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Carboniferous age for the East Greenland "Devonian" basin: Paleomagnetic and isotopic constraints on age, stratigraphy, and plate reconstructions

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ABSTRACT

New paleomagnetic and isotopic data from East Greenland indicate that this classical "Devonian" basin was partly formed in Carboniferous. The basin preserves a stratigraphically linked magnetic reversal pattern of primary character. Paleomagnetic data indicate that the two stratigraphically lowermost intrabasinal angular unconformities, identified on each side of the basin, in fact correlate as one unconformity. This implies a 2 km reduction of the estimated basin thickness, and thus that the unconformity represents a major depositional hiatus. Successions below the unconformity are taken to be Devonian (Givetian) in age, on the basis of correlation with paleomagnetic reference poles. However, we argue that the overlying strata are Carboniferous, rather than Devonian, in age, on the basis of a ca. 336 Ma ^{40}Ar/^{39}Ar extrusive age for a basalt flow and paleomagnetic data. A Carboniferous age for the strata has significant implications for vertebrate evolution; fossils of a terrestial tetrapod, *Ichthyostega*, are found above the unconformity. *Ichthyostega* is regarded as the earliest fossil of an animal known to walk on land; however, our data suggest that these dry footsteps are much younger than previously believed. Our results are also significant for plate reconstructions. Paleomagnetic data indicate that the lower part of the basin was deposited at low southerly latitudes. Sediments above our Early Carboniferous unconformity were deposited approximately at lat 4°N, indicating that the continent had drifted northward. A minor pole-longitude misfit between Devonian and Carboniferous poles from East Greenland and North America implies (1) a closer pre–Labrador Sea Greenland–North America fit; (2) counterclockwise block rotations (10°–15°) of the study area; or (3) a combination of both. The East Greenland "Devonian" basin formed along the Caledonian spine of Euramerica, and counterclockwise block rotation may have occurred between sinistral faults resulting from continued relative movement between Baltica and Laurentia during Devonian and Carboniferous time.

INTRODUCTION

The East Greenland "Devonian" basin formed as an intramontane supradetachment basin (Hartz and Andresen, 1995) within the Caledonian orogen (Bütler, 1959; Haller, 1971). Devonian deposits generally are in large north-south–trending grabens, most recently suggested to be controlled by major left-lateral faults (Larsen and Bengaard, 1991). Herein we report the first paleomagnetic data from the East Greenland Devonian deposits. These data cast doubts on the proposed Devonian age of the entire basin sedimentary succession and challenge traditional facies correlations across the basin.

GEOLOGIC SETTING AND PALEOMAGNETIC SAMPLING

Devonian deposits unconformably overlie Late Proterozoic to Ordovician sedimentary rocks and, in some localities, overlie Precambrian gneiss (Fig. 1A; Bütler, 1959). Basin fill is estimated to be >8 km thick and consists mainly of coarse terrestrial clastics and minor fine-grained lacustrine deposits (Olsen and Larsen, 1993). Bütler (1959) reported that the stratigraphy of the basin can be divided into the following four series: the Basis series, suggested to be late-Middle Devonian (Givetian); the late Givetian to Frasnian Kap Kolthoff series; the early Famennian Kap Graah series; and the Famennian Celsius Bjerg series. Each series is separated by angular unconformities, and the ages are identified on the basis of vertebrate fossils (Jarvik, 1961; Friend et al., 1983).

In a reexamination of the lithostratigraphy of the basin, Olsen and Larsen (1993) divided the deposits into four new groups based on sedimentary facies correlations. Their revised stratigraphy combines rocks across marked angular unconformities, however, which we find awkward. We therefore favor the stratigraphic subdivision proposed by Bütler (1959). Our studies have focused on paleomagnetic and isotopic sampling of the Basis, Kap Kolthoff, and Kap Graah series in two
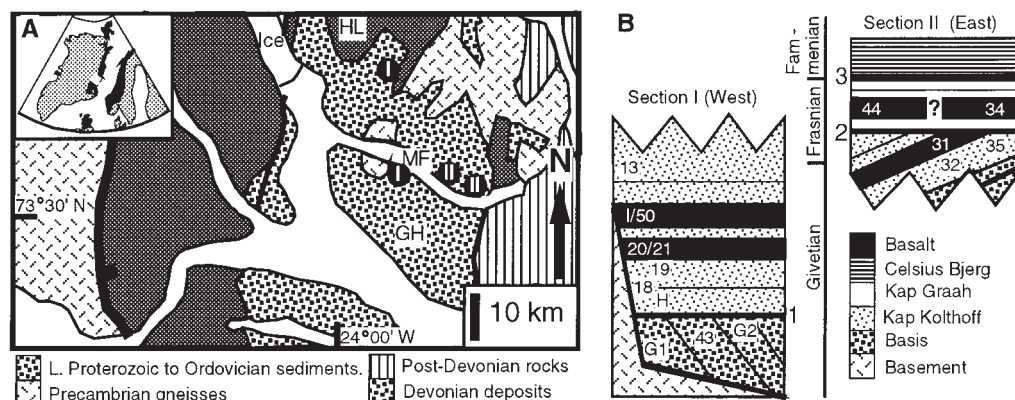

Figure 1. A: Map of field area in East Greenland. Location is marked by white box in index map, where black marks extent of Caledonides before opening of North Atlantic Ocean. Thin lines—faults; thick lines—fjord region detachment zone; black circles—sample locations; MF—Moskusoksefjord; HL—Hudson Land; GH—Gauss Halvø (I/II marks section I and II, each compiled from two localities). B: Simplified stratigraphic column of Devonian deposits in Moskusoksefjord is after Bütler (1959). Numbers within columns refer to sampling sites. Thin lines mark bedding and thick lines mark unconformities (1, 2, and 3).

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Figure 2. Examples of thermal demagnetization, approximate sampling positions, magnetostratigraphy, and suggested paleomagnetic correlation between sections I and II. Note that unconformities in two sections are correlated rather than placing section II on top of section I, i.e., introducing second unconformity (Fig. 1B). In Zijderveld diagrams, solid symbols represent points in horizontal plane, open symbols represent points in vertical plane. In stereoplot, closed symbols represent positive inclinations, open symbols represent negative inclinations. All data are shown in bedding-corrected coordinates. Section II stereoplots show individual sample directions, whereas section I stereoplots, for reasons of simplicity, are shown as site-mean directions with α_{95} confidence circles.
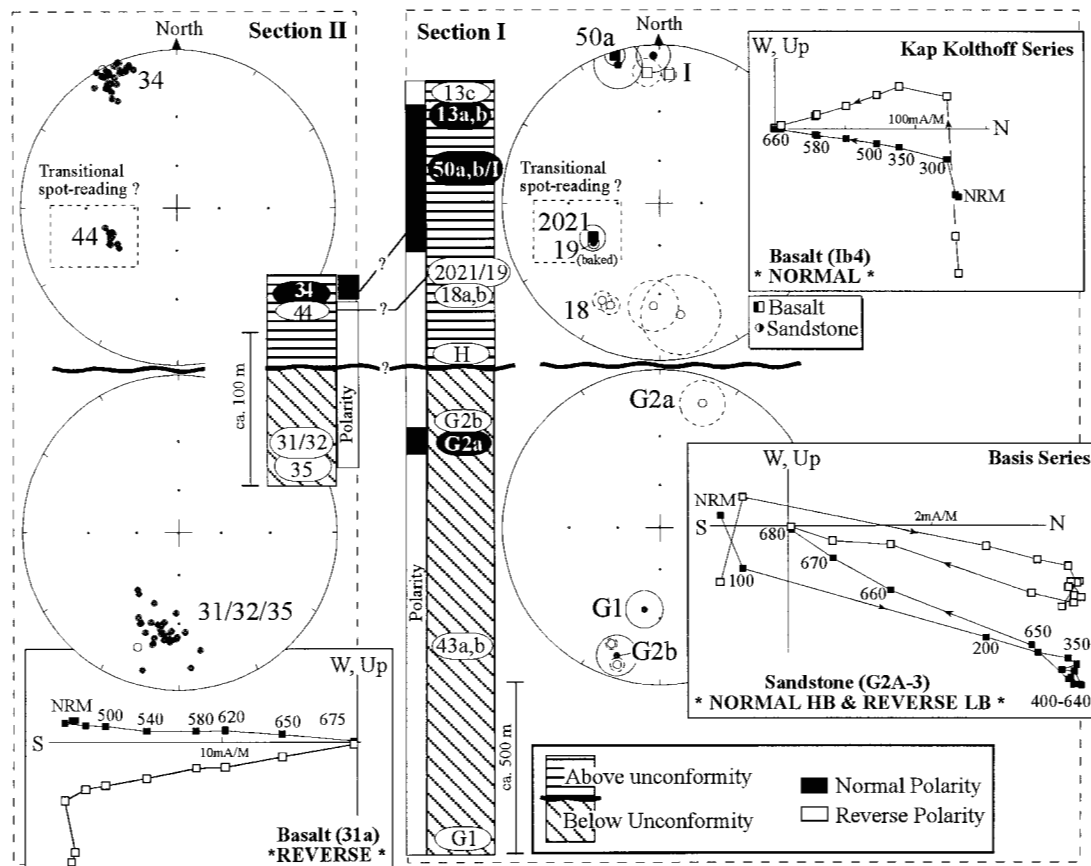
TABLE 1. MEAN DIRECTIONS OF
EAST GREENLAND "DEVONIAN" BASIN (LAT. 73.7°N, LONG. 23.7°W)

| S/P | In-situ | | | | | Bedding corrected | | | |
	Dec	Inc	N	α_{95}	k	Dec	Inc	α_{95}	k
Above unconformity:									
I/N	353.1	-1.4	5	16.9	21.5	352.6	-2.4	11.7	43.4
I/R	193.5	-21.9	4	21.8	18.7	192.4	-20.6	21.3	19.6
II /N	333.9	3.8	33*	1.7	213.3	333.5	4.8	1.7	213.3
C/M	358.8	8.6	10	14.6	11.9	358.1	7.6	13.4	14.0

Paleomagnetic south-pole:
Latitude = 20.1°S, Longitude = 338.3°E, dp/dm = 6.8°/13.5°

S/P	Dec	Inc	N	α_{95}	k	Dec	Inc	α_{95}	k
Below unconformity:									
I/N	020.4	6.1	11*	9.7	23.3	019.1	-10.5	9.7	23.3
I/R	194.7	-3.0	4	28.0	11.7	197.7	6.1	24.6	14.9
II/R	176.3	13.5	3	6.4	377	190.5	22.5	7.7	256.6
C/M	188.5	3.0	8	14.6	15.4	195.2	13.0	11.6	23.9

Paleomagnetic south-pole:
Latitude = 9.1°S, Longitude = 321°E, dp/dm = 6°/11.8°

Anomalous basalt sites:
Combined I (44), II (20 and 21/ baked sandstone 19); cf. Figs. 2 & 3 and text

	Dec	Inc	N	α_{95}	k	Dec	Inc	α_{95}	k
	244.1	40.8	3	13.3	87.5	243.7	42.0	11.7	111.5

Note: S/P = Section and polarity (C/M = Combined/ Mixed)
 Dec/Inc = mean declination/ inclination.
 N = number of sites (or samples*) (total number of samples included in statistics = 374).
 α_{95} = 95% confidence circle.
 k = precision parameter.
 dp/dm = semi-axis of the 95% confidence ovals.

sections across two previously defined intrabasinal unconformities (Fig. 1, A and B).

Section I

The Basis series represents the oldest Devonian deposits in East Greenland (Fig. 1B; Bütler, 1959). The unit is only exposed in west-central Moskusoksefjord (Fig. 1A) and consists of conglomerates interfingering with red sandstones which dip 35° to 70° eastward (sites G1, 43, and G2). The Kap Kolthoff series is between the first and second intrabasinal unconformities, and the lowermost part of this series was sampled in east-central Moskusoksefjord (Fig. 1A, sites H, 18, and 19). The stratigraphically highest of these sites (site 19) was sampled directly below a 10-m-thick basalt flow (sites 20 and 21). A second basalt flow located 250 m stratigraphically above the first basalt was also sampled in two sites (sites 1 and 50). In the upper part of the Kap Kolthoff series, a red conglomeratic sandstone, the Snehvide Formation of Olsen and Larsen (1993), was sampled at two localities at east-central Dybendal (Fig. 1A, site 13).

Section II

In eastern Moskusoksefjord, the Basis and Kap Kolthoff series are mapped as conformable and are separated from the Kap Graah series by an angular unconformity (Fig. 1B; Bütler, 1959). Sandstone and basalts of the Kap Kolthoff series were sampled in three sites (Fig. 1B; sites 31, 32, and 35). Basalts within the lowermost Kap Graah
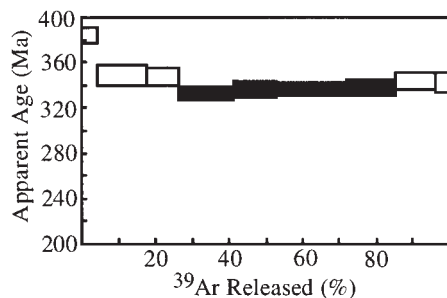
Figure 3. Furnace step-heating spectra for plagioclase from lowermost basalt in Kap Graah series (site 44). Shaded steps (4–7, 59.1% of released ^{39}Ar) define near-plateau age of 335.6 ± 3.1 Ma (2σ confidence level, including J-value). These steps all yield >90% radiogenic ^{40}Ar.
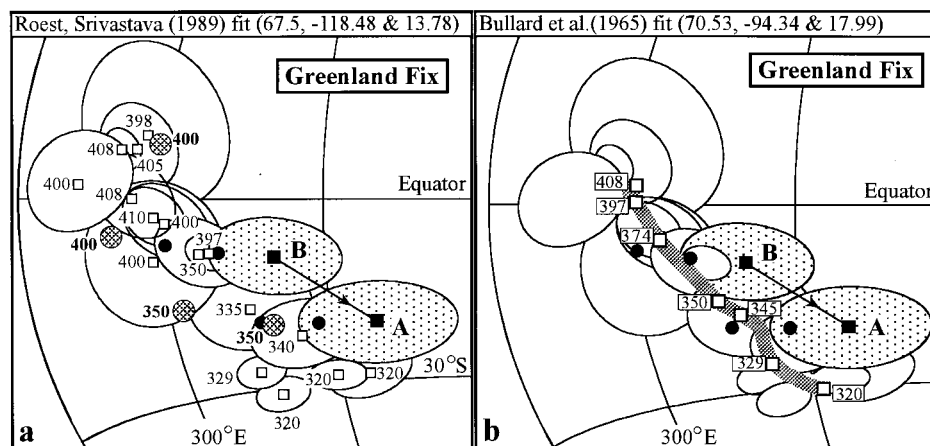

Figure 4. a: Devonian and Carboniferous poles from Laurentia (North America and Scotland; open squares with 95% confidence ovals) and Baltica (patterned larger circles with bold age numbers) in North American coordinates (Bullard et al., 1965, fit, lat 88°N, long 27°W, Euler angle = –38°) and subsequently rotated into Greenland coordinates (Labrador Sea closed) using fit of Roest and Srivastava (1989). Reference poles 410–320 Ma were listed in Torsvik et al. (1996) (except entry 20 in Table 1). b: As in a, but using Bullard et al. (1965) fit for Labrador Sea reconstruction (Euler pole and rotation angle calculated from their Greenland-Europe and Europe–North America fits). For diagram simplicity, only Laurentia error ellipses and smooth spline path derived from Laurentia and Baltica data (smoothing parameter = 200; graded according to Q-factor; cf. procedure in Torsvik et al., 1996) are shown. In both fits, Greenland poles plot to east but overlap with Devonian and Carboniferous poles. Misfit is best reduced with original Bullard et al. (1965) fit. Misfit can also be reduced by invoking local block rotations on vertical axes for poles B (below unconformity) and A (above unconformity). Black circles indicate effect of compensating for local counterclockwise rotations about vertical axis in 10° and 20° steps. Note that pole A is in much better correspondence with Early Carboniferous poles than previously claimed Devonian (Frasnian) age.

series were sampled directly above this locality (Fig. 1B, site 34). The lowest basalt horizon in the Kap Graah series was also sampled 10 km farther northwest (site 44). Within the ~10-m-thick basalt horizon, thin (<5 cm) layers of sand are discernible, indicating that some basalt horizons may include more than one flow.

PALEOMAGNETIC RESULTS

The natural remanence magnetization (NRM) was measured with a JR5A (Trondheim) and a 2G Squid (Ann Arbor) magnetometer. The NRM stability of 430 samples was tested by stepwise thermal demagnetization (MMTD60 furnace), and ancient remanence components were isolated using a least square algorithm.

In section I, at least four polarity transitions are identified, and in two red sandstone units (G2 and 13) both polarities occasionally were identified in individual samples (Fig. 2, site G2A). Characteristic remanence components in red sandstones are carried by hematite; this is also commonly the case for the basalts (Fig. 2), which are typically of high-temperature deuterically oxidized (class II–III) character, remanence being carried by low-titanium titanomagnetites and hematite. Sites below the Basis–Kap Kolthoff unconformity (section I) are dominated by reverse polarity directions and south-southwest declinations and positive inclinations (Fig. 2). The overlying strata are dominated by normal polarity components and north-northwest declinations.

The angular unconformity in section II previously has been interpreted to represent the second unconformity in the Devonian basin (Fig. 1B). However, paleomagnetic directions from sections I and II concur extremely well (Fig. 2 and Table 1), indicating that the two unconformities are in fact the same. Note, for example, the directional similarity between basalt site 34 of section II with normal polarity sites from section I (above unconformities), and south-southwest–directed reverse polarity directions with positive inclinations (sites 31, 32 and 35, Section II) that

match sites G1 and G2b from section I (Fig. 2 and Table 1). The unusual paleomagnetic signature of samples from basaltic sites 44 (section II) and 20/21 (section I) provides an important correlation "fingerprint" (Fig. 2). The basalt above the unconformity in section I and II represents the same flow and not two separate flows, as previously thought. Anomalous directional results from these basaltic flows (44 and 20/21) are interpreted as a spot reading during a field reversal (probably reverse [R] to normal [N]; sites 18 [R] → 20/21 [transitional] → 50/I [N]). Remagnetization of both flows is ruled out, because this anomalous, steep, positive, west-southwest direction is not compatible with any Devonian or younger directions from Laurentia. In addition, sites 18 and 19 provide a positive contact test; baked sandstone (site 19) directionally conforms to the overlying basalts (site 20/21), whereas sandstones from site 18 (20 m below 20/21) yield southwesterly declinations and negative inclinations (Fig. 2).

Fold tests were statistically insignificant at the 95% confidence level. However, sites above both unconformities are practically flat lying, whereas sites below unconformities have north-northeast–south-southwest fold axes that are subparallel to the remanence directions. The stratigraphically linked reversal pattern, when combined with the transitional directions in both sections (Fig. 2), clearly indicates a primary, early diagenetic origin of the remanence components.

^{40}Ar/^{39}Ar RESULTS

Plagioclase from the basalt flow at site 44 was dated by ^{40}Ar/^{39}Ar furnace step heating at the Massachusetts Institute of Technology (MIT) argon laboratory. The release spectrum yields a near-plateau age of 335.6 ± 3.1 Ma. (Fig. 3). Analytical and statistical details follow those in Hodges and Bowring (1995), except that a newer version (3.1.3) of the MIT Ar isotopic analysis program was used. The plagioclase cooling age is interpreted to date the time of extrusion of the basaltic lava.

DISCUSSION

The paleomagnetic signatures across the Basis–Kap Kolthoff and Kap Kolthoff–Kap Graah unconformities in the eastern and western side of the Devonian basin are broadly similar. Therefore, we argue that they are time correlative and do not represent two different unconformities within the basin. This implies that the cumulate stratigraphic thickness of the basin actually is <6 km, rather than the earlier reported >8 km. A stratigraphic link between the two unconformities at each side of the basin is not depicted in existing maps or profiles (Bütler, 1959; Olsen and Larsen, 1993). Additional mapping is needed to evaluate the validity of the new proposed structural and stratigraphic model of the basin.

Paleomagnetic poles from below (B, Fig. 4) and above (A, Fig. 4) the first Devonian unconformity are significantly different. Compared with

Figure 5. Early Carboniferous reconstruction (inset: mid-Late Devonian reconstruction) based on combined Laurentia and Baltica smooth path (Fig. 4b). Labrador Sea and North Atlantic reconstruction used Bullard et al. (1965) fits, which minimize paleomagnetic pole misfit (see Fig. 4). Paleomagnetic south poles (North American coordinates) used for reconstructions are 8.6°S and 288.1°E (ca. 374 Ma) and 21.5°S and 300.8°E (ca. 345 Ma; based on smooth path in Fig. 4b). GGF—Great Glen fault system; MTFZ—Møre-Trøndelag fault zone. Patterns show proxy Early Carboniferous basins of North Atlantic region.
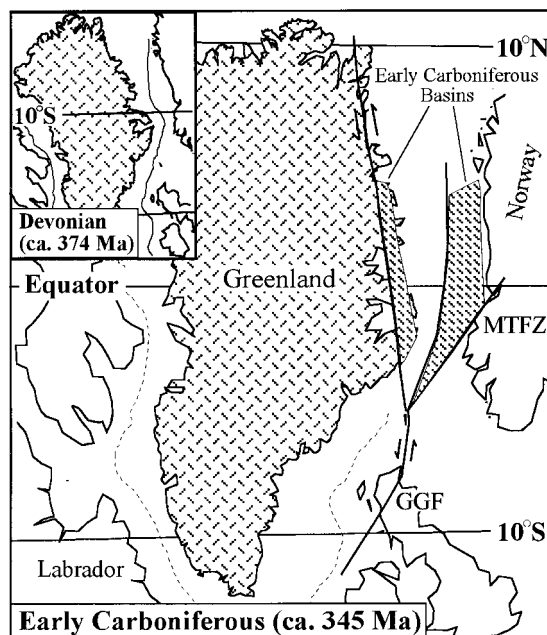
Laurentian (North America and Scotland) and Baltic poles, pole B partly overlaps Middle to Late Devonian poles (Givetian and Frasnian), whereas pole A plots within the Early Carboniferous (Fig. 3B). The latter relation is at clear variance with the previously postulated Late Devonian, or Frasnian, age (ca. 377–367 Ma; Harland et al., 1990). The paleomagnetic reference poles for this time interval are not well constrained (Fig. 4). Pole A, however, clearly plots in the vicinity of Carboniferous reference poles, and within the 345–329 Ma segment of a combined Laurentia-Baltica apparent polar wander path (Fig. 4B). A Carboniferous age is further confirmed by the ca. 336 Ma $^{40}Ar/^{39}Ar$ age from the lowermost basalt (site 44) in the Kap Graah series.

If this Carboniferous age is representative, it has serious paleontological and evolutionary implications. The tetrapod *Ichthyostega* (Jarvik, 1961), regarded as the earliest well-preserved fossil of animals that walked on land, occurs in the deposits above our sampling sites. *Ichthyostega*, found in the Celsius Bjerg series, had been regarded as having evolved during the mid–Late Devonian (Fammenian) (Jarvik, 1961; Friend et al., 1983).

The East Greenland poles overlap with the Laurentia and Baltic poles after reconstructing the Labrador Sea, and the collective data imply a near-equatorial position of Greenland (Fig. 5) during Late Devonian and Early Carboniferous time. A minor, systematic, easterly offset of both Greenland poles is indicated by our data when compared with published reference poles (Fig. 4); the overall misfit of these poles is, however, minimized in a Bullard et al. (1965) fit. This may indicate that the amount of pre-drift, Labrador Sea extension previously has been underestimated. Alternatively, the fits can be improved by invoking Late Devonian to Early Carboniferous, local, counterclockwise block rotation of the basin. Because Baltica had docked obliquely against Laurentia from the south (Torsvik et al., 1996), the resulting sinistral transpression could have caused strain partitioning between local rotations, folding, and left-lateral faulting. Although we envision the "Devonian" basin of East Greenland as a supradetachment basin (Hartz and Andresen, 1995), rather than a basin controlled by strike-slip faults (Larsen and Bengaard, 1991), such local block rotations are compatible with a link to well-known left-lateral faults within the Caledonian orogen, such as the Great Glen fault in Scotland and/or the Møre-Trøndelag fault zone in west-central Norway (Fig. 5).

ACKNOWLEDGMENTS

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