have occurred between 616 and 600 Ma.

### Palaeomagnetic data

The natural remanent magnetization (NRM) was measured on a JR5A spinner magnetometer with a sensitivity of $10^{-5}$ A/m. A total of 133 specimens from the 13 dyke sites, and an additional 38 specimens from the host rock (mainly anorthosites and noritic dykes) were demagnetised. Both alternating field (2G demagnetiser) and thermal (MMTD1 furnace) demagnetisation were employed. Although both methods yielded similar components, thermal demagnetisation was preferred for the majority of the specimens, mainly because alternating field demagnetisation gave rise to spurious components attributed to Gyroremanent magnetisation (GRM) at some sites (Stephenson 1981). Characteristic remanence components were calculated using principal component analysis (Kirschvink 1980).

Examples of thermal demagnetization behaviour of samples from the Egersund dykes are shown in Fig. 3 and summarized in Table 2. Most sites reveal steep downward pointing characteristic remanence components (ChRC), with maximum blocking temperatures close to 580°C, in accord with magnetite as the dominant magnetic mineral. One site (site 4; Table 2) did not yield consistent directions, and was excluded from further analysis. The remaining 12 sites display some variability in remanence quality, with Fisher precision parameter $k$ ranging from 11 to 132.

Secondary components, with maximum unblocking temperatures between 300 and 450 °C and steep positive inclinations, are also present at most sites (Figs 3a and d). As may be seen from Fig. 4, these low stability components yield a mean direction almost identical to the present day field. They probably constitute a young overprint of viscous origin, and are not further elaborated here.

Of the 12 sites that yielded meaningful mean ChRC directions, three (sites 3, 7 and 9) plot slightly outside the main cluster (Fig. 4).

**Table 2.** Site mean directions and locations for the Egersund dykes. $J$, mean NRM intensity; $N$, number of demagnetised samples/sites; $n$, number of samples/sites used to calculate means. Dec., mean declination; Inc, mean inclination; $\alpha_{95}$, 95 per cent confidence circle of mean; $k$, Fisher precision parameter; UTM location: grid coordinates of individual sites using WGS 84 map datum; VGP, virtual geomagnetic pole; $dp/dm$, semi-axes of 95 per cent confidence around the pole and Plat: corresponding palaeolatitude of Egersund area.

| Site | $J$ | $n$ ($N$) | Dec. | Inc | $\alpha_{95}$ | k | UTM location | | |
|---|---|---|---|---|---|---|---|---|---|
| | (A m$^{-1}$) | | (°) | (°) | (°) | | Zone | $x$ | $y$ |
| **Egersund dykes** | | | | | | | | | |
| 1 | 0.260 | 8 (10) | 67 | 76 | 14.8 | 15 | 32VLK | 2845 | 7537 |
| 2 | 0.440 | 8 (8) | 126 | 89 | 18.0 | 11 | 32VLK | 2853 | 7542 |
| 3 | 0.197 | 14 (16) | 146 | 32 | 11.1 | 14 | 32VLK | 2486 | 8500 |
| 4 | 0.617 | 7 (7) | (73) | (−6) | (38) | (4) | 32VLK | 2437 | 8198 |
| 5 | 0.741 | 9 (11) | 113 | 59 | 8.4 | 39 | 32VLL | 2223 | 0510 |
| 7 | 0.257 | 5 (12) | 259 | 74 | 10.9 | 50 | 32VLK | 4428 | 6589 |
| 9 | 0.080 | 11 (14) | 179 | 41 | 13.7 | 12 | 32VLK | 3074 | 7392 |
| 10 | 1.238 | 7 (10) | 144 | 78 | 6.2 | 132 | 32VLK | 4009 | 7612 |
| 12 | 0.901 | 7 (9) | 119 | 67 | 9.8 | 13 | 32VLK | 2562 | 8058 |
| 13 | 0.417[a] | 7 (9) | 122 | 59 | 6.9 | 77 | 32VLK | 3077 | 7424 |
| 14 | 0.033 | 7 (7) | 87 | 83 | 11.7 | 28 | 32VLK | 5447 | 6152 |
| 15 | 2.523[a] | 6 (10) | 133 | 54 | 20.6 | 11 | 32VLK | 2434 | 8914 |
| 16 | 0.732 | 9 (10) | 128 | 50 | 7.1 | 53 | 32VLK | 3773 | 9910 |

[a]After removal of specimens with anomalous intensities attributed to lightning strikes
Mean Egersund dykes (excluding site 4)
**12(13) 137 68 12.8 12**
**VGP, 24.8N, 34.9E, dp = 17.9, dm = 21.4 (Plat = 50.7)**
Mean Egersund dykes (excluding site 3, 4, 7 and 9)
**9 (13) 120 69 10.0 28**
**VGP, 31.4 N, 44.1 E, dp = 14.5, dm = 17 (Plat = 52.8)**

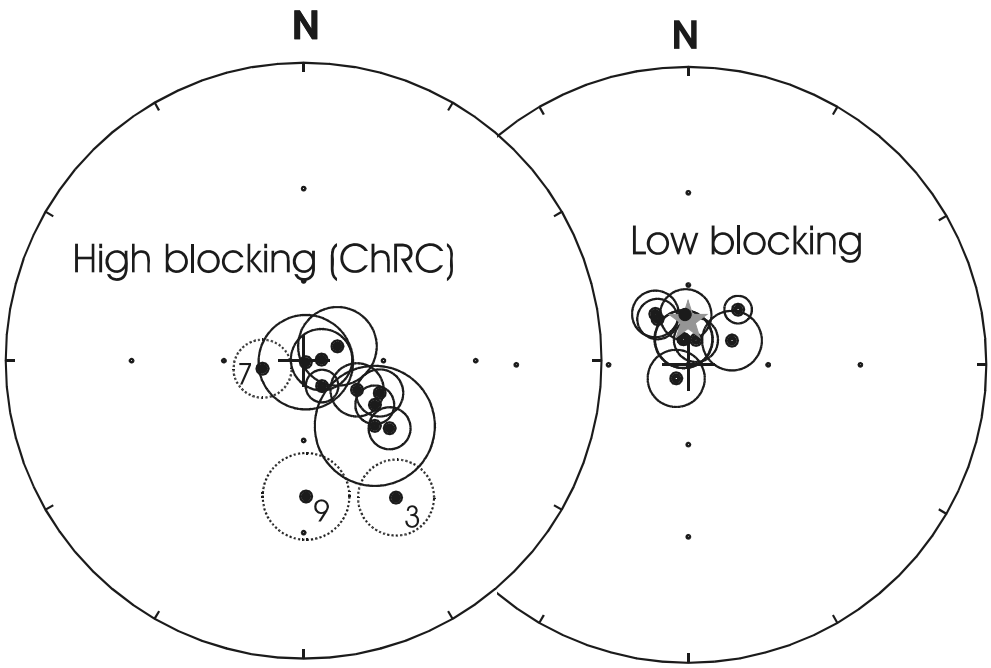


**Figure 4.** Site mean directions for the Egersund dykes. Characteristic remanence components (left) and low stability components (right) shown with $\alpha_{95}$ confidence circles for individual sites. Star in right hand diagram indicates the direction of the present day field. The three sites shown with stipled confidence circles (3, 7 and 9) were omitted when computing the final mean and pole position (see text for discussion).

Sites 3 and 9 have shallower inclinations than the remaining sites, and also show evidence of a more complex remanence structure with several overlapping components (*cf.* Fig. 3d). Site 7 has a more westerly declination than the main group. Mean directions and pole positions were calculated both for all 12 sites, and after removal of the three sites mentioned above. Data for both alternatives are presented in Table 1. We note that removing the three outliers has a limited effect on pole position and palaeolatitude, changing the latter from 51° to 53°. However, an improvement in statistical precision together with the complex nature of the remanence of the shallow sites, leads us to prefer the second alternative, yielding a palaeomagnetic pole at 31.4N, 44.1E ($dp = 14.5$; $dm = 17.0$), which

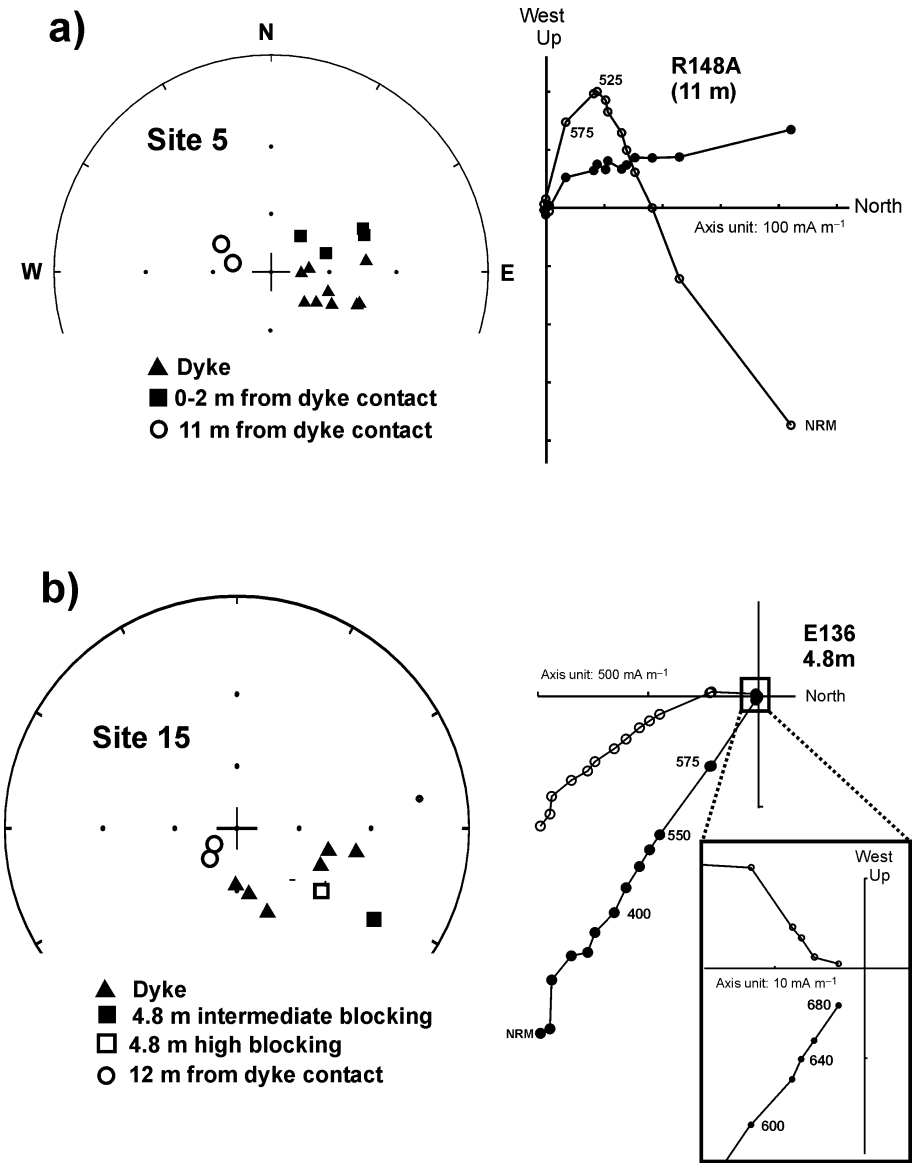


**Figure 5.** Contact tests for sites 5 and 15. Dyke widths are 20 and 6 m, respectively. Stereonets show characteristic remanence directions for dykes (triangles), baked zone in host rock (squares) and unbaked host rock (circles), respectively. Orthogonal vector plots give examples of thermal demagnetization of host rock samples at moderate distances from dyke contacts, showing dual component remanences reflecting both dyke and host rock (RIC) characteristic remanence directions. Inset at lower left shows enlargement of the final demagnetization steps for the site 15 specimen. Dyke width at the sites is 30 m for site.

compares favourably with the earlier studies of Storetvedt (1966) and Poorter (1972) (Table 4).

In view of the questions that have been raised about the possibility of remagnetization of the dyke system (Eneroth 2002; Eneroth & Svenningsen 2004), contact tests were performed at three of the sites; 5, 15 and the anomalously shallow site 9.

Results of the contact tests for sites 5 and 15 are presented in Fig. 5. Site 5 is in the largest dyke, which has a width of approximately 20 m at the site location. As may be seen in Fig. 5a, the host rock close to the dyke margins is completely overprinted with the dyke direction, while specimens at a larger distance from the dyke show both a partial dyke overprint and retention of a steep westerly and upwards pointing direction in the highest blocking temperature range. This latter direction has been found by several authors (Poorter 1972; Stearn & Piper 1984; Brown & McEnroe 2004) to be the characteristic remanence direction in the Sweconorwegian host rocks. A similar pattern for the 6 m wide dyke at site 15 is illustrated in Fig. 5(b), with the specimens at 4.8 m distance from the margin showing influence of both the dyke- and Sweconorwegian directions, while the specimens at 12 m seem unaffected by the dyke. Clearly, the results at both sites constitute strong, if not conclusive evidence that remanence in the Egersund dykes is indeed primary.

The contact test attempted at the anomalously shallow site 9, shows a more complex relationship between remanence in the host rock, baked zone and dyke (Fig. 6). The dyke and the contact magnetization clearly differ, whilst non-baked RIC samples show the typical upward pointing inclinations with westerly declinations and almost single component behaviour. We suspect that sites 3 and 9 might represent low-temperature hydrothermal remagnetizations, probably of Late Ordovician origin when compared with the apparent polar wander (APW) path for Baltica. Similar remagnetizations

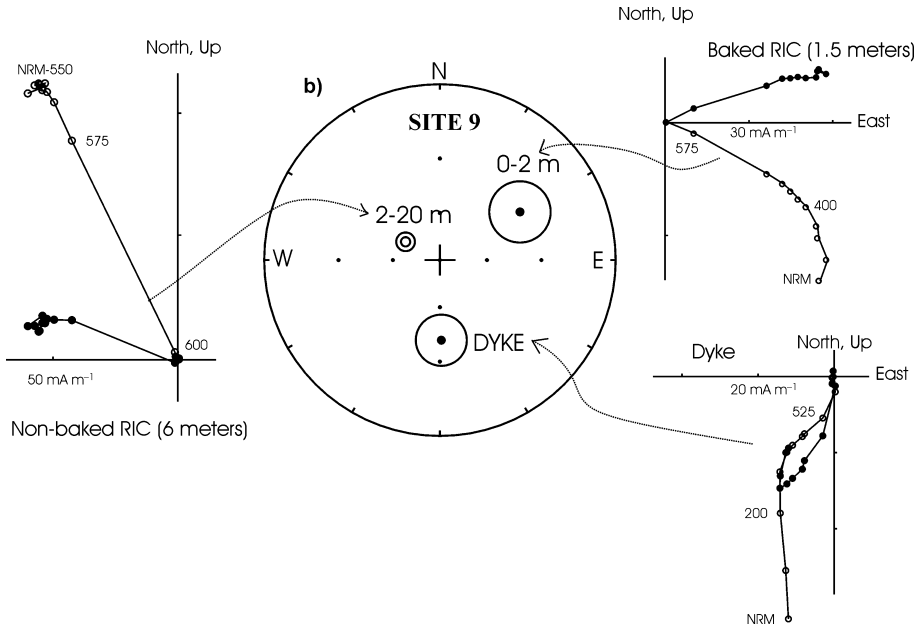


**Figure 6.** Contact test for site 9 (dyke width 4 m), showing mean remanence directions for the dyke, baked zone in host rock (0–2 m) and unbaked host rock (2–20 m), respectively. Orthogonal vector plots show examples of thermal demagnetization behaviour for each group.

**Table 3.** Site mean directions for Sveconorwegian rocks of the RIC. See Table 2 for legend.

| Site | Rock type | $J$ (A m$^{-1}$) | $n$ ($N$) | Dec. (°) | Inc (°) | $\alpha_{95}$ (°) | $k$ | UTM location Zone | $x$ | $y$ |
|---|---|---|---|---|---|---|---|---|---|---|
| **Sweconorwegian rocks** | | | | | | | | | | |
| 6 | Norite | 0.295 | 9 (10) | 028 | −66 | 16 | 11 | 32VLK | 2552 | 8100 |
| 8 | Norite | 0.834 | 6 (7) | 273 | −70 | 8.9 | 58 | 32VLK | 5578 | 6307 |
| 11 | Norite | 0.902 | 7 (10) | 240 | −77 | 8.4 | 53 | 32VLK | 3998 | 7392 |
| Host 5 | Gneiss | 0.602 | 2 (2) | 292 | −66 | (24.0) | (106) | 32VLL | 2223 | 0510 |
| Host 9 | Anorthosite | 0.184 | 7 (7) | 292 | −65 | 2.2 | 736 | 32VLK | 3074 | 7392 |
| Host 15 | Anorthosite | 0.600 | 2 (2) | 222 | −70 | (15.1) | (274) | 32VLK | 2434 | 8914 |
| Mean Sweconorwegian rocks (excluding site 6) | | | | | | | | | | |
| **5(6)** | **269** | **−72** | **11.0** | **49** | | | | | | |
| **VGP: 45.9S, 238.4E, dp = 17.0, dm = 19.3 (Plat = 56.7)** | | | | | | | | | | |

(Caradoc?) are identified in SW Sweden (Scania) and attributed to Baltica-Avalonia docking by Torsvik & Rehnstrøm (2003).

The three sampled noritic dykes, may be used together with anorthosite samples from the three contact test sites (i.e. those taken at sufficient distance from the dykes to avoid any thermal dyke influence) to provide a total of six sites in the RIC/RVGC (Table 3), although the number of samples at two of these sites are limited. Thermomagnetic curves for the norites are reversible with a single Curie point of 580°C indicating pure magnetite as the dominant magnetic phase. The anorthosites show evidence of both magnetite and hemoilmenite, with the bulk of the remanence being unblocked between 550 and 580°C, but with directional stability being retained up to 680°C in some cases. After the removal of lower stability secondary components (Fig. 7a), both rock types reveal a consistent high quality ChRC with steeply dipping reverse directions (Fig. 7). Fig. 8 and Table 3 summarize the statistics from the six RIC sites. Removal of one deviating site (Fig. 7) leads to a pole position of 45.9S, 238.4E, ($dp = 17.0$, $dm = 19.3$) and a local palaeolatitude of 57°. This is in broad agreement with the findings of previous studies (Poorter 1972; Stearn & Piper 1984; Brown & McEnroe 2004) as shown in Table 4 and Fig. 11. Thus, the main problem in the RIC, seems to be the timing rather than the direction of remanence, which will be briefly discussed in the later sections.

## Rock magnetic properties

Various rock magnetic methods were employed in an attempt to determine the nature and stability of the remanence carriers, including thermomagnetic curves, coercivity spectrum analysis and optical microscopy. We also measured the anisotropy of magnetic susceptibility (AMS), in part to test for potential remanence deflections (Cogne 1987). Mean anisotropy values for all Egersund dyke sites are below 5 per cent, suggesting that remanence deflections are not significant. However, anisotropy in the anorthosites and norites of the RIC is above 50 per cent in some cases, indicating that remanence deflection might be a significant source of error both in this and all previous palaeomagnetic studies of the Sweconorwegian rocks. The AMS results are not further elaborated here.

Reflected-light microscopy (Fig. 9) reveals relatively large titanomagnetite as the dominant magnetic mineral phase in all the dykes,

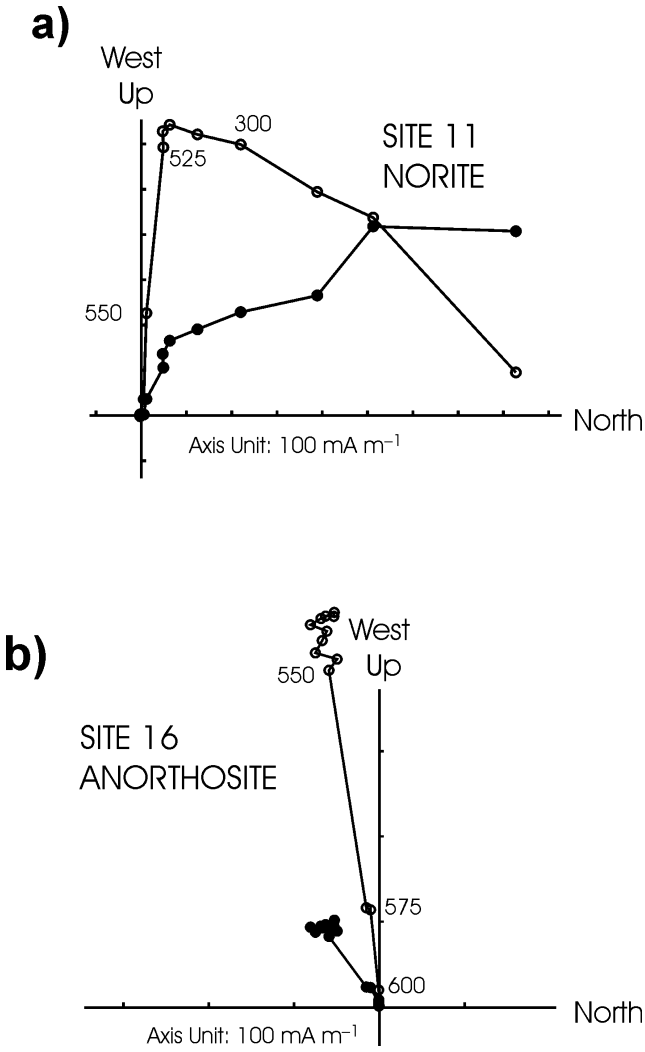


**Figure 7.** Examples of thermal demagnetization behaviour of RIC (a) and RVGC (b) specimens. Conventions as in Fig. 3.

with ilmenite lamellae attesting to high temperature oxidation and a relatively slow initial cooling rate. Quite severe secondary low temperature oxidation is evident at several sites (Fig. 9b and c). However, isothermal remanent magnetisation (IRM) (Fig. 10a) versus field curves reach saturation below 200 mT, showing no evidence of high coercivity phases such as hematite.

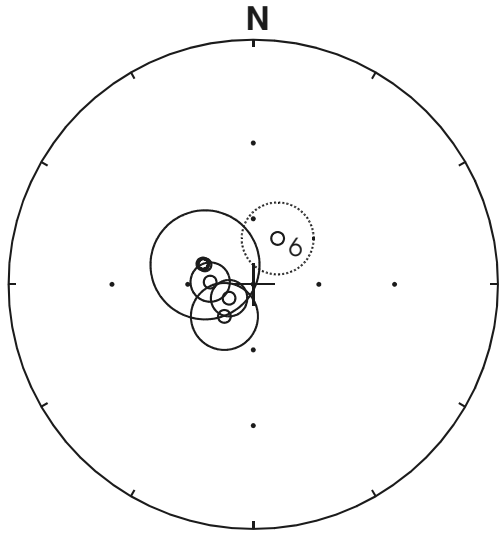


**Figure 8.** Site mean directions for RIC and RVGC. Conventions as in Fig. 4.

Thermomagnetic curves, (Figs 10b, c and d) were obtained in air on a horizontal translation balance with a heating/cooling cycle of 100 min in a field of 0.7 Tesla. Although the detailed behaviour varies between sites, they all show Curie points close to 580°C, suggesting that the magnetic phase has a composition close to pure magnetite. Hysteresis measurements, performed on a Molspin vibrating sample magnetometer, yield mean $J_{rs}/J_s$ ratios of 0.16, suggesting PSD grains of moderate stability. (Dunlop 1986; Dunlop & Özdemir 1997), although interpretation of this ratio in terms of domain state is somewhat ambiguous when mixtures of different grain sizes and varying titanomagnetite compositions are involved (Tauxe *et al.* 1996; Dunlop 2002).

## INTERPRETATION

### Egersund dykes

Fig. 4 and Table 2 summarize site mean directions from the Egersund dykes. After excluding sites 3, 7 and 9 as discussed above, the Egersund dykes average to 120° (declination) and +69° (inclination). This yields a palaeolatitude for Southwest Baltica of 53°

**Table 4.** Selected pole postions for Baltica 1100–550 Ma.

| Formation | Location | Age | Pole | $dp/dm$ or $A_{95}$ | Palaeo-latitude | Reference |
|---|---|---|---|---|---|---|
| Winter Coast sediments | 66N, 40 E | 555 ± 3 | 25N, 312E | 2/4 | 24 | Popov *et al.* (2002) |
| Egersund dykes | 58 N, 6 E | 616 ± 3 | 28N, 52E | 15/18 | 46 | Storetvedt (1966) |
| Egersund dykes | 58 N, 6 E | 616 ± 3 | 22N, 51E | 16/21 | 42 | Poorter (1972) |
| Egersund dykes | 58 N, 6 E | 616 ± 3 | 31N, 44E | 15/17 | 53 | This study |
| Neoproterozoic combined | 70N, 31E | ≈ 750 | 28N, 197E[b] | 8 | 8 | Meert & Torsvik (2003) |
| Hunnedalen dykes | 59N, 7E | 848 ± 27 | 41S, 222E | 10/11 | 62 | Walderhaug *et al.* (1999) |
| Egersund anorthosite | 58N, 6E | 869 ± 14[a] | 42S, 200E | 9 | 71 | Brown & McEnroe (2004) |
| RIC/RVGC | 58N, 6E | 869 ± 14[a] | 46S, 238E | 17/19 | 57 | This study |
| RIC/RVGC combined | 58N, 6E | 869 ± 14[a] | 43S, 213E[b] | 5 | 68 | Meert & Torsvik (2003) |
| Bamble intrusions mean | 59N,10E | ≈1060 | 3N, 217 E[b] | 15 | 24 | Meert & Torsvik (2003) |

[a]Age based on $^{40}Ar/^{39}Ar$ dates on biotite; not U-Pb age (930 Ma) used by original authors (see text for discussion).
[b]Pole polarity inverted.

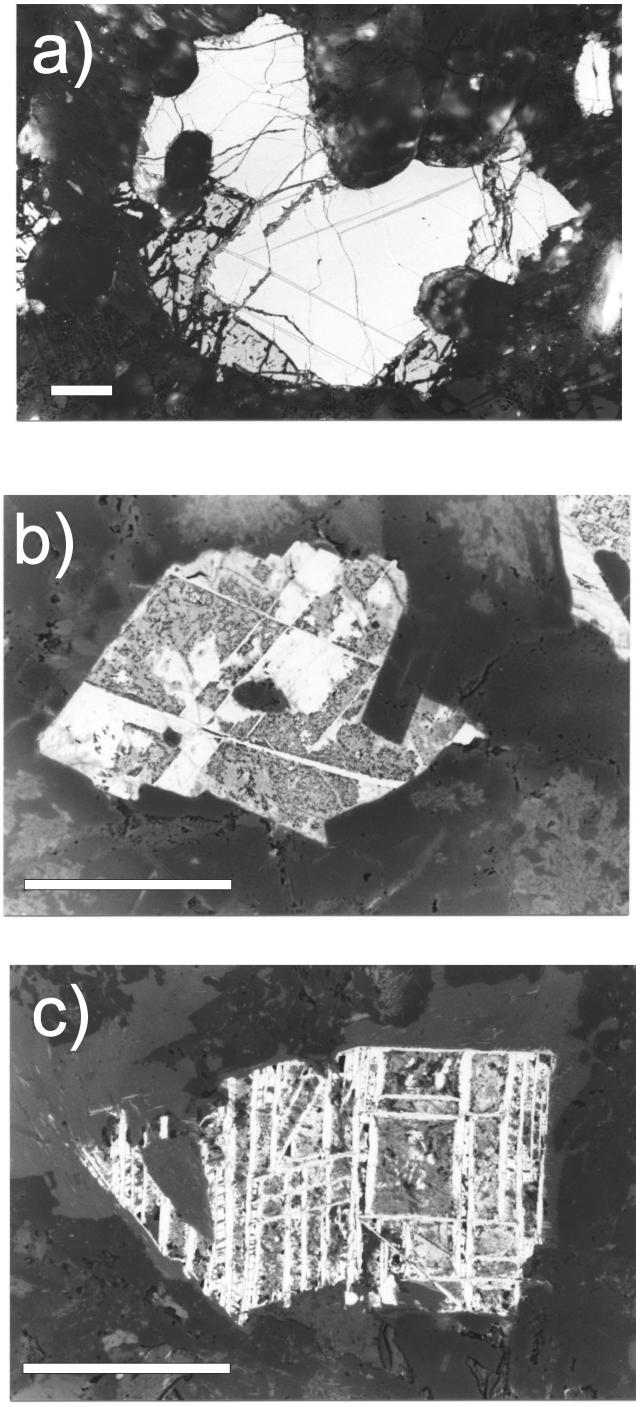


**Figure 9.** Reflected light micrographs of titanomagnetite grains from the Egersund dykes. Length of scale bars = 100 $\mu$m.

(+16°/−13°) at around 616 Ma (the U-Pb baddeleyite age). The Egersund pole (Table 2) overlaps with earlier studies of the same dykes (Fig. 11) but also plots in the vicinity of well-established Early Ordovician poles from Baltica. However, the Egersund dykes are undeformed, U/Pb and Ar–Ar ages differs only marginally, and two positive contact tests and an opposite polarity compared to the host rocks convincingly point to a primary origin. Hence, the similarity between Ediacaran poles and Early Ordovician poles (Fig. 11) is in our view coincidental, and not due to remagnetization.

### Egersund host-rocks (RIC)

The Egersund dykes are of opposite polarity to the sites in the host rocks (mean inclination = −72°; palaeolatitude = 57°). This in itself suggests a positive regional stability test for the Egersund dykes. We combined four RIC sites with site 5 from RVGC (only two samples) since they are identical (Fig. 8). The dated noritic dyke (869 ± 14 Ma) is somewhat anomalous in declination, but we have no reasons to assume that this dyke is different in age from the other dykes. The RIC is dated to between 929 and 932 Ma (U-Pb zircon) but the 869 Ma $^{40}Ar/^{39}Ar$ biotite age (this study) and $^{40}Ar/^{39}Ar$ hornblende ages of 875 ± 20 and 867 ± 2 Ma from RVGC are in our opinion more realistic estimates for remanence acquisition since they date uplift/cooling between 300 and 525°C.

The RIC/RVGC palaeomagnetic directions are also similar to the 848 ± 27 Ma Hunnedalen dykes (Fig. 11). These data are also of the same magnetic polarity, leading Walderhaug *et al.* (1999) to the conclusion that the RIC/RVGC record a younger regional uplift event which we date to 869 Ma, and remanences in the RIC should **not** be associated with the existing U-Pb ages (c. 932 Ma).

## NEOPROTEROZOIC-EDIACARAN POLES FROM BALTICA

The Precambrian palaeogeographic position for Baltica and its relation to other continents is patchy and poorly understood. For the times when Baltica is considered to be part of the Rodinia supercontinent there are three undisputed data-sets:

(i) Sveconorwegian poles (∼970–1100 Ma) suggesting low-to-subtropical latitudes for Baltica.

(ii) The Egersund anorthosites (interpreted here as 870 Ma uplift magnetizations as described in the previous section) and the Hunnedalen dykes (850 Ma) in SW Norway indicating very high latitudes.

(iii) 700–800 Ma sedimentary poles (not well dated) from Northern Norway/Russia that demonstrate equatorial latitudes.

During and after Rodinia breakup, we have demonstrated that Baltica had returned to intermediate-to-high latitudes (50–75°S) by ∼616 Ma (Fig. 12). In the 1100–616 Ma range, severely interpolated apparent polar wander (APW) rates do not exceed 10 cm/yr., latitudinal velocities are always less than 8 cm yr$^{-1}$ (*ca.* 4 cm yr$^{-1}$ on average), thus indicating 'normal' plate tectonic speeds. For the remaining part of the Ediacaran and the Lower Cambrian, palaeomagnetic poles from Baltica are profoundly confusing, and accepting all published results would lead to an untenable APW path (Meert *et al.* 2006). Similarly confusing results on other continents have led to proposals or True Polar Wander during this time period (Kirschvink *et al.* 1997), but this interpretation is contentious (Meert 1999). Although some component of true polar wander cannot be ruled out, we prefer to explain the disparate Baltica data more conventionally in terms of remagnetization, poor age constraints and tectonic coherency affecting individual results. In this respect, the most robust result from this period appears to be the 555 Ma Winter Coast sediment pole of Popov *et al.* (2002) shown in Fig. 11. A simple post-600 Ma continuation of the Baltica APW path involving only the Egersund, Winter Coast, and (non-contentious) Ordovician poles (Fig. 11) would indicate a *ca.* 30° Northward shift of Baltica (from the position depicted in Fig. 12) by the Late Ediacaran, followed by a return to higher latitudes by the Early Ordovician. We stress, however that emphasizing other available poles leads to different conclusions (see Meert *et al.* 2006,

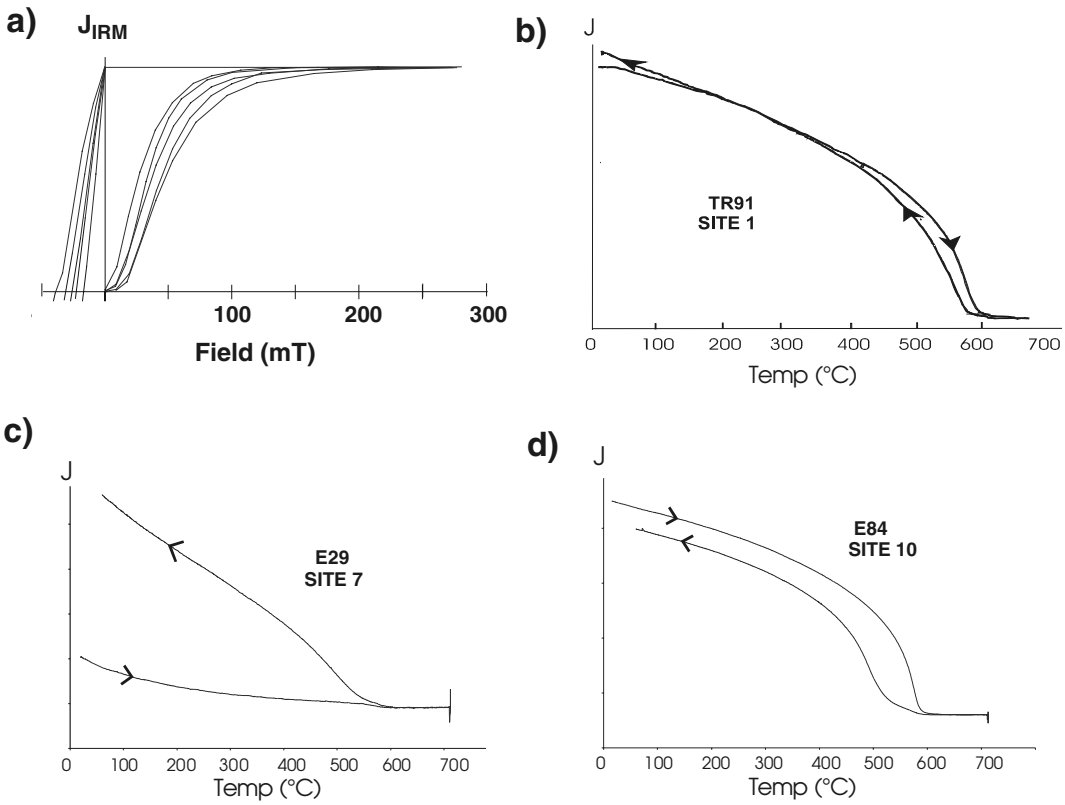


**Figure 10.** Representative examples of isothermal remanence versus field curves (a) and thermomagnetic curves (b–d) from the Egersund dykes.

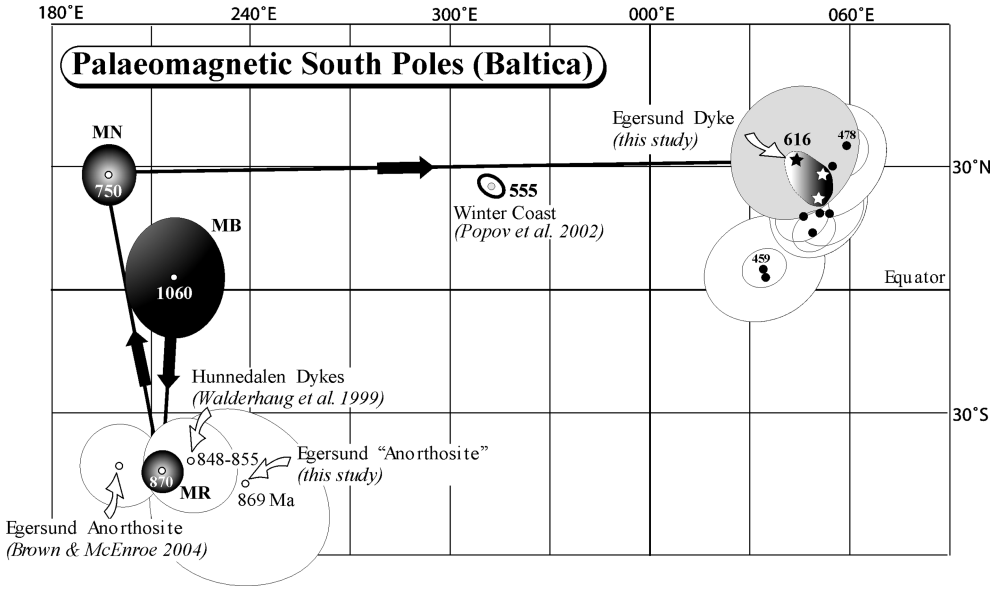


**Figure 11.** Selected pole positions for Baltica. Early- and Mid-Ordovician poles listed in Torsvik & Rehnstrøm (2003). All other poles are specified in Table 4. Galls projection.

for discussion), and new robust data from the Late Ediacaran and Early Cambrian are clearly desirable.

Ediacaran palaeomagnetic poles from Laurentia are also chaotic, thus making it hard to make any conclusive statements about the relative position of Baltica versus Laurentia during this period. Palaeomagnetic results from the only rocks that are contemporaneous with the Egersund dykes, i.e. the 615 ± 2 Ma (U-Pb baddeleyite) Long Range dykes (Kamo *et al.* 1989) in Labrador (Canada) are highly ambiguous yielding four different results (pick high or low latitude position to your preference). However, if the Iapetus Ocean opened between Baltica and Laurentia around this time, Laurentia must be close to the Baltic margin. The Egersund result, therefore, suggests that the higher latitude options for Laurentia are more plausible. Younger Ediacaran poles from Laurentia (as for Baltica) are equally

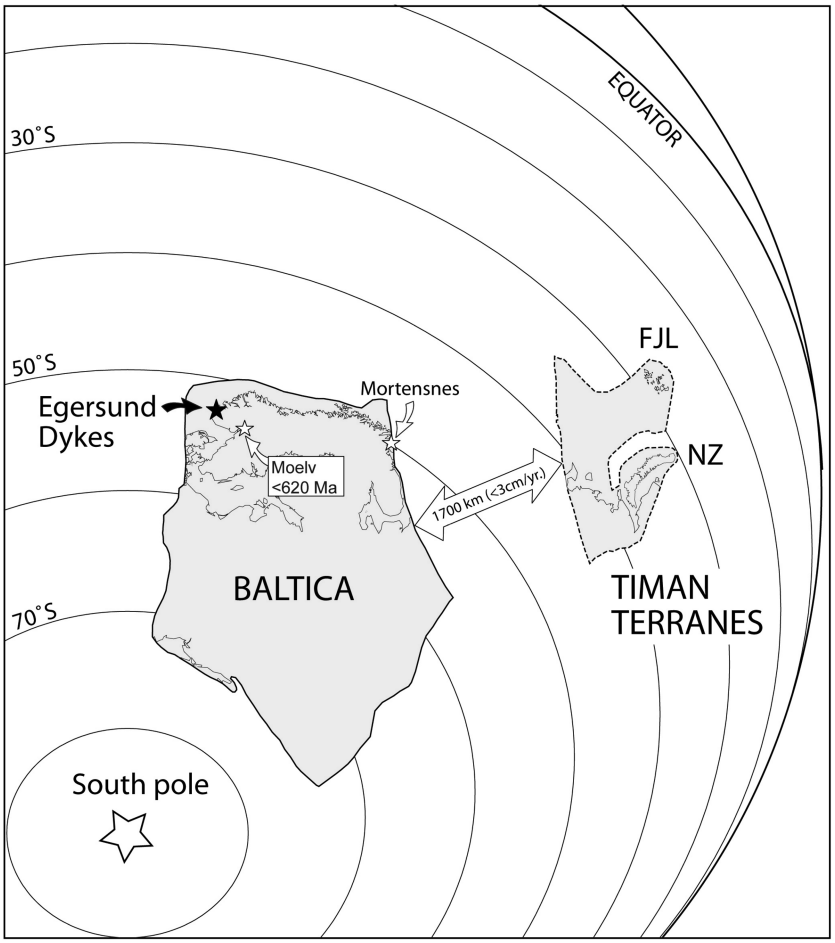


**Figure 12.** Reconstruction of Baltica at 616 Ma based on the result in this study. Stars indicate locations of the <620 Ma Moelv Tillite (Bingen *et al.* 2005) and the Mortensnes glacial deposits (North Norway). A tentative location of the Timan terranes is shown. These terranes coalesced with Baltica at around 550 Ma (see text). FZ, Franz Josef Land; NZ, Novaya Zemlya.

ambiguous and cannot yet be used for detailed palaeogeographic reconstructions towards the dawn of the Cambrian.

## BALTICA AND VARANGERIAN GLACIATIONS

Neoproterozoic and Vendian glacial deposits are recorded on many continents, some evidently deposited at low latitudes and thereby suggesting that Earth was affected by global glaciation events (e.g. Hoffman & Schrag 2002). In the Varangerfjord area of northern Norway, two stratigraphically separate glacial units, the Smalfjord (lower) and Mortensnes (upper) formations, occur (Edwards 1984). Halverson *et al.* (2005) argue that the Smalfjord formation represents the worldwide 'Marinoan' (*ca*. 635 Ma) glaciation based on the presence of characteristic $\delta^{13}$C anomalies and a cap carbonate. On the basis of sequence stratigraphy, the Mortensnes formation is presumed to correlate with the Moelv tillite in Southeast Norway (Fig. 12). These two latter deposits have been suggested to represent the 'Gaskiers' (580 Ma) glaciations (Bingen *et al.* 2005; Halverson *et al.* 2005), but lack distinctive features such as a cap carbonate. The Neoproterozoic glacial formations in Norway are in general poorly dated. Recently however, U/Pb dating of detrital zircons has constrained the deposition of the Moelv Tillite to less than 620 ± 14 Ma (Bingen *et al.* 2005).

Palaeomagnetic data from the Egersund dykes clearly demonstrate that Baltica was located at relatively high latitudes close to the time of the Varangerian glaciation, stretching from *ca*. 50°S (present Caledonian margin) to *ca*. 75°S (present Southern Urals) (Fig. 12). These data certainly do not rule out the postulate of a global glaciation, but no global 'Snowball Earth' glaciation is required to account for the glacial deposits on Baltica (see also Bingen *et al.* 2005).

Williams (1975, 1993) has proposed an alternative explanation for Neoproterozoic low latitude glaciations. If the Earth's orbital obliquity were substanitially higher (>54°) than the present value of 23.5°, the Earths climatic zonation would reverse, and glaciation would preferentially occur at equatorial latitudes. This model does not provide a ready explanation for the Varanger and Moelv glacial deposits, since glaciations would be largely constrained to latitudes below 40° (Williams 1993).

We will emphasize that the Ediacaran definition of Baltica was very different from its Palaeozoic boundaries. During the Ediacaran (Fig. 12), today's northern part of the northwestern margin of Baltica changed from an extensional tectonic regime to an active margin. These changes, termed the Timanide (or Timanian) Orogeny, represent a period of active accretion in which various microcontinental blocks in the Timan-Pechora, northern Ural and Novaya Zemlya areas were united with Baltica to form a much expanded terrane area at *ca*. 555 Ma (Gee *et al.* 2000; Rehnström *et al.* 2002; Roberts &

Siedlecka 2002; Roberts & Olovyanishnikov 2004; Cocks & Torsvik 2005). Vendian magmatism, metamorphism and tectonic activity in the Timan-Pechora-Rybachi-Varanger region was broadly contemporaneous with the Varangerian glacial event. In Fig. 12, we have tentatively shown the Timan Terranes as a single unit (for reasons of simplicity) at some distance from Baltica, indicating that they may have been located at lower latitudes than Baltica before their final Late Ediacaran convergence (*ca*. 555 Ma).

## CONCLUSIONS

Palaeomagnetic data from the Egersund dykes yield moderately steep magnetisations that witness an intermediate-to-high latitude position of Baltica. Contact tests provide strong evidence that the magnetization is primary. One dyke yields a $^{40}Ar/^{39}Ar$ biotite age of $600 \pm 10$ Ma, only marginally younger than the previous U-Pb baddeleyite age ($616 \pm 3$ Ma). We therefore, conclude that remanence acquisition took place between 600 and 616 Ma, and that Baltica was located at latitudes higher than 50° during this time.

The magnetic signature of the RIC and RVGC host rocks differs from the Egersund dykes, the magnetic polarity is opposite, and palaeomagnetic results are broadly similar to earlier published results. A noritic dyke from the RIC yields a $^{40}Ar/^{39}Ar$ biotite age of $869 \pm 14$ Ma and approximately 60 million years younger than U-Pb zircon ages from RIC. 869 Ma is considered as a cooling age and is concordant with $^{40}Ar/^{39}Ar$ hornblende ages from the RVGC. Comparable magnetizations and $^{40}Ar/^{39}Ar$ ages from RIC-RVGC clearly suggest that the magnetizations are not primary but represent uplift/cooling ages. This is also sustained by similarity in magnetic signature with the *ca*. 850 Ma Hunnedalen dykes (Walderhaug *et al.* 1999). We therefore, argue that the remanence recorded in RIC-RVGC is related to approximately 870 Ma uplift/cooling through 300–525 °C.

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