Age and paleomagnetic signature of the Alnø carbonatite complex (NE Sweden): Additional controversy for the Neoproterozoic paleoposition of Baltica

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Abstract

A paleomagnetic investigation of the Alnø carbonatite complex dikes was undertaken in an attempt to refine the apparent polar wander path for Baltica. The currently available paleomagnetic database for the Ediacaran–Cambrian segments of the Baltica APWP is marked by disparate (and often supposedly) coeval poles. This has led to remarkable conclusions about rapid rates of drift or true polar wander. Our study shows that the Alnø Complex (584 ± 7 Ma) is coeval with the Fen Carbonatite Complex (583 ± 15 Ma) via $^{40}Ar/^{39}Ar$ dating of biotite and K-feldspar. We identify three components of remanent magnetization in the Alnø Complex. The first is a low unblocking/coercivity component with a mean declination of 51.2° and inclination of +70.2° ($k = 22$, a95 = 8.3°). A paleopole calculated from this direction falls at 62.7°N, 101°E. The high coercivity and unblocking components show a large spread in both declination and inclination. A somewhat artificial grouping of shallow–intermediate vectors (inclinations less than 60°) yields a mean direction with a declination of 108.1° and an inclination of 10.5° ($k = 5.3$, a95 = 32.1°). This direction is statistically indistinguishable from that obtained by Piper [Piper, J.D.A., 1981. Magnetic properties of the Alnøn complex. Geol. Foren. Stock. Forhandlingar, 103, 9–15 (Part 1)] and yields a paleomagnetic pole at 3.5°N, 269°E. Conversely, the remaining high unblocking/coercivity components (inclinations > 60°) yields a second grouping with a mean declination of 28° and inclination of 76.8° ($k = 24$; a95 = 16.1°; Fig. 5E). This direction is indistinguishable from the present Earth's field at the site. We conclude that the Alnø Complex poles (and indeed many of the Ediacaran poles for Baltica) should be viewed with scepticism when used for paleogeographic/geodynamic models.
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Keywords: Baltica; Alnø; Carbonatite; $^{40}Ar/^{39}Ar$ dating; Paleomagnetism

1. Introduction

The latest Neoproterozoic was a pivotal time in Earth history, with the breakup of the supercontinent of Rodinia and possible "Snowball Earth" conditions setting the scene for the Ediacaran and subsequent Cam-

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brian biologic explosion (Knoll, 1996; Hoffman et al., 1998; Meert and Torsvik, 2003). In this context, reliable paleomagnetic data are crucial to demonstrating whether or not the pre-Ediacaran glaciations were truly global in nature, or may to a large extent be explained by the (latitudinal) positions of individual continents. Specifically for Baltica, a key question is whether the widespread Vendian tillites may be explained simply by a high latitude position for Baltica, or alternatively constitute evidence for extensive low-latitude glaciations. The Vendian glacials, however, are not well dated and may well be post-Snowball Earth, making a global correlation problematic (see Bingen et al., 2005; Meert, 2007).

Unfortunately, the existing paleomagnetic data for Baltica in the Neoproterozoic time period are ambiguous. While the bulk of existing data seems to indicate either high-to-intermediate (>30°) latitudes (e.g., Torsvik et al., 1995, 1996; Torsvik and Rehnström, 2001; Meert et al., 1998; Bingen et al., 2005; Walderhaug et al., 2007), several recent paleomagnetic studies have suggested that Baltica occupied intermediate-to-low (Popov et al., 2002, 2005; Iglesia-Llanos et al., 2005) or equatorial (Piper, 1981; Eneroth, 2002; Eneroth and Svenningsen, 2004) paleolatitudes during the 610–550 Ma interval, thus lending support to the concept that Vendian glaciations in Baltica were part of a "Snowball Earth" scenario (Table 1). The latter studies indicating low paleolatitudes for Baltica are also controversial. In addition, the Snowball Earth episodes are now considered pre-Ediacaran (>635 Ma), so if the low-latitude results for Baltica are correct, then there may have been a separate (post-Ediacaran) low-latitude glaciation (Gaskiers?) represented by the Moelv tillite (Bingen et al., 2005; Meert, 2007).

Eneroth (2002) and Eneroth and Svenningsen (2004) reported an equatorial paleolatitude derived from the 608 ± 1 Ma (U–Pb) Sarek dike swarm. Eneroth and Svenningsen (2004) argued for a primary remanence in the dikes, but have subsequently withdrawn the papers because of incorrect orientations (Eneroth, 2006a,b). Thus, the Sarek paleomagnetic results should not be used to establish the position of Baltica during the Neoproterozoic.

Table 1
Paleomagnetic Poles from Baltica (Ediacaran–Early Ordovician)

Pole name	Q^a	Dec[b]	Inc[c]	a95[d]	GLat[e]	GLon[f]	Plat[g]	Plon[h]	Age[i]
1. Swedish Limestone	5	335	−52	13.4	58.3	13.9	3.3	34.79	458
2. Swedish Limestones	5	116	67	9	58	13	29.75	55.06	475
3. Swedish Limestones	6	138	62	5.1	59	15	17.96	45.83	475
4. St. Petersburg Limestone	5	130.4	73.1	3.6	58	30	33.12	58.18	478
5. Andrarum Limestone	3	51	57	6.8	55.7	14	51.72	110.32	500
6. Tornetrask Fm/Dividal Group	4	57	66	8.9	68.2	19.5	55.89	115.53	535
7. Winter Coast	6	279	41.3	3	65.5	39.8	25.17	312.11	555
8. Arkhangelsk	6	120	−31.7	3.9	65.6	40.5	28.3	290.0	555
9. Zolotitsa	6	298.9	37.7	2.3	65.5	40.0	31.7	292.9	555
10. Verkhotina	5	305	35.9	2.2	64.8	40.5	32.2	297.0	555
11. Mean 7–10	6	296.1	37	10.6	65.0	40	29.6	298.1	555
12. Volhynia lavas	4	269	66	2.4	52.8	28.3	36	333.0	555
13. Fen Complex	4	203	−49	8	59.3	9.3	56.73	151.17	583
14. Alnø steep—this study	4	51.2	70.2	8.3	62.5	17.5	62.7	101	584
15. Alnø shallow—this study	3	108	10.5	32.1	62.5	17.5	3.5	269	584
16. Alnø Piper	3	107.2	1.6	9.3	62.5	17.5	7.6	272	584
17. Egersund Dikes	6	120	69	10	58.4	6.2	31.4	44.1	608

Notes: References by pole numbers: (1–3) Torsvik and Trench (1991); (4) Smethurst et al. (1998); (5 and 6) Torsvik and Rehnström (2001); (7) Popov et al. (2002); (8) Iglesia-Llanos et al. (2004); (9 and 10) Popov et al. (2005); (11) this study; (12) Nawrocki et al. (2004); (13) Meert et al. (1998); (14) this study steep component; (15) this study shallow component; (16) Piper (1981); (17) Walderhaug et al. (2007).

[a] *Q*-value based on Van der Voo (1990).
[b] Declination.
[c] Inclination.
[d] Alpha-95 circle of 95% confidence about the mean direction.
[e] Site latitude.
[f] Site longitude.
[g] Paleomagnetic pole latitude.
[h] Paleomagnetic pole longitude.
[i] Age determination by pole (1–6) fossil correlation; (7–12) U–Pb zircon; (13–16) $^{40}Ar/^{39}Ar$ biotite; (17) U–Pb zircon and $^{40}Ar/^{39}Ar$ biotite.
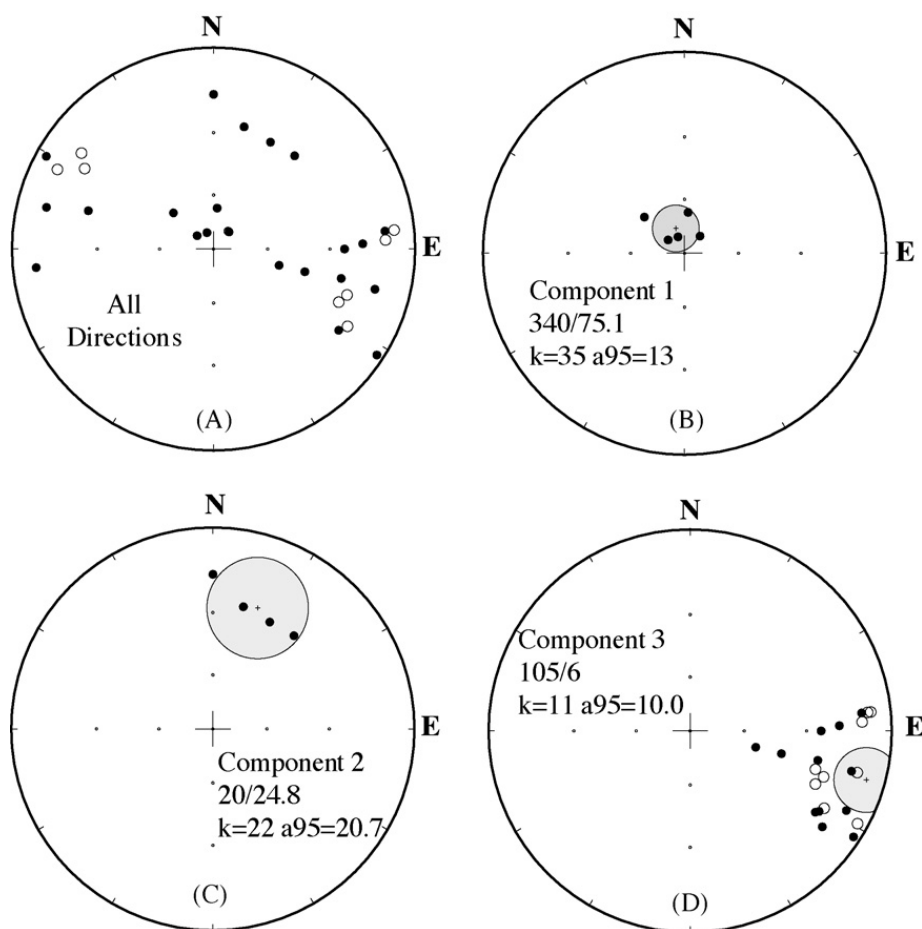
Fig. 1. (A) All directional data from the study by Piper (1981) for the Alnø Complex in Sweden; (B) grouping of steep directions in the Piper (1981) study; (C) Northerly and shallow components from the Piper (1981) study; (D) Southeasterly and shallow components (some sites reversed) that Piper (1981) claimed as the primary remanence for the Alnø Complex.

Piper (1981) conducted a paleomagnetic study of the Alnø carbonatite complex, obtaining a confusing array of directions in the various rock types of the complex. The results encompassed at least three different components, with mean inclinations ranging from 2° to 76° (Fig. 1). Taking the lowest inclination component to be the primary magnetization, Piper (1981) concluded that Baltica was at equatorial latitudes at the time of formation of the complex. Piper reports a paleomagnetic pole for the Alnø Complex at 7.6°N, 272°E. The mean Alnø Complex pole (Table 1) would situate Baltica in latitudes from ∼0°S to 30°S.

Popov et al. (2002) reported a dual-polarity magnetization from the Winter Coast sedimentary section in Russia. U–Pb dating of interbedded volcanic rocks yield an age of 555 ± 3 Ma and the resultant paleomagnetic pole falls at 25.3°N, 212.2°E. These paleomagnetic results were further supported by subsequent studies in the same area (Iglesias-Llano et al., 2004; Popov et al., 2005) although paleomagnetic studies of coeval basaltic flows hint at a possible inclination shallowing problem

in the sedimentary studies (Nawrocki et al., 2004). The mean Winter Coast pole (Table 1) would situate Baltica in latitudes from ∼5°S to 40°S.

These equatorial latitude studies stand in marked contrast to results obtained from the Fen carbonatite complex (Meert et al., 1998; Piper, 1988; Poorter, 1972). The Fen Complex (583 ± 15 Ma) is similar in age and composition to Alnø. The paleomagnetic signature of the Fen rocks is both simpler and more consistent than observed in the Alnø Complex, with the three separate studies of the Fen Complex all yielding paleolatitudes between 25° and 37° (reference location Oslo). The Fen Complex results are still more southerly than indicated by the Alnø results of Piper (1981) or by Popov et al. (2002) for the Winter Coast sedimentary sequence. In the case of the Fen pole, Baltica stretches from 25° to 55° south latitude.

We have resampled the Alnø Complex with two main goals in mind; (first), a paleomagnetic reexamination of the rocks in the complex to see if any of the directional complexity may be resolved with the aid of a new sam-

pling strategy and a more thorough rock magnetic study, and (second) to date the complex using ^{40}Ar/^{39}Ar step heating. Since this geochronologic method was also used by Meert et al. (1998) to date the Fen Complex, a well-constrained age for the Alnø Complex should elucidate any links in timing between the two carbonatite events.

2. Geology and sampling

The Alnø Complex (Fig. 2) is a Late Precambrian carbonatite–alkaline complex that intruded Early Proterozoic migmatites and gneisses (Kresten, 1990) a few kilometres northeast of the city of Sundsvall, Sweden (62.5°N, 17.5°E). It is one of two similar complexes in Scandinavia/Baltica, the other being the Fen Complex in SE Norway (Fig. 2).

The main intrusive event has been argued to have occurred at ca. 550 Ma (Brueckner and Rex, 1980). K/Ar phlogopite and Rb/Sr whole-rock ages vary between 610 and 530 Ma (Kresten, 1990), and this has been considered by some as indicating repeated intrusive episodes during a time interval of 80 Ma. The Fen Complex (SE Norway; Fig. 2) displays a similar range of isotopic ages, but the most recent age determinations (Dahlgren, 1994; Meert et al., 1998) suggest an age of 583 ± 15 Ma for the Fen Compex. We will demonstrate later that ^{40}Ar/^{39}Ar ages from Fen and Alnø are identical and both complexes probably intruded within a few million years.

The "chronological" evolution of the Alnø Complex according to Kresten (1979, 1980, 1990) and Morogan and Woolley (1988) has been summarized as follows:
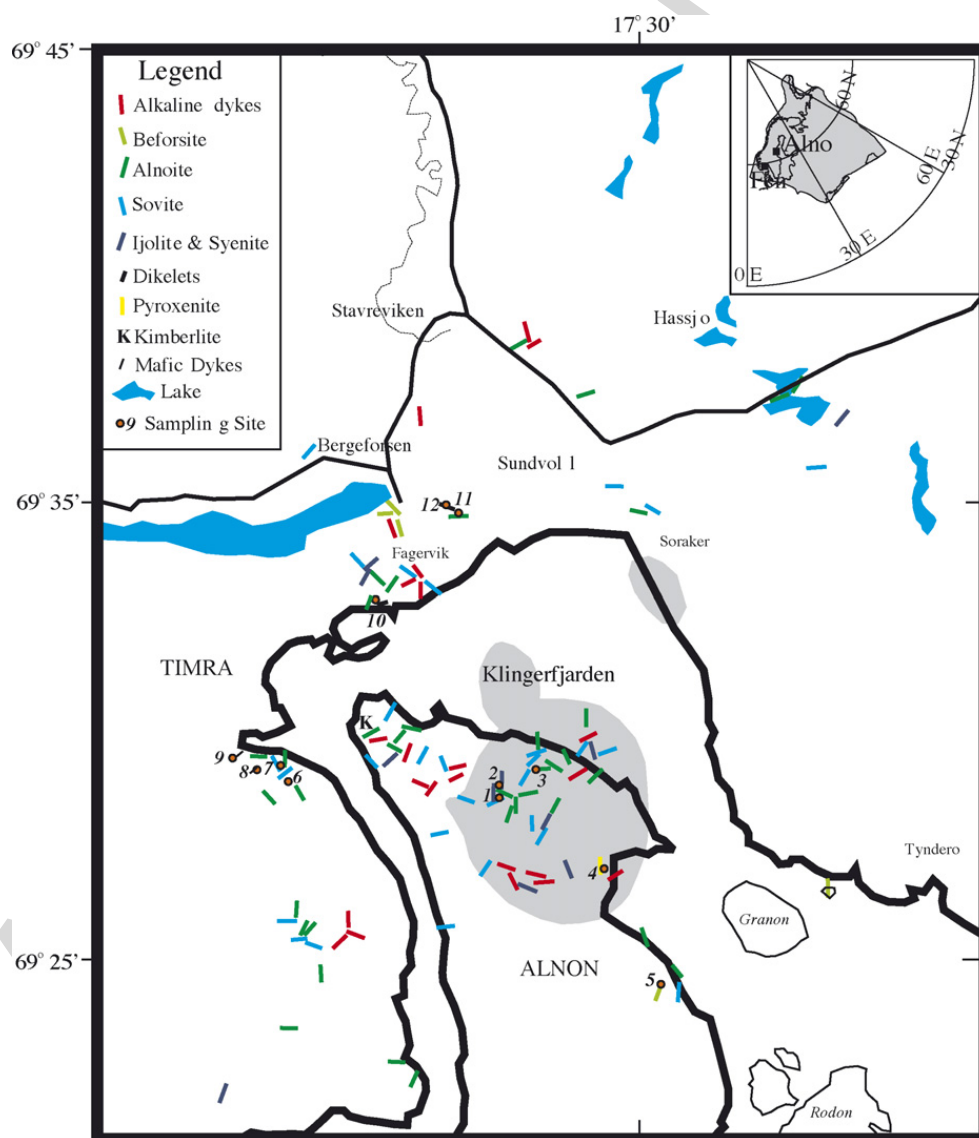

Fig. 2. Map of the Alnø Complex in central Sweden modified from Kresten (1986) (see also inset map for location of Fen and Alnø). The main carbonatite complex is located on the island of Alnøn. Site locations are shown by dots (numbers keyed to Table 2).

1. Intrusion of pyroxenite/sövite/ijolite (Långarshol-men), accompanied by fenitization and brecciation of the country rocks.
2. Intrusion of pyroxenite/ijolite (main complex), fen-itization of the country rocks and emplacement of nephelinite and phonolite dikes.
3. Intrusion of nepheline syenite (main complex), emplacement of tinguaite and trachyte dikes.
4. Intrusion of sövite/silico-sövite (main complex), fen-itization of the host rocks.
5. Intrusion of sövite/silico-sövite at Bäräng and feniti-zation of the country rock.
6. Emplacement of alnöite, alvikite, and Beforsite dikes.

Paleomagnetic sampling was concentrated mainly on the dikes radiating out from the main complex. A total of 93 samples were collected from 10 different locali-ties (Fig. 2) using a gasoline-powered drill. At several of these localities more than one type of dike was sampled, and each dike was treated as a separate entity when com-puting statistics (Table 2). All samples were oriented in the field using both magnetic and sun compass.

2.1. $^{40}Ar/^{39}Ar$ experiments

Biotite separates from one alnöite dike (Sample A6—palaeomagnetic sampling Site 6 in Table 2) were dated with the $^{40}Ar/^{39}Ar$ step-heating (furnace) tech-nique. Sample preparation and analytical procedures were similar to Arnaud et al. (1993) and Torsvik et al. (1998b) for the $^{40}Ar/^{39}Ar$ facility at Université Blaise-Pascal/CNRS, Clermont-Ferrand, France. Biotite and K-feldspar separates from a sövite dike (sample Alnø1, see site description Alnø Stop 8 in Lundqvist et al., 1986) and sövite (sample Alnø2, see site description Alnø Stop 7 in Lundqvist et al., 1986) were dated with the $^{40}Ar/^{39}Ar$ step heating as well, at the Geological Survey of Norway (NGU). Sample preparation and analytical procedures follow Eide et al. (2002). Ages referred to in the text include uncertainty in *J*-value and are quoted at the 1σ level.

2.1.1. Sample Alnø1

Steps 8–16 (872–1224 °C) of the 16-step release spec-trum (Fig. 3a) for biotite represent the most regular part of the spectrum. The chosen steps correspond to the highest K-portion of the sample, and are assumed to be released from the most retentive part of the grains. The weighted mean plateau age (WMPA) for these steps is 578.5 ± 4.4 Ma, covering 77% of the ^{39}Ar released during the experiment. The first part of the spectrum is characterized by high initial ages, associated with the
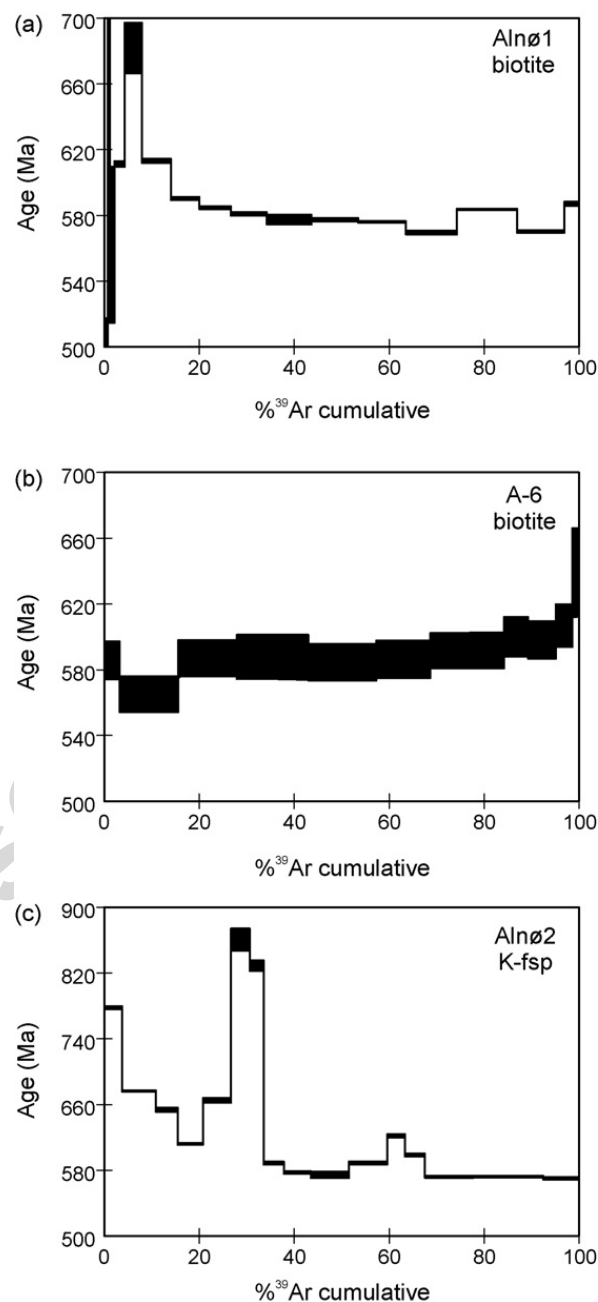
Fig. 3. $^{40}Ar/^{39}Ar$ biotite (a and b) and K-feldspar (c) spectra ($\pm 1\sigma$ about each step) for Alnø samples that show apparent age as a function of the cumulative fraction of ^{39}Ar released. Note that Sample A6 (larger errors) was measured at the argon facility at Université Blaise-Pascal, Clermont-Ferrand (France) whilst Alnø1–2 were measured at the NGU argon facility in Trondheim. Data are reported in Table 2.

presence of excess argon. All steps are too radiogenic to utilize inverse isochron analysis (Table 3).

2.1.2. Sample A6

The 13-step release spectrum for crushed biotite (Fig. 3b) yields two statistical weighted mean plateau ages, 588.8 ± 10.0 Ma (step 1–8) and 595.9 ± 10.2 Ma (step 3–12), both covering 84% of the ^{39}Ar liberated dur-

Table 2
Paleomagnetic directions

Site	Rock type	J (mA/m)	χ (10e−3)	Q_n	N	Low blocking					High blocking				
						Dec	Inc	α_{95}	k	n	Dec	Inc	α_{95}	k	n
1a	Sövite dikes	38	2.84	0.33	7	43	72	4.9	187	6	34	66	9.9	38	7
1b	Nepheline. Syenite	122	2.41	1.23	2	22	73	16.5	231	2	246	79	51	26	2
2	Ijolite	198	5.97	0.81	7	97	82	23.4	16	4	–	–	–	–	0
3a	Alnøite	1779	10.7	4.04	6	37	51	10.8	39	6	101	−3	9.3	52	6
3b	Nepheline Syenite	94	7.24	0.32	3	53	54	22.7	30	3	–	–	–	–	0
4	Pyroxenite	64	1.67	0.93	10	30	84	6.0	87	8	76	70	14.1	16	8
5	Beforsite dike	1835	103	0.43	7	33	75	6.4	90	7	99	−28	8.1	91	5
6a	Alnøite dike	1727	65.6	0.64	7	76	58	8.9	47	7	97	34	9.1	103	4
6b	Søvite dike	300	47.4	0.15	3	82	60	–	–	1	83	53	12.9	92	3
7a	Søvite dike	298	4.61	1.57	7	340	73	29.1	76	2	139	−15	10.2	57	5
7b	Alnøite dike	2.97	0.54	0.13	7	86	63	17.4	16	6	–	–	–	–	0
10a	Thin dike	643	35.6	0.44	3	64	62	64.1	17	2	–	–	–	–	0
10b	Alnøite dike	1376	41.8	0.80	8	18	57	10.0	85	4	30	65	19.1	24	4
11	Diabase dike	287	16.1	0.43	6	327	71	19.2	24	4	343	74	6.4	112	6
12	Thin dikes	1352	31.3	1.05	12	102	58	14.6	11	11	119	20	6.9	44	11
Mean	15 dikes[a]				93	51.2	70.2	8.3	22	73					
Mean	6 dikes[b]										108	10.5	32.1	5.3	40
Mean	5 dikes										28	76.8	16.1	24	27

Note: J = Natural remanent magnetization intensity; Q_n = Koenigsberger ratio defined as ($\mu_0 J_{NRM}/\chi B$) with B set to 50 µT; χ = bulk susceptibility; N = number of samples collected, n = number of samples used in the analysis; Dec = declination; Inc = inclination; a95 = circle of 95% confidence about the mean direction; k = Fisher precision parameter.

[a] Pole: 62.7°N, 101°E.

[b] Pole: 3.5°N, 269°E.

Table 3
Complete ^{40}Ar/^{39}Ar data tables

Temperature (°C)	^{40}Ar/^{39}Ar	^{38}Ar/^{39}Ar	^{37}Ar/^{39}Ar	^{36}Ar/^{39}Ar	^{39}Ar[a]	F^{39}Ar[b]	%40*[c]	^{40}Ar*/^{39}Ar$_K$	Age (Ma)	±1σ
Alnø1 (Biotite), $J = 0.006434$ (±0.9%), 0.4 mg										
511	68.779	0.085	2.406	62.363	1.09	0.68	73.60	50.62	508.92	8.55
567	117.052	0.045	4.454	144.524	0.74	1.15	64.00	74.94	710.32	9.37
628	240.640	0.111	0.276	622.254	1.56	2.12	23.60	56.78	562.07	47.55
684	65.302	0.012	0.006	8.944	3.45	4.28	95.90	62.64	611.25	1.72
727	95.021	0.028	0.024	80.128	5.78	7.90	75.10	71.33	681.76	15.40
783	70.848	0.015	0.000	26.973	9.74	13.99	88.70	62.86	613.06	1.26
824	61.093	0.010	0.003	3.253	9.63	20.02	98.40	60.11	590.21	0.96
872	**60.195**	**0.012**	**0.004**	**2.449**	**10.59**	**26.64**	**98.80**	**59.45**	**584.67**	**0.94**
913	**59.674**	**0.011**	**0.006**	**2.220**	**12.12**	**34.23**	**98.90**	**59.00**	**580.86**	**1.06**
958	**59.406**	**0.014**	**0.000**	**2.702**	**15.03**	**43.64**	**98.60**	**58.59**	**577.39**	**2.91**
999	**58.694**	**0.010**	**0.000**	**0.373**	**15.76**	**53.50**	**99.80**	**58.56**	**577.20**	**1.09**
1039	**58.623**	**0.010**	**0.000**	**0.642**	**15.99**	**63.51**	**99.60**	**58.41**	**575.93**	**0.50**
1078	**58.239**	**0.008**	**0.014**	**1.878**	**17.19**	**74.27**	**99.00**	**57.67**	**569.60**	**1.14**
1120	**59.342**	**0.010**	**0.018**	**0.002**	**20.26**	**86.95**	**100.00**	**59.32**	**583.60**	**0.45**
1169	**58.737**	**0.009**	**0.043**	**3.376**	**15.94**	**96.93**	**98.30**	**57.73**	**570.11**	**0.67**
1224	**59.732**	**0.011**	**0.142**	**0.010**	**4.91**	**100.00**	**100.00**	**59.73**	**586.98**	**1.16**
A6 (Biotite), $J = 0.013490$ (±1.0%), 5.0 mg										
600	28.854	0.032	2.168	3.629	0.20	3.18	96.80	28.43	585.69	11.55
700	27.758	0.019	0.332	2.002	0.78	15.56	98.00	27.27	565.06	10.78
750	**28.621**	**0.018**	**0.035**	**0.419**	**0.78**	**27.92**	**99.60**	**28.50**	**586.97**	**11.08**
800	**28.660**	**0.018**	**0.031**	**0.389**	**0.96**	**42.97**	**99.60**	**28.55**	**587.77**	**13.46**
850	**28.506**	**0.018**	**0.027**	**0.473**	**0.91**	**57.31**	**99.50**	**28.37**	**584.61**	**11.10**
900	**28.675**	**0.018**	**0.028**	**0.712**	**0.72**	**68.68**	**99.30**	**28.47**	**586.38**	**11.30**
950	**29.128**	**0.019**	**0.028**	**1.258**	**0.53**	**77.06**	**98.70**	**28.77**	**591.55**	**10.79**
1000	**29.304**	**0.019**	**0.035**	**1.841**	**0.45**	**84.17**	**98.20**	**28.77**	**591.71**	**10.93**
1050	**30.274**	**0.019**	**0.044**	**3.543**	**0.33**	**89.31**	**96.60**	**29.25**	**600.09**	**11.97**
1100	**30.112**	**0.019**	**0.058**	**3.379**	**0.37**	**95.12**	**96.70**	**29.14**	**598.17**	**11.51**
1150	31.338	0.020	0.086	5.922	0.22	98.60	94.50	29.64	606.82	13.03
1200	38.287	0.026	0.172	23.535	0.07	99.70	82.20	31.51	639.05	27.16
1400	129.705	0.081	0.398	269.972	0.02	100.00	39.70	51.60	953.10	146.93
Alnø2 (K-fsp), $J = 0.006436$ (±0.9%), 0.9 mg										
494	90.153	0.090	3.078	23.333	4.32	3.75	92.80	83.68	777.74	1.74
549	75.191	0.060	1.947	16.363	8.16	10.85	93.90	70.60	676.14	0.70
633	68.617	0.056	0.663	3.022	5.34	15.49	98.80	67.79	653.58	2.67
669	65.195	0.043	0.500	8.526	6.08	20.77	96.20	62.72	612.08	1.23
720	71.449	0.060	0.603	7.829	6.81	26.69	96.80	69.20	664.90	2.77
776	116.476	0.117	1.761	73.873	4.50	30.60	81.50	94.90	860.47	13.48
820	106.872	0.090	1.221	55.672	3.36	33.52	84.80	90.58	829.10	6.44
875	**65.253**	**0.024**	**0.266**	**18.108**	**4.94**	**37.81**	**91.80**	**59.92**	**588.72**	**1.60**
912	**61.789**	**0.019**	**0.125**	**10.871**	**6.53**	**43.48**	**94.80**	**58.57**	**577.42**	**1.69**
957	**60.453**	**0.011**	**0.094**	**7.565**	**9.31**	**51.58**	**96.30**	**58.21**	**574.36**	**3.77**
996	**62.219**	**0.019**	**0.125**	**7.679**	**9.24**	**59.60**	**96.30**	**59.95**	**588.97**	**1.77**
1035	**68.259**	**0.021**	**0.296**	**14.819**	**4.29**	**63.33**	**93.60**	**63.90**	**621.80**	**2.00**
1109	**62.862**	**0.021**	**0.147**	**5.966**	**4.84**	**67.54**	**97.20**	**61.10**	**598.60**	**1.64**
1159	**58.943**	**0.016**	**0.061**	**3.360**	**11.79**	**77.79**	**98.30**	**57.94**	**572.06**	**1.11**
1212	**58.822**	**0.015**	**0.025**	**2.786**	**16.86**	**92.43**	**98.60**	**57.98**	**572.43**	**0.97**
1258	**58.679**	**0.019**	**0.052**	**3.202**	**8.71**	**100.00**	**98.40**	**57.72**	**570.21**	**1.57**

[a] *Note*: ^{39}Ar ($\times 10^{-16}$ mol).

[b] Cumulative ^{39}Ar gas released during the experiment (%).

[c] %40* = % radiogenic ^{40}Ar of total ^{40}Ar released; samples Alnø1 and Alnø2 were analyzed at the Geological Survey of Norway (NGU); sample A6 was analyzed at Université Blaise-Pascal/CNRS, Clermont-Ferrand, France. Bold steps were used to calculate the age (see text). Uncertainties in J-values were less than 1% and are quoted (1σ) without J-value error in this table. Ages referred to in the text include uncertainty on the J-value and are quoted at the 2σ level. Including 1σ inter and intra-laboratory errors for the biotites (Alnø1 578.5 ± 4.4 Ma and A6 588.8 ± 10.0 Ma) yields a Simple Mean of 584 ± 7 Ma (weighted mean of 580 ± 4 Ma). Alnø1 (Sövite dike), 62.4420°N, 17.4350°E; A6 (Alnöite dike), 62.4599°N, 17.3509°E; Alnø2 (Sövite), 62.4414°N, 17.4662°E.

ing the experiment. The last steps of the release spectrum from the biotite, however, show a gradual rise in apparent ages over the last 15–20% of the gas, and we therefore prefer the 588.8 ± 10.0 Ma age; exclusion of the first two steps of the experiment from this calculation (and an evaluation of all errors both intra- and inter-laboratory) yields an overlapping WMPA of 589.0 ± 10.1 Ma for 69% of the gas. All steps are too radiogenic to utilize inverse isochron analysis. We do notice, however, that steps 3–8 and 3–12 yield a good fit to the data-points (MSDW = 0.12 and 0.23) and line-fit ages (584–587 Ma) not very different from the WMPA age, but $^{40}Ar/^{36}Ar$ ratios are quite different from the atmospheric value (295.5). Sample A6 has consistently low, Cl-correlated ^{38}Ar. K/Ca ratios for both samples likewise indicated Ar-release from a fairly uniform, high-K biotite (Table 3).

2.1.3. Sample Alnø2

The 16-step release spectrum for K-feldspar (Fig. 3c) is more complex than those for the biotites, in particular the first seven steps. Steps 8–11 (875–996 °C) and 14–16 (1159–1258 °C) however yield ages that are very similar or only slightly younger than the biotite ages (Table 3). The WMPA age for steps 8–16, 579.4 ± 4.4 Ma, is within error of the biotite ages of samples Alnø1 and A6 and would seem to support a fairly rapid post-emplacement cooling of the Alnø Complex.

Including 1σ inter and intra-laboratory errors for the biotite samples (Alnø1 578.5 ± 4.4 Ma and A6 588.8 ± 10 Ma) yields a simple mean of 584 ± 7 Ma. The geochronologic data from the Fen Complex are very similar (583 ± 15 Ma; Meert et al., 1998) to the data described above for the Alnø Complex. Carbonatites are almost exclusively formed in extensional tectonic environments (Burke et al., 2003), and Dahlgren (1994) suggested that both complexes formed during early phases of the opening of the Iapetus Ocean; the overlapping ages for both supports their contemporaneity.

2.2. Paleomagnetic results

All rock magnetic and paleomagnetic measurements were performed at the University of Bergen paleomagnetic laboratory. Demagnetization was carried out on standard 1 in. specimens, utilizing a JR5A spinner magnetometer housed in a field free room. Both thermal and alternating field (AF) demagnetization were employed at all sites, using a MMTD1 furnace and a 2G demagnetizer with a maximum field of 300 mT, but due to better component separation the majority of samples were demagnetized thermally. Results from the different dikes are summarized in Table 2. Fig. 4 shows examples

of thermal demagnetization and AF demagnetization results from different dike types. The present study confirms the general picture presented by Piper (1981) of variable quality and direction of remanence, with most specimens yielding multiple components. Mean bulk susceptibility values and natural remanent magnetization (NRM) intensities are given for each site in Table 2. The mean Koenigsberger ratio (Q_n) was calculated for each of the sites and ranges from a low of 0.14 (Site 7b) to a high of 4.0 (Site 3a). In general, if the remanence is thermal in origin, rocks with Q-values less than 0.5 would suggest unstable multi-domain grains, with values for true single domain (SD) magnetite usually exceeding 10 (Dunlop and Özdemir, 1997).

Site mean directions for all vector components (Fig. 5A) are scattered. Low blocking and low coercivity components from 15 dikes are well grouped and yield a mean declination of 51.2° and inclination of 70.2° ($k = 22$, a95 = 8.3°; Fig. 5B). A paleopole calculated from this direction falls at 62.7°N, 101°E.

The high coercivity and unblocking components show a large spread in both declination and inclination with a smearing of directions from the SW-shallow towards the NE-steep (see Fig. 5C). It is not possible to separate these components further based on rock magnetic/petrologic characteristics. Therefore, we employ a somewhat artificial grouping of shallow–intermediate vectors (inclinations less than 60°) yielding a mean direction with a declination of 108.1° and an inclination of 10.5° ($k = 5.3$, a95 = 32.1°; Fig. 5D). This direction is statistically indistinguishable from that obtained by Piper (1981) and yields a paleomagnetic pole at 3.5°N, 269°E. Conversely, the remaining high unblocking/coercivity components (inclinations > 60°) yields a second grouping with a mean declination of 28° and inclination of 76.8° ($k = 24$; a95 = 16.1°; Fig. 5E). This direction is indistinguishable from the present Earth's field at the site.

2.3. Rock magnetic results

Isothermal remanence acquisition (IRM) curves (Fig. 6) show that most specimens saturate in fields around 100 mT, confirming the predominance of relatively unstable grains.

Thermomagnetic curves (Fig. 7) were obtained in air on a horizontal translation balance with a heating/cooling cycle of 100 min and a field of 0.7 T. Initial Curie points vary between 425 and 580 °C, indicative of titanomagnetite with varying titanium content. Pyroxenite curves (Fig. 7a) also show the presence of a second Curie point at around 320 °C, consistent with pyrrhotite. In some
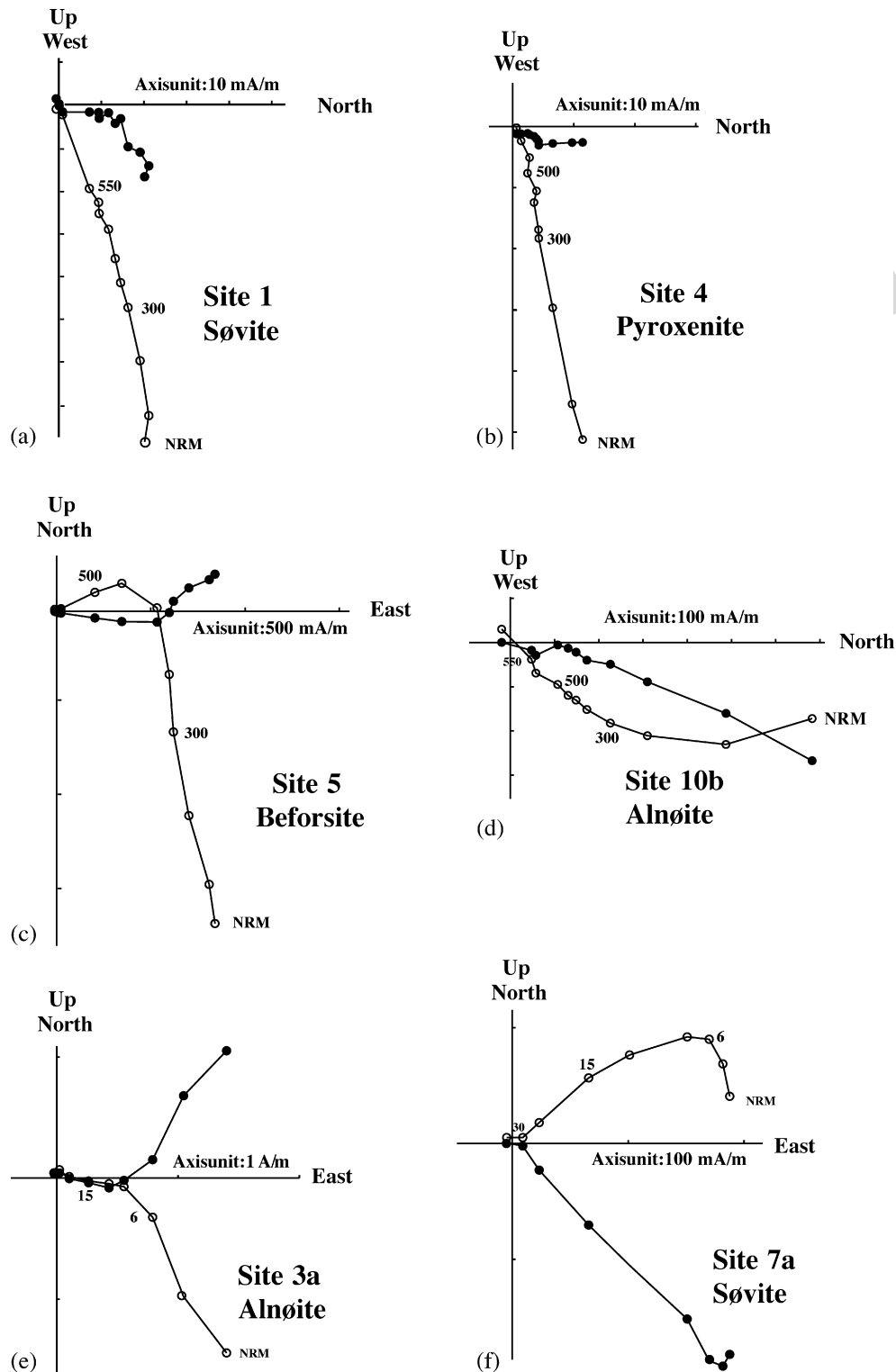
Fig. 4. Examples of thermal (a–d) and AF (e and f) demagnetization behaviour. Site 1 Søvite (a) and Site 4 Pyroxenite (b) samples both showing two steep but distinct components. Site 5 Beforsite sample (c) showing a steep component unblocking between 100 and 400 °C followed by a shallow component unblocking at higher temperatures. Site 10 Alnøite sample (d) showing more complex interplay between components. AF demagnetization of Site 3 Alnøite (e) and Site 7 Søvite (f) showing partially overlapping two-component magnetizations, and remanent coercivities below 30 mT.
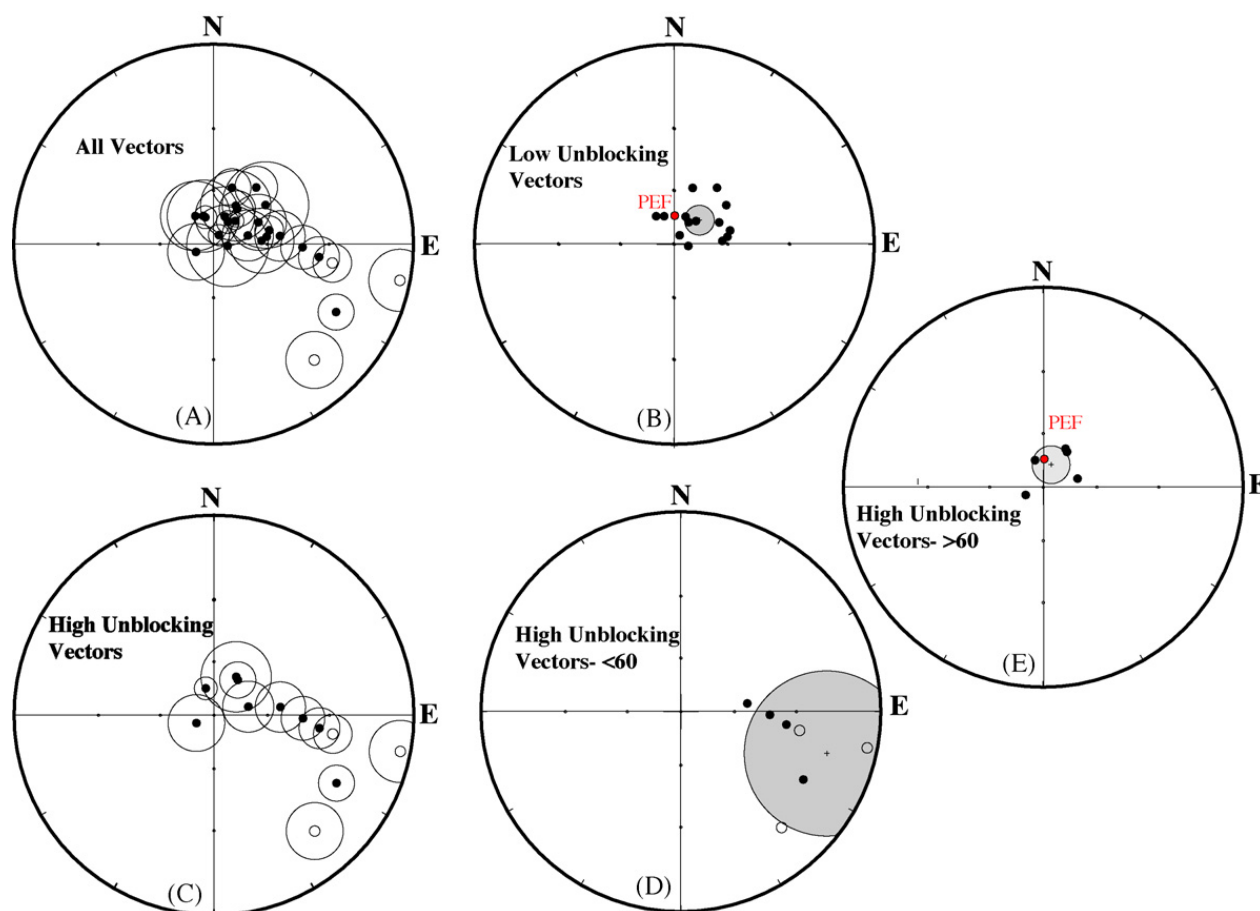
Fig. 5. Site mean directions from this study reported in Table 2. (A) All sites; (B) mean of low temperature and low coercivity components from 15 sites; (C) all high unblocking or high coercivity components; (D) high unblocking or coercivity components with inclinations less than 60°; (E) high unblocking or coercivity components with inclinations greater than 60°. The present Earth's field direction for Alnö is shown in figures (B) and (E) for comparison to the mean direction.

instances, Curie points appear to be below the maximum unblocking temperatures found for the same rocks (compare Beforsite results in Figs. 4c and 7b), suggesting that the highest unblocking components are influenced
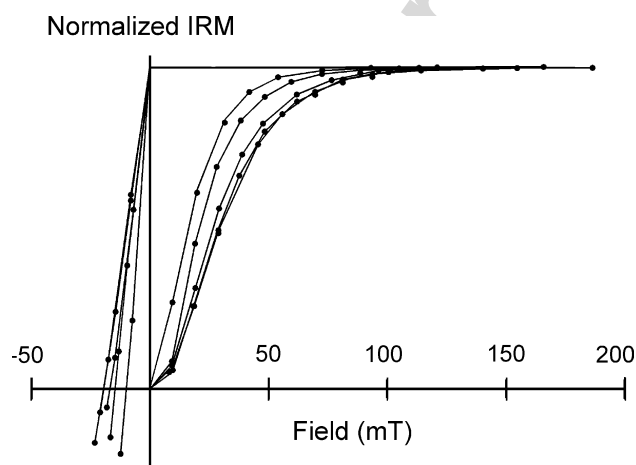
Fig. 6. Normalized isothermal remanence acquisition and backfield coercivity curves for samples from Alnö dikes. Most samples saturate in fields around 100 mT.

by mineral alteration during thermal demagnetization treatment, presumably single phase oxidation of titanomagnetite to a composition closer to pure magnetite.

Optical microscopy confirms that titanomagnetite is the dominant magnetic mineral in most of the dikes (Fig. 7b–d), as well as the presence of pyrrhotite in the pyroxenite (Fig. 7a). The titanomagnetite shows little evidence of primary high temperature exsolution, while secondary mineral alteration of the magnetic mineral grains shows large variation (compare Fig. 7b and c), ranging from no visible oxidation to almost complete replacement by non-opaque mineral phases. The contact rocks in the region are magnetically unstable, and thus there is no possibility to determine which of the components represents a primary magnetization. The shallow to intermediate component (also found in Piper, 1981) shows a dual-polarity magnetization (if we include the results of Piper, 1981) although the reversals test is negative. If we accept that the steeper group of components (Fig. 5B) is primary, it leads to the inference that components with maximum blocking temperatures
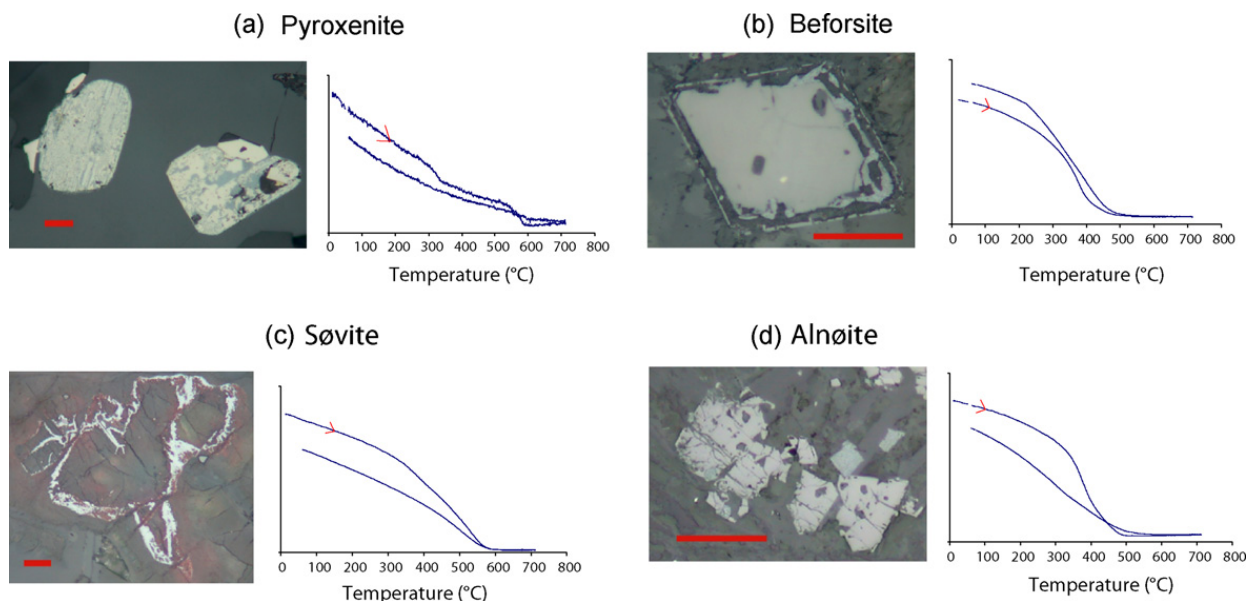
Fig. 7. Examples of reflected light micrographs and thermomagnetic curves from four different types of dikes. (a) Pyroxenite dike; grains with intergrown magnetite and pyrrhotite; (b) Beforsite dike; homogeneous titanomagnetite grains with a significant titanium content lowering the Curie point; (c) Søvite dike showing secondary alteration and a Curie point close to pure magnetite; (d) Alnøite dike with titanomagnetite grains. Scale bars on micrographs are 50 μm long.

below 300 °C and coercivities down to 6 mT represent a primary remanence in Precambrian rocks. On the other hand, making the opposite choice, i.e. taking the shallow component to be the older as advocated by Piper (1981), results in a problematic apparent polar wander (APW) path for the Ediacaran–Cambrian interval (discussed below).

3. Discussion

The $^{40}Ar/^{39}Ar$ ages from the Alnø and Fen Complexes are statistically identical: 583 ± 15 Ma (Fen, Meert et al., 1998) and 584 ± 7 Ma (Alnø, this paper). Dahlgren (1994) argued that these complexes formed during the early drift phases associated with the opening of the Iapetus Ocean. Carbonatite complexes in Laurentia that are thought to be coeval with the Baltic carbonatites include the St. Honore complex (Quebec, Valle and Dubuc, 1970) and the Sarfartoq complex (Greenland, Secher and Larsen, 1980). Despite the identical ages for Fen and Alnø, their high temperature and coercivity poles do not match. The Fen Complex mean direction is $D = 203°$, $I = -49°$ whereas the mean direction for the Alnø Complex is $D = 107°$, $I = +6°$ (Piper, 1981) and from our study $D = 108°$, $I = 10.5°$ (Figs. 1D and 5D). Our low-temperature and coercivity mean direction is $D = 51.2°$, $I = +70.2°$ (Fig. 5B).

The paleogeography for this time interval is contentious. Eneroth and Svenningsen (2004) argued that Baltica occupied equatorial latitudes around 610 Ma.

Recently, Walderhaug et al. (2007) published geochronologic and paleomagnetic data from the Egersund dikes indicating high latitudes for Baltica at 608 ± 8 Ma (>50°S). Torsvik and Rehnström (2001) obtained paleomagnetic data from the Early Cambrian Tornetrask Formation and the Late Cambrian Alum Shales in Sweden, both of which fall close to the paleomagnetic pole from the Fen Complex in Norway. Torsvik and Rehnström (2001) argued for minimal apparent polar wander during the Vendian to Late Cambrian time based on these three studies. In contrast, Popov et al. (2002) argued for a more convoluted apparent polar wander path (APWP) by including the Alnø results of Piper (1981). Alternative paths for the Baltica continent during the Ediacaran are discussed below.

4. A(n) (im)possible APW path for Baltica?

Table 1 only lists well-dated (therefore we have excluded the Nyborg pole of Torsvik et al., 1995) and modern studies of Ediacaran to Early Ordovician paleomagnetic poles for Baltica (shown in Fig. 8A). The Egersund dike pole (608 ± 8 Ma; Walderhaug et al., 2007) forms the starting point for any discussion of APW path's. The pole is well dated, adequately sampled (12 dikes) and is confirmed as primary based on a positive baked contact test. The Fen and Alnø Complexes are of a similar age, but the high temperature and coercivity directions are distinct. Neither the Fen nor the Alnø studies were able to provide any definitive evi-
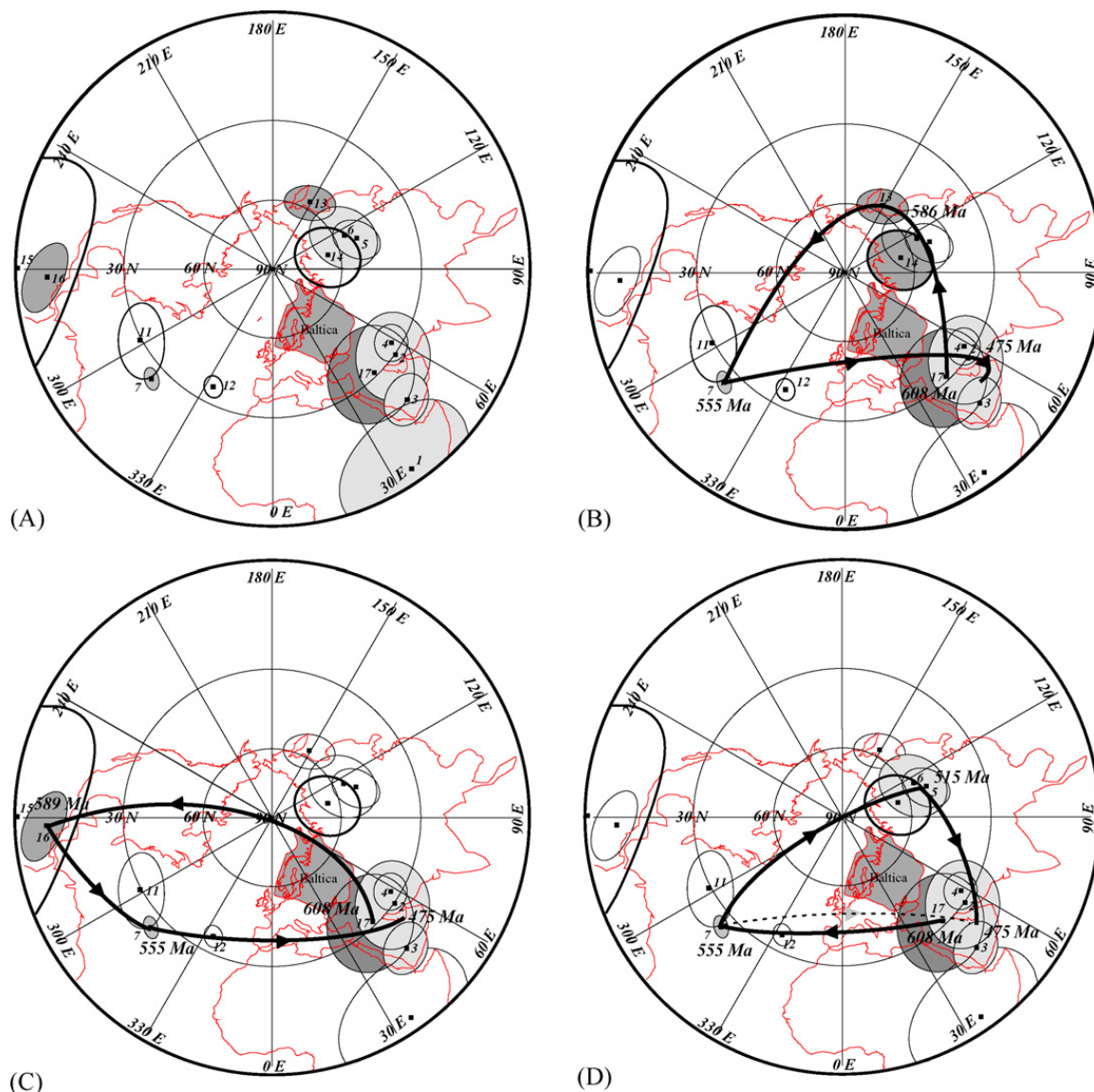
Fig. 8. (A) Paleomagnetic poles listed in Table 1 (numbers are coded to table); (B) possible apparent polar wander path (APWP) from Egersund dikes pole (608 Ma) to Fen-Alnø (589 Ma; steep component) to the Winter Coast pole (555 Ma) and back to the Early Ordovician poles (475 Ma); (C) APWP going from Egersund (608 Ma) to Alnø (589 Ma; shallow component) to Winter Coast (555 Ma) and to the Early Ordovician poles (475 Ma); (D) Egersund dikes (608 Ma) to Winter Coast (555 Ma) to Tornetrask-Alum Shale (515 Ma) and to the Early Ordovician (475 Ma). Also shown (dashed line) is a simple path from Egersund (608 Ma) to Winter Coast (555 Ma) to Early Ordovician poles (475 Ma).

dence for a primary remanence. The Fen Complex pole falls close to Permo-Triassic poles from dikes within the Oslo Rift (Torsvik et al., 1998b), but the biotite argon system shows no disturbance. The Alnø Complex pole (based on high temperature or coercivity components) shows tremendous variability in inclination and the overall grouping is poor (Figs. 1D and 5D). The low-temperature and coercivity components from Alnø are statistically indistinguishable from the Fen Complex pole and the Alum Shale–Tornetrask poles (Fig. 8A). The 555 Ma Winter Coast pole (Fig. 8A; note that we plot the Winter Coast pole with a different polarity than that originally interpreted by the original authors; see

also Cocks and Torsvik, 2005) is well dated and shows strata-bound reversals. Subsequent studies by Nawrocki et al. (2004), Iglesia-Llanos et al. (2005) and Popov et al. (2005) have further constrained this pole for Baltica.

The Tornetrask/Dividal and Alum shale (Torsvik and Rehnström, 2001) have a dual-polarity magnetization and also fall close to the Fen Complex pole, but otherwise have no field tests for a primary magnetization. The most reliable grouping is derived from Early Ordovician studies (Torsvik and Rehnström, 2003; Fig. 8A).

No matter how the path is evaluated (Fig. 8B–D), episodes of rapid APW must be explained. The following analysis is not meant to be exhaustive,

but merely to show the current complexity of the Ediacaran–Cambrian APW path for Baltica. Fig. 8B shows the Egersund–Fen–Winter Coast–Early Ordovician APW path. Although the APW rates along the Egersund–Fen segment are high (~37 cm/year), much of this is rotational motion. The Fen–Winter Coast segment shows an APW rate of ~35 cm/year and the Winter Coast–Early Ordovician segment yields a APW rate of ~13 cm/year. Fig. 8C shows a potential APW path from Egersund–Alnø–Winter Coast–Early Ordovician swathe. The Egersund–Alnø segment yields APW rate exceeding 70 cm/year with a much slower return trip through Winter Coast (14 cm/year) and

back to the Early Ordovician poles (~13 cm/year). Fig. 8D shows a possible path from Egersund–Winter Coast–Tornetrask/Alum–Early Ordovician. In terms of APW rates, this path yields the lowest values with none exceeding 30 cm/year. A solution involving Egersund–Winter Coast–Early Ordovician yields APW rates less than 17 cm/year (Fig. 8D dashed line return).

From a paleomagnetic and geodynamic perspective, most of the above solutions seem unreasonable. Although rapid rates of APW have been proposed for Cambrian and Ediacaran times (see Evans, 1998; Kirschvink et al., 1997) none of the more complex paths are supported by APWP's from other continents (see
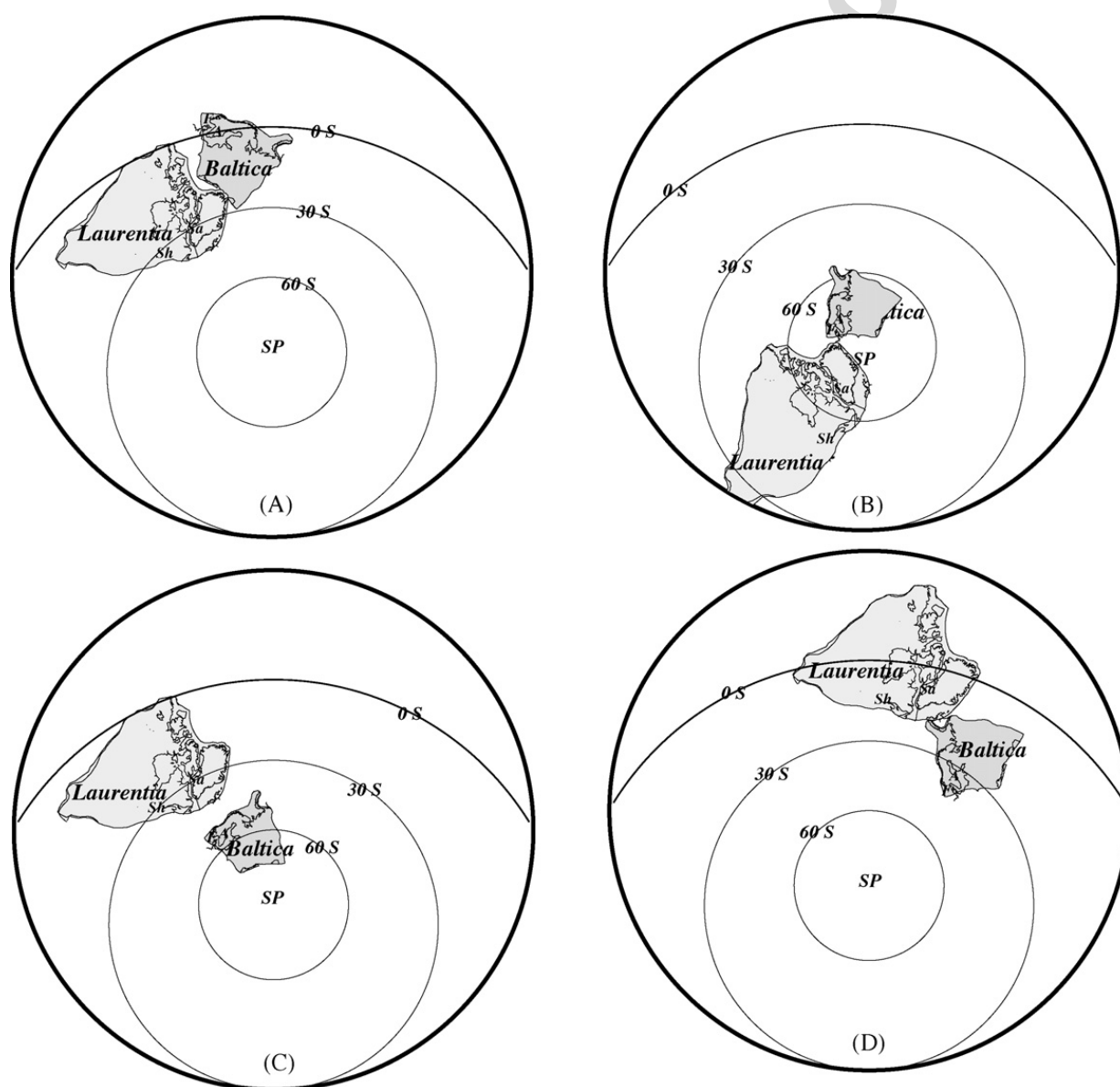

Fig. 9. (A) ~600 Ma reconstruction using the shallow Alnø directions (Baltica) and the Long Range dikes A-component; (B) ~600 Ma reconstruction using the Egersund dikes pole and the VGP calculated from Long Range dikes B-direction; (C) ~600 Ma reconstruction using the Egersund dikes pole and the Long Range dikes A-component; (D) ~550 Ma reconstruction using the Winter Coast pole (Baltica) and the Skinner Cove (Laurentia) poles. A = Alnø Complex; F = Fen Complex; Sa = Sarfartoq Complex; Sh = St. Honore Complex.

Meert, 1999; Torsvik et al., 1998a). Nevertheless, we cannot dismiss the possibility of extreme polar wander, but it seems a more ad hoc solution to explain such disparate poles from Baltica. At present, we note that many of the paleomagnetic poles from Baltica for the Ediacaran–Cambrian interval lack conclusive evidence for their primary nature. One possible mechanism to help constrain our choice of these myriad paths would be to use paleomagnetic data from other continents to constrain the reconstructions. The problem is that neither of Baltica's assumed closest neighbors (e.g. Siberia and Laurentia) have well-defined APWP's for this time interval (Meert and Torsvik, 2003). An alternative method would be to use paleobiogeographic information coupled to paleomagnetic data (e.g. Meert and Lieberman, 2004) or to simply examine paleogeographic connections between Baltica and Laurentia. Fig. 9A shows a paleoreconstruction at ~600 Ma using the shallow Alnø directions (Baltica) and Long Range dikes A-component (Laurentia, Murthy et al., 1992). Fig. 9B employs the Egersund dikes direction compared to the VGP from the Long Range Dikes B-Direction (Laurentia, Murthy et al., 1992). Fig. 9C shows a ~600 Ma reconstruction using the Egersund dikes pole and the Long Range dikes A-direction. Fig. 9D shows a ~550 Ma reconstruction using the Winter Coast pole (Baltica) and the Skinner Cove pole (Laurentia, McCausland and Hodych, 1998). Fig. 9C appears to be the most consistent with previous models for Iapetus Ocean opening (Meert and Torsvik, 2003; Dalziel, 1997); however, the uncertainty regarding the Long Range Dikes poles precludes any definitive conclusions. At present, we suggest that the Ediacaran–Cambrian data from Baltica should be viewed with extreme caution. Further we argue that in the absence of more robust paleomagnetic data for the ~580–590 Ma from Baltica, the Alnø pole should not be used in paleoreconstructions. The best-constrained paleomagnetic poles are from the Egersund dikes ($Q = 6$; Walderhaug et al., 2007) and the Winter Coast and related volcano-sedimentary units (Popov et al., 2002, 2005; Nawrocki et al., 2004; Iglesia-Llanos et al., 2005). It should be noted that if the Volhynia lavas (Nawrocki et al., 2004) and the Winter Coast area sediments (see Table 1) are coeval, then the predicted inclination for the Winter Coast sediments based on the Volhynia lavas pole is ~60°. The average of inclinations from the sedimentary rocks is ~37° and thus inclination shallowing (with $f \sim 0.4$) may be an issue in the studies of sedimenatary rocks from the Winter Coast area. Further detailed studies on coeval igneous rocks may help ascertain whether inclination shallowing has occurred in the Winter Coast sediments.

5. Summary and conclusions

Paleomagnetic data from the 584 ± 7 Ma Alnø Complex of central Sweden yields a complex magnetic signature. It is possible to isolate two components of magnetization from the dikes. The low-temperature and low coercivity component yields a well-defined direction ($D = 51.2°$, $I = 70.2°$, a95 = 8.3°). The paleomagnetic pole calculated from this direction falls close to the pole from the 583 ± 13 Ma Fen pole (Meert et al., 1998) and poles from the Cambrian aged Dividal–Tornetrask–Alum Shales (Torsvik and Rehnström, 2001). The shallower component (when combined with similar results from Piper, 1981), yields a mean $D = 105.6°$, $I = 7.9°$ ($k = 9.1$, a95 = 9.6°).

Our new $^{40}Ar/^{39}Ar$ date of 584 ± 7 Ma age for the Alnø Complex demonstrates that it intruded within a few million years of the Fen Complex in SE Norway, strongly suggesting a genetic link between the two, despite a geographical separation of almost 600 km.

The spatial distribution of Ediacaran–Early Cambrian poles from Baltica is confusing at best and it is as yet not possible to construct a reliable APW path for this time period. Reasons for this may include unrecognised remagnetizations. For example, in our experience, even $^{40}Ar/^{39}Ar$ minerals with low closure temperatures (K-feldspar: 150–400 °C; biotite: 280–350 °C, McDougall and Harrison, 1998) may record the true intrusion age whilst the palaeomagnetic signature can be reset by low-temperature hydrothermal processes (e.g. Torsvik et al., 1998a,b). This is also a warning signal for assigning U/Pb ages to palaeomagnetic data unless strong stability tests for a primary remanence exists. Other reasons for the Ediacaran complexity may be attributed to recording problems (e.g. incomplete removal of overprints), inclination shallowing in sediments, or a joker in the pack: True Polar Wander? Our paleomagnetic study of the Alnø Complex, combined with an examination of other Ediacaran-age paleopoles from Baltica indicate that the Neoproterozoic–Ediacaran APWP for Baltica is poorly constrained and all conclusions (including geodynamic models) should be viewed with extreme caution pending the acquisition of new high-quality paleomagnetic data.

Acknowledgements

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