

# The Early Carboniferous Magerøy dykes, northern Norway: palaeomagnetism and palaeogeography

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**Abstract** – Palaeomagnetic data from the 337 Ma Magerøy dykes (northern Norway) are of exceptionally high quality, and a positive contact test along with an existing regional result from the Silurian Honningsvåg Igneous Suite attests to a primary Early Carboniferous magnetic signature. The palaeomagnetic pole (S14.8°, E320.1°,  $dp/dm = 4.4/8.6^\circ$ ) is the first Early Carboniferous pole from Baltica, and implies that northernmost Norway–Greenland, the Barents Sea and Svalbard were located at tropical to low northerly latitudes at this time. Northward drift during Carboniferous times (5–6 cm/yr) as demonstrated from palaeomagnetic data is also reflected in the sedimentary facies in the Barents Sea realm, that is, a change from tropical (Early Carboniferous) to subtropical (20–30° N) carbonates and evaporites in the Late Carboniferous. The Magerøy dykes are continental tholeiites which intruded into a set of NW–SE-trending normal faults parallel to the Trollfjorden–Komagelva Fault Zone and the Magerøysundet Fault immediately to the north and south of Magerøya, respectively. These, and many other NW–SE-trending faults (onshore and offshore), were active during Late Palaeozoic extension, and the dykes were probably contemporaneous with the earliest syn-rift sedimentation in the Barents Sea (for example, the Nordkapp Basin).

Keywords: Norway, palaeomagnetism, Carboniferous, palaeogeography.

## 1. Introduction

Palaeomagnetic studies are the only quantitative basis for reconstructing continents in pre-Jurassic times, and as such, the greater the volume of data available for such reconstructions, the more detailed a picture of previous continent configurations can be recreated. For the palaeocontinent of Baltica, comprising much of what is now Scandinavia, there has been a gap in the palaeomagnetic database for the Carboniferous period. However, with the precise dating of dolerite dykes on the island of Magerøya, in the far north of Norway (Lippard & Prestvik, 1997), an opportunity to collect such data is presented.

The bedrock of Magerøya forms part of the Middle and Upper Allochthon of the Norwegian Caledonides, which were emplaced onto the Baltoscandian margin of Baltica during the Scandian orogeny in Late Silurian to Early Devonian times (Andersen, 1981). The presence of several unmetamorphosed dolerite dykes cutting the regionally metamorphosed (biotite to kyanite zone) Silurian metasediments has been known for some time (Andersen, 1981, 1984). The dykes were studied geochemically and dated by the K/Ar method by

Roberts, Mitchell & Andersen (1991). However, it was with the publication of an  $^{40}\text{Ar}/^{39}\text{Ar}$  mineral age determination on one of the dykes, *c.* 337 Ma (Lippard & Prestvik, 1997), that the dykes became an interesting target for palaeomagnetic study. In this account we thus report on the first Early Carboniferous palaeomagnetic data from Baltica, and discuss their palaeogeographic implication.

## 2. Geology and sampling

Most of Magerøya comprises low- to medium-grade metasedimentary rocks of the Magerøy Supergroup (Andersen, 1984), which contain fossils of Early Silurian (Llandovery) age (Føyn, 1967). These rocks, together with plutonic rocks of the Honningsvåg Intrusive Suite (Robins, 1998), constitute the Magerøy Nappe (Ramsay & Sturt, 1976; Andersen, 1981). In the western part of the island, the subjacent Kalak Nappe Complex includes the Gjesvær Migmatite Complex. The dykes have been found in several different places along the lineament between Næringen and Gjesvær, but there is uncertainty as to the degree of connectivity between the various dyke-segments. The dykes in central Magerøya were originally found and mapped

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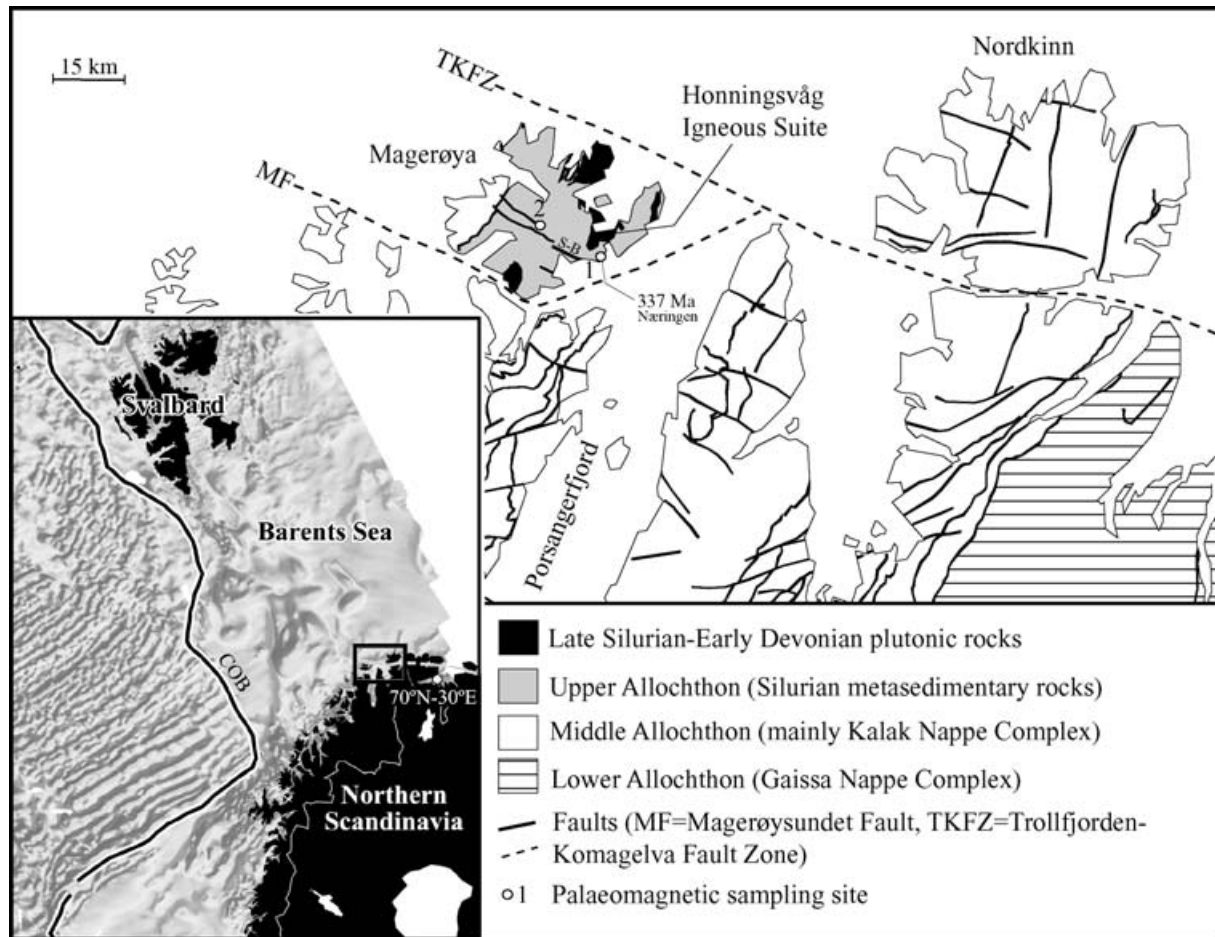


Figure 1. Simplified tectonostratigraphic map of northwestern Finnmark and prominent onshore faults/lineaments (Koistinen *et al.* 2001). TKFZ – Trollfjorden–Komagelva Fault Zone (proposed extension from the Varanger Peninsula to the east of the map area; Gabrielsen & Færseth, 1989). MF – Magerøysundet Fault; S–B – Sarnes–Baklia area. Lower left-hand diagram shows a magnetic anomaly map of Norway and adjacent ocean areas (Olesen *et al.* 1997; Mosar, Lewis & Torsvik, 2002). COB – Continent–Oceanic Boundary. The black box corresponds to the area of the main map in this figure.

by T. B. Andersen (unpub. Cand. Real thesis, Univ. Bergen, 1979). Further to the southeast in the Sarnes–Baklia area (Fig. 1), three more dykes were noted by Lippard & Prestvik (1997). Finally, a dyke at Næringen (Fig. 1) is located opposite the town of Honningsvåg (Andersen, 1981). All the different dykes are roughly parallel to each other.

K–Ar dating was first conducted on clinopyroxene from three widely separated samples from a dyke in the interior part of Magerøya, yielding an unweighted mean age of  $293 \pm 22$  Ma (Roberts, Mitchell & Andersen, 1991). However, the reliability of the K–Ar method has been questioned, owing to problems with both argon loss and excess argon. The  $^{40}\text{Ar}/^{39}\text{Ar}$  ages of  $337 \pm 0.4$  Ma (plagioclase) and  $340 \pm 4$  Ma (whole rock) obtained from the Næringen dyke (Lippard & Prestvik, 1997) have a higher geological significance.

Geochemical analyses of the different dykes show that the dykes in the Sarnes–Baklia area (Fig. 1) are very similar in composition to the dykes in the interior of Magerøya (Lippard & Prestvik, 1997). Petrograph-

ically, the dykes comprise plagioclase, clinopyroxene, magnetite, ilmenite and pseudomorphs after olivine, with varying degrees of alteration. Geochemically, the dykes are of tholeiitic composition approaching that of basaltic andesites (Roberts, Mitchell & Andersen, 1991; Lippard & Prestvik, 1997).

For the purposes of this study, the dyke at Næringen (dyke 1) dated by Lippard & Prestvik (1997) and the more northerly of the dykes in the interior of Magerøya (dyke 2) were sampled and drilled for palaeomagnetic studies (Fig. 1). At Næringen, the dyke cuts biotite zone metamorphic rocks (Andersen, 1984) and displays a positive surface expression. The dyke shows jointing perpendicular to its margins, and is between 12 and 15 m wide. Unfortunately, exposures of the dyke contacts were poor, which made it impossible to sample. Thirty-three borehole cores were drilled in a line perpendicular to the margin of the dyke, each core providing enough material for at least two specimens. Samples of the metasedimentary host rocks, mostly quartzitic schists and phyllites, were taken at a distance of 100 metres from the dyke.

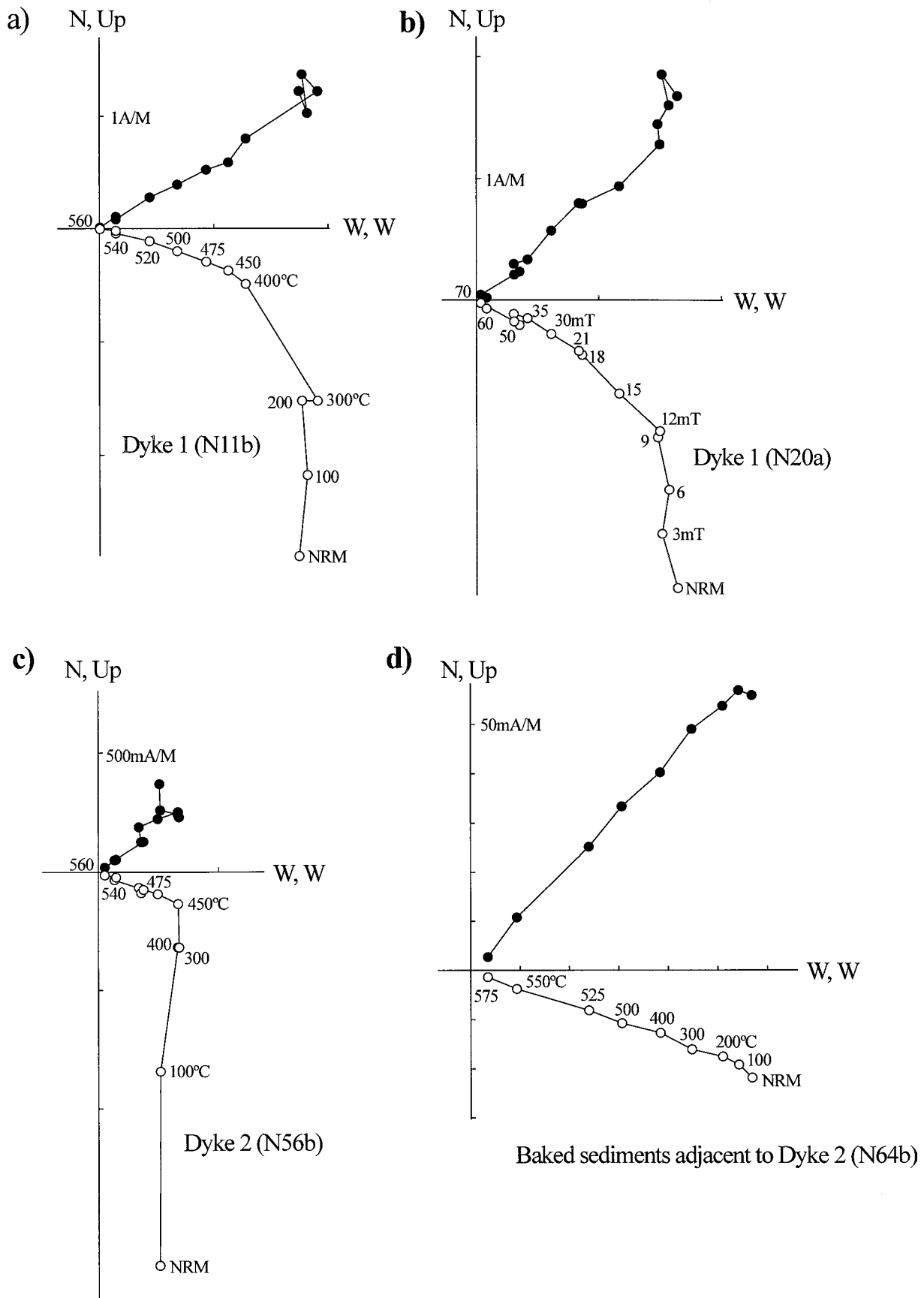


Figure 2. Orthogonal vector plots showing typical examples of thermal (a, c–d) and AF (b) demagnetization from dyke samples (a–c) and a dyke 2 contact sediment sample (d). In vector plots, closed (open) symbols denote points in the horizontal (vertical) plane. NRM – Natural remanent magnetization.

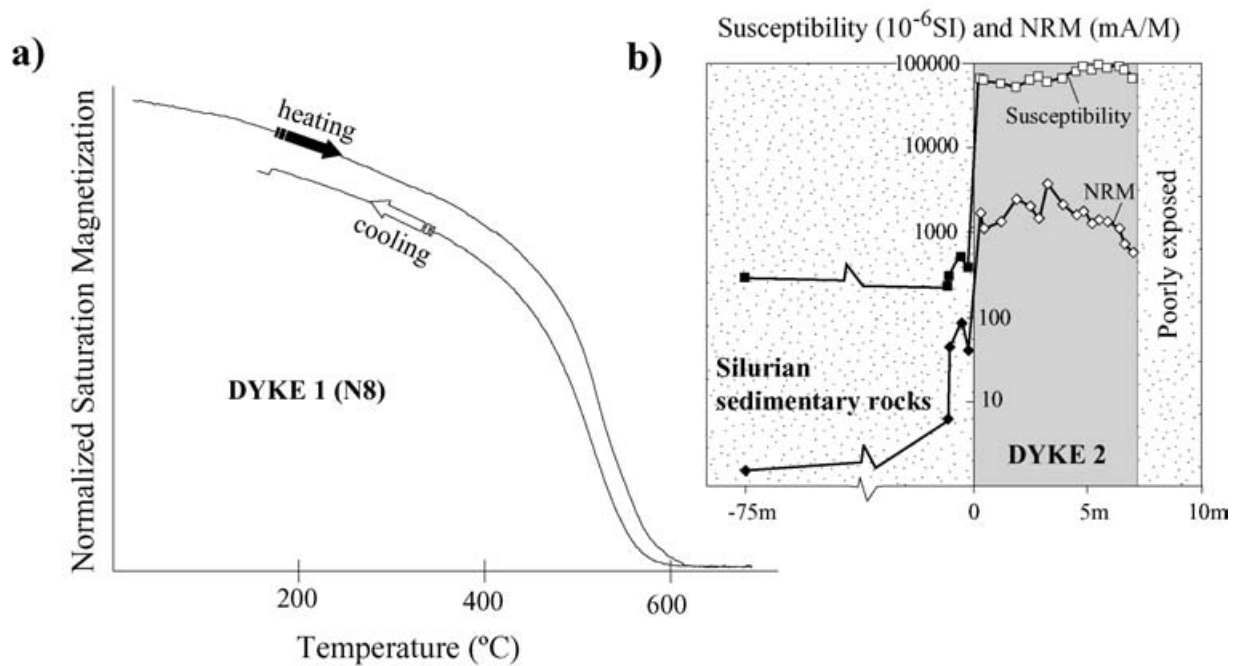


Figure 3. (a) Typical Curie temperature curves for dyke 1 samples. (b) Variation in bulk susceptibility and NRM intensity (logarithmic scale) for dyke 2 and the contact (baked) sedimentary rocks.

In the interior of the island, the dykes cut garnet to kyanite zone metamorphic rocks (Andersen, 1984), have negative surface expressions and are often difficult to recognize in the field. Along a stream section, one dyke was located and sampled. At this point, the dyke, has a rusty weathering colour and appears dark green to black on freshly cut surfaces, and is poorly jointed. The dyke is 7 m wide and shows aureole zones of baked sedimentary rock up to a metre in width. Eighteen borehole cores were drilled in the dyke, with a further five samples drilled in the baked contact zone (only one contact properly exposed). Samples of metasedimentary rocks were also collected at distances of 75 and 100 m from the dyke.

### 3. Laboratory experiments

The natural remanent magnetization (NRM) was measured on a JR5A spinner magnetometer in a low-magnetic field environment at the Geological Survey of Norway (Trondheim). The stability of NRM was tested with thermal (MM-TD-60 furnace) and alternating field (AF; in-house built two-axis tumbler) demagnetization. Bulk susceptibility was measured on a Barthington MR-2 system whilst Curie-temperatures were measured on an in-house built translation bridge.

#### 3.a. Dykes

NRM intensity averages to 3 (dyke 1) and 1.7 A/m (dyke 2) whilst bulk susceptibility averages to 51 (dyke 1) and 62 ( $10^{-3}$  SI) (dyke 2). Maximum un-

blocking temperatures of 560–575 °C (Fig. 2a,c), Curie temperatures at around *c.* 580 °C (Fig. 3a) and AF stability up to 70–80 mT (Fig. 2b) indicate magnetite as the primary remanence carrier. Curie curves are almost reversible, except for a small lowering in the saturation magnetization during cooling, which probably indicates some oxidation during heating and cooling (Fig. 3a). Petrographically, the opaque mineralogy of the dykes is dominated by magnetite with lamellae of ilmenite. Grain size is typically  $\sim 100 \mu\text{m}$ , but smaller grain sizes close to, and perhaps below, the limit of optical resolution are present. The presence of lamellae indicates high-temperature deuteric oxidation and exsolution during late-stage crystallization.

Demagnetization of the dykes produced excellent results for all the tested samples, and typical examples of demagnetization behaviour are shown in Figure 2a–c. A steep, downward-dipping component is demagnetized at low to intermediate temperatures or AF fields; this component (LB) plots close to the present-day field (Fig. 4a,b) and is not further elaborated. The high temperature components (HB) are characterized by shallow, downward-dipping inclinations with NE declinations (Figs 2, 4). This component is probably representative of the magnetic field at the time of crystallization, and HB components from dykes 1 and 2 are identical (Fig. 4).

#### 3.b. Baked contact test (dyke 2)

The baked metasedimentary rocks adjacent to the northeast margin of dyke 2 ( $< 1.1$  m) provided valuable data to confirm that the magnetization in the dykes

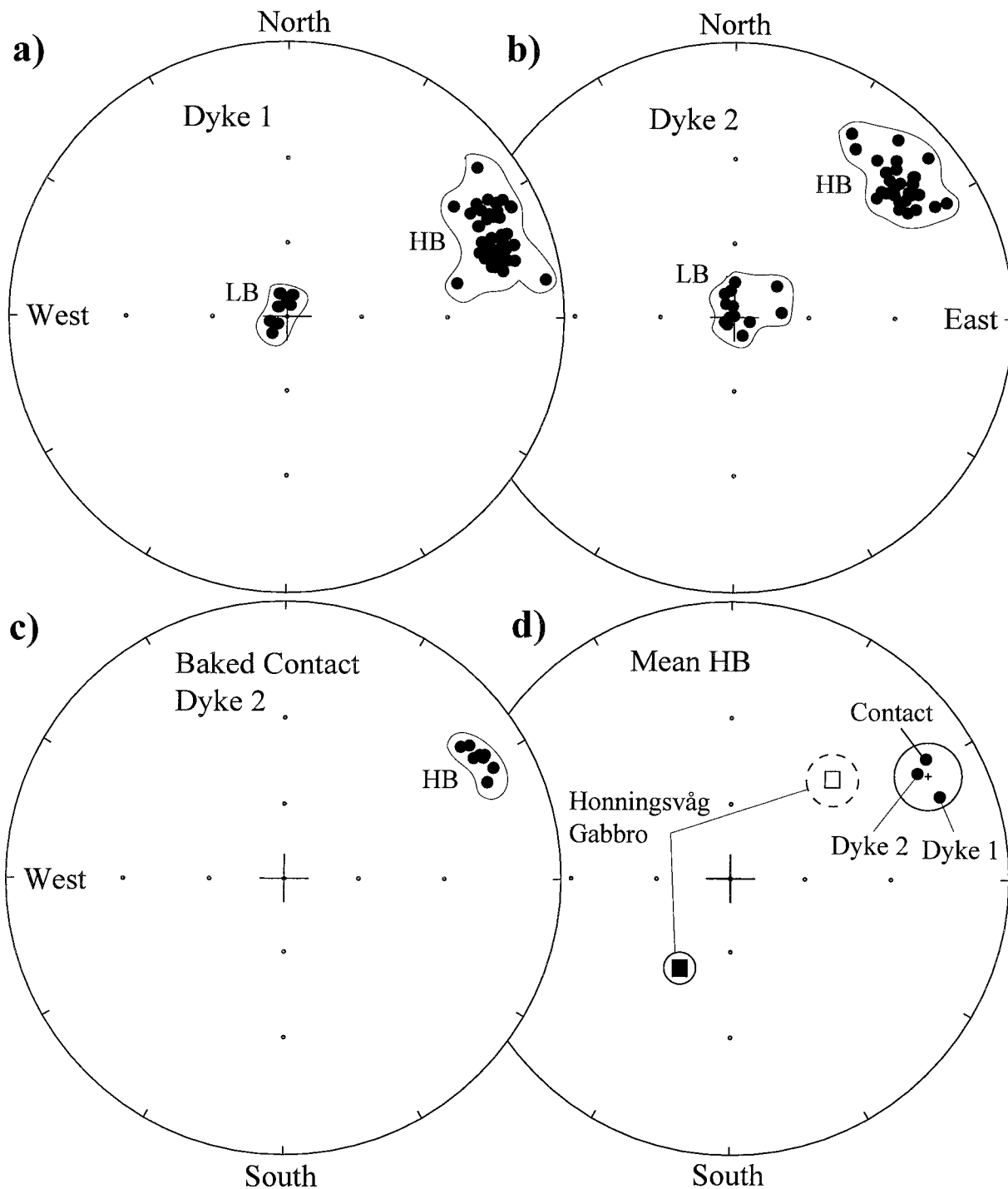


Figure 4. Characteristic remanence components obtained for dykes 1–2 (a,b), baked contact (c,d) mean directions (dykes 1–2, baked contact) along with mean directions (dual-polarity) obtained from the nearby Late Silurian Honningsvåg Gabbro (Torsvik *et al.* 1992; see location in Fig. 1). In equal-angle stereoplots, open (closed) symbols denote negative (positive) inclinations. Circles in (d) are  $\alpha_{95}$  confidence ellipses.

is the original magnetization acquired in the dykes at the time of their crystallization and cooling. The baked metasediments show the same high-temperature component as the dykes (Figs 2, 4), and the NRM intensity in the sediments increases markedly toward the dyke contact (Fig. 3b). Within one metre of the dyke contact the NRM intensity varied between 40 and 84 mA/M, at 1.1 m the NRM intensity was reduced to

6.2 mA/M, and at a distance of 75 m the NRM intensity averaged 1.1 mA/M (Fig. 3b). The baked contact records almost univectorial components (identical to the dyke HB component) and does not record LB components of more recent age as those observed in the dykes. The LB component in the dykes is probably carried by large titanomagnetite grains as a relatively unstable (viscous) remanence.

Table 1. Palaeomagnetic results from the Magerøy dykes and a baked contact zone

Site	Dec°	Inc°	$\alpha_{95}$	k	N
Dyke 1 (Strike 095°, vertical)	68.4	12.2	2.4	101	41
Dyke 2 (Strike 115°, site dip unknown)	60.4	14.8	2.9	99	30
Baked contact zone	58.3	11.1	2.7	423	8
Mean for all specimens:	64.3	13.1	1.9	84	79
	Pole: S14.4, E318.1, dp/dm = 1/1.9				
Mean 'sites':	62.4	12.7	8.4	214	3*
	Pole: S14.8, E320.1, dp/dm = 4.4/8.6				

Dec°/Inc° = Mean declination/inclination;  $\alpha_{95}$  = 95 % confidence cone around the mean direction; k – precision parameter; N = number of specimens (\*sites); Pole – palaeomagnetic pole; dp/dm – semi-axis around the mean pole; mean sampling co-ordinates – 71° N, 25.7° E. Dyke 1 is dated to  $337.3 \pm 0.4$  Ma ( $^{40}\text{Ar}/^{39}\text{Ar}$  plagioclase plateau age) or  $337.1 \pm 1.0$  Ma (inverse isochron age) (Lippard & Prestvik, 1997).

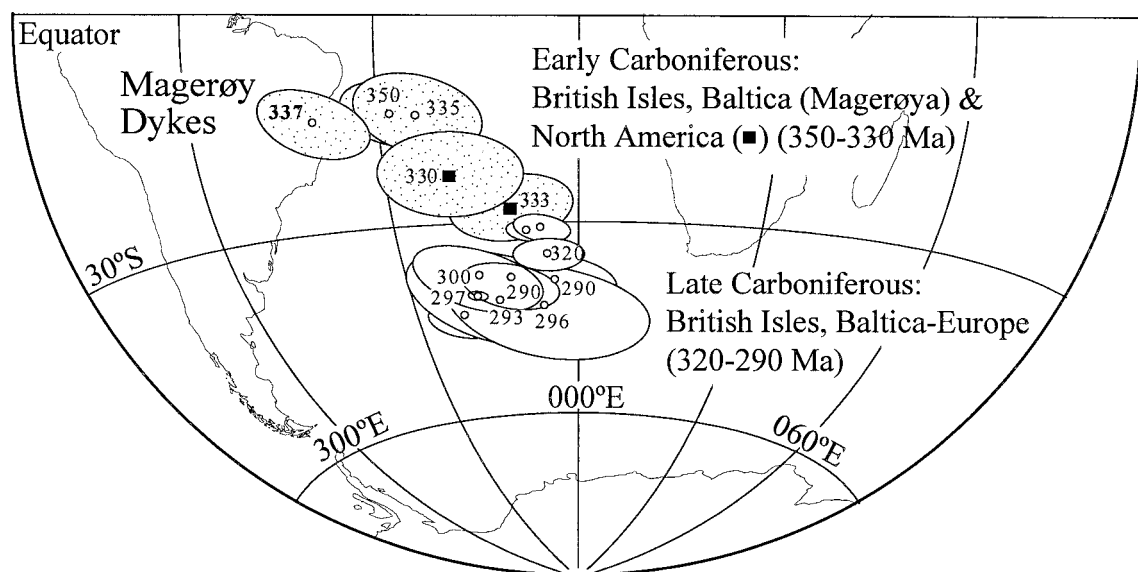


Figure 5. Early (stippled pattern) and Late Carboniferous southpoles from the British Isles, Baltica (including our new Magerøya 337 Ma pole) and North America (equal-area projection). The poles are shown in European co-ordinates with dp/dm confidence ellipses (Early Carboniferous North American poles rotated to Eurasia using a Bullard, Everett & Smith (1965) fit). Note that there is a slight misfit between Early Carboniferous poles from North America. Poles are selected (some ages upgraded in the light of newer isotopic ages) from Torsvik *et al.* (1996, 2001), except the inclusion of the c. 335 Ma Derbyshire Lava pole (Piper *et al.* 1991).

### 3.c. Metasedimentary rocks

The Silurian metasedimentary rocks sampled at 75 m away from both dykes showed generally low NRM intensities (typically  $\leq 1$  mA/M). None of the samples produced a meaningful demagnetization path and are all characterized by highly erratic directional behavior. Conversely, Torsvik *et al.* (1992) reported stable and well-defined dual-polarity palaeomagnetic components from the nearby Silurian Honningsvåg Gabbro (Fig. 1), 2 km away from dyke 1. These components are different and clearly older than those observed in the Magerøy dykes (Fig. 4d) and attest to the fact that the dyke components cannot have originated by a regional-scale and penetrative remagnetization event on Magerøya.

### 4. Interpretation and discussion

High-temperature components of normal polarity from two dykes and one baked contact are identical (Fig. 4), and we infer that a combined palaeomagnetic pole (S14.8°, E320.1°, dp/dm = 4.4/8.6°; Table 1) is representative for the time when the dykes were emplaced, at c. 337 Ma. Provided that the island of Magerøya has not undergone younger rotations relative to the Baltican plate and that secular variation is reasonably averaged out, then this is the first Early Carboniferous palaeomagnetic pole reported for Baltica. A comparison with Early Carboniferous poles from the British Isles and North America clearly sustains an Early Carboniferous age for the Magerøy pole (Fig. 5). The Magerøy pole overlaps with contemporaneous poles from Scotland

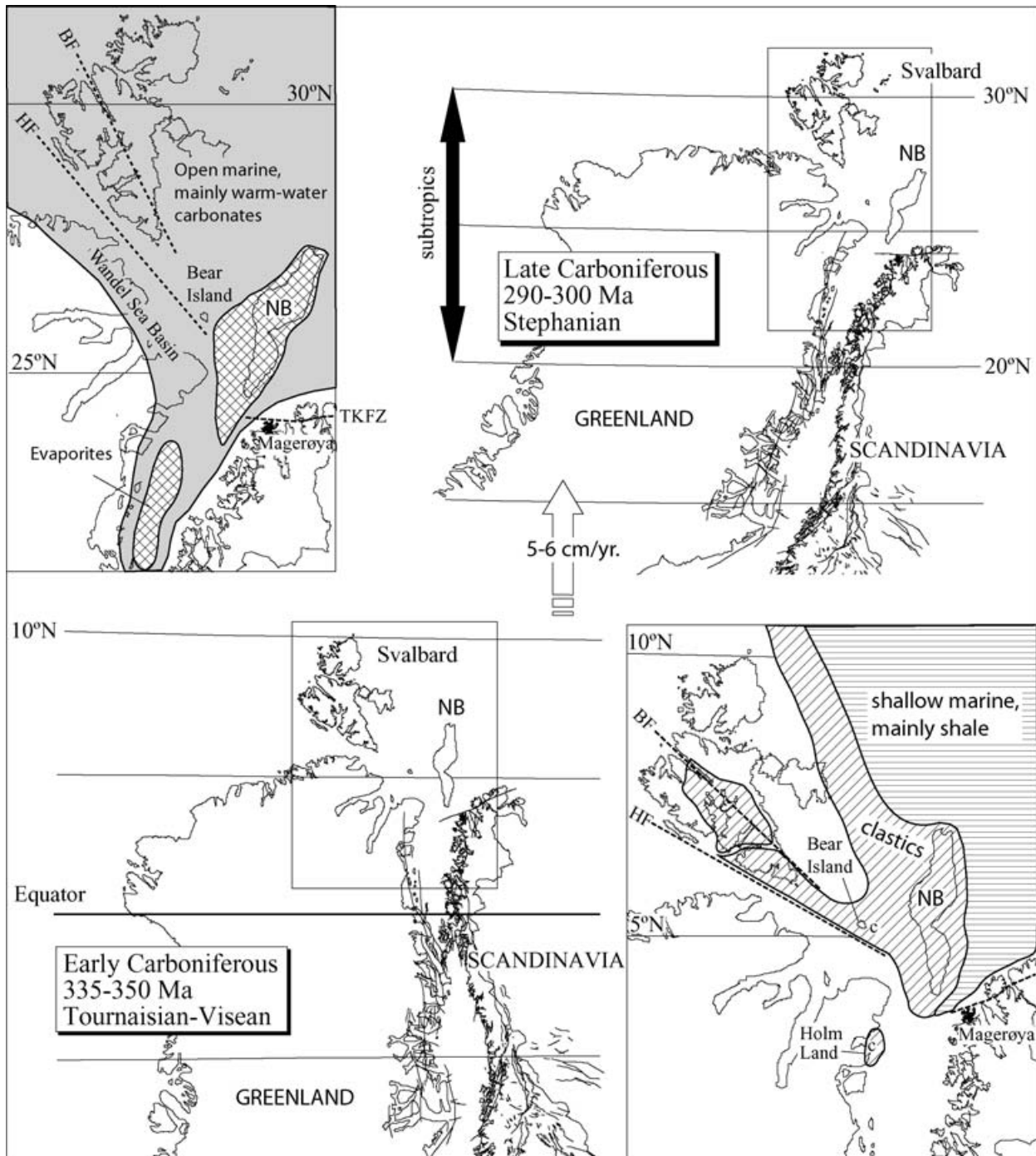


Figure 6. Northern Laurussia (North Greenland, North Norway, Barents Shelf and Svalbard) reconstructed according to Early Carboniferous data from the British Isles and Magerøya (mean southpole 335–350 Ma:  $14.5^{\circ}$  S,  $329.3^{\circ}$  E;  $A95 = 12.2^{\circ}$ ;  $N = 3$  poles; Fig. 5) and Late Carboniferous data from Europe (mean southpole 290–300 Ma:  $39.8^{\circ}$  S,  $348.5^{\circ}$  E,  $A95 = 3.7^{\circ}$ ;  $N = 10$  poles; Fig. 5). Relative fits of Eurasia (Norway)–Greenland–Svalbard after Torsvik *et al.* 2001 (Model II). Inset diagrams show sedimentary facies patterns draped on the same reconstructions (compiled and simplified from Ziegler, 1988; Worsley, 1986; Stemmerik, 2000; Bugge *et al.* 2002; Torsvik *et al.* 2002). TKFZ – Trollfjorden–Komagelva Fault Zone; BF – Billefjorden Fault Zone; HF – Hornsund Fault; c – coal (local occurrences). NB – Nordkapp Basin. Reconstruction implies a northward latitudinal drift-rate of 5–6 cm/yr (minimum velocities since palaeolongitude is indeterminable from palaeomagnetic data) during Carboniferous times. Including North American poles in our Early Carboniferous mean pole calculation will result in a slightly more northerly position in the Early Carboniferous and hence the latitudinal drift rates between the Early and Late Carboniferous would be reduced to *c.* 4 cm/yr. Conversely, Late Carboniferous poles from North America (in a Bullard, Everett & Smith (1965) fit) fully match those from Europe, and inclusion of those poles in calculating a mean Late Carboniferous pole will not significantly change the reconstruction.

(Kinghorn Lavas: Torsvik *et al.* 1989) and Central England (Derbyshire Lavas: Piper *et al.* 1991). For as yet unknown reasons, these Early Carboniferous poles (*c.* 350–335 Ma) plot at slightly lower latitudes than the North America poles (*c.* 333–330 Ma), but in general, there is a systematic pole track from Early Carboniferous to Late Carboniferous times (Fig. 5) for the North Atlantic bordering continents (Laurussia). This systematic pole change implies that Laurussia drifted northwards during Late Palaeozoic times.

The NW–SE-trending fault- and joint-systems commonly developed on Magerøya (Andersen, 1981) are parallel or sub-parallel with the Magerøysundet Fault to the south of Magerøy (Fig. 1), and to the postulated extension of the Trollfjorden–Komagelva Fault Zone north of Magerøya (Gabrielsen & Færseth, 1989). Originally, these faults formed during Late Palaeozoic extension along the margin of Baltica (Lippard & Roberts, 1987), but are known to have been reactivated as rifting occurred during the progressive opening of the Barents Sea. Local, basaltic magmatism accompanying the rifting led to emplacement of the dolerite dykes (Roberts, Mitchell & Andersen, 1991). The dykes are thus important markers for the timing of this extensional event. The dykes themselves are not deformed by later faulting.

The Magerøy pole indicates that the island of Magerøya (palaeolatitude =  $6.4^{+4.5}_{-4.3}$ ° N), and by implication northern Baltica, was situated at low latitudes during Early Carboniferous times. Since then, essentially northward movement of Baltica (Torsvik *et al.* 2001) has resulted in the present-day position of the plate. The palaeogeographic position of Baltica during Carboniferous times is supported by the contemporaneous sedimentation found in the Barents Sea basins (Fig. 6). During Late Devonian–Early Carboniferous time, the Nordkapp Basin to the north of Magerøya displays (sedimentary) seismic facies which correlate with sedimentary facies typical of cored tropical humid coaly fluvial deposits, giving way to the carbonates and evaporates typical of warm and dry subtropical latitudes during the Late Carboniferous–Early Permian (Bugge *et al.* 1995, 2002). This would support a progressive northward movement of Baltica during this time period, as indicated by the palaeomagnetic reconstruction (Fig. 6). The calculation of the latitudinal rate of drift results in an average movement rate of 5–6 cm per year.

The reconstruction of Norway–Greenland during Carboniferous times is further supported by sedimentary successions present in basins along the coast of northern Greenland where small basins on Holm Land contain coal-bearing siliciclastics deposited during the Early Carboniferous (Surlyk, 1991). The Wandel Sea Basin onshore North Greenland and the Finnmark Platform near Norway both show the development of fluviatile sediments during the Tournasian (354–342 Ma; Stemmerik, 2000). Later sedimentation in the Viséan (342–327 Ma) was also of a non-marine

nature, being dominated by alluvial fans and floodplain deposits. Similarly, both Svalbard and Bear Island expose evidence of coal-bearing clastic sedimentary sequences at this time (Steel & Worsley, 1984; Worsley, 1986; Worsley *et al.* 2001). It is only at around 320 Ma (Late Carboniferous) and onwards that evaporites and significant carbonate platforms are found in the Wandel Sea Basin (Stemmerik & Håkansson, 1991; Stemmerik, 2000). Svalbard also shows the development of an evaporite basin, with areas of salt deposition (Steel & Worsley, 1984). Bear Island shows a progression through siliciclastics, indicative of tropical (humid) climate, to shallow-marine platform carbonates (Worsley *et al.* 2001).

## 5. Conclusions

The study of dykes from the island of Magerøya in northern Norway (Finnmark) has provided the first palaeomagnetic data for Baltica during Early Carboniferous times. The tholeiitic dykes are dated to 337 Ma, and intrude an Early Silurian metasedimentary succession. The dykes parallel NW–SE onshore and offshore extensional faults related to Late Palaeozoic extension and rifting in the Barents Sea. Each of the dykes and the baked contact zone to one of them shows a well-defined high-temperature component that we infer to represent the primary magnetic field present at the time of crystallization. The palaeomagnetic data imply that Magerøya (NW Baltica) and the Barents Sea realm were located at low northerly latitudes during Early Carboniferous times. Subsequent northward drift during the Carboniferous is reflected in the sedimentary facies, that is, a change from tropical (humid) conditions in Early Carboniferous time to subtropical carbonates and evaporites in Late Carboniferous time.

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