Tectonic Significance of the Fen Province, S. Norway: Constraints from Geochronology and Paleomagnetism[1]

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ABSTRACT

The Fen Central Complex (FCC) and associated satellite dikes of the Fen Province in southern Norway record a magnetization dating to 583 Ma. The paleomagnetic pole calculated from these rocks falls at 56° N, 150° E (dp = 7°, dm = 10°) and compares favorably with two previous investigations. The mean inclination in our study is slightly steeper than that of one of the earlier studies and we attribute this to the fact that previous investigators inadvertently sampled younger (late Paleozoic/early Mesozoic) dikes in the area. The age of the Fen paleomagnetic pole is constrained by two consistent $^{40}Ar/^{39}Ar$ ages from these rocks, which average 583 ± 15 Ma, along with previously published ages ranging from 523–601 Ma. The Fen Central Complex, along with associated intrusions, were emplaced during minor extensional activity that occurred after continental separation between Baltica and Laurentia. This interpretation is consistent with our 580 Ma paleoreconstruction, which shows that Baltica had rifted and rotated from its 615 Ma position adjacent to Greenland. We interpret the ages and the tectonics to reflect opening of an ocean basin from north to south during the latest Neoproterozoic to earliest Paleozoic time (615–540 Ma). The polarity option for the Fen pole remains an important and open question due to recent suggestions of a true polar wander event in the mid-Cambrian; however, we consider that the south polarity option offers the simplest tectonic model for the rifting of Rodinia and opening of the Iapetus Ocean between Baltica and Laurentia. Finally, we note the similarity of the Fen paleomagnetic pole to paleomagnetic poles of Permo-Triassic age in Baltica and urge caution in the unequivocal use of the Fen pole as primary until further substantiated by coeval poles from Baltica.

Introduction

The suggestion by McMenamin and Schulte-McMenamin (1990), Dalziel (1991, 1992, 1997) and Hoffman (1991) of the Rodinia supercontinent has spurred interest in the Neoproterozoic interval from 1100–540 Ma. The proposed tectonic changes that occurred across the Precambrian/Cambrian boundary are particularly intriguing because they coincide with the biotic explosion of multicellular life following a period of extensive glaciation and dramatic changes in the isotopic composition of seawater (McMenamin and Schulte-McMenamin 1990; Derry et al. 1992; Meert and Van der Voo 1994; Saylor et al. 1995). The exact configuration and duration of the supercontinent is the subject of much debate (Bond et al. 1984; Piper 1987; Hoffman 1991; Dalziel 1997; Veevers et al. 1997). One of the major problems in detailing the nature of the supercontinent is the lack of high-quality paleomagnetic data from the various continental blocks that comprised Rodinia (Van der Voo and Meert 1991; Torsvik et al. 1996; Meert and Van der Voo 1997). Although the Neoproterozoic paleomagnetic database is expanding, many of the new results merely show that the older data were flawed and should not be used for testing continental reconstructions (Meert et al. 1997; Torsvik et al. 1996; Smethurst et al. 1998). Paleomagnetists now recognize that, in order to make a substantial contribution to pre-Mesozoic tectonic models, it is critical to join their paleomagnetic results with a sensible interpretation of the age of the paleomagnetic pole and understand the geologic implications of the result (Van der Voo 1990; Torsvik et al. 1996).

One of the critical advances made in the field of Precambrian paleomagnetism is the ability to attain high-precision ages using the U-Pb and $^{40}Ar/^{39}Ar$ systems on the same rocks as those used for paleomagnetic study. Indeed, without tight age

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constraints, paleomagnetic results from Precambrian rocks are useless (Van der Voo and Meert 1991; Briden et al. 1993; Torsvik et al. 1996). Of equal importance in solving tectonic problems is the recognition that subsequent remagnetization events may obscure the original magnetization. In fact, the combination of imprecise ages and remagnetization is the bane of Proterozoic paleomagnetic studies.

Recent controversial proposals regarding the birth of the Iapetus Ocean (Grunow et al. 1996; Dalziel 1997), the possibility of a true polar wander (TPW) event in the early Cambrian (Kirschvink et al. 1997), and the suggestion by Williams et al. (1995) that the late Neoproterozoic continental glaciations occurred at extremely low latitudes all require high quality paleomagnetic and geochronologic data in order to fully resolve these controversies. The paleomagnetic database for Baltica was recently evaluated by Torsvik et al. (1996) in an effort to define key poles and identify significant gaps in the database. A potentially critical pole is the 580 Ma Fen Central Complex (FCC) result (Poorter 1972; Piper 1988) because it terminates the Vendian database for Baltica. The next-youngest paleomagnetic pole is the ca. 481 Ma pole from Swedish limestones; therefore a significant gap exists in the paleomagnetic database for Baltica between these two end members (Torsvik and Trench 1991). Two troubling features of the paleomagnetic pole from the Fen carbonatite complex (Poorter 1972; Piper 1988) are its resemblance to the Permian field direction for Baltica and its dissimilarity to a contemporaneous, although poorly constrained, paleomagnetic pole from the Alnö carbonatite complex in Sweden (Piper 1981). Dahlgren (1987) conducted an extensive field, geochemical, petrologic, and geochronologic investigation of the FCC and related dikes of the Fen Province and noted that several of the dikes sampled by Piper (1988) were severely altered, even possibly in the Permian. For these reasons we returned to the Fen Province and sampled some of the fresh dikes which Dahlgren used for a Rb-Sr isochron of 578 ± 24 Ma along with numerous dikes of Permo-Triassic age that are reported elsewhere (Torsvik et al. 1998).

Geology of the Fen Complex

The FCC is situated near Lake Norsjø and the town of Ulefoss in southern Norway near the western margin of the Permo-Carboniferous Oslo Rift (figure 1). The FCC intrudes the Middle Proterozoic Telemark gneisses that have been strongly affected by tectonic and hydrothermal activity related to the Oslo rift, and is only 12 km west of the large, alkaline Permian plutonic massifs. Both the FCC and a similar carbonatite complex at Alnö, Sweden, were likely emplaced during minor extensional activity in the Baltic platform during the drift phase subsequent to the initial opening of the Iapetus Ocean (sensu stricto; Dahlgren 1984, 1994). The FCC, which is the type area for carbonatites (Brøgger 1921), consists of different carbonatite intrusions with subordinate amounts of alkaline rocks at the present surface. Generally, the rocks within the FCC are strongly affected by post-magmatic alteration processes, but the satellite intrusions within the Fen Province, which include damtjernite (=an ultramafic lamprophyre with primary calcite), carbonatites and phonolitic sheet intrusions, have escaped these alteration processes to a certain degree (Dahlgren 1987, 1994). The alteration most likely occurred in two episodes, the first during the final stages of the Fen magmatic event and the second related to the Permo-Carboniferous Oslo rifting event with its associated magmatic and hydrothermal activity. A systematic field investigation of the Fen region conducted by Dahlgren (1987) identified more than 300 consanguineous satellite intrusions into the Telemark gneisses over a 1500 km^2 area. The region attributed to the Fen Province was also invaded by several hundred younger dikes emplaced during the formation of the Oslo rift (figure 1).

Previous age determinations in the Fen Province relied on the K-Ar system on both whole rock and mineral separates (Verschure et al. 1983). Seven phlogopite and whole rock ages from the damtjernitic dikes ranged from 523–601 Ma with a definite cluster around 575 Ma. Additional ^{207}Pb/^{204}Pb-^{206}Pb/^{204}Pb ages on whole rock carbonatite samples by Andersen and Taylor (1988) yielded an age of 539 ± 14 Ma. Dahlgren (1994) noted that the two most uranium-rich samples, which strongly control the Pb-Pb age of Andersen and Taylor (1988), were rich in pyrochlore, which are mostly metamict in the Fen rocks and thus may record too young an age because of U-loss and/or Pb-mobility. Indeed, when the two uranium-rich samples were omitted from the regression, a Pb-Pb age of 573 ± 60 Ma was obtained. Similarly, a Rb-Sr age of 550 ± 7 Ma obtained on mineral separates from a phonolitic dike (Andersen and Sundvoll 1986) depended strongly on the biotite fraction. However, these biotites show abundant signs of alteration, so that Rb and/or radiogenic Sr loss and a too-young age is a likely result. Regression of their results, omitting an altered biotite fraction, yielded an age of 583 ± 41 Ma (Dahlgren 1994). Dahlgren (1994) suggested

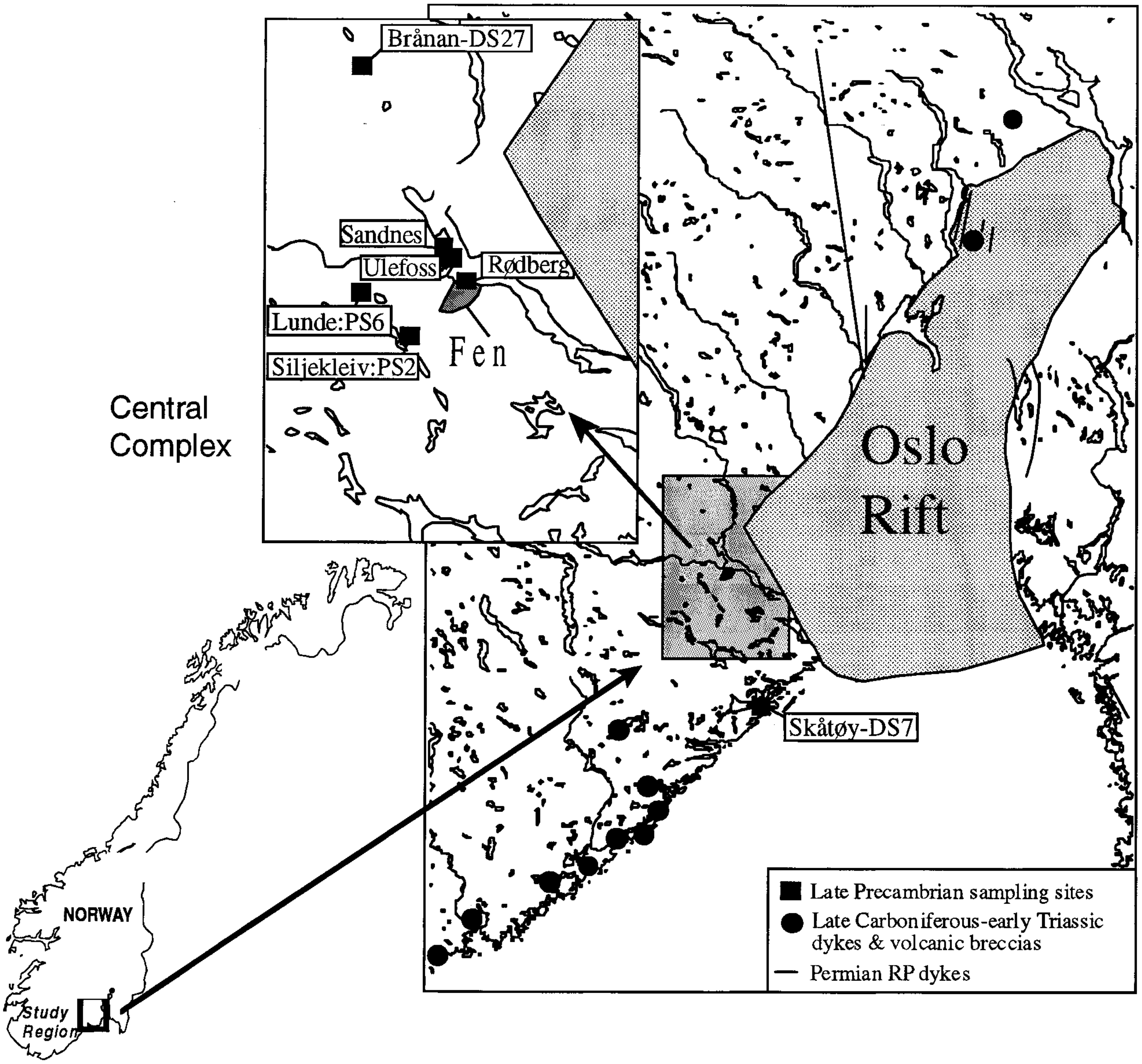

Figure 1. Site map of southern Norway showing the location of the Fen Central Complex (small inset), the Fen Province (middle inset) and the Permo-Carboniferous Oslo Rift (light shading) along with paleomagnetic sampling sites and locations of late Paleozoic–early Mesozoic dikes.

that an age of 578 ± 24 Ma, obtained on 10 unaltered phlogopite macrocrysts from well-preserved damtjernitic dikes sampled throughout the Fen Province, recorded the best age estimate for the Fen magmatic event.

Previous Paleomagnetic Work

The FCC was previously sampled for paleomagnetic study by Poorter (1972) Storetvedt (1973) and Piper (1988). Both Poorter (1972) and Storetvedt (1973) performed their paleomagnetic measurements on samples of rødberg (="redrock"), a hematite-rich rock that occurs in the eastern part of the FCC (figure 1). It is well established that this rock formed through post-magmatic hydrothermal-metasomatic alteration processes of various carbonates (Brøgger 1921; Sæther 1957), most notably from ankerite-bearing varieties (Andersen 1983, 1987). Locally, the hematite content reaches ore-grade, and iron was formerly mined over a few centuries from this part of the carbonatite complex (Sæther 1957).

Poorter (1972) performed alternating field demagnetization (AF) on the Rødberg samples and obtained a virtual geomagnetic pole position (VGP) of

63° N, 142° E ($\alpha 95 = 3.5°$). Storetvedt (1973) obtained similar results to those of Poorter (1972), but it is difficult to ascertain exactly which dikes Storetvedt (1973) sampled and it is likely that many of them were younger Permo-Triassic dikes. Piper (1988) conducted a more thorough sampling of the FCC concentrated on the phonolitic dikes. He obtained a paleomagnetic pole using data from 20 sites at 50° S, 144° E ($dp = 4.9°$, $dm = 7.9°$). The paleomagnetic directions obtained by Piper (1988) are only slightly steeper than the Permian field direction for Baltica (Torsvik et al. 1998) and are quite distinct from a poorly determined pole from the contemporaneous Alnö Complex (Piper 1981). Because the Alnö Complex is located some distance from the influence of the Oslo Rift thermal episode, this directional difference between the two coeval complexes may be important; however, the paleomagnetic pole from Alnö is poorly constrained and forms the focus of work in progress by the authors. Nevertheless, Piper (1988) concluded that the pole obtained from the Fen Central Complex was not likely reset during the formation of the Oslo Rift. He argued that the presence of a dual-polarity magnetization combined with the lack of resetting in the surrounding country rocks indicated a primary magnetization. However, as noted above, it is likely that the dikes that showed opposite polarity in Piper's (1988) study were late-phase (Triassic) intrusions emplaced during the final formation of the Oslo Rift (Torsvik et al. 1998). Because the FCC is situated near the Oslo Rift, because numerous younger dikes are present, and because of the resemblance of paleomagnetic directions to the Permian and Triassic field for Baltica, we conducted additional paleomagnetic and rock magnetic studies combined with $^{40}Ar/^{39}Ar$ dating of the Fen Province rocks in order to substantiate further this important paleomagnetic pole from Baltica.

Paleomagnetic Sampling

Generally the rocks from the FCC are variably altered by post-magmatic alteration processes. Therefore we focused our sampling on satellite dikes, which on the basis of careful petrographic inspection and geochemical analyses, represent the least-altered rocks available from the Fen Province (Dahlgren 1987, 1994). Because Poorter (1972) treated the Rødberg samples using mostly blanket AF demagnetization, which is usually unsuccessful at completely demagnetizing hematite-bearing rocks, we also collected a suite of samples from these rocks in order to verify the earlier results.

Samples were either drilled in the field using a portable gasoline-powered drill or collected as hand-samples and later drilled in the lab. Samples were oriented using magnetic compass, and sun compass readings were taken at each site to correct for any local magnetic deviation. Each site was located using a portable global positioning system (figure 1; listing in table 1). The samples were then cut to individual cylindrical specimens with a volume of 11.2 cm^3. Bulk susceptibilities for each site were calculated, and the values ranged from 422–87,755 $\times 10^{-6}$ (table 1). Intensities of natural remanent magnetization (NRM) ranged from 10^{-4} to 5.8 A/m.

Demagnetization of the samples was carried out on pilot specimens using an ASC-Instruments TD-48 thermal demagnetizer or an AF demagnetizer, and then measured on a Minispin spinner magnetometer in the magnetically shielded laboratory at Indiana State University. A majority of samples showed clearer demagnetization trajectories using stepwise thermal demagnetization, and this procedure was used to treat the majority of samples. Samples from site DS7 and DS27 exhibited a tendency not to reach a stable endpoint during thermal demagnetization, and several of these samples were treated using AF methods up to 120 mT. The AF treatment was successful in isolating a stable direction in a few samples from those sites.

Results

The paleomagnetic results from the Fen satellite dikes and Rødberg samples are listed in table 1. Linear trajectories from samples were calculated by least-squares fit using the program of Torsvik et al. (1996). With the exception of sites DS7 and DS27, all sites showed consistent directions between samples and sites (figure 2*b,c,d,* and *e*). Samples from the sites DS7 and DS27 often showed a tendency to move toward the characteristic direction observed in the majority of samples, but many became weak or exhibited viscous behavior prior to reaching a stable endpoint. By far the most common behavior observed during stepwise demagnetization was seen in samples that showed clear linear trajectories toward a characteristic south/southwest and up direction following the removal of a weak overprint. Site DS7 (table 1, figure 2*a*) had several samples that terminated near the characteristic direction observed in the majority of samples and others that became viscous prior to reaching the S/SW-intermediate up direction. Figure 2*a* shows these two populations with the majority of

Table 1. Paleomagnetic Results

Site	Site Lat, Long	N	Mean Bulk Susceptibility (x 10-6 SI)	DEC	INC	k	α95	VGP LAT	VGP LONG	dp	dm
Ulefoss (HT)	59° 17.71′ N 09° 15.82′ E	22	69,500	207°	−49°	35	5.3	55.2° N	145.4° E	5°	7°
Ulefoss (LT)		22		219°	+77°	9°	11°	37.9° N	350° E	19°	21°
Sandnes (HT)	59° 18.53′ N 09° 14.60′ E	6	655	215°	−43°	25	11.2°	47.1° N	136.0° E	11°	18°
DS27 (HT)	59° 29.55′ N 09° 08.00′ E	6	87,750	189°	−25°	16	17°	42.8° N	177° E	9°	18°
DS27 (LT)		8		192°	+45°	26	11°	03° S	358° E	9°	14°
DS7 (HT)	58° 51.77′ N 09° 28.81′ E	12	52,000	182°	−28°	19	10°	46° N	186° E	9°	14°
DS7 (HT)[a]		5		179°	−47°	117	7°	59° N	192° E	6°	9°
PS2 (HT)	59° 13.69′ N 09° 11.30′ E	12	4112	207°	−46°	27	9°	53.2° N	147.1° E	7°	11°
PS2 (LT)		12		020°	+82°	9	15°				
PS6 (HT)	59° 16.83′ N 09° 06.81′ E	8	422	204°	−49°	44	8°	56.2° N	149.1° E	7.3°	11.1°
PS6 (LT)		5		346°	+81°	36	13°				
Rødberg (HT)	59° 16.65′ N 09° 18.11′ E	25	1987	207°	−55°	54	4°	60.2° N	140.3° E	4°	5.7°
MEAN[b]	7 Sites	84		200°	−46°	37	10°	55° N	155° E	8°	13°
MEAN[c,d]	6 Sites	78		203°	−49°	77	8°	56° N	150° E	7°	10°

Notes: (LT) = Low unblocking temperature component; (HT) = High unblocking temperature component; N = number of samples used to calculate the mean; DEC = Mean Declination; INC = Mean inclination; k = kappa precision parameter; α95 = cone of 95% confidence about the mean direction; VGP Lat, Long = Latitude and Longitude of the virtual geomagnetic pole calculated from the site location and the mean direction; dp,dm = angles of 95% confidence oval about the paleomagnetic pole in the co-latitude direction (dp) and at a right angle to the co-latitude direction (dm).

[a] Site mean for DS7 calculated from samples that showed a steeper direction and reached a stable endpoint.

[b] Mean directional data using all results.

[c] Mean directional data minus site DS27.

[d] Demagnetization plots for several samples are located in the data depository.

samples exhibiting a southerly and shallow ($<-30°$) inclination; the mean used to calculate the paleomagnetic pole included only those samples from site DS7 which showed the southerly and intermediate-up stable endpoint directions. Site DS27 did not show any clear distinction between individual sample populations and was not used to calculate the mean direction used for the tectonic interpretation. Figure 2*f* shows the clear difference between the majority of samples and the mean directions calculated from sites DS7 and DS27.

The overall mean direction, $D = 203°$, $I = -49°$ ($k = 77$, $\alpha95 = 8°$) is calculated from individual site mean high temperature (or coercivity) components and the samples from DS7 as noted above (table 1). The south paleomagnetic pole obtained from this mean falls at 56° N, 149.8° E (dp = 7°, dm = 10°). In order to identify the magnetic carriers in the samples from the Fen Province, we undertook a number of rock magnetic tests including Curie temperature analysis, isothermal remanence acquisition studies (IRM), and three-component IRM studies. In all cases, the remanence showed a major contribution from Ti-poor magnetite.

^{40}Ar/^{39}Ar Dating of the Fen Dikes

Biotite and phlogopite separates from two dike samples, a damtjernite (DS7) and a phonolite (PS2), were dated with the ^{40}Ar/^{39}Ar step-heating (furnace) technique. Sample preparation and analytical procedures were similar to those described by Arnaud et al. (1993) and Torsvik et al. (1998) for the ^{40}Ar/^{39}Ar facility at Université Blaise-Pascal/CNRS, Clermont-Ferrand, France. Intralaboratory uncertainties are quoted at the one sigma level (1σ).

Sample DS7 comprises phenocrysts of clinopyroxene (aegerine-augite), phlogopite, oxides, some feldspar and accessory titanite and apatite in a groundmass containing these same minerals plus analcite. Large phlogopite phenocrysts are clearly magmatically zoned and fresh. Some secondary alteration in the rock is expressed by chlorite development in the groundmass (replacing a combination of fine-

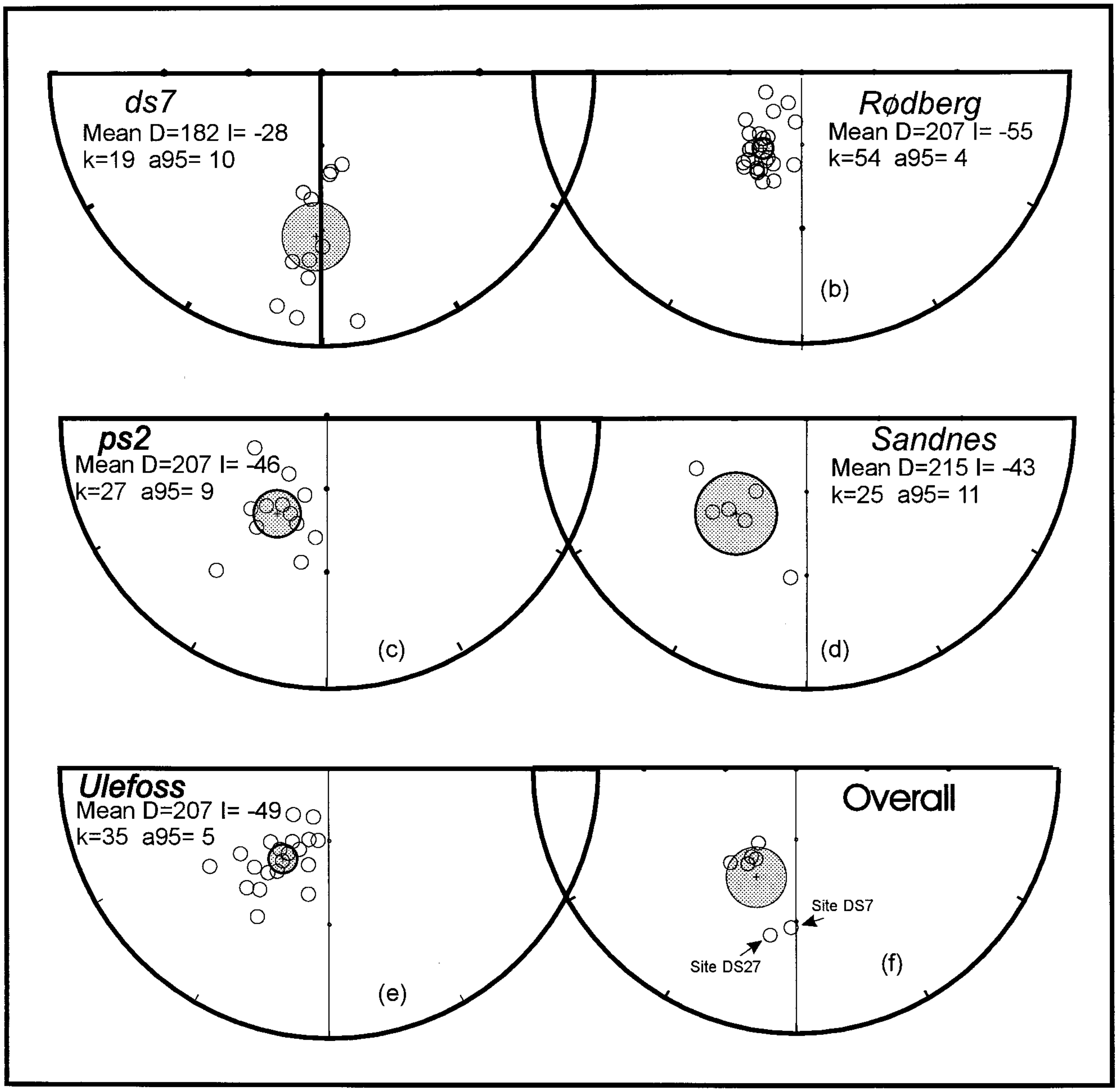

Figure 2. Site mean directions for (*a*) Site DS7, (*b*) Rødberg Site, (*c*) Site PS2, (*d*) Sandnes Site, (*e*) Ulefoss Site, and (*f*) mean results from all sites including DS27 and PS6. Note that the overall means from sites DS7 and DS27 are significantly shallower than the other sites as discussed in the text. Open circles represent (−) inclinations.

grained pyroxene, phlogopite and glass), alteration of pyroxene phenocrysts along cleavage-fractures and nearly complete sericitization of nepheline. The nepheline was altered to muscovite (sericite) plus analcite. This alteration took place when the matrix phlogopite was altered to chlorite. Phlogopite from DS7 was separated into two fractions: one uncrushed fraction of coarse (2–3 mm) phlogopite "books" (plucked directly from hand specimen) and one crushed and sieved size-fraction.

Sample PS2 has remarkably fresh, clear, primary magmatic textures and comprises euhedral phenocrysts of concentrically zoned, green, pleochroic aegerine-augite, coarse slightly resorbed biotite plates, feldspar, and accessory zircon, apatite, titanite, nepheline and oxides. Due to the relatively high abundance of mafic minerals in a matrix of K-feldspar and nepheline, this rock has been classified as a mela-phonolite (Dahlgren 1987). Aegerine persists as very fine needles in the groundmass. Biotite phenocrysts are partially resorbed and imply that the biotite was an early phase in the magma and is

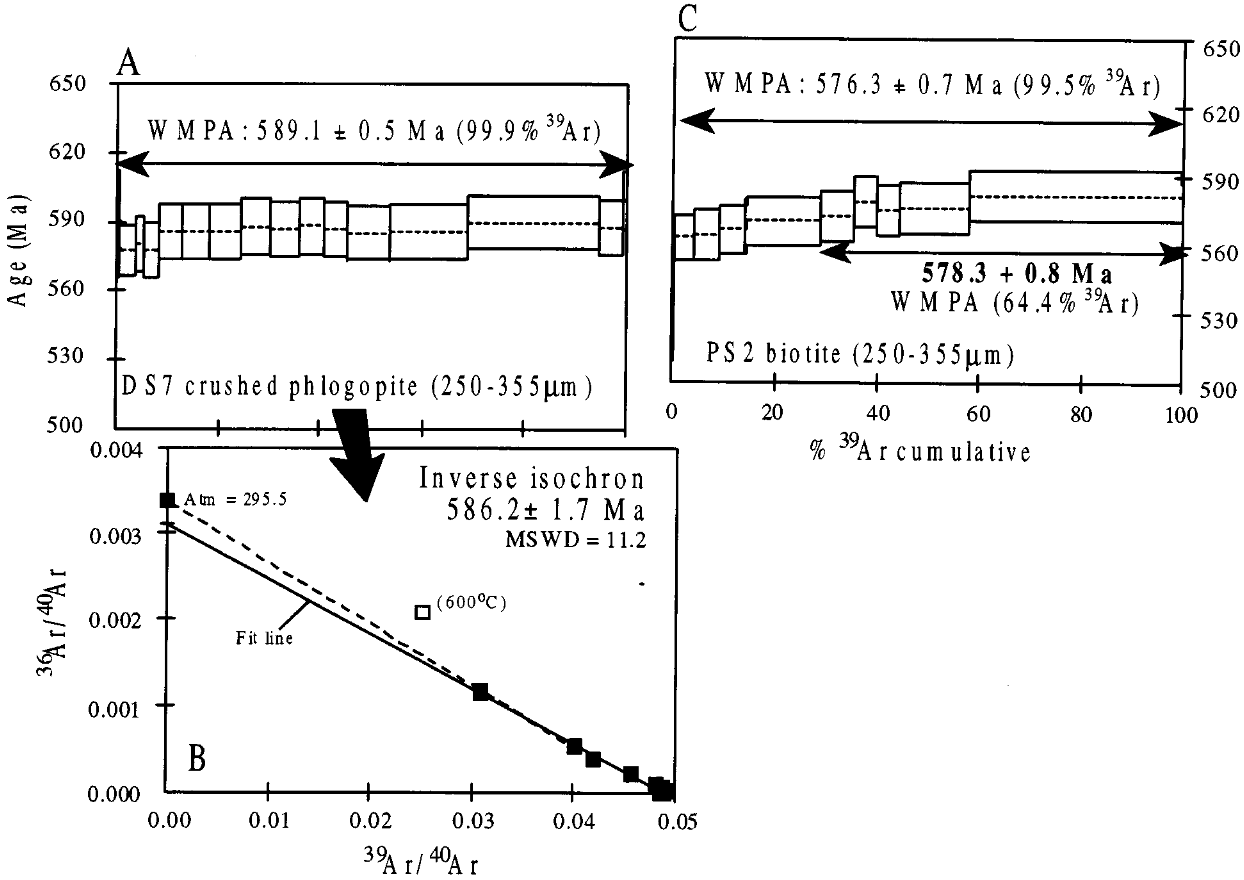

Figure 3. (*a*) Stepwise ^{40}Ar/^{39}Ar release spectra for sample DS7 yielding a weighted mean plateau age of 589 ± 0.5 Ma and (*b*) an inverse isochron plot for the same sample with an age intercept of 586 ± 1.1 Ma. (*c*) Stepwise ^{40}Ar/^{39}Ar release spectra for sample PS2 that yields a weighted mean plateau age of 576 ± 0.7 Ma. Individual stepwise degassing data can be found in the appendix.

in disequilibrium with the aegerine- and feldspar-dominated rock. One crushed, size-fraction (250–355 μm) of PS2 biotite was analyzed (figure 3*c*).

The 20-step release spectrum for crushed phlogopite DS7a (figure 3*a*,*b*) yields a weighted mean plateau age (WMPA) of 589.1 ± 0.5 Ma for 99.9% of the ^{39}Ar liberated during the experiment. Inverse isochron treatment of the data yields a good fit of a line to the datapoints (MSWD = 1.17), especially when the very radiogenic nature (age) of the sample is taken into consideration. The line-fit produces an age-intercept of 586.2 ± 1.1 Ma with a ^{40}Ar/^{36}Ar ratio of 322.3 ± 9.9; the former falls nearly within uncertainty of the WMPA and the latter is very close to the atmospheric value (295.5). The 12-step spectrum for the coarse, uncrushed phlogopite book (DS7b) from the same sample is statistically indistinguishable from DS7a (analytical data are listed in the appendix, available free of charge from *The Journal of Geology*.

The first six steps of the release spectrum from biotite PS2 affect a slight, gradual rise in apparent ages over ca. 35% of the gas before reaching a visual plateau for the remainder of the analysis. The data define a statistically valid WMPA of 576.3 ± 0.7 Ma for 99.5% ^{39}Ar. Exclusion of the first six steps of the experiment from the calculation yields a WMPA of 578.3 ± 0.8 Ma for 64.4% of the gas. Although the two WMPA results are nearly the same within uncertainty, the slight rise in ages in the early portion of the analysis could arguably be due to minor, post-crystallization Ar-loss event(s), and we utilize the older age from the latter portion of the experiment in subsequent discussion. All steps were too radiogenic to utilize inverse isochron analysis.

Both samples DS7 and PS2 had consistently low, Cl-correlated Ar. K/Ca ratios for all three samples likewise indicated Ar-release from a fairly uniform, high-K biotite/phlogopite (data listing in appendix). Both uncrushed (DS7a) and crushed (DS7b) phlogopite separates exhibited very stable behavior during analysis, and isochron analysis indicates no excess Ar. The Ar-systematics of the phlogopites were apparently undisturbed by minor, secondary alteration identified optically, and we confidently adopt the age of 589.1 ± 0.5 Ma as the crystallization age of the lamprophyric (damtjernite) rock. The apparent crystallization age of PS2, 578.3 ± 0.8 Ma, is significantly different from the DS7 experimental result at the quoted intralaboratory uncertainty. This difference could represent real differences in the time of crystallization of the damtjernitic and phonolitic rock types within the FCC magmatic system or, as noted previously, could be due to slight, younger Ar-loss in the case of PS2. However, we note that when interlaboratory uncertainties are taken into account in the interpretation, these intralaboratory age differences become insignificant. Taking into account these differences, we obtain an age of 578 ± 10 Ma for sample PS2 and 588 ± 10 Ma for sample DS7, giving a combined mean age of 583 ± 15 Ma for the FCC.

Discussion

Paleomagnetic Implications. Our paleomagnetic directions and pole from the Fen Province in this study are comparable to those from previous studies (figure 4*a*, Piper 1988; Poorter 1972). Our mean direction in our study shows slightly steeper inclinations than Piper ($I = -49°$ versus $-44°$), and the mean direction from our Rødberg samples is nearly identical to that of Poorter (1972). We attribute the slight difference in our directions to the possibility that Piper (1988) inadvertently sampled several younger dikes in the FCC, including the two sites in his study that show an apparently normal polarity. Torsvik et al. (1998) have noted that the main Permian thermal overprint observed in rocks near the rift shows a shallower inclination than observed in this study (figure 4*b*). Furthermore, the error envelopes of the Permian and Fen poles do not overlap, providing some confidence that the Fen directions are primary and date from the time of emplacement. The fact that the dikes are fresh and show only minor alteration with preserved primary igneous textures and that they yield consistent age determinations using a variety of different methods (K-Ar, Rb-Sr, U-Pb, Pb-Pb and ^{40}Ar/^{39}Ar) argue strongly for a primary magnetization that dates from the time of intrusion at 583 ± 15 Ma.

Nevertheless, we urge some caution in any unequivocal acceptance of the Fen Province pole as

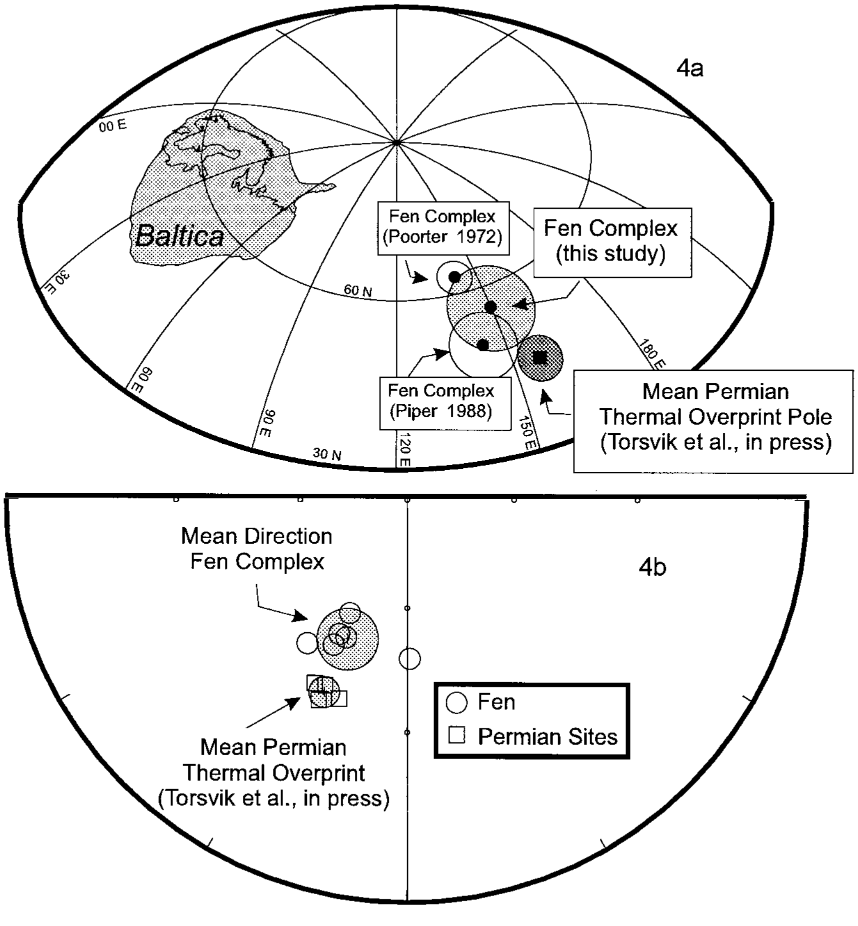

Figure 4. (*a*) Comparison of paleomagnetic poles from this study and that of Piper (1988) and Poorter (1972), along with a mean Permian-age thermal overprint pole from Torsvik et al. (1998); (*b*) Stereographic plot showing the directional data used to calculate the Fen pole in (*a*) along with site mean data from the Permian thermal overprint study of Torsvik et al. (1998). The directions are similar, but the error envelopes do not overlap, and the Fen directions are slightly steeper than the Permian overprint directions.

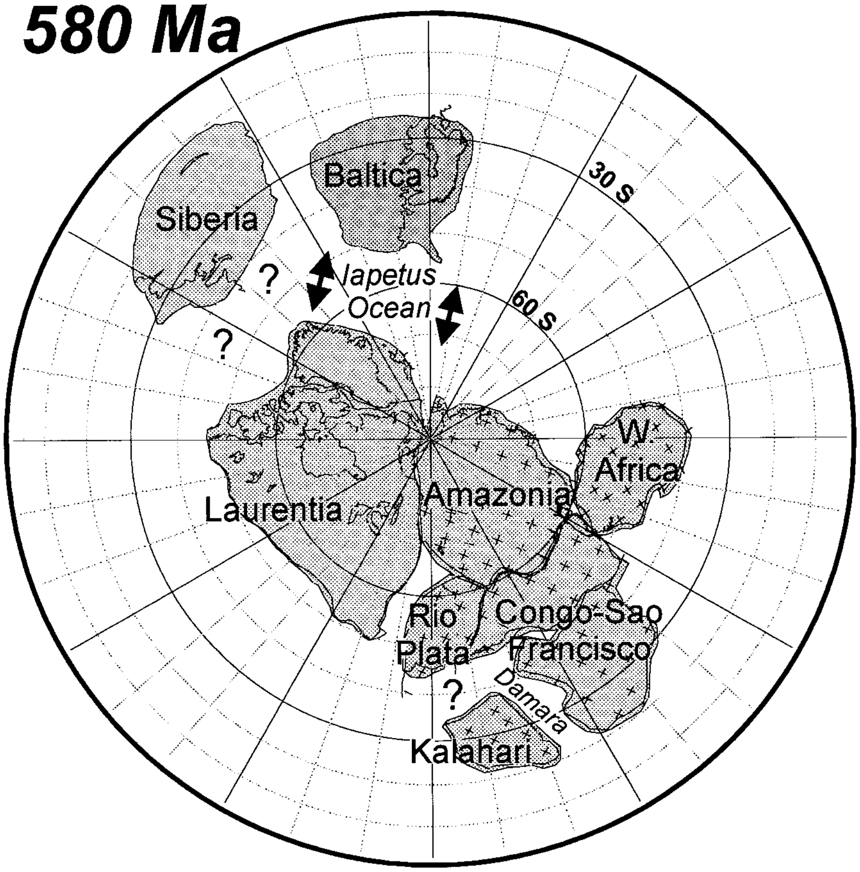

Figure 5. 580 Ma reconstruction (south-pole centered equal-area projection) based on paleomagnetic data from this study. Siberia is positioned according to the compilation of Smethurst et al. (1998), Laurentia according to Dalziel (1997), Amazonia and Rio Plata and West Africa according to Weil et al. (1998); the Congo-Sao Francisco and Kalahari cratons are placed adjacent to the South American cratons slightly modified from the Weil et al. (1998) fit. Baltica has rifted and rotated away from its former position adjacent to Greenland during the initial opening of the Iapetus Ocean. (?) indicates an ocean basin of unknown dimensions.

primary because the directions do resemble the Permo-Triassic field directions for Baltica. This observation, combined with the proximity of the FCC to the Oslo Rift, necessitates some reservation in using this pole.

Given these caveats regarding the primary nature of the magnetization, we present a paleoreconstruction based on the Fen pole (figure 5). Torsvik et al. (1996) made the suggestion that the opening of Iapetus between Baltica and Laurentia commenced prior to 600 Ma, based on the previously published ages and pole for the Fen complex and other Vendian-age poles from Baltica and Laurentia. Our results are compatible with this suggestion.

We prefer a south-pole option for the Fen paleomagnetic pole at 56° N, 150° E because it represents the simplest path between the Fen pole (583 Ma) and a mean pole calculated from the 481 Ma Swedish limestones (Torsvik et al., 1996). The previously published Fen poles resulted in a slight continental overlap between Baltica and Amazonia (Torsvik et al. 1996), which led Kirschvink et al. (1997) to argue for a north-pole option for the Fen pole reported herein. The north polarity option also guaranteed Kirschvink et al. (1997) a sufficiently long apparent polar wander (APW) path (98° versus 75°) to support their contention of a TPW event in the Cambrian.

Our south-pole preference is defended for several reasons. First, we note that the new age constraints and pole for Baltica at 583 Ma negate any continental overlap and place Baltica adjacent to the Siberian craton. Secondly, we note that accepting both the polarity interpretation of Kirschvink et al. (1997) and the Rodinia model of Dalziel (1997), requires a minimum drift rate for Baltica in excess of 25 cm/yr during the Vendian opening of the Iapetus Ocean (pre-600 Ma) or an additional episode of TPW in the Vendian (Torsvik et al. 1998). We also note that the linkage of paleomagnetic poles 100 m.y. apart is a rather tenuous position from which to argue for a TPW event midway between these two endpoints and that parsimony dictates the south-pole option for the Fen paleomagnetic pole at 56° N, 150° E. We concede that APW for the 100 m.y. interval between the Fen igneous event and the Swedish limestone deposition may include significant, but as of yet, undetected motion.

Tectonic Implications. Applying the south-polarity option to our model of the opening of the Iapetus Ocean (c. 615 Ma) results in a large rotation of Baltica with respect to its pre-rift configuration and a movement toward slightly lower paleolatitudes. The position of Baltica in figure 5 is consistent with the post-drift setting proposed by Dahlgren (1994) for the carbonatite complexes at Fen and Alnö. The opening of the ocean between Amazonia/Rio Plata cratons and Laurentia likely began at roughly the same time as evidenced by 615 Ma ages from the Long Range dikes (Kamo et al. 1989) and other contemporaneous, or slightly younger, igneous activity along the Laurentian margin (Torsvik et al. 1996 and references therein). The actual drift phase of the Amazonia and Rio Plata cratons and their subsequent collision with East Africa may have occurred at around 565 Ma (Trompette 1995; Meert 1998). In our model, rifting proceeds from north to south in present-day coordinates along the eastern side of Laurentia.

Powell (1995) and Dalziel (1997) have argued that a second supercontinental assemblage, called Pannotia, existed for a geologically fleeting moment near the Vendian-Cambrian boundary. The supercontinent consisted of a fully united Gondwana juxtaposed against the eastern margin of Laurentia just prior to rifting. The model depends on the exact timing of Gondwana assembly and the age of the rift-drift transition along the eastern margin of Laurentia. Given the uncertainties in both the geochronologic and paleomagnetic database for this interval, the existence of Pannotia remains an open question. However, we would argue that if Pannotia did exist, Baltica would not have been part of the supercontinental assembly.

Conclusions

The FCC and associated satellite dikes of the Fen Province in southern Norway record a magnetization dating to 583 ± 15 Ma. The paleomagnetic pole calculated from these rocks falls at 56° N, 150° E (dp = 7°, dm = 10°) and compares favorably with two previous investigations (Piper 1988; Poorter 1972) although the mean direction in our study is slightly steeper than that of Piper (1988). This slight discrepancy is most likely due to the fact that Piper inadvertently sampled younger dikes in the area. The age of our pole is constrained by two consistent $^{40}Ar/^{39}Ar$ ages from the rocks at 583 ± 15 Ma along with previously published ages noted above. We urge caution in the unequivocal use of these tectonic models in global reconstructions due to the similarity of the Fen pole to Permo-Triassic age poles from Baltica. The Fen Province igneous rocks were emplaced during minor extensional activity during the drift phase of continental separation between Baltica and Laurentia. This interpretation is consistent with our 580 Ma paleoreconstruction which shows that Baltica had rifted and rotated from its 615 Ma position adjacent to Greenland. We interpret the ages and our reconstruction to reflect opening of an ocean basin from north to south during the latest Neoproterozoic to earliest Paleozoic time (615–540 Ma). The polarity option for the Fen pole remains an open question; however, we consider the south polarity option as described above to offer the simplest tectonic model for the rifting of Rodinia and opening of the Iapetus Ocean between Baltica and Laurentia.

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