ELSEVIER

Earth and Planetary Science Letters 169 (1999) 71–83

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Geochronology and palaeomagnetism of the Hunnedalen dykes, SW Norway: implications for the Sveconorwegian apparent polar wander loop

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Received 14 July 1998; revised version received 15 March 1999; accepted 15 March 1999

Abstract

The post-Sveconorwegian Hunnedalen dyke swarm intrudes the high-grade Proterozoic gneiss complex of SW Norway. The dykes yield a Sm–Nd whole-rock-mineral date of 855 ± 59 Ma and a $^{40}Ar/^{39}Ar$ biotite plateau date of 848 ± 27 Ma (2σ). The consistency of these two age determinations suggests that 850 Ma approximates the intrusion age of the swarm. Palaeomagnetic data from the dykes match palaeomagnetic directions obtained from Late Sveconorwegian massive-type anorthosites (932–929 Ma) in SW Norway. The collective palaeomagnetic data (mean pole: latitude = 43.7°S, longitude = 213.3°E, A_{95} = 4.6°) have uniform magnetic polarity, and, when considered in the context of the new geochronologic data, require that remanence acquisition in Sveconorwegian rocks (massif-type anorthosites and gneissic basement) of SW Norway is, in fact, not Sveconorwegian in age, but rather younger and related to a regional metamorphic/hydrothermal feature at ca. 850 Ma. The new age data question the validity of a counter-clockwise Sveconorwegian apparent polar wander loop in the Baltic data-sets and therefore require a critical re-evaluation of Rodinia Supercontinent fits based on palaeomagnetic data.

Keywords: paleomagnetism; geochronology; upper Proterozoic; Grenvillian orogeny

1. Introduction

Neoproterozoic palaeomagnetic data for Baltica have most recently been summarised by Pesonen et al. [1,2] and Elming et al. [3]. Data coverage is fairly dense for Sveconorwegian intrusive and metamorphic rocks (ca. 1100–920 Ma), but sparse for the remainder of the Precambrian. In the compilations of Pesonen and co-workers, a counter-clockwise apparent polar wander (APW) loop is proposed between 1100–800 Ma. In the most recent analysis of palaeomagnetic data from Laurentia and the cratons of Loretta, Sao Francisco, Congo and Kalahari, Weil et al. [4] argue that all of these continental blocks show a similar APW loop to that of Baltica in the 1000–800 Ma range. This is pivotal in sustaining the postulated Rodinia Supercontinent [5,6] during

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0012-821X/99/$ – see front matter
PII: S0012-821X(99)00066-7

the Neoproterozoic. We will demonstrate, however, that the Sveconorwegian–Grenvillian loop, at least as defined by Baltica palaeomagnetic data, is highly suspect.

From Baltica, high quality poles in the ca. 920–800 Ma range are urgently needed to test the Sveconorwegian–Grenvillian APW loop assumption because the existing data are of questionable reliability in terms of remanence acquisition timing as well as the actual isotopic ages of the studied rocks. The Hunnedalen dykes, SW Norway (Fig. 1), post-date peak Sveconorwegian orogenic activity and are potential targets to explore Neoproterozoic APW. In this paper, Sm–Nd and biotite $^{40}Ar/^{39}Ar$ geochronologic data on the Hunnedalen swarm are reported. These data complement petrographic, geochemical and geochronologic data presented by Maijer and Verschure [7]. New palaeomagnetic data were obtained from six sampling sites (Fig. 1b) and are compared to the original findings of Poorter [8].

2. Geological setting

The Hunnedalen swarm occurs in the Rogaland and Vest Agder Gneiss Complex (RVGC) in southwest Norway (Fig. 1). The RVGC was penetratively deformed under high-grade conditions during the Sveconorwegian orogeny between 1050 and 980 Ma, and subsequently intruded by granitic plutons and the Rogaland Igneous Complex, which mainly consists of massif-type anorthosites (Fig. 1b). These anorthosite bodies yield U–Pb zircon intrusion dates between 932 and 929 Ma [9]. The Hunnedalen dyke swarm (Fig. 1b) post-dates any Sveconorwegian ductile deformation. All dykes are NE–SW trending and vertical with few wall irregularities and off-shoots, suggesting that no significant relative rotations have occurred in the region surrounding the dykes. The dykes are generally coarse-grained and lack glassy chilled margins, thus suggesting emplacement at depth. The dykes comprise two-pyroxene monzonoritic rocks with minor brown biotite, Fe–Ti oxides, apatite, K-feldspar and quartz. Biotite has high TiO_2 content (4.0–7.2 wt%) and is thus considered as a late-magmatic mineral [7]. Silica whole rock content is close to 51% and Mg number is in the range 0.35–0.40, suggesting extensive magma differentiation before intrusion [7]. Another, but NW–SE trending dyke system, the Egersund swarm, has been dated to 655–644 Ma (Rb–Sr and Sm–Nd [10] and Walderhaug et al. in prep.) and 616 ± 3 Ma (U–Pb baddeleyite [11]).

3. Isotope data

The sample for Sm–Nd dating was collected at the centre of the 9 m thick dyke at site 3 (Fig. 1b). The sample was crushed and clean separates obtained using conventional techniques. Clear fractions of clinopyroxene and plagioclase as well as two fractions of impure plagioclase–pyroxene intergrowths (mx1, mx2; Table 1) were analysed at the Mineralogical-Geological museum, University of Oslo. Procedures of chemical separation, isotope dilution and mass-spectrometry are described by Mearns [12]. Sm–Nd isotopic data yield an internal isochron age of 855 ± 59 Ma, mainly controlled by the pyroxene fractions (Fig. 2a, Table 1). MSWD is low (0.59), and the large standard error is in essence due to the restricted spread in the Sm/Nd ratios. The isochron has an initial ratio of 0.51162 ± 6 which corresponds to an $\varepsilon_{Nd\,i}$ value of +1.7.

The $^{40}Ar/^{39}Ar$ incremental heating experiment on biotite from site 2 was conducted in the $^{40}Ar/^{39}Ar$ laboratory at the Université Blaise Pascal et Centre National de la Recherche Scientifique (Clermont-Ferrand, France) with general analytical protocol and irradiation parameters similar to [13]. Prior to $^{40}Ar/^{39}Ar$ furnace step-heating, clean, hand-picked biotite was packed in Sn-foil and irradiated at the

Table 1
Sm–Nd isotopic data

Sample	$^{147}Sm/^{144}Nd$	$^{143}Nd/^{144}Nd$ [a]
HD-1 WR	0.1360	0.512385 ± 7
HD-1 cpx1	0.1698	0.512570 ± 7
HD-1 pl	0.1163	0.512270 ± 7
HD-1 mx1	0.1371	0.512376 ± 7
HD-1 mx2	0.1393	0.512396 ± 7
HD-1 cpx2	0.1411	0.512407 ± 7

WR = whole rock, cpx = clinopyroxene, pl = plagioclase fraction, mx = mixed fraction.
Isochron age = 855 ± 59 Ma (MSWD = 0.59). $^{143}Nd/^{144}Nd$ initial ratio = 0.51162 ± 6.[a] (*2σ standard error).

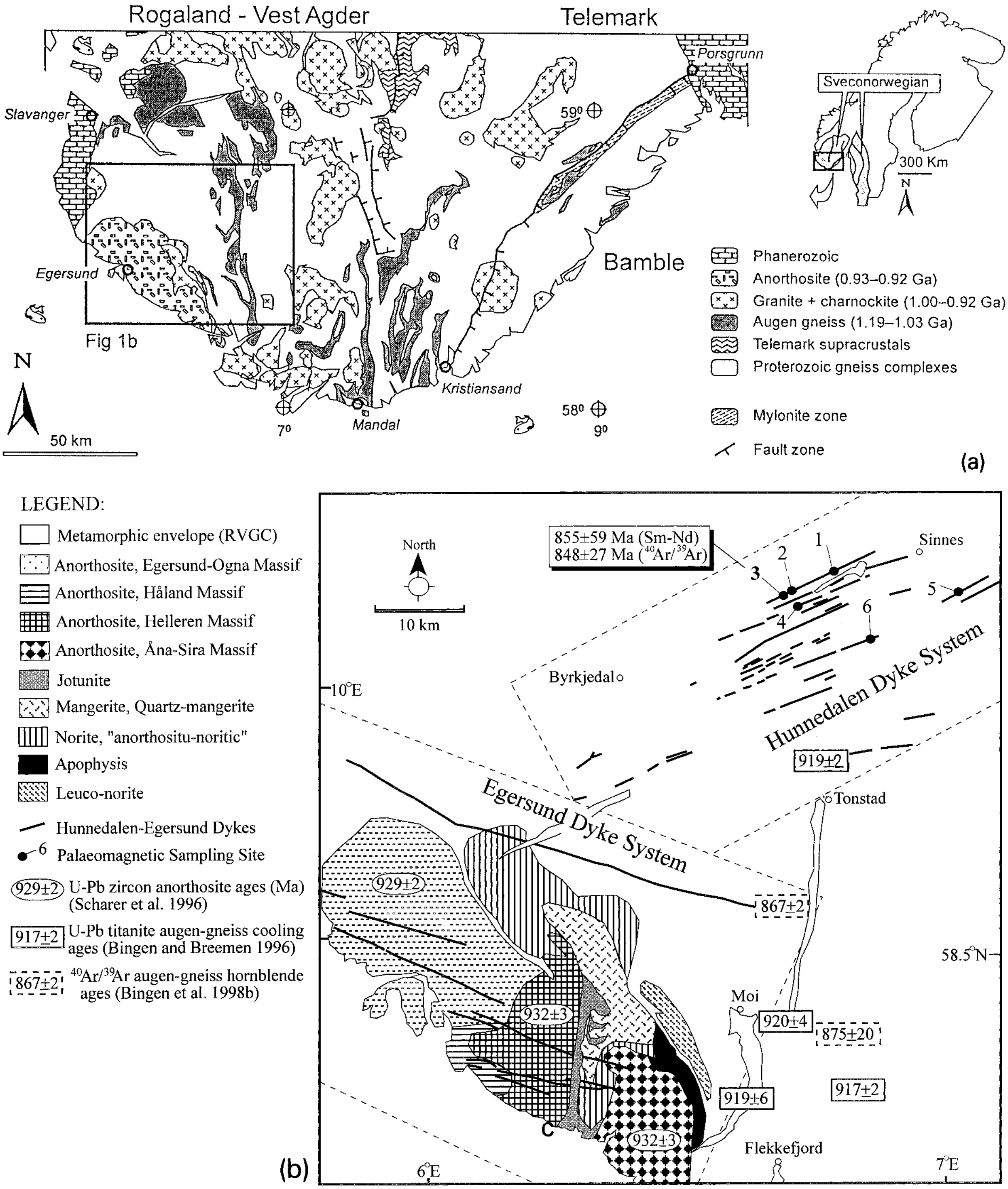

Fig. 1. (a) Simplified geologic map of the Sveconorwegian province of southern Norway (after [27]). (b) Geologic sketch map of the sampling area in south-west Norway (see Fig. 1a for location). Palaeomagnetic and geochronologic (sites 2 and 3) sampling sites of the Hunnedalen dyke swarm are denoted with numbers *1–6*. See legend for further details.

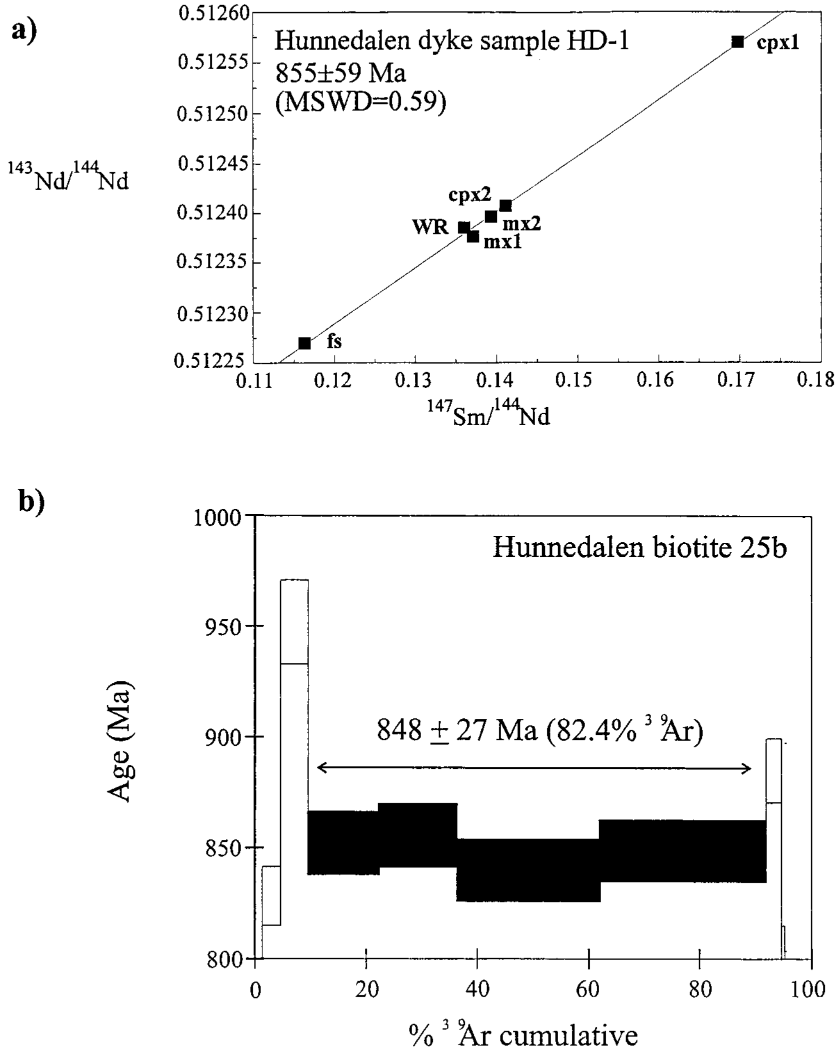

Fig. 2. (a) Sm–Nd isochron diagram for a site 3 sample (cf. Table 1 for legend). (b) $^{40}Ar/^{39}Ar$ biotite spectrum for a site 2 sample (cf. Table 2) that shows apparent age as a function of the cumulative fraction of ^{39}Ar released. Height of boxes indicates analytical error ($\pm 1\sigma$) about each step. We cite uncertainties at the 2σ level and include uncertainties in J-value for the 848 ± 27 Ma plateau age (filled boxes).

Siloé reactor in Grenoble, France. Following irradiation, the sample was repacked in Al-foil and loaded into a furnace; step-heating was done in a classical fashion with temperature increments as in Table 2. The ages we cite in the text (either final plateau or isochron ages) are at 2σ with the error in J-value.

The biotite experiment (Fig. 2b and Table 2) yields a well-defined weighted mean plateau age of 848 ± 27 Ma (82.4% of the cumulative ^{39}Ar gas). Irregular, climbing, low-volume steps in the early part of the experiment (preceding the plateau) are correlated with low and irregular K-contents as well as elevated Cl. Apparent ages drop precipitously at the end of the experiment in several small-volume, high-temperature steps that correspond to a Cl-spike and a clear drop in K-content. Low-temperature irregularities are attributed to minor alteration (not observed in mineral separates) and possible inhomogeneous K-distribution on grain margins; the high-temperature drop in apparent ages is primarily a function

Table 2
$^{40}Ar/^{39}Ar$ biotite furnace step heating of sample HUN25B ($J = 0.0041650$; weight = 5 mg)

T (°C)	$^{40}Ar/^{39}Ar$	$^{38}Ar/^{39}Ar$	$^{37}Ar/^{39}Ar$	$^{36}Ar/^{39}Ar$	^{39}Ar	^{39}Ar (%)	$^{40}Ar^{*}$ [a] (%)	$^{40}Ar^{*}/^{39}K$	Age (Ma)	$\pm 1\sigma$
600	94.625	0.145	0.352	55.385	0.009	0.19	83.0	78.57	510.77	18.19
700	90.146	0.075	0.427	8.592	0.054	1.41	97.2	87.68	561.58	10.52
750	141.755	0.084	0.239	6.430	0.148	4.73	98.7	139.90	828.29	13.38
800	166.939	0.098	0.043	0.443	0.217	9.60	99.9	166.79	951.63	19.17
850	***145.065***	***0.085***	***0.028***	***0.194***	***0.562***	***22.22***	***99.9***	***144.98***	***852.26***	***14.05***
900	***145.702***	***0.086***	***0.061***	***0.000***	***0.627***	***36.30***	***100.0***	***145.68***	***855.53***	***14.44***
950	***142.395***	***0.084***	***0.031***	***0.000***	***1.143***	***61.97***	***100.0***	***142.37***	***839.98***	***13.99***
1000	***144.251***	***0.084***	***0.076***	***0.080***	***1.337***	***91.99***	***100.0***	***144.21***	***848.64***	***13.84***
1050	151.940	0.087	0.760	0.000	0.119	94.65	100.0	152.04	885.05	14.32
1100	133.185	0.091	1.933	0.000	0.028	95.28	100.0	133.47	797.50	17.34
1200	144.183	0.164	2.496	0.000	0.010	95.50	100.0	144.58	850.38	47.14
1400	142.375	0.125	0.108	453.216	0.201	100.00	7.7	10.92	80.23	11.78

Individual temperature steps are listed with 1σ errors (excluding J). A weighted mean plateau age of 848 ± 27 Ma (2σ error including error in J) was calculated for temperature steps 850–1000°C (82.4% gas) (in bold italics). Individual steps were weighted both by length (gas volume) and individual age uncertainty. The monitor mineral was the Fish Canyon Tuff feldspar (27.4 Ma, [14]). Irradiation parameters (flux, salts, and shielding) were calculated after [13]. We used a radio frequency furnace for the biotite analysis. The furnace has regular temperature calibration by means of an optical pyrometer correlated to precise furnace power output.
[a] $^{40}Ar^{*}$ = radiogenic ^{40}Ar.

of exhaustion of K-derived argon gas near fusion temperatures. The plateau age is statistically similar to the Sm–Nd age. An isochron was impossible to calculate because of the high radiogenic content of individual sample steps.

4. Palaeomagnetic data

The natural remanent magnetisation (NRM) was measured with superconducting and spinner magnetometers. NRM stability was tested by both thermal (MMTD60 furnace) and alternating field (AF) demagnetisation (2-axis tumbler). Characteristic remanence components were calculated with the least square analysis implemented in the **SIAPD computer program** [1]. Thermomagnetic curves were obtained in air on a horizontal translation balance.

NRM intensities and bulk susceptibilities range between 0.016–24 A/m and 0.7–80 $\times 10^{-3}$ (SI units), respectively. No systematic lateral variations in magnetic properties across individual dykes were detected. AF demagnetisation (Fig. 3a) gives median destructive fields between 2.5 and 58 mT. Most samples carry at least a small fraction of high coercivity grains, hence the maximum available AF field of 100 mT is insufficient to demagnetise all the remanence. Thermal demagnetisation essentially gives square-shouldered discrete unblocking curves with the bulk of the remanence commonly removed within a narrow temperature range below 580°C. (Fig. 3b). Removal of soft secondary components leaves well-defined steeply negative characteristic remanence components (ChRc) with NW declinations (Fig. 3d, Table 3). Apart from a clustering near the present day field direction, the secondary overprints do not define a coherent direction.A contact test was performed at site 3. In general, the remanence in the coarse-grained host rock is more erratic in direction than in the dykes themselves, but after removal of spurious secondary components, the same directions as in the dykes were largely retrieved. However, the test has limited value in elucidating the relative ages of remanence, as the remanence directions in the entire RVGC (listed in [2]) are known to be almost identical to those in the dykes (see later).

Most thermomagnetic curves yield reversible Curie temperatures at about 580°C (Fig. 3e), consistent with thermal demagnetisation of almost pure magnetite as the dominant magnetic mineral. The exception is site 4, where the dyke has a reddish, weathered appearance. Here the secondary compo-

[1] http://www.ngu.no/geophysics

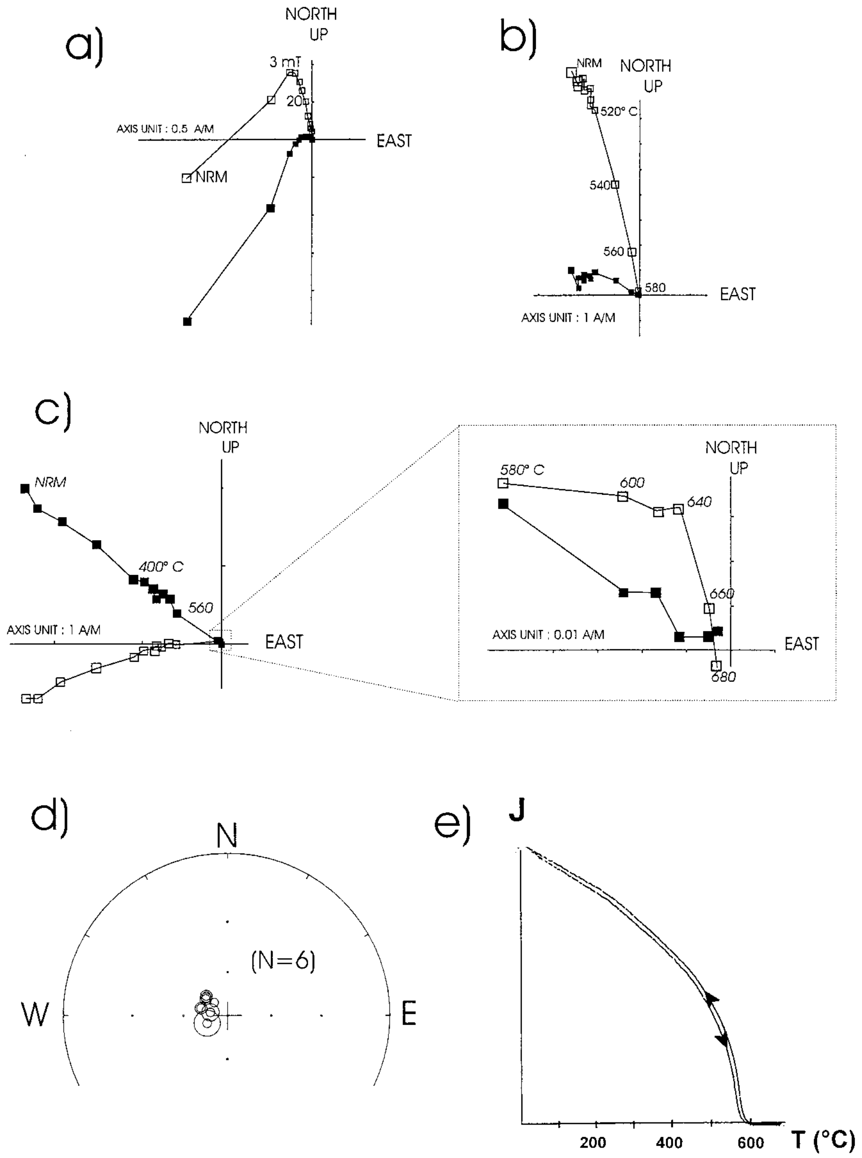

Fig. 3. (a) AF demagnetisation of a site 1 sample. (b) Thermal demagnetisation of a site 6 sample. (c) Example of anomalous blocking temperature behaviour for a site 4 sample, where the right hand diagram shows an enlargement of the final demagnetisation steps. The ChRc is identified above 640°C in this specimen after removal of a dominant secondary component. (d) Mean ChRc directions from all six sites with associated α_{95} confidence limits. (e) Representative thermomagnetic curve showing a reversible Curie point of 580°C.

nent is not removed until above 600°C, after which the ChRc is retrieved as a component typically constituting less than 1% of the NRM intensity, with maximum blocking temperatures corresponding to pure hematite (Fig. 3c).

With the exception of site 4, isothermal remanence curves saturate below 300 mT and hysteresis measurements give J_{rs}/J_s ratios between 0.05 and 0.15. This indicates grains approaching the true multi-domain size range [15], apparently at odds with the very stable ChRc observed in the dykes. This apparent contradiction is clarified by reflected light microscopy, scanning electron microscopy (SEM) and energy dispersive X-ray spec-

Table 3
Palaeomagnetic data from the Hunnedalen dykes (mean location 58.9ºN and 7ºE)

Site	N	D (°)	I (°)	k	α_{95}
1	10	281	−78	91	6
2	13	308	−71	252	4
3	8	313	−70	327	4
4	13	249	−75	74	9
5	15	315	−77	178	3
6	10	286	−71	174	4
Site mean	6*	294	−75	115	6
VGP:	41ºS, 222ºE, dp/dm = 10/11				

N = Number of samples/sites*; D(°)/I(°) = Mean declination/inclination; α_{95} = 95% confidence circle; k = precision parameter; VGP = virtual geomagnetic pole; dp/dm = semi-axes of 95% confidence around the pole.

trometry (EDXS) that reveal the presence of two distinct magnetite phases:

(1) Well crystallised grains with large separate magnetite and ilmenite regions, typically several hundred μm in size, attesting to the slow cooling at depth of this dyke suite. Grains are fresh in appearance with little or no indication of low temperature oxidation. These are the most abundant magnetic phases and probably dominate the bulk magnetic properties. No titanium is detected in the iron-enriched regions, ruling out secondary magnetic partitioning, and thus suggesting multi-domain behaviour.

(2) A set of pure magnetite grains with sizes ranging from 10 μm down to the limit of optical resolution hosted in silicates. The small sizes make detailed inspection difficult under the optical microscope, but the grains appear to be primary in origin. We infer that the very stable ChRc is carried by this second phase.

The anomalous blocking temperatures of site 4 are also elucidated by microscopy. The bulk of the magnetite in this dyke is present as secondary crack fill, while intergrown hematite/ilmenite grains apparently carry the stable ChRc. No indications of secondary magnetic mineral formation were found at any of the other sites.

To further elucidate the origin of the stable ChRc, low temperature demagnetization experiments were performed on one specimen from each site by cooling twice to −196ºC in liquid nitrogen, and measuring the remaining remanence. Thereafter the specimens were given a saturation isothermal remanent magnetization (SIRM) by exposing them to a field of 4 T in a pulse magnetizer, before the cooling experiment was repeated. Results are summarised in Table 4. Cooling magnetite through its isotropic point at −143ºC causes a large decrease in multidomain remanence through the decoupling of domain walls, while remanence in smaller pseudo-single-domain and single-domain grains where shape anisotropy is the controlling factor, remains largely untouched [16]. For sites 1,2,3,5 and 6 the reduction in remanent intensity is small for the NRM (0–17%), but much larger for the SIRM (43–62%). We take this as additional support for the ChRC being carried preferentially in the smaller grains. Interestingly, for site 4 where the magnetite fraction is clearly secondary in origin as discussed above, the situation is opposite, with the NRM showing a larger decrease than the SIRM (Table 4).

5. Discussion

In Rogaland and Vest Agder, the intrusion of massif-type anorthosite at 932–929 Ma and granitic plutonism at ca. 930 Ma was associated with a pulse

Table 4
Relative change in remanent intensity for one specimen from each site after two cooling cycles to −196ºC for NRM and SIRM respectively

	Site 1	Site 2	Site 3	Site 4	Site 5	Site 6
NRM decrease (%)	5	−19	0	45	13	17
SIRM decrease (%)	46	62	57	19	45	43

The same specimens were used for both sets of experiments. Intensity increase for the NRM of the site 2 specimen is due to removal of a soft secondary component close to the present day field.

of thermal metamorphism and was followed by regional cooling and unroofing (Fig. 1b and Fig. 5). In the RVGC, titanite U–Pb dates range from 927 to 907 Ma and hornblende $^{40}Ar/^{39}Ar$ dates in pyroxene-rich samples range from 928 to 902 Ma [17,18]. These dates probably reflect a phase of fast regional cooling through about 600–500°C shortly after intrusion of the anorthosites. A second group of hornblende $^{40}Ar/^{39}Ar$ dates in pyroxene-poor or pyroxene-free samples range from 893 to 855 Ma. These overlap with Rb–Sr whole-rock-(brown) biotite ages (895–853 Ma) and K–Ar biotite ages (878–853 Ma) from the same area [19]. They are attributed to a late-Sveconorwegian low-grade metamorphic or hydrothermal event [17].

The Hunnedalen dykes yield corresponding Sm–Nd internal isochron and biotite $^{40}Ar/^{39}Ar$ plateau dates of 855 ± 59 and 848 ± 27 Ma, respectively (Fig. 2). These dates are similar to Sm–Nd and Rb–Sr internal isochron dates of 835 ± 47 and 834 ± 9 Ma obtained by Maijer and Verschure [7] on the same dyke. The Hunnedalen dyke age determinations are somewhat younger than, but nevertheless overlap with, the late-Sveconorwegian mineral ages in the RVGC (895–853 Ma). Thus, they probably correspond to an intrusion age of the swarm at ca.

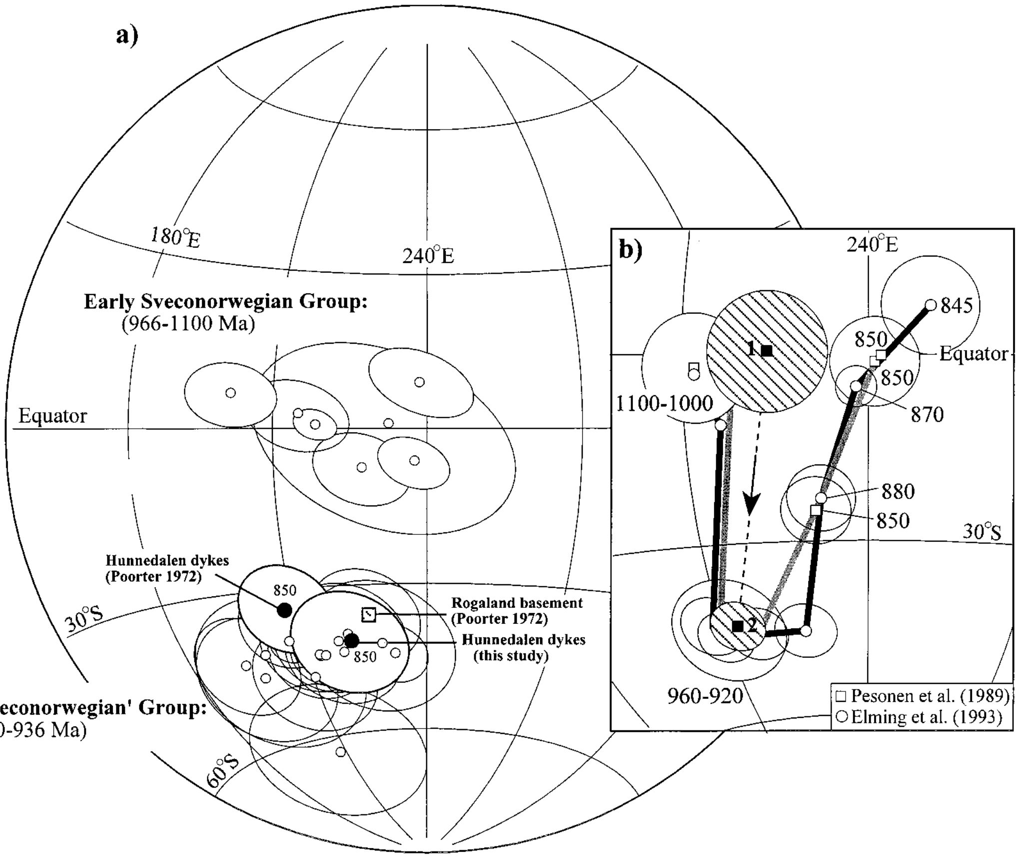

Fig. 4. (a) A compilation of the most reliable Sveconorwegian poles, all derived from isotopically dated rocks in southern Norway, in addition to a few Early Sveconorwegian poles from southern Sweden (Table 5). Poles are shown with dp/dm ovals. Note that the Hunnedalen poles (solid circles marked 850; [8] and this study) fall within the group of Late Sveconorwegian poles. A pole from the Rogaland basement (RVGC; [8]), not listed in Table 5, is included for comparison (cf. text). Equal area projection. (b) A counter-clockwise Sveconorwegian APW loop as postulated by Pesonen et al. [1] and Elming et al. [3]. The loops are similar, but differ somewhat in age progression. In contrast we argue for only two groups (1 and 2) of Sveconorwegian poles, and group 2 is argued to be ca. 850 Ma. Numbers refer to millions of years. Mean poles are shown with A_{95} circles.

850 Ma, although we cannot rule out that they reflect unroofing or remobilization of the entire area at this time.

The demagnetisation data from the Hunnedalen dykes are generally of high quality, and high-unblocking site-mean directions form a clustered group with north-west declinations and steep negative inclinations (Fig. 3d, Table 3). The corresponding palaeomagnetic pole compares to that of Poorter [8] (Fig. 4a and Table 5). In fact, *all* rocks in the Sveconorwegian domain of SW Norway, i.e. the Rogaland Igneous Complex (Table 5) and RVGC [8], have an almost identical magnetisation (Fig. 4a), and they have uniform (normal?) magnetic polarity.

Since the identical magnetic directions in the dykes and the surrounding RVGC rule out the possibility of proving a primary origin of remanence through a contact test, a large scale regional remagnetization of the dykes and surrounding RVGC cannot be ruled out. If this is indeed the case, *all* published Sveconorwegian palaeomagnetic data from SW Norway would have to be rejected. There is, however, no clear evidence for a tectonothermal event in SW Norway (<850 Ma) intense enough to reset the high stability remanence in the dykes as well as in the diverse assembly of surrounding rocks. The Caledonian orogeny is not a candidate, as this would give a much shallower remanence direction than we observe. Taken together with the rock magnetic evidence discussed above, this leads us to favour a primary cooling remanence as the most likely alternative.

The age of the magnetic remanence of the Hunnedalen dykes is probably best estimated by the biotite (closure temperature ca. 300–350°C) $^{40}Ar/^{39}Ar$ plateau value of 848 ± 27 Ma, regardless of the exact significance of this age determination (intrusive or metamorphic cooling), because the closure temperature for the Sm–Nd system is poorly known. Estimating the true temperature at which the lock-in of remanence in a rock took place is problematic. In a slowly cooled regime, geologic blocking temperatures are significantly lower than laboratory unblocking temperatures [20,21]. Thermochemical effects normally widen the temperature gap between unblocking and the lock-in of remanence even further. In the Rogaland Igneous Complex and RVGC, it is unlikely that any magnetic remanence pre-dates the regional titanite cooling age (927–907 Ma). The widespread distribution of late-Sveconorwegian mineral ages in the range 895–853 Ma (hornblende $^{40}Ar/^{39}Ar$, K/Ar biotite and Rb–Sr whole-rock–biotite ages) (compilation in [22]) suggests that the magnetic signature in the Sveconorwegian domain of south-western Norway may be as young as 890–850 Ma, and thus explains the apparent palaeomagnetic

Table 5

Palaeomagnetic poles from the Hunnedalen dykes (A), and a compilation of some of the most reliable and *isotopically dated* Late (B) and Early Sveconorwegian (C) rocks in southern Norway (Rogaland Vest-Agder and Bamble regions; Fig. 1)

Formation (area)	Ref.	α_{95}	Lat.	Long.
A. 850 Ma dykes SW Norway				
Hunnedalen	P03-043	5	−34.0	208.0
Hunnedalen	this study	6	−41.0	222.0
B. Late Sveconorwegian plutons SW Norway (936–929 Ma) [a]				
Håland-Helleren Massif	P03-012	5.2	−41.1	212.5
Åna-Sira Massif	P03-011	6.5	−46.3	197.4
Hidra body	P03-008	5.8	−43.1	219.7
Rogaland farsundite	P03-005	7.5	−63.4	207.8
Garsaknat body	P03-009	6.2	−39.6	221.4
Rogaland farsundite	P03-004	3.5	−43.9	232.2
Bjerkheim-Sokndal lopolith	P03-015	5.8	−47.6	210.6
Bjerkheim-Sokndal lopolith	P03-014	5.7	−40.9	218.9
Bjerkheim-Sokndal lopolith	P03-017	8	−41.8	229.3
Bjerkheim-Sokndal lopolith	P03-016	3.4	−43.5	215.0
Egersund anorthosite complex	P03-018	2	−43.5	213.7
Egersund anorthosite	P03-030	5	−43.3	194.0
Egersund anorthosite	P03-029	4.6	−37.0	207.0
Egersund anorthosite	P03-028	8	−42.0	200.0
C. Early Sveconorwegian dykes and intrusions (1100–966 Ma)				
Falun dolerite (Sweden)	*P01-005*	*5.6*	*−6.1*	*237.6*
Nilstorp dolerite sill (Sweden)	P01-009	9.7	9.0	238.5
Årby dolerite (Sweden)	P01-004	7	−7.3	227.4
Bamble Nenset-Gumøy hyperite	P03-020	8.4	3.0	215.0
Bamble Intrusions	P03-035	22.6	1.1	232.6
Bamble Intrusions	P03-032	7.7	6.6	201.4
Bamble Intrusions	P03-034	3.5	0.9	218.4

'Bamble' compatible poles from three dated Early Sveconorwegian dolerites (966–995 Ma; Rb–Sr) in southern Sweden are also listed. Ref. = reference pole number listed in [2]; Lat./Long. = pole latitude/longitude; ages of Norwegian formations listed in Torsvik and Eide [22]; Swedish ages listed in [2].

[a] These Sveconorwegian poles in SW Norway are argued to reflect late 'unroofing' with an age of 850 Ma since the poles are compatible with the ca. 850 Ma Hunnedalen dykes (see text).

similarity between the Hunnedalen dykes, the Rogaland Igneous Complex (Table 5) and the RVGC (e.g. [8]) (Fig. 4a).

Most of the remanence in the Rogaland Igneous Complex and RVGC is carried by magnetite of relatively high stability [23]. In particular, the anorthosites have maximum blocking temperatures well above 500ºC. If a late-Sveconorwegian metamorphic or hydrothermal event [17] is indeed responsible for the post 900 Ma mineral ages and magnetic signature, it would therefore have to be of some significance, although a temperature approaching the laboratory unblocking temperatures is not required.

If, on the other hand, the remanence acquisition in the Rogaland Igneous Complex and RVGC started close to the 932–929 Ma intrusion age of the anorthosites, this would imply negligible polar wander for the period between 930 and 850 Ma. Given the uniform polarity of all the remanence in the area, it seems unlikely that remanence acquisition took place over a prolonged period of slow cooling. We therefore favour a relatively short lived post-900 Ma metamorphic or hydrothermal event as the most probable origin of all the remanence.

The estimated 850 Ma age pole for the Hunnedalen dykes differs from previously listed 850 Ma poles for Baltica (Fig. 4a,b). Pesonen et al [1] listed three 850 Ma mean poles (pole numbers 31–33 in their appendix; see also [2]) plotted in Fig. 4b. These 850 Ma poles are crucial to the postulate of a counter-clockwise Sveconorwegian APW loop between 1100–800 Ma, and they were used by Weil et al. [4], although a more recent compilation is given in [3]. A careful inspection of the palaeomagnetic basis for calculating the 850 Ma mean poles [1] shows that these are based on: (1) non-dated rocks, (2) data from older rocks or anomalous site-data from older rocks (assumed remagnetizations), and/or (3) palaeomagnetic data from rocks recently demonstrated to be as young as 616 ± 3 Ma (Egersund dykes; U–Pb age of [11]). In the most recent compilation of Baltic palaeomagnetic data for the same time period [3] the shape of the Sveconorwegian APW loop is similar to that of [1], but with a different age calibration (Fig. 4b).

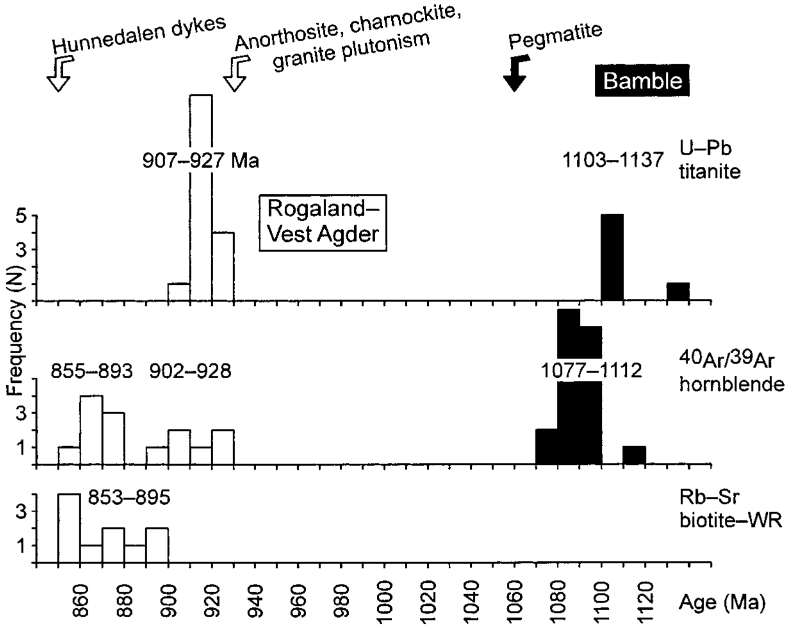

Fig. 5. Compilation of U–Pb titanite, $^{40}Ar/^{39}Ar$ hornblende and Rb–Sr biotite-WR data from Rogaland Vest Agder, and Bamble regions (see Fig. 1a). Ages are listed in Torsvik and Eide [22] and originate from several sources [17–19,25,26]. Not selected for the plot are U–Pb titanite data more than 1% discordant, $^{40}Ar/^{39}Ar$ hornblende spectra displaying probable excess radiogenic Ar, Rb–Sr biotite–WR data inside the Caledonian green biotite-in isograd, and Rb–Sr biotite–WR data in Bamble which show no regional systematics.

In light of new geochronologic data from SW Norway (summary in [22]), we argue that the traditional form of the Sveconorwegian APW loop is not viable, and that the distribution of Sveconorwegian poles for Baltica essentially defines two coherent groups:

(1) A group of early Sveconorwegian poles (ca. 1100–966 Ma, Fig. 4a and Table 5). In southern Norway, all poles are derived from ca. 1100 Ma rocks within the Bamble sector (Fig. 1a), an area that was last affected by high-grade Sveconorwegian metamorphism between 1150 and 1100 Ma (see Fig. 5; [24]). This group yields a mean pole that in essence corresponds to the 1100–1050 Ma grand mean poles of [1,3]. The exact magnetization age for this group is uncertain, but probably lies within the 1100–966 Ma range (directionally similar poles from S Sweden have the youngest ages; Table 5). Within the Bamble region, titanite U–Pb cooling dates range from 1137 to 1103 Ma [2], hornblende $^{40}Ar/^{39}Ar$ dates from 1112 to 1081 Ma [25,26] (Fig. 5), and a post-kinematic pegmatite has an interpreted intrusion age of $1060 + 8/-6$ Ma [28]. This ca. 1060 Ma hydrothermal event may represent a palaeomagnetic maximum age for group 1 poles in southern Norway. On the assumption that Group 1 are NORTH poles (normal polarity) (Fig. 4a and Table 5), they suggest palaeolatitudes at around 30°S for southern Scandinavia (Fig. 6).

(2) A second group of late Sveconorwegian poles with a magnetisation age of ca. 850 Ma (Fig. 4a, Table 5), or perhaps within the 890–850 Ma range. In SW Norway, data are almost exclusively derived from the Rogaland Igneous Complex and the RVGC. We stress once again that poles from the Rogaland Igneous Complex (932–929 Ma), the RVGC and the Hunnedalen dykes (ca. 850 Ma) are all similar (Table 5; Fig. 4a). The 'same' group of poles was originally assigned magnetization ages between 960 and 920 Ma [1,3], but should be re-assigned a magnetization age of ca. 850 Ma. This group therefore also replaces the 880–845 Ma mean poles of Pesonen et al. [1] and Elming et al ([3]; Fig. 4b). Group 2 poles yield palaeolatitudes for Baltica in excess of 60°S (Fig. 6), hence substantial southward movement of Baltica is indicated during or shortly after the Sveconorwegian orogeny.

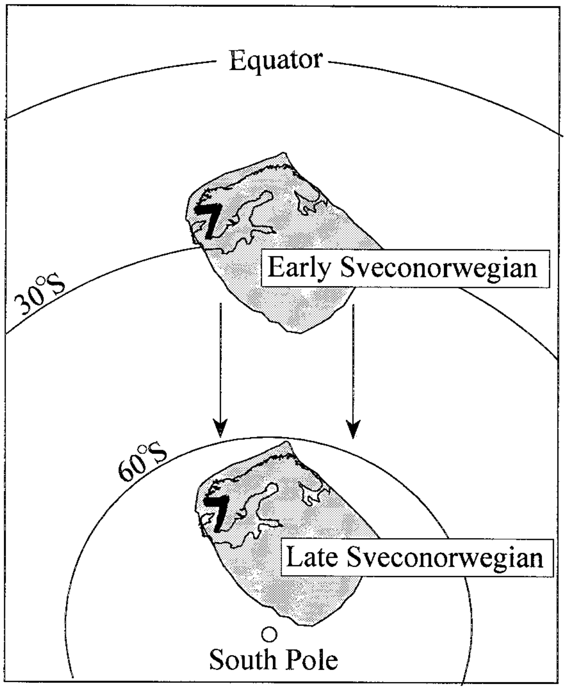

Fig. 6. Palaeoposition of Baltica according to pole-means for early and late Sveconorwegian poles (see Fig. 4a and b). The southerly hemisphere position for Baltica assumes that the poles plotted in Fig. 4 (Table 5) are north poles. The Sveconorwegian domain in southern Scandinavia is shown in black.

6. Conclusions

The Hunnedalen dyke swarm probably intruded at ca. 850 Ma, as judged from concordant Sm–Nd internal isochron and biotite $^{40}Ar/^{39}Ar$ plateau ages of 855 ± 59 and 848 ± 27 Ma respectively.

The palaeomagnetic pole for the Hunnedalen dykes is identical to poles derived from older plutonic and metamorphic Sveconorwegian rocks in SW Norway; these latter poles are here interpreted to record a late Sveconorwegian metamorphic or hydrothermal event immediately prior to or contemporaneous with intrusion of the Hunnedalen dykes. This event is recognised throughout the Rogaland and Vest Agder region [17], but not recorded isotopically in the Bamble sector.

Previously listed 850 Ma mean poles for Baltica are suspect since they are derived from rocks with older, younger and unknown ages, and anomalous data from older rocks. A mean pole with latitude

= 43.7°S and longitude = 213.3°E (A_{95} = 4.6°), based on both the Rogaland Igneous Complex and the Hunnedalen dykes, probably represents the best ca. 850 Ma magnetization age pole for Baltica.

A Sveconorwegian–Grenvillian counter-clockwise APW loop is not supported by the high quality data-sets from Baltica.

Rodinia Supercontinent reconstructions based on 1100–850 Ma palaeomagnetic data are still at an early stage, and require careful evaluation of palaeomagnetic (and isotopic data) from all proposed 'Rodinia' continental elements.

Acknowledgements

Constructive comments on earlier versions of the manuscript by Andrew Warnock, John Geissman, Mike Cosca and an anonymous reviewer are gratefully acknowledged. Thanks also to Eirik Hauger for his cheerful companionship in the field. ***[RV]***

References

[1] L.J. Pesonen, T.H. Torsvik, S.-Å. Elming, G. Bylund, Crustal evolution of Fennoscandia — palaeomagnetic constraints, Tectonophysics 162 (1989) 27–49.

[2] L.J. Pesonen, G. Bylund, T.H. Torsvik, S.-Å. Elming, S. Mertanen, Catalogue of palaeomagnetic directions and poles from Fennoscandia: Archaean to Tertiary, Tectonophysics 195 (1991) 151–207.

[3] S.-Å. Elming, L.J. Personen, M.A.H. Leino, A.N. Khramov, N.P. Mikhailova, A.F. Krasnova, S. Mertanen, G. Bylund, M. Terho, The drift of the Fennoscandian and Ukrainian shields during the Precambrian: a paleomagnetic analysis, Tectonophysics 223 (1993) 177–198.

[4] A.B. Weil, R. Van der Voo, C. Mac Niocall, J.G. Meert, The Proterozoic supercontinent Rodinia: paleomagnetically derived reconstructions for 1100 to 800 Ma, Earth Planet. Sci. Lett. 154 (1998) 13–24.

[5] I.W.D. Dalziel, On the organization of American plates in the Neoproterozoic and the breakout of Laurentia, GSA Today 2 (11) (1992) 237–241.

[6] I.W.D. Dalziel, Neoproterozoic–Paleozoic geography and tectonics: reviews, hypothesis, environmental speculations, Geol. Soc. Am. Bull. 109 (1997) 16–42.

[7] C. Maijer,R.H. Verschure, Petrology and isotope geology of the Hunnedalen monzonoritic dike swarm, SW Norway: the Hunnedalen dike swarm as a possible late expression of Egersund anorthosite magmatism, Norges Geol. Undersøk. Bull. (in press).

[8] R.P.E. Poorter, Palaeomagnetism of the Rogaland Precambrian (Southwestern Norway), Phys. Earth Planet. Inter. 5 (1972) 167–176.

[9] U. Schärer, E. Wilmart, J.-C. Duchesne, The short duration and anorogenic character of anorthosite magmatism: U–Pb dating of the Rogaland complex, Norway, Earth Planet. Sci. Lett. 139 (1996) 335–350.

[10] B. Sundvoll, The age of the Egersund dyke-swarm, SW Norway: some tectonic implications, Terra Cognita 7 (1987) 180.

[11] B. Bingen, D. Demaiffe, O. van Breemen, The 616 Ma old Egersund basaltic dike swarm, SW Norway, and late Neoprotorozoic opening of Iapetus ocean, J. Geol. 106 (1998) 565–574.

[12] E.W. Mearns, Sm–Nd ages for Norwegian garnet peridotite, Lithos 19 (1986) 269–278.

[13] N.O. Arnaud, M. Brunel, J.M. Cantagrel, P. Tapponier, High cooling and denudation rates at Kongur Shan, eastern Pamir (Xinjiang, China) revealed by $^{40}Ar/^{39}Ar$ alkali feldspar thermochronology, Tectonics 12 (1993) 1335–1346.

[14] G.T. Cebula, M.J. Kunk, H.H. Mehnert, C.W. Naeser, J.D. Obradovich, J.F. Sutter, The Fish Canyon Tuff, a potential standard for the ^{40}Ar–^{39}Ar and fission-track dating methods (abs.), Terra Cognita Proc. ICOG 6 (1986) 139–140.

[15] D.J. Dunlop, Hysteresis properties of magnetite and their dependence on particle size: a test of pseudo-single-domain remanence models, J. Geophys. Res. 91 (B9) (1986) 9569–9584.

[16] S. Levi, R.T. Merrill, Properties of single-domain, pseudo-single-domain and multi-domain magnetite, J. Geophys. Res. 83 (1978) 309–323.

[17] B. Bingen, A. Boven, L. Punzalan, J. Wijbrans, D. Demaiffe, Hornblende $^{40}Ar/^{39}Ar$ geochronology across terrane boundaries in the Sveconorwegian province of SW Norway, Precambrian Res. 90 (1998) 159–185.

[18] B. Bingen, O. van Breemen, U–Pb monazite ages in amphibolite- to granulite-facies orthogneisses reflect hydrous mineral breakdown reactions: Sveconorwegian Province of SW Norway, Contrib. Mineral. Petrol. 132 (1998) 336–353.

[19] R.H. Verschure, P.A.M. Andriessen, N.A.M. Boelrijk, E.H. Hebeda, C. Maijer, H.N.A. Priem, E.A.T. Verdurmen, On the thermal stability of Rb–Sr and K–Ar biotite systems: evidence from coexisting Sveconorwegian (ca 870 Ma) and Caledonian (ca 400 Ma) biotites in SW Norway, Contrib. Mineral. Petrol. 74 (1980) 245–252.

[20] G. Pullaiah, E. Irving, K.L. Buchan, D.J. Dunlop, Magnetization changes caused by burial and uplift, Earth Planet. Sci. Lett. 28 (1975) 133–143.

[21] D. Walton, Time–temperature relations in the magnetization of assemblies of single domain grains, Nature 286 (1980) 245–247.

[22] T.H. Torsvik, E.A. Eide, NGU GEOCHRON: Database and analysis package for Norwegian isotope geochronology, Geological Survey of Norway, Open file report 98.003, 1998, pp. 54.

[23] J.E.F. Stearn, J.D.A. Piper, Palaeomagnetism of the Sve-

conorwegian mobile belt of the Fennoscandian shield, Precambrian Res. 23 (1984) 201–246.
[24] L. Kullerud, S.H. Dahlgren, Sm–Nd geochronology of Sveconorwegian granulite facies mineral assemblages in the Bamble shear belt, south Norway, Precambrian Res. 64 (1993) 389–402.
[25] M.A. Cosca, R.K. O'Nions, A re-examination of the influence of composition on argon retentivity in metamorphic calcic amphiboles, Chem. Geol. 112 (1994) 39–56.
[26] M.A. Cosca, K. Mezger, E.J. Essene, The Baltica–Laurentia connection: Sveconorwegian (Grenvillian) metamorphism, cooling, and unroofing in the Bamble Sector, Norway, J. Geol. 106 (1998) 539–552.
[27] E.M. Sigmond, M. Gustavson, D. Roberts, Berggrunnskart over Norge, 1:1 million, Norges Geologiske Undersøkelse, 1984.
[28] C. Baadsgaard, Chaplin, W.L. Griffin, Geochronology of the Gloserheia pegmatite, Froland, southern Norway, Norsk Geol. Tidsskr. 64 (1984) 111–119.