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The Tornquist Sea and Baltica–Avalonia docking

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Abstract

Early Ordovician (Late Arenig) limestones from the SW margin of Baltica (Scania–Bornholm) have multicomponent magnetic signatures, but high unblocking components predating folding, and the corresponding palaeomagnetic pole (latitude = 19°N, longitude = 051°E) compares well with Arenig reference poles from Baltica. Collectively, the Arenig poles demonstrate a midsoutherly latitudinal position for Baltica, then separated from Avalonia by the Tornquist Sea.

Tornquist Sea closure and the Baltica–Avalonia convergence history are evidenced from faunal mixing and increased resemblance in palaeomagnetically determined palaeolatitudes for Avalonia and Baltica during the Mid-Late Ordovician. By the Caradoc, Avalonia had drifted to palaeolatitudes compatible with those of SW Baltica, and subduction beneath Eastern Avalonia was taking place. We propose that explosive vents associated with this subduction and related to Andean-type magmatism in Avalonia were the source for the gigantic Mid-Caradoc (c. 455 Ma) ash fall in Baltica (i.e. the Kinnekulle bentonite). Avalonia was located south of the subtropical high during most of the Ordovician, and this would have provided an optimum palaeoposition to supply Baltica with large ash falls governed by westerly winds.

In Scania, we observe a persistent palaeomagnetic overprint of Late Ordovician (Ashgill) age (pole: latitude = 4°S, longitude = 012°E). The remagnetisation was probably spurred by tectonic-derived fluids since burial alone is inadequate to explain this remagnetisation event. This is the first record of a Late Ordovician event in Scania, but it is comparable with the Shelveian event in Avalonia, low-grade metamorphism in the North Sea basement of NE Germany (440–450 Ma), and sheds new light on the Baltica–Avalonia docking.

Keywords: Tornquist sea; Baltica; Avalonia; Palaeogeography; K-bentonites; Collision; Remagnetisation

1. Introduction

The Trans-European Suture Zone (TESZ; Fig. 1) has a long history and its early development includes the amalgamation of Avalonia and Baltica along the Thor Suture. Late Ordovician suturing between these two plates eliminated the Tornquist Sea that had separated these palaeocontinents during most of the Ordovician (Cocks and Fortey, 1982, 1990; Torsvik and Trench, 1991a; McKerrow et al., 1991; Torsvik et al., 1993, 1996). The TESZ was further developed and/or rejuvenated through Variscan and Alpine orogenic events and is now largely concealed by deep sedimentary basins of late Palaeozoic to Tertiary age

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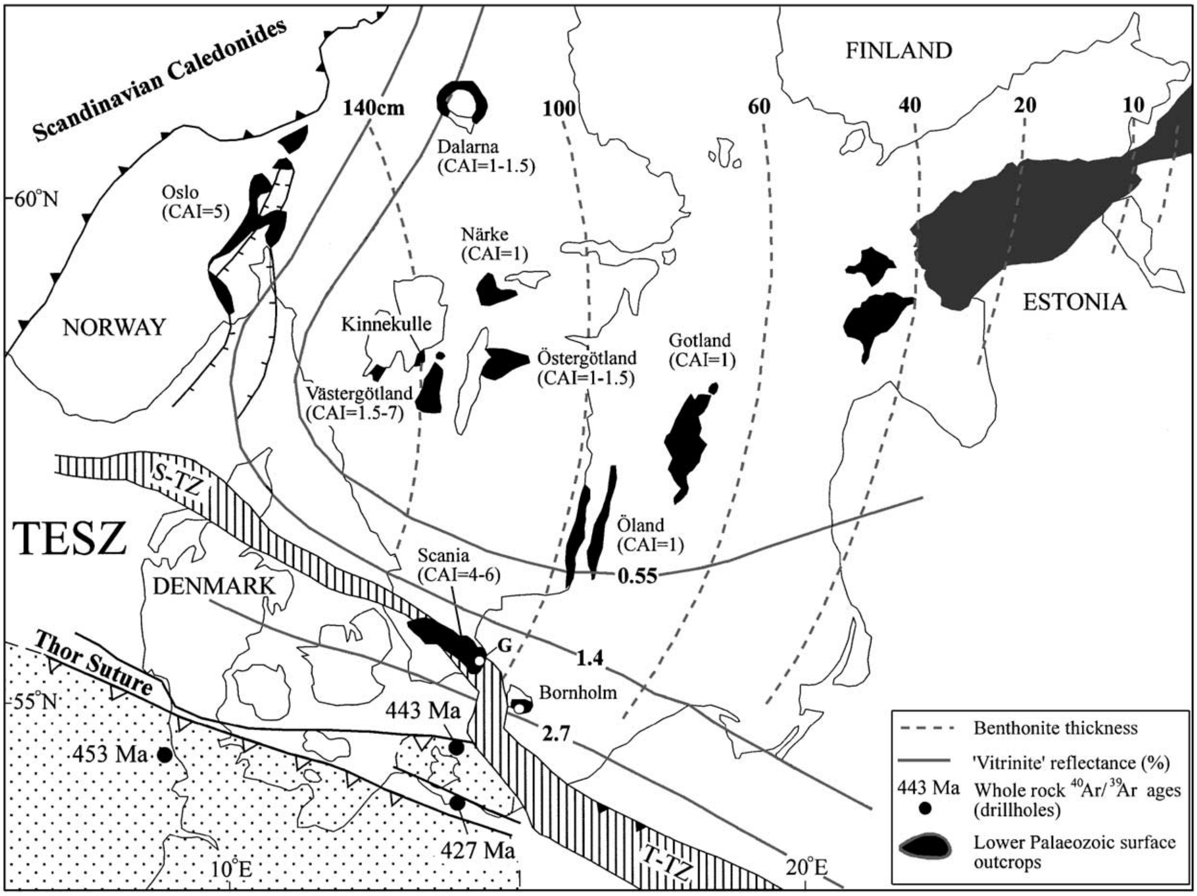


Fig. 1. Scandinavian Caledonide and Tornquist margin (Trans-European Suture Zone; TESZ; Pharaoh, 1999) of Baltica and the location of Gislövshammar (G) (SE Scania) and the island of Bornholm. Map also shows distribution of Cambrian to Silurian surface outcrops, conodont alteration indexes (CAI; Bergström, 1980) from Ordovician limestones, Cambrium Alum shale 'vitrinite-like' reflectance isolines (0.55–2.7%; Buchardt et al., 1997) and isopach map of the Kinnekulle K-bentonite (c. 140–0 cm from west to east; Bergström et al., 1995). $^{40}Ar/^{39}Ar$ whole-rock ages from drill holes (interpreted as low-grade metamorphic ages) from Frost et al. (1981; 453 Ma) and Dallmeyer et al. (1999; 443 and 427 Ma). S-TZ = Sorgenfrei–Tornquist Zone; T-TZ = Tornquist–Teisseyre Zone.

(Pharaoh, 1999). The geological record is therefore to a large extent only known from borehole information (e.g. McCann, 1998).

The Scania area of Sweden is located at the SW edge of Baltica (Fig. 1) and is transected by the Sorgenfrei–Tornquist Zone (S-TZ). S-TZ is part of the TESZ, it was mostly active during late Palaeozoic and Mesozoic times, and lies north of the older Thor Suture (nomenclature after Berthelsen, 1998). The bedrock is dominated by Precambrian gneisses and granites covered by Cambrian to Silurian and Meso-zoic–Tertiary deposits. The Precambrian and Palaeozoic rocks were intruded by a large number of Permo-Carboniferous dykes (294 ± 4 Ma; K/Ar; Klingspor, 1976); the NW–SE orientation of which is parallel to the S-TZ. The Palaeozoic geology of the island of Bornholm (Fig. 1) resembles that of Scania, but Permo-Carboniferous dykes are largely absent.

During the Cambrian and most of the Ordovician, Scania and Bornholm lay on a passive shelf margin, but in Late Ordovician–Early Silurian times these areas formed the foreland to the Avalonia–Baltica collision. With the geological evidence for collisional activity along the Thor Suture (see review in Pharaoh, 1999), some indication of elevated temperatures should be expected in these otherwise weakly or

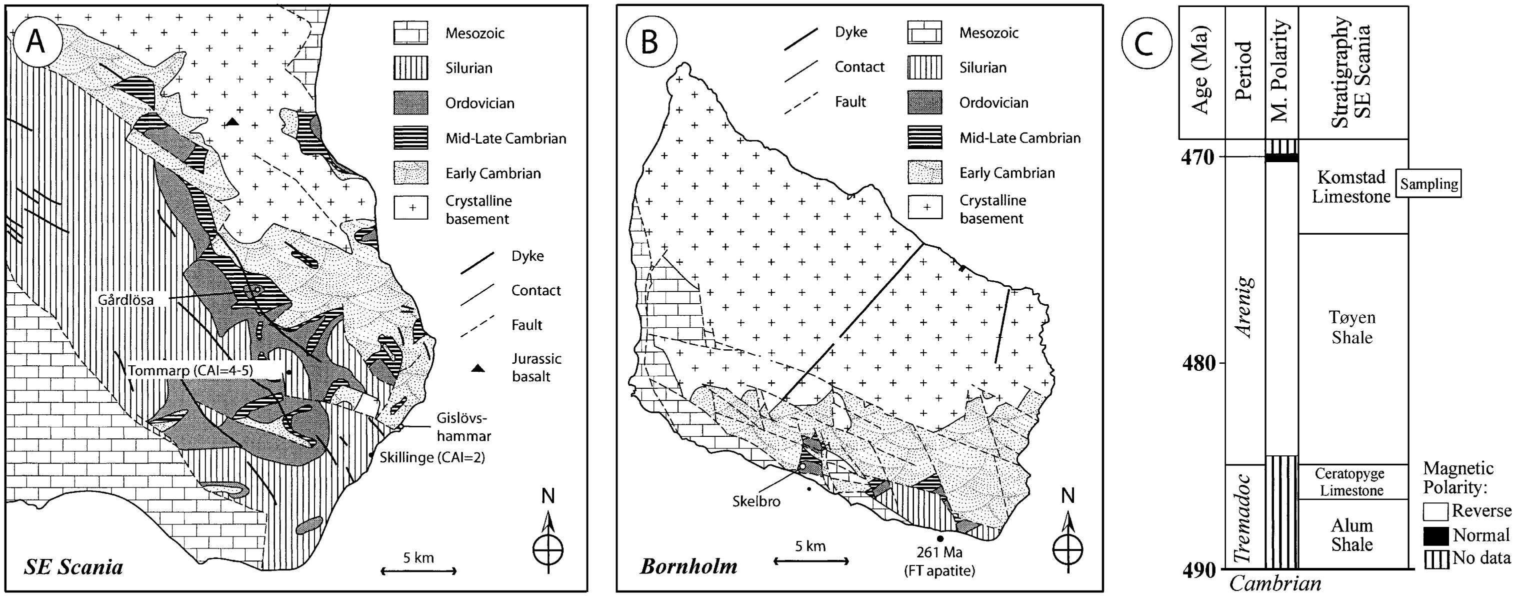


Fig. 2. (A) Simplified geological map of SE Scania and the Gislövshammar and Gårdlösa sampling locations. Dykes are of Permo-Carboniferous age. Tommarp CAI from Mid-Ordovician limestone (Bergström, 1980); Skillinge CAI from Upper Silurian limestone (Jeppsson and Laufeld, 1986). (B) Simplified geological map of Bornholm and the location of the Skelbro site (Komstad Limestone). An offshore locality of Silurian tuffaceous sandstone yielding a FT apatite age of 261 Ma is shown (Hansen, 1995; see text). Marked dykes at Bornholm are Precambrian in age. (C) Stratigraphic position of the Komstad Limestone and sampling levels (six sites). Magnetic polarity after Torsvik (1998). Time scale of Tucker and McKerrow (1995).

nondeformed thin Cambro–Ordovician platform sediments. Indeed, Ordovician limestones from Scania show high conodont colour alteration indexes (CAI = 4–6), and vitrinite-like reflectance (R_o) values for the Cambro–Ordovician Alum shales (Fig. 1) show an apparent increase toward the Thor Suture (Bergström, 1980; Buchardt et al., 1997).

CAI and R_o values suggest thermal disturbance in Scania, but neither data set offers unequivocal temporal constraints for this heating. Conversely, magnetic overprinting or remagnetisation can provide temporal constraints if a well-defined apparent polar wander (APW) path exists. This contribution is threefold. First, we report on the magnetic signature of the Komstad Limestone Formation in Scania and Bornholm (Figs. 1 and 2) and demonstrate a Late Ordovician magnetic overprint in Scania that we link with the docking of Baltica with Avalonia. Secondly, we develop an Ordovician closure model for the Tornquist Sea that complies with geological and geophysical constraints. Thirdly, we propose that Late Ordovician volcanic ash remnants in Baltoscandia (Kinnekulle K-bentonite) were produced during eruption from a volcanic centre in Avalonia now represented by calc–alkaline intrusions and ash flows in central England. This carries important implications not only for palaeogeography and palaeotectonic reconstructions, but also for models of atmospheric circulation.

2. Sampling details

The Komstad Limestone Formation is a tongue of the Baltoscandian Orthoceras Limestone and reaches a stratigraphic thickness of 10–15 m in SE Scania and 5 m at Bornholm (Nielsen, 1995). We have sampled the Komstad Limestone at Gislövshammar and Gårdlösa (Scania) and Skelbro (Bornholm). Four sites from Gislövshammar were collected at different stratigraphic levels, covering a thickness of 4.5 m within the *Asaphus expansus* and *Megistaspis limbata* trilobite zones (Late Arenig—Fig. 2). The lower few metres at Gislövshammar were not sampled (basal Komstad and Tøyen shale) due to inaccessibility (only mapped by scuba diving; Nielsen, 1995). The Gårdlösa section is located 15 km NNW of Gislövshammar, and we sampled one site that covers 1 m of the lower part of the *M. limbata* trilobite zone (Gårdlösa-4a locality in Nielsen, 1995). The Skelbro section is located at the island of Bornholm, 60 km SE of Gislövshammar, and immediately to the northeast of the S-TZ (Fig. 1). Our sampling site embraces 1.6 m of the Komstad Limestone within the *M. limbata* and *Megistaspis simon* trilobite zones. The Gislövshammar, Gårdlösa and Skelbro sections are gently tilted ($\leq 8°$), but the age of tilting/folding is not constrained.

3. Palaeomagnetic experiments

The Natural Remanent Magnetization (NRM) was measured with a JR5A and a 2G DC Squid magnetometer, and the stability of NRM was tested by thermal and alternating field (AF) demagnetisation. Characteristic remanence components were calculated with least square regression analysis (http:/www.geodynamics.no). Thermomagnetic analysis (TMA) was carried out on a horizontal translation balance.

3.1. Scania

NRM intensity for Scania samples (Gislövshammar and Gårdlösa) average to 6 mA/m. Samples behaved exceptionally well to both thermal and AF demagnetisation, and three magnetisation components have been readily identified. A low unblocking or low-coercivity component (LB) has northerly declinations and steep positive inclinations (Fig. 3A and B). LB is demagnetised between 100 and 275 °C or in AF fields below 8–10 mT. An intermediate component (IB) has southerly declinations and positive inclinations, demagnetised below 375–525 °C or in AF fields less than 20–30 mT. Finally, a high unblocking or high-coercivity component (HB) has SE declinations and steep positive inclinations (Fig. 3A and B). Component HB has maximum unblocking temperatures in the 520–580 °C range. The thermal demagnetisation spectra and TMA (Curie temperatures c. 560–580 °C; Fig. 3C) point to magnetite as the bulk remanence carrier. Samples were thermochemically unstable and a substantial increase in saturation magnetisation was observed during cooling. Isothermal remanent magnetisation curves were saturated in fields below 500 mT and remanence coercivity forces were typically 40 mT (Fig. 3D).

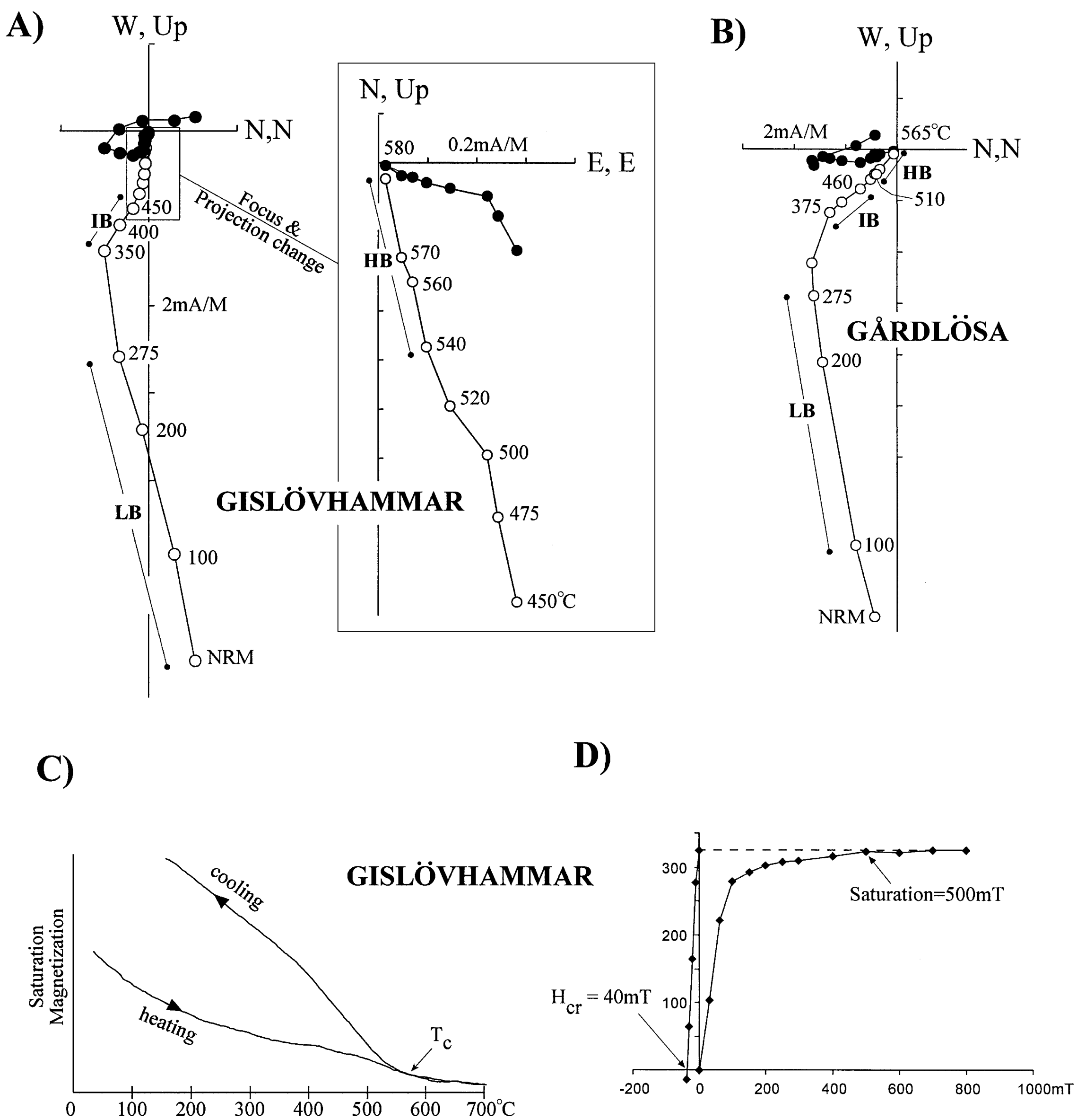


Fig. 3. (A) Typical example of thermal demagnetization of a Komstad Limestone sample from Gislövshammar (Scania). Right-hand diagram shows a blow-up of the central part of the left-hand diagram, and projected in the E–W plane. In orthogonal vector plots, solid (open) symbols denote points in the horizontal (vertical plane). LB, IB and HB denote low-, intermediate- and high-blocking components (cf. text). Numbers are in degrees Celsius. (B) Example of thermal demagnetisation of Komstad Limestone sample from Gårdlösa (Scania). (C) Typical thermomagnetic analysis of a Komstad Limestone sample; T_c = Curie temperature. (D) Typical isothermal-remanent acquisition curve for a Komstad Limestone sample; H_{cr} = remanence coercivity force.

Site-means for all three remanence components are very well grouped (Fig. 4A and Table 1). The difference in bedding between the five sites is small, but component HB passes a classic positive fold test at the 95% confidence level (Fig. 4A). A prefold origin for component IB is also indicated by an increase in the statistical parameter k during stepwise unfolding (Fig. 4A), but the test is not statistically significant. Conversely, component LB shows a decrease in k during unfolding (suggesting a postfold origin), but the test is not statistically significant. LB components, however, are similar to the present earth's field direction/axial dipole field (Fig. 4A) and probably represent a Cenozoic-to-

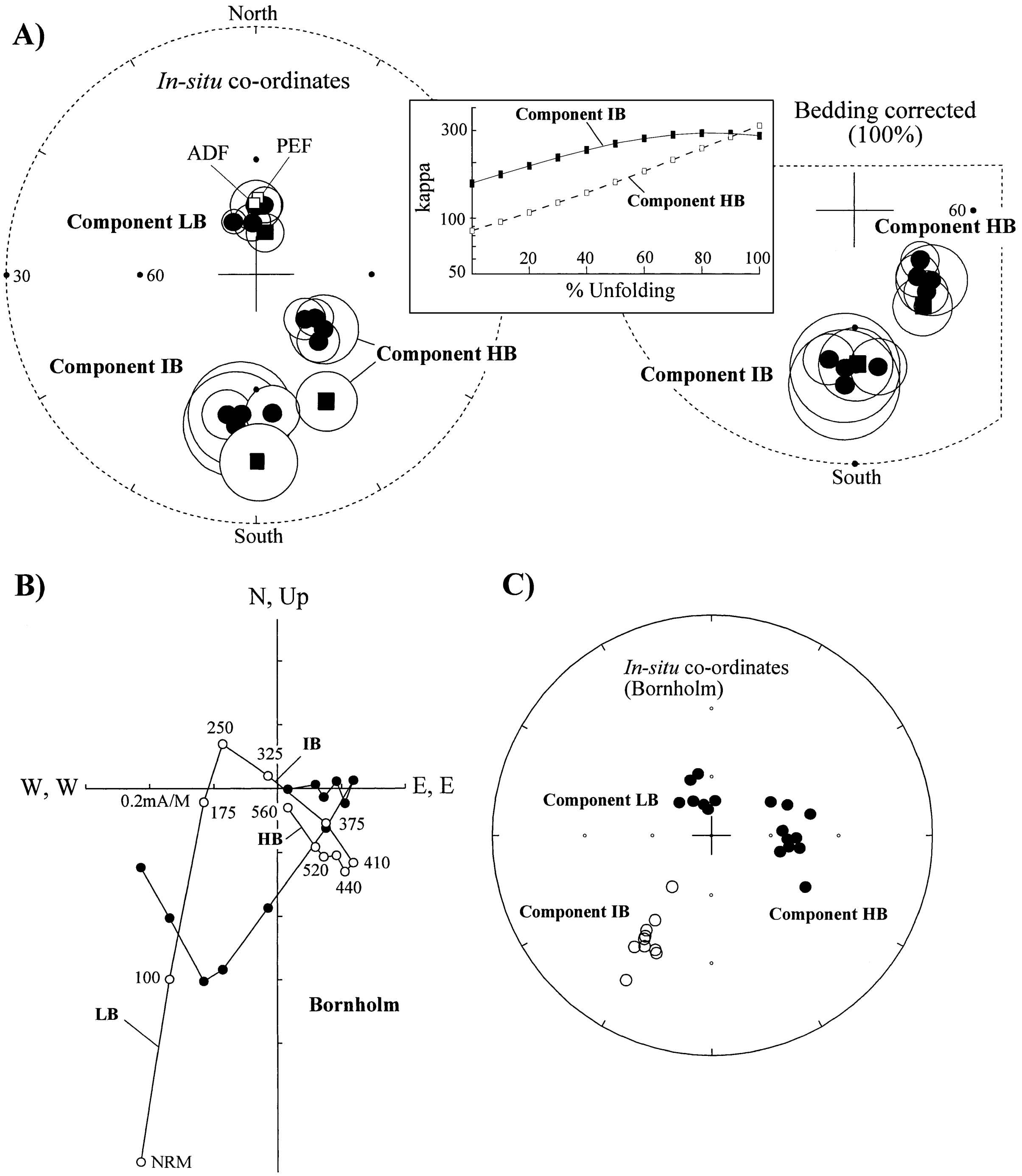


Table 1
Site means (IB and HB) from the Early Ordovician (Late Arenig) Komstad Limestone

Site (strike/dip)	Component IB, Dec°/Inc°	N	α_{95}	Component HB, Dec°/Inc°	N	α_{95}
Scania						
1 (64/4°SE)	186/54	3	12.5	129/67	6	8.8
2 (64/4°SE)	173/54	10	6.5	137/66	12	5.4
3 (58/6°SE)	188/51	5	12.3	133/73	10	5.4
4 (52/2°SE)	192/53	7	5.9	127/71	12	4.4
5 (268/8°N)	180/43	10	8.5	151/53	11	7.2
Mean sites	184/51	5#	6.1	137/66	5#	8.4
Bedding corrected	182/50		4.5	137/64		4.4[a]
Bornholm						
6 (088/4°S)	212/ – 33	10	6.7	091/51	10	8.9
Bedding corrected	213/ – 36			096/51		
Combined sites	–	–	–	127/65	6#	11.5
Bedding corrected	–	–	–	128/63		9.2

Palaeomagnetic poles	Lat.	Long.	(dp/dm)	Interpreted magnetic ages
Scania IB (bedding corrected)	4°S	012°E	(4/6)	Late Ordovician (Ashgill)
Scania HB (bedding corrected)	18°N	044°E	(6/7)	Early Ordovician (Late Arenig—primary)
Bornholm IB (in situ)	46°N	149°E	(4/8)	Permian (250–260 Ma)
Bornholm HB (bedding corrected)	22°N	081°E	(8/12)	Early Ordovician (Late Arenig—primary)
Combined Scania and Bornholm HB (bedding corrected)	19°N	051°E	(11/15)	Early Ordovician (Late Arenig—primary)

Sampling locations are Gislövshammar (sites 1–4), Gårdlösa (site 5) (mean coordinates Scania: 55.5°N and 14.3°E) and Bornholm (site 6—Skelbro coordinates: 55.1°N, 14.9°E). Average sampling: 55.3°N, 14.6°E; Dec°/Inc° = Mean declination/inclination; N = samples (# sites); α_{95} = 95% confidence circle; IB/HB = intermediate/high unblocking temperatures or coercivity components; Lat. = latitude; Long. = longitude; dp/dm = semiaxes of the cone of 95% confidence about the pole.

[a] Positive fold test at the 95% confidence level.

Recent viscous magnetisation; LB is not further evaluated.

3.2. Bornholm

Bornholm samples (Skelbro) yielded an order of magnitude lower NRM intensities (mean 0.6 mA/m). Three remanence components were also identified from Bornholm (Fig. 4B). LB and HB components are broadly similar to those from Scania, but IB components differ. IB shows southwest declinations with negative inclinations (Fig. 4B,C). LB and IB components were demagnetised at mean temperatures of c. 200 and 450 °C, respectively. Component HB had

Fig. 4. (A) Komstad Limestone Scania site means shown in in situ (left diagram) and bedding-corrected (right diagram; only HB and IB) coordinates. Note that both stereoplots are magnified and they only show 30–90° inclinations. Mean directions are plotted with α_{95} confidence circles. In stereoplots, open (closed) symbols denote negative (positive) inclinations. ADF = Axial Dipole Field; PEF = Present Earth Field; Centre diagram shows the variation in the statistical precision parameter kappa (k) for component IB and HB as a function of percentage unfolding. Component HB, 100% unfolded, is statistically better than the in situ distribution (95% confidence level). (B) Example of thermal demagnetisation of a Komstad sample from Skelbro (Bornholm). (C) Distribution of sample directions from Skelbro.

maximum unblocking temperatures of 570 °C. Thermomagnetic analysis and the thermal unblocking spectra indicate magnetite as the prime remanence carrier.

4. Primary data and refinement of the Baltic APW path

HB components from Bornholm are broadly similar to those from Scania, but yield somewhat more easterly declinations (compare Fig. 4A and C). A combined bedding-corrected palaeomagnetic pole, however, is not significantly different from a pole based exclusively on Scania data (Fig. 5A); we use the combined pole (Table 1) in the subsequent discussion. All our samples from the Komstad Limestone are late Arenig in age (c. 471 Ma), and the HB pole fully matches the Arenig poles from Baltica (Fig. 5A). HB is of reverse magnetic polarity, which is the expected late Arenig polarity (Fig. 2), and we consider component HB as primary. The remanence is probably of biogenetic/early diagenetic origin and carried by magnetite.

The Palaeozoic APW path for Baltica was last revised in detail by Torsvik et al. (1996). Since then, a new Early Ordovician palaeomagnetic pole has been reported from Russia (Smethurst et al., 1998; 478 Ma

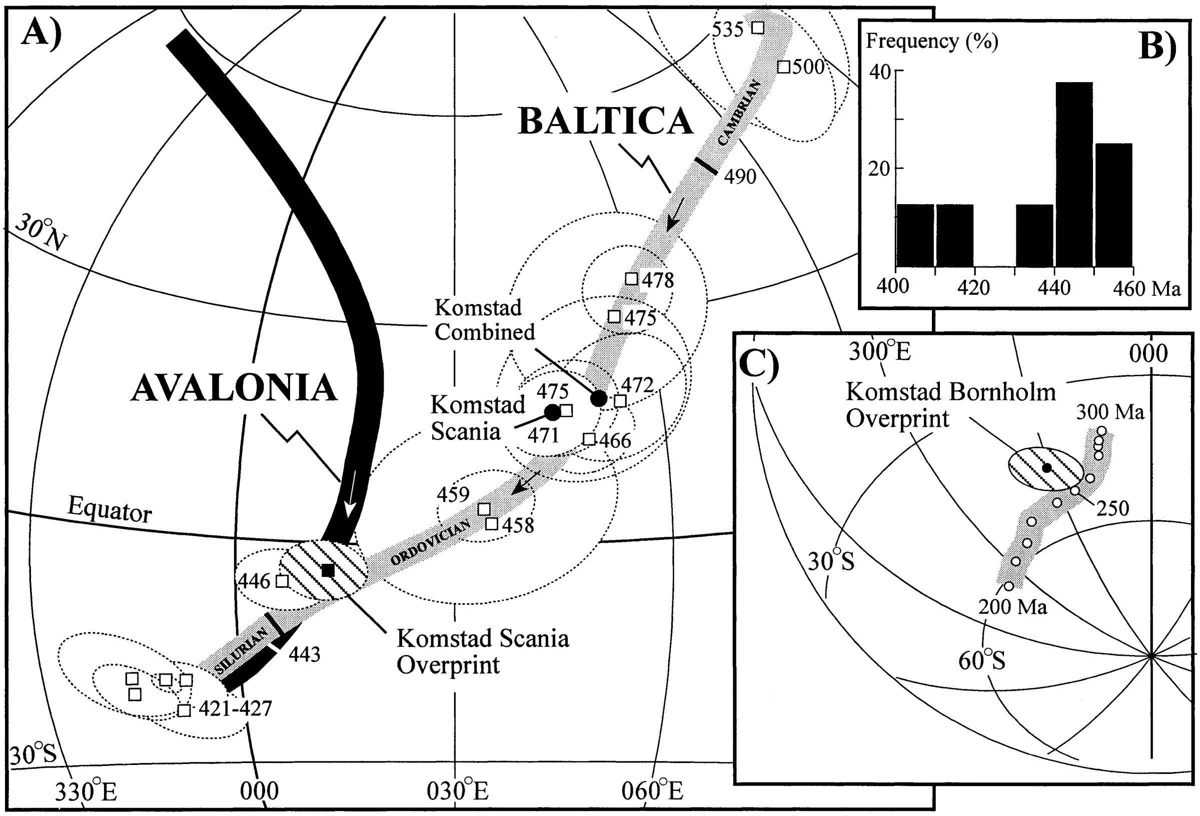


Fig. 5. (A) Cambrian to Mid-Silurian palaeomagnetic poles from Baltica shown with 95% confidence ellipses and a spherically smoothed spline path (Table 2). Equal area projection. Komstad HB pole (primary) is shown with solid circles (combined or only based on Scania sites) while the Komstad IB pole from Scania (proposed Late Ordovician, Ashgill, overprint) is shown with patterned error ellipses. The APW path for Avalonia redrawn from Torsvik et al. (1993). Small numbers are in million years. (B) Compilation of $^{40}Ar/^{39}Ar$ whole-rock ($\geq$ 400 Ma) ages from the North Sea (Frost et al., 1981). Nearly 40% of published ages are confined to the 440–450 Ma interval and probably relate to Caledonian low-grade metamorphism, which we link with Baltica–Avalonia docking. Note the APW path convergence of Baltica–Avalonia at 440–450 Ma and the location of the IB Scania pole at the intersection of the paths (Ashgill). (C) The IB pole from Bornholm compared with a Late Palaeozoic–Mesozoic reference APW path for Europe–North America (Torsvik et al., 2001). The Bornholm overprint pole plots close to c. 250–260 Ma mean poles.

pole in Fig. 5A), two new Cambrian poles were reported from Sweden (Torsvik and Rehnström, 2001; 500 and 535 Ma poles in Fig. 5A), and we incorporate our new Komstad Limestone HB pole (combined Scania–Bornholm) in the APW path construction. The numeric ages of these poles and revised ages for Ordovician and Silurian poles follow the time scales of Tucker and McKerrow (1995) and Tucker et al. (1998). A spherical smooth spline was fitted to the poles (Table 2). The Ordovician and Silurian section of the APW path is broadly similar to that of Torsvik et al. (1996), except with the revised time calibration. The Cambrian section is new, since no reliable Cambrian data existed previously, and the old path of

Table 2
Compilation of the most reliable (i.e. assumed primary, age is well-known and tectonic coherence) Early Cambrian to Silurian palaeomagnetic poles from Baltica, and a new/refined APW path (spherical smoothed spline)

Formation	Stratigraphic age	Age range	Mean	Q	P	α_{95}	Plat	Plon	Splat	Splon	Pole reference
Ringerike Sandstone (HB)	S (Early Ludlov–Middle Pridoli)	424–418	421	7	M	9.1	−19	344.0	−15.4	345.6	Douglass (1988)
Gotland Medby limestone	S (Early Ludlov)	423–421	422	3	N	8.0	−23	351.0	−16.5	346.3	Claesson (1979)
Gotland Follingbo limestone	S (Late Wenlock)	427–425	426	3	N	6.0	−21	344.0	−19.2	349.3	Claesson (1979)
Gotland Dacker limestone	S (Late Wenlock)	427–425	426	4	N	2.0	−19	349.0	−19.2	349.3	Claesson (1979)
Gotland Visby limestone (HB)	S (Early Wenlock)	428–426	427	5	N	5.1	−19	352.0	−19.5	350.0	Trench and Torsvik (1991)
			432						−19.0	353.8	interpolated
			437						−16.3	358.7	interpolated
			441						−12.2	3.4	interpolated
Oslo limestone	O (Late Ashgill)	449–443	446	5	M	5.4	−5.3	6.5	−7.6	10.2	Böhm (1989)
			450						−3.8	17.4	interpolated
			454						0.0	25.2	interpolated
Swedish limestone I(N)	O (Late Llanvirn–Mid Caradoc)	465–452	458	5	N	13.4	3.0	35.0	3.9	33.0	Torsvik and Trench (1991b)
Västergötland (N3)	O (Mid Llandeilo–Early Caradoc)	462–455	459	6	N	4.8	5.0	34.0	5.0	34.8	Torsvik and Trench (1991c)
Västergötland (N1–N2 and R1–R3)	O (Early Llanvirn–Early Llandeilo)	468–463	466	6	M	4.4	14	49.0	12.7	45.6	Torsvik and Trench (1991c)
Komstad limestone	O (Late Arenig)	470–472	471	6	R	9.2	19	51.0	18.9	50.5	This study
Gullhögen (R1+R2)	O (Late Arenig–Early Llanvirn)	474–469	472	6	R	6.8	18.7	54.0	20.3	51.3	Torsvik et al. (1995)
Swedish limestones I(R)	O (Arenig–Llanvirn)	485–464	475	6	R	5.1	18.0	46.0	24.9	53.9	Torsvik and Trench (1991b)
Swedish limestones	O (Arenig–Llanvirn)	485–464	475	5	R	9.0	30.0	55.0	24.9	53.9	Perroud et al. (1992)
St. Petersburg limestone	O (Late Tremadoc–Early Llanvirn)	488–468	478	5	M	3.6	34.7	59.1	30.0	57.3	Smethurst et al. (1998)
			485						41.2	69.5	interpolated
			490						46.9	80.3	interpolated
			495						50.7	92.1	interpolated
Andrarum limestone	C (Late Cambrian)	500	500	3	R	6.8	52	111	52.6	102.9	Torsvik and Rehnström (2001)
Torneträsk formation	C (Nemakitian–Daldynian)	540–530	535	4	R	8.9	56	116	56.0	118.1	Torsvik and Rehnström (2001)

Q = Quality factor (Van der Voo, 1993); P = Polarity (N = Normal, R = Reverse, M = Mixed); Plat/Plon = latitude/longitude original poles; Splat/Splon = latitude/longitude for spline path; individual poles were weighted by the Q factor and a low smoothing parameter (200) was applied (see method descriptions in Torsvik et al., 1992, 1996).

Torsvik et al. (1996) was interpolated between Neoproterozoic (Vendian) and Early Ordovician (Arenig) times.

5. A Late Ordovician remagnetisation event in Scania

IB components from Scania are of reverse polarity, and the palaeomagnetic pole falls on the Late Ordovician segment of the APW path for Baltica (Fig. 5A). The IB pole plots west of Mid-Llandeilo to Mid-Caradoc normal polarity poles, but overlaps with an Ashgill dual-polarity pole from the Oslo region. An Ashgill magnetic overprint is therefore indicated. The difference between in situ and bedding-corrected IB poles is minor (a few degrees of arc), but given (1) that folding/tilting of the rocks is most likely post-Early Silurian (Lindström, 1960), (2) the indication of a prefold magnetisation, and (3) that the IB pole (in either coordinates) matches Late Ordovician poles from Baltica, we employ the bedding-corrected pole (Table 1; Fig. 5A).

Component IB from Scania is the first record of a Late Ordovician magnetic overprinting event in southern Sweden. SE Scania is situated 150 km from the predicted early Palaeozoic margin of Baltica (Thor Suture), and the Late Ordovician remagnetisations may record the collision of Baltica with Avalonia. The IB component is demagnetised in the 375–525 °C range, and if purely thermal in origin, this would suggest considerable reheating in the Late Ordovician. However, magnetic overprinting could be thermoviscous (TVRM) or thermochemical (TCRM) in origin, hence the thermal unblocking temperatures may not be relevant. Furthermore, a minor component overlap with the primary HB component may result in an overestimate of the upper unblocking temperatures.

CAI (4–6) from Scania indicate considerable reheating of the rocks in the region (Fig. 1), although it is difficult to assess the regional pre-Carboniferous significance of the reheating due to the extensive Permo-Carboniferous magmatic activity in the area (see Olsson, 1999). The Gislövshammar section is devoid of exposed Permo-Carboniferous dykes, and no remagnetisations of such ages are encountered in our data. At Tommarp (Fig. 2A), 10 km NW of Gislövshammar, Bergström (1980) reported CAI values of 4–5 from a Mid-Caradoc limestone (Skagen Limestone) that indicate temperatures of 190–400 °C (Epstein et al., 1977). Large dykes are not known in this area, hence, considerable pre-Carboniferous regional reheating could be in evidence. It has appeared perplexing that Jeppsson and Laufeld (1986) remark that Upper Silurian conodonts show relatively low CAI in the very same region where Ordovician CAI are high (see, e.g. Fig. 2A). Different burial levels with a steep thermal gradient can hardly explain this observation, but a Late Ordovician thermal event as we have recognised can readily explain high Ordovician but low Silurian conodont CAI.

R_o values for the Cambro–Ordovician Alum shales (Buchardt et al., 1997) show an apparent increase toward the Thor Suture (Fig. 1), and values of 1.4–2.7% would correspond to temperatures of c. 175–225 °C, assuming a heating or burial time of less than 10 million years (Sweeney and Burnham, 1990). The high palaeotemperatures suggested by Ordovician CAI values and Cambrian Alum Shale R_o values have been explained by Late Silurian–Devonian subsidence (e.g. Buchardt and Lewan, 1990), and Samuelsson and Middleton (1998) argued for a 6.5-km deep basin at the "edge of the Caledonian mountain range" with peak foreland burial in the Mid-Devonian. However, we find no trace of Devonian remagnetisation in the Komstad Limestone, leaving this explanation for the high Ordovician heating values very improbable.

6. The origin of Late Ordovician remagnetisations

When approaching the subject of burial and thermal histories, subsidence curves can be useful in evaluating regional trends related to tectonic episodes through time. The Cambro–Ordovician shelf sequences in Baltica are only a few hundred metres thick, but following collision with Avalonia a rapidly subsiding foredeep along the SW margin of Baltica (Denmark, N Germany and Poland) developed through the Silurian. Examination of subsidence curves (e.g. Brangulis et al., 1993; Vejbærk et al., 1995) shows a minor increase in subsidence at the Ordovician–Silurian boundary, but burial depths for the Komstad Limestone (<100 m) at that time would not be enough to remagnetise the rocks by simple burial and temperature elevation. The remagnetisation must therefore have had a different origin and probably relates to a TCRM caused by tectonic fluids (Oliver, 1986). During convergence of Baltica and Avalonia, the continental margin of Baltica was probably buried beneath northeastward-verging thrust sheets (e.g. Berthelsen, 1992; England et al., 1997) that forced fluids from the margin sediments into the foreland basins. If these fluids were sufficiently hot (100–300 °C), the geothermal gradient would be temporarily elevated (Oliver, 1986), and low-grade metamorphism (including elevated R_o values) and Late Ordovician remagnetisation could be explained without great burial. A Late Ordovician low-grade metamorphic event is suggested from $^{40}Ar/^{39}Ar$ ages from deep boreholes in the North Sea (Frost et al., 1981; see also Torsvik, 1998) and NE Germany (Dallmeyer et al., 1999). Whole-rock slate ages of 443 and 427 (Fig. 1) were interpreted by Dallmeyer et al. (1999) to date Caledonian low-grade metamorphism at the two time intervals. $^{40}Ar/^{39}Ar$ whole-rock ages from the North Sea peak at 440–450 Ma (Fig. 5B), and the Westerland Well (located near the Thor Suture; Fig. 1) yielded an age of 453 ± 2 Ma (Frost et al., 1981). Low-grade metamorphism, mostly yielding Late Ordovician ages (c. 440–450 Ma), is probably contemporaneous with the Scania IB component recorded in the SW Baltic foreland (this study) and is likely to relate to tectonic fluids, since Late Ordovician burial alone is inadequate to explain this remagnetisation phenomena.

Tectonic fluids have also been suggested as a cause for hydrocarbon migration (Oliver, 1986), and Elmore et al. (1987) and McCabe et al. (1987) have suggested that precipitation of secondary magnetite could be related to hydrocarbon brines. A detailed magneto-mineralogical and optical examination of the Komstad Limestone is beyond the scope of this paper, but it is worthwhile pointing out that hydrocarbon inclusions are indeed present in calcite veins (Jensenius, 1987), and the underlying Cambrian Alum shale (Fig. 2C) was probably the source rock for the hydrocarbons.

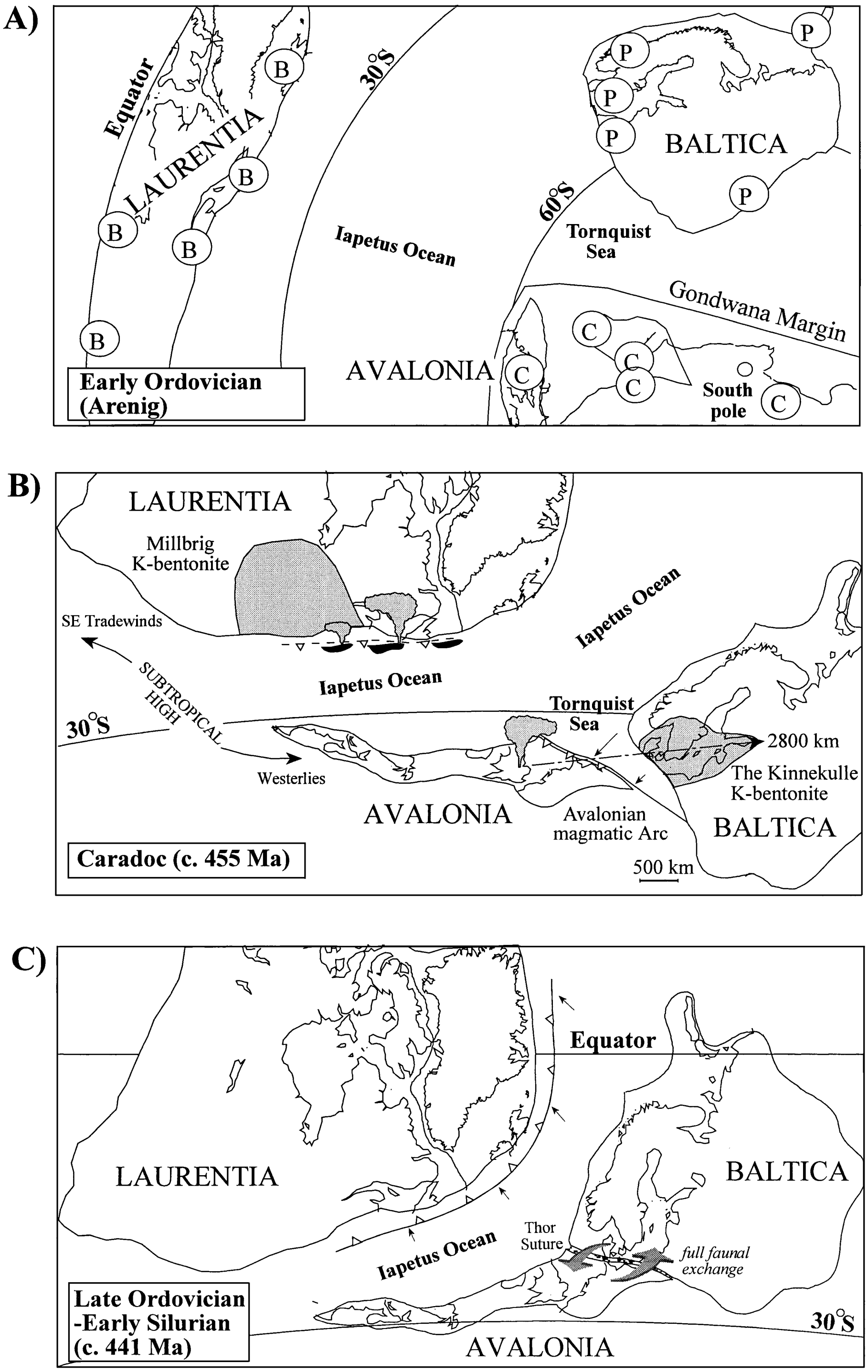
7. Permian overprinting in Bornholm

The Bornholm IB pole is Permian in age (c. 250–260 Ma; Fig. 5B). Permo-Carboniferous remagnetisations have been reported from Scania (e.g. Torsvik and Trench, 1991b; Perroud et al., 1992), but always recorded as being in the vicinity of Scania dykes; we have no knowledge of such dykes at our sampling locality. Studies of fluid inclusions in the Komstad Limestone (including our Skelbro locality) suggest that Bornholm has attained postdepositional temperatures at around 200 °C (Jensenius, 1987). Temporal constraints are unknown from these studies, but fission track (FT) ages (Hansen, 1995) from tuffaceous Silurian sandstone (10 km southeast of Skelbro; Fig. 2B) provide temporal insight—FT zircon ages are close to the depositional age (c. 420 Ma), although apatite gave an age of 261 ± 23 Ma (1σ). Based on the track length distribution, Hansen (1995) interpreted this age as a cooling/uplift age and proposed that Silurian sediments were heated to 130–190 °C prior to 261 Ma. This age corresponds well with our IB overprint estimate (c. 250–260 Ma; Fig. 5B).

The Late Ordovician (Ashgill) remagnetisation from Scania is not recorded at our Bornholm site. Several explanations can be forwarded, but maximum unblocking temperatures for the Bornholm and Scania IB components are statistically concordant. An earlier, but as not yet identified Late Ordovician remagnetisation in Bornholm, could therefore theoretically have been masked by a younger Permian remagnetisation.

8. Avalonia and Baltica convergence and the tale of K-bentonites

The Avalonia–Baltica convergence story and the destruction of the intervening Tornquist Sea were first inferred on faunal and palaeomagnetic grounds (Cocks and Fortey, 1982, 1990; McKerrow et al., 1991; Torsvik and Trench, 1991a; Torsvik et al., 1993, 1996; Cocks et al., 1997; Cocks, 2000), but with contributions and refinements from tectonic, sedimentary, petromagmatic, seismic and isotope data (see reviews in Pharaoh, 1999; McCann and Krawczyk, 2001). Avalonia and the European Massifs were located at high southerly latitudes during the Early Ordovician, and fringed the northern margin of Gondwana (Fig. 6A). Avalonia separated from Gondwana during the Arenig–Llanvirn, and closure of the Tornquist Sea is indicated by the Late Ordovician converging APW paths for Baltica and Avalonia (Fig. 5A) and


A)
Equator
LAURENTIA
30°S
B
B
B
B
B
B
Iapetus Ocean
P
P
P
P
P
BALTICA
60°S
Tornquist
Sea
Gondwana Margin
C
C
C
C
C
AVALONIA
South
pole
Early Ordovician
(Arenig)
B)
LAURENTIA
Millbrig
K-bentonite
SE Tradewinds
Iapetus Ocean
SUBTROPICAL
HIGH
Iapetus Ocean
Tornquist
Sea
30°S
2800 km
Westerlies
The Kinnekulle
K-bentonite
AVALONIA
Avalonian
magmatic Arc
BALTICA
Caradoc (c. 455 Ma)
500 km
C)
Equator
LAURENTIA
BALTICA
Thor
Suture
Iapetus Ocean
full faunal
exchange
Late Ordovician
-Early Silurian
(c. 441 Ma)
30°S
AVALONIA

faunal mixing. The exact nature and timing of Avalonia–Baltica collision, however, is not readily observed in the geological record—protuberant orogenic structures or high-pressure rock products are missing or buried, and the collision is therefore often described as a soft docking event, and governed by strike-slip convergence. In Avalonia, Late Ordovician folding, faulting and igneous activity is known from the Shelve area (Welsh Borderlands) and may relate to Avalonia–Baltica docking. This early Ashgill Shelveian event (Woodcock, 1990; Toghill, 1992) is broadly coeval with Taconic (455–442 Ma) deformation along the Laurentian margin (Robinson et al., 1998), and an Ashgill cooling event (446–449 Ma) was recorded in Western Baltica nappes (Andersen et al., 1998; Torsvik, 1998; Eide et al., 1999). The tectonic setting for the latter is uncertain since we do not know whether these cooling ages relate to interaction between Baltica and Avalonia or Baltica and an Iapetian (?) island arc or microcontinent.

The Tornquist Sea may have had a substantial E–W width, undetectable from palaeomagnetic data. Late Ordovician faunal exchange does not prove that the Tornquist Sea was fully closed, but points to the fact that the Tornquist Sea was not a significant faunal barrier in the Caradoc and Ashgill. Another source of information, volcanic ash remnants (K-bentonites), may shed some important light on the destruction of the Tornquist Sea, and notably on the E–W distance between Baltica and Avalonia.

K-bentonites are preserved as clay-rich layers in marine sediments, and many Palaeozoic K-bentonites have been tied to Plinian eruptions associated with subduction-related magmatism (Huff et al., 1992, 1996). In Baltica, Ordovician K-bentonites are widespread. They vary in age from Llandeilo to Ashgill, but the thickest and most regionally important is the Mid-Caradoc (*D. multidens* graptolite zone) Kinnekulle K-bentonite (KKb) in Sweden (Bergström et al., 1995). The KKb has a maximum thickness of 2 m and extends for more than 1000 km in an E–W pattern (Fig. 1), and the preserved ash volume converted to dense rock equivalent of silicic magma has been estimated at nearly 1000 km^3 (Huff et al., 1996); this estimate is compatible with Earth's largest known prehistoric eruption in Indonesia (Rose and Chesner, 1990).

KKb has been dated to 457 ± 2 Ma (U/Pb zircon age cited in Tucker and McKerrow, 1995) and 455 ± 2 Ma ($^{40}Ar/^{39}Ar$ biotite; Min et al., 2001) and is said to be coeval with the Milbrig K-bentonite in North America (454 ± 2 Ma; Tucker et al., 1990). Both units show compositional affinity with volcanic arc granites and indicate generation along convergent continental plate margins (Huff et al., 1992). Huff et al. (1992) argued for a common volcanic centre within the Iapetus Ocean, but for the volcanic source of the KKb, we forward a different explanation that is rooted in Late Ordovician palaeogeography and tropospheric wind patterns (Fig. 6B). A correlation between KKb and Millbrig has also been previously rejected by Haynes et al. (1995), and isotope ages (see review in Min et al., 2001) suggest that Millbrig is a few million years younger than KKb.

From Baltica there is no evidence for a volcanic source for the KKb, but in Avalonia (S. England), Late Ordovician calc–alkaline magmatism has been linked to Tornquist Sea closure with subduction beneath Avalonia (Pharaoh et al., 1993; Noble et al., 1993; Torsvik, 1998). Magmatic ages vary between 442 and 457 Ma, but peak magmatic activity probably occurred between 449 ± 13 and 457 ± 20 Ma. This Late Ordovician magmatism (Fig. 6B) could have been the source of considerable volumes of volcanic ash, and U/Pb ages overlap with the age of the KKb.

The atmospheric circulation pattern results from the interaction of the sun's radiation and deflection of air masses due to the rotation of the earth (Coriolis force).

Fig. 6. (A) Early Ordovician reconstruction of Laurentia, Baltica and NW Gondwana (after Torsvik and Trench, 1991a; Torsvik et al., 1996) and the distribution of Arenig–Llanvirn platform trilobites (Cocks and Fortey, 1990): B = Bathyurid, P = Ptychopygine/Megalaspid, C = Calymenacean, D = Dalmanitacean. (B) Mid-Caradoc (c. 455 Ma) reconstruction of Laurentia, Baltica and Avalonia. In this reconstruction the Kinnekulle K-bentonite in Baltica is linked to the Avalonian magmatic arc, and ash fall-out was transported with westerlies. Palaeomagnetic south poles (455 Ma) used for Caradoc reconstruction are as follows: Avalonia: latitude = 0.5°, longitude = 013.8° (Torsvik et al., 1993); Baltica (Table 2; 454 Ma pole); Laurentia = latitude = – 16°, longitude = 328.5° (Torsvik et al., 1996). The time of Taconian thrusting onto Laurentia is 455 Ma (Robinson et al., 1998), although magmatism in the arc was still in progress (until 442 Ma). The Millbrig K-bentonite is younger than the Kinnekulle K-bentonite (see Min et al., 2001). Also note that Avalonia was located south of the subtropical high (c. 25°) during the Ordovician. (C) Late Ordovician–Early Silurian (c. 441 Ma) reconstruction. Baltica and Avalonia reconstructed according to the 441 Ma pole in Table 2 (Avalonia is assumed 'fixed' with respect to Baltica at this time). Laurentia after Torsvik et al. (1996).

Climatic zones broadly reflect latitude, but the distribution of continents, oceans, mountain ranges, as well as large-scale climatic oscillations, modifies the general pattern (Parrish, 1982). At present, the subtropical high-pressure zones are located at 20–30° latitude, and in most palaeoclimatic modelling the subtropical high is placed at 30° latitude. Since a faster spinning Earth would displace the subtropical high equatorward, an estimated 12% faster rotation in the Ordovician would push the subtropical high to 25° latitude (Christiansen and Stouge, 1999). Avalonia and SW Baltica were located south of the Late Ordovician subtropical high (say 25°). We therefore argue that the KKb was associated with a Mid-Caradoc calc–alkaline magmatic event in Avalonia, and that westerlies (Fig. 6B) brought huge ash fall-outs over Baltica. Volcanic vents on an arc or microplate, which were undergoing collision with Laurentia (Fig. 6B), were probably the source for the slightly younger Millbrig K-bentonite (Huff et al., 1996); and NW-directed dispersion pattern of pyroclastic material, as indicated by present map distribution (Fig. 6B), might have been caused by Caradoc SE trade winds. Independent of this perhaps speculative Ordovician palaeoclimatic model, the thickness distribution of the KKb (Fig. 1) clearly requires a palaeowest source area, and in the Caradoc reconstruction, the Avalonian magmatic arc is the prime candidate to supply Baltica with massive ash falls. However, even with a narrow Tornquist Sea, ashes must have been dispersed nearly 3000 km eastward (Fig. 6B).

9. Conclusions

(1) The late Arenig Komstad Limestone in Scania and Bornholm records primary HB components, and a combined palaeomagnetic pole matches well with other Arenig-aged poles from Baltica. The SW margin of Baltica was located at 45°S in the late Arenig, and Baltica was strongly rotated by comparison with its present orientation. Baltica and the Gondwanan margin (including Avalonia) were separated by the Tornquist Sea.

(2) During most of the Ordovician, both Baltica and Avalonia moved northward while undergoing counter-clockwise rotations. Avalonia moved significantly faster after rifting from the northern margin of Gondwana, but slowed down to rates comparable to those of Baltica by the Late Ordovician. Avalonian palaeolatitudes were broadly compatible with those of Baltica during the Caradoc, and subduction beneath Avalonia took place. Huge Caradoc (c. 455 Ma) ash falls in Baltica signify a position near a major magmatic arc, and the age and the thickness distribution of the Kinnekulle bentonite suggest that magmatism in Avalonia was the source of the KKb. The location of Avalonia south of the subtropical high during most of the Ordovician would have provided an optimum palaeoposition to smother Baltica with large ash falls governed by westerlies.

(3) Scania records a Late Ordovician (Ashgill) remagnetisation event (IB component). This event is broadly comparable with the Shelveian event in Avalonia, and records a Caledonian thermal (fluid?) event that we link with Avalonia–Baltica collision. This event is synchronous with Caledonian low-grade metamorphism in the North Sea, NE Germany, and a cooling event in Western Norway at 440–450 Ma.

(4) Late Ordovician closure of the Tornquist Sea is readily supported by the faunal record. Benthic faunas from Avalonia began to mix with Baltic faunas in the Caradoc, and by the Ashgill, British and Scandinavian faunas were similar at species level.

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