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Palaeomagnetic results from the Middle Carboniferous rocks of the Hornsund region, southern Spitsbergen: preliminary report

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ABSTRACT: Palaeomagnetic investigation of the Upper Carboniferous clastic Hyrnefjellet Formation from opposite limbs of the Hyrnefjellet Anticline in southern Spitsbergen (Svalbard Archipelago) uncovered two components of NRM. Direction C1 (D = 224.6°; I = –27.9°; κ = 22.40; α95% = 5.6°) is of prefolding origin and most probably of near-primary origin. High Tb spectra above 575°C indicate hematite as the carrier of C1. Acquisition of the C1 component may be related to an early diagenetic crystallization of hematite, not excluding a detrital origin of the NRM. A paleopole calculated for the C1 component (Φ = 23.3°N; Λ= 147.7°E) falls into the Late Devonian–Early Carboniferous sector of APWP for Baltica. This result suggests that Svalbard remained in the present day orientation with respect to Baltica since the Carboniferous time. A second component with intermediate unblocking temperatures, determined in the Hyrnefjellet Formation deposits, is labelled C2. Its mean orientation for *in situ* position is D = 11.2°; I = 69.2° (κ = 44.05; α95% = 6.3°), thus being similar to Late Mesozoic directions for Baltica. After 100% tectonic correction for tilting of anticline limbs and axis, the C2 component orientation is D = 265.7°; I = 59.7°, thus being distant from any directions for Baltica. Detailed analysis suggest that the C2 component is most probably of synfolding origin, and it was formed during the Tertiary Alpine Tectonic Event.

Key words: Arctic, Spitsbergen, Palaeozoic, palaeomagnetism, palaeogeography, tectonics.

Introduction

Geologic formations of Spitsbergen, the largest island of the Svalbard Archipelago, play a key role in the understanding of the geotectonic evolution of the Arctic crust. It has been suggested (Harland and Wright 1979, Harland 1997) that during the Early Palaeozoic, Svalbard was divided into three widely disparate terranes (Fig. 1A), which were amalgamated by large scale left lateral displacements (up to 200 km) in the Devonian time following the closure of the Iapetus Ocean and the Baltica-Laurentia collision. The Early Palaeozoic positions of the once

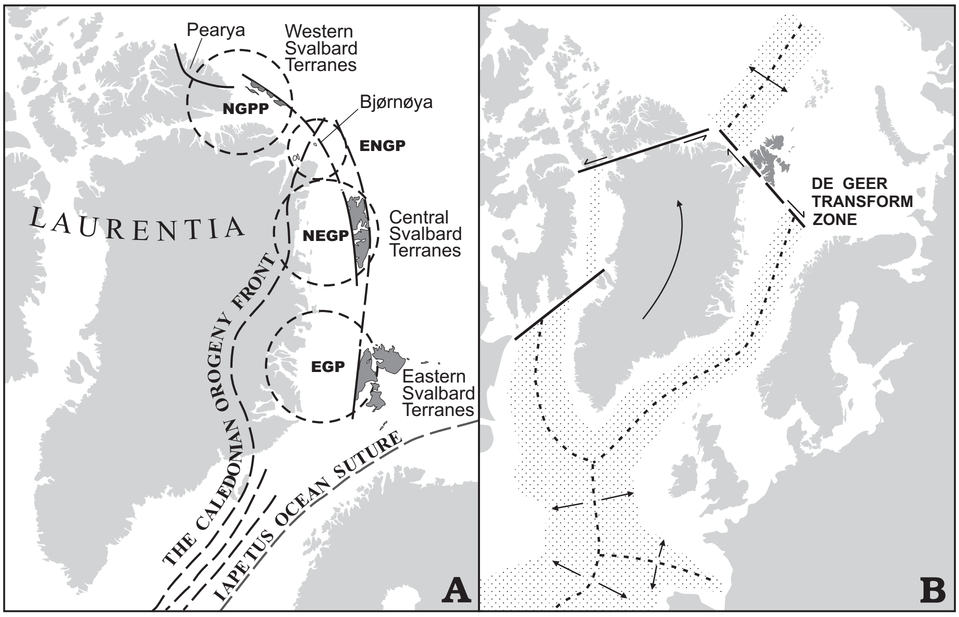


Fig. 1. A – Hypothetical disposition of Svalbard's crustal components (terranes) before the Caledonian orogeny (after Harland 1997). Encircled are provinces: EGP – East Greenland Province; NEGP – Northeast Greenland Province; ENGP – Eastern North Greenland Province; NGPP – North Greenland Pearya Province. B – Early Tertiary configuration of the continents and oceans in the Arctic region (after Harland 1997); dashed lines indicate spreading centers, punctate area – oceanic crust, solid lines – transform faults, arrows – direction of plate movements, De Geer transform-fault zone is indicated by dashed line.

separated terranes that now constitute the Svalbard Archipelago, as well as the role of the major N-S trending fault zones that traverse the islands in this assembly are controversial (*e.g.* Birkenmajer 1975, Craddock *et al.* 1985, Ziegler 1988, Müller and Spielhagen 1990, Lyberis and Manby 1993, Manby *et al*. 1994, Gee and Page 1994, Harland 1997, Lyberis and Manby 1999). Recent reconstructions (*e.g.* Harland 1997) show Svalbardian (Late Devonian) terranes dispersed along paleolatitudes parallel with the eastern margin of Greenland. Other authors have suggested, however, that the motion along the fault zones was accomplished by the Early Devonian time (Manby *et al.* 1994, Lyberis and Manby 1999). These two competing hypotheses can be verified using palaeomagnetic research. This research may also help to reveal the Early Palaeozoic palaeogeography of the Hornsund Terrane that forms part of the Western suspected Terrane, identified by Harland and co-workers (Harland and Wright 1979, Harland 1997). Moreover, palaeomagnetic results may help to identify the scale and timing of possible tectonic movements along the N-S traversing faults that show evidence of repeated reactivation since Palaeozoic time. These faults modified tectonic pattern of the Late Cretaceous–Palaeocene West Spitsbergen Fold Belt in the Hornsund region.

Prior to the opening of the North Atlantic–Arctic Ocean Basins in Late Cretaceous–Early Palaeogene time, Svalbard was adjacent to northern Greenland (*e.g.* Bullard, Everett and Smith 1965, Birkenmajer 1972, 1977, 1981; Srivastava 1985, Rowley and Lottes 1988, Ziegler 1988, Dóre 1991, Lyberis and Manby 1993). The simultaneous opening of the Basins was accompanied by right-lateral motion along the De Geer Fracture Zone (Fig. 1B), and resulted in the separation of the Svalbard-Greenland blocks (*e.g.* Manby and Lyberis 1996). It is implicit that, Svalbard was part of Laurussia in the Late Silurian to Cenozoic time interval, but it is not certain whether Svalbard was rigidly amalgamated either to Greenland or Eurasia, mostly because of activity of large N-S trending faults (offshore and onshore) traversing Svalbard Archipelago.

The hypothesis that Baltica and Svalbard were united already in the Palaeozoic can be verified using palaeomagnetic investigation, as both units should share a common, post-Devonian apparent polar wander path (APWP). Previous palaeomagnetic studies carried out to test this hypothesis have been either equivocal or contradictory. Some authors conclude that palaeomagnetic data support a common history of Baltica and Svalbard (Torsvik *et al.* 1985, Watts 1985, Jeleńska and Lewandowski 1986, Nawrocki 1999) while others suggest the opposite because the palaeomagnetic poles they have obtained for the two blocks do not fall on the same APWP's (Vincenz *et al.* 1981, 1984; Jeleńska 1985, Jeleńska and Vincenz 1987). It should be stressed, however, that palaeomagnetic results of the early 80's could suffer incomplete laboratory magnetic cleaning, resulting in poorly defined NRM components due to a rather crude resolution of magnetometers operated at that time. Modern equipment used for the purpose of this study (see chapter "Methods of study" for details), allows us to obtain precise results that would aid to resolve the controversy surrounding the Late Palaeozoic–Mesozoic Svalbard-Baltica spatial relationships, and contribute significantly to geological reconstructions of the North Atlantic-Arctic for this time interval.

In this paper we report on the first results obtained from the Middle Carboniferous Hyrnefjellet Formation of the Hornsund region in southern Spitsbergen.

Geological setting

The study area is located in the southwestern Spitsbergen (Fig. 2A), namely in the southeastern Wedel-Jarlsberg Land and the western Torell Land (Fig. 2B, C). Structurally, the area encompasses a part of the boundary zone between the Hornsund and the Southern Basin suspected terranes that are juxtaposed along the West Spitsbegen Thrust Front (Harland 1997). The area provides an access to a variety of the pertinent Palaeozoic and Early Mesozoic formations subjected to different phases of deformations, which are fairly well-known geologically (*e.g.* Birkenmajer 1990, Dallman 1992, Ohta and Dallman 1999).

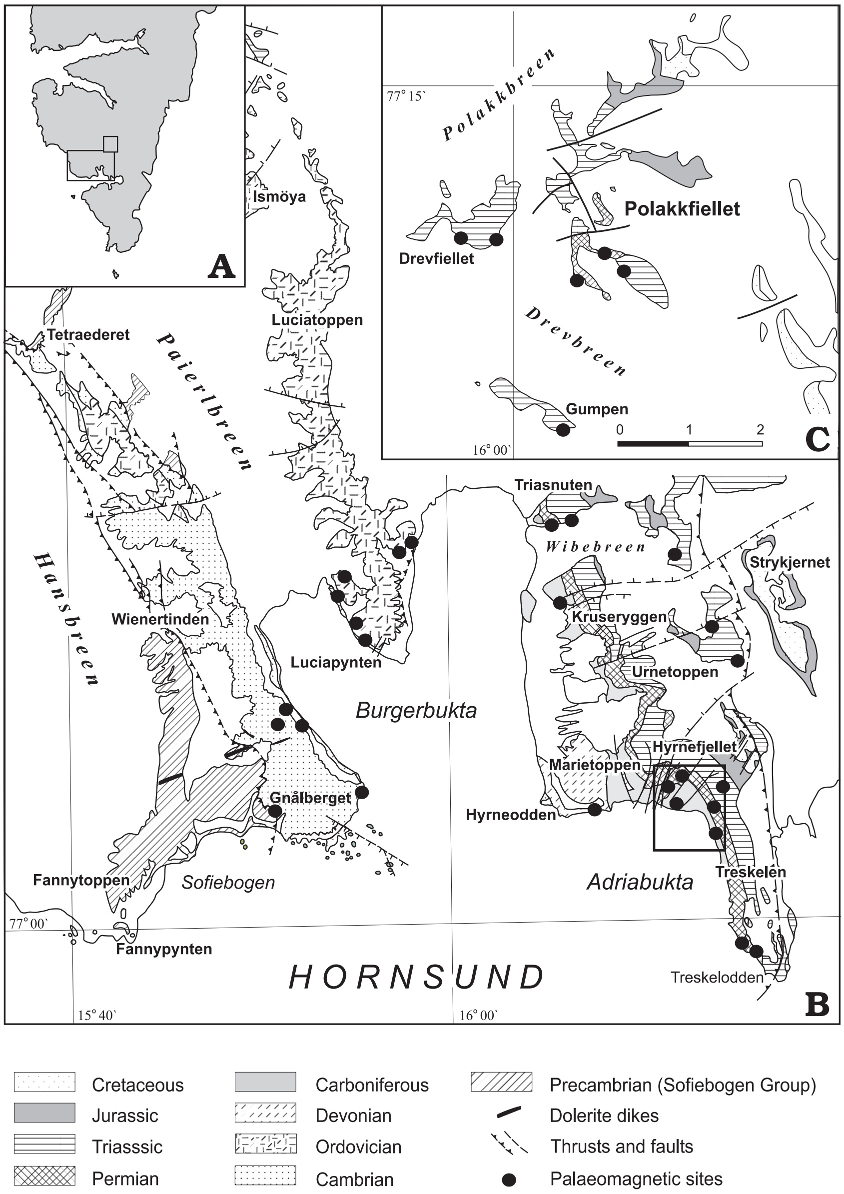


Fig. 2. A – Contour map of the southern Spitsbergen – areas of palaeomagnetic studies are marked by squares. B, C – Location of palaeomagnetic sites in the Palaeozoic and Early Triassic formations of the Hornsund area – the Hyrnefjellet Anticline is marked by square (geology after Birkenmajer 1990).

Palaeomagnetic samples have been collected from geological formations ranging in age from the Cambrian to the Triassic (Fig. 2B, C). In this paper we present palaeomagnetic results from fine-grained, red-coloured sandstones of the Hyrnefjellet Fm. The palaeomagnetic samples have been collected from horizontally bedded parts of the Hyrnefjellet Fm. There is no direct evidence of the Hyrnefjellet Fm. age as the fossils are lacking. However, on the basis of the fossils contained in the Adriabukta Series, underlying the Hyrnefjellet Fm. and in the Upper Treskelodden Formation overlying it, Birkenmajer (1984a, b) assigned the age of the Hyrnefjellet Fm. to Middle Carboniferous, *i.e.* Middle Bashkirian to Late Moscovian. Deposition of the Hyrnefjellett Beds can be related to weathering and erosion, which took place after tectonic movements of the Adriabukta Phase (Birkenmajer 1964, 1984a). The Hyrnefjellet Fm. represents fresh-water, deltaic depositional system developed under warm, arid conditions. The red colour of rock and the lack of plant detritus suggest oxic conditions during sedimentation and early diagenesis (Birkenmajer 1964, 1984a).

The palaeomagnetic samples were collected from opposite limbs of the Hyrnefjellet Anticline, which is situated inside the Sørkapp-Hornsund mobile Alpine zone in southern Torell Land (Fig. 2B). The Hyrnefjellet Anticline is a close angle antiform with upright axial plane and its axis is tilted 12° to SSE. The width of the fold can be estimated to 1 km.

Methods of study

Samples for the palaeomagnetic investigation were collected from surface outcrops, seven samples from each of two sites. The site is defined here as a separate place within an individual limb of the Hyrnefjellet Anticline, confined to 3–4 beds. Each of the hand samples were independently oriented using a magnetic compass. From each of 14 hand samples several (usually 5–7) core specimens with a 2.4 cm

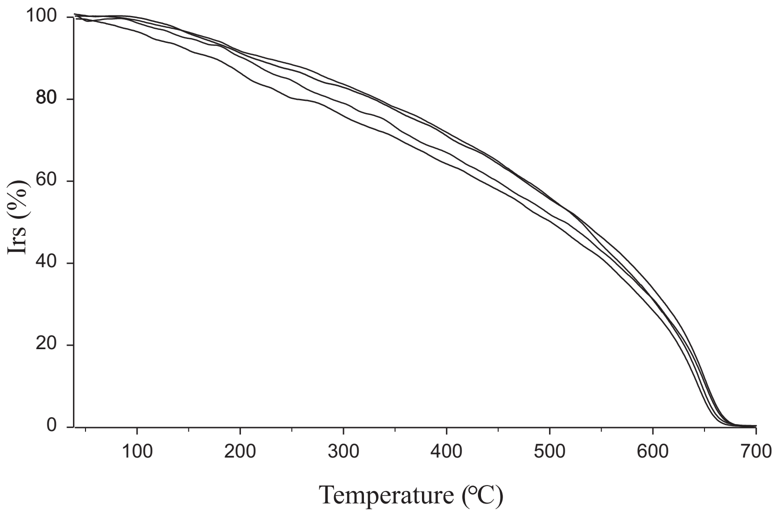


Fig. 3. Plot of decay of saturated magnetization (Irs) with temperature in four samples from the Carboniferous Hyrnefjellet Fm. Note maximum Tb of 675°C characteristic for hematite.

East limb of the Hyrnefjellet Anticline

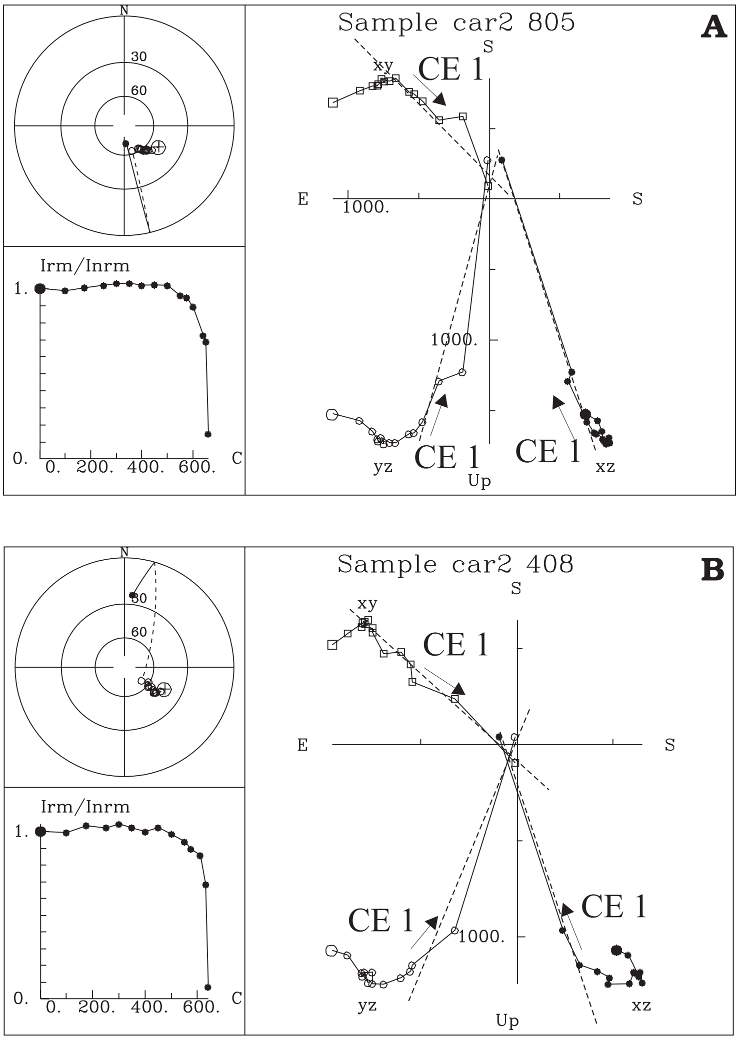
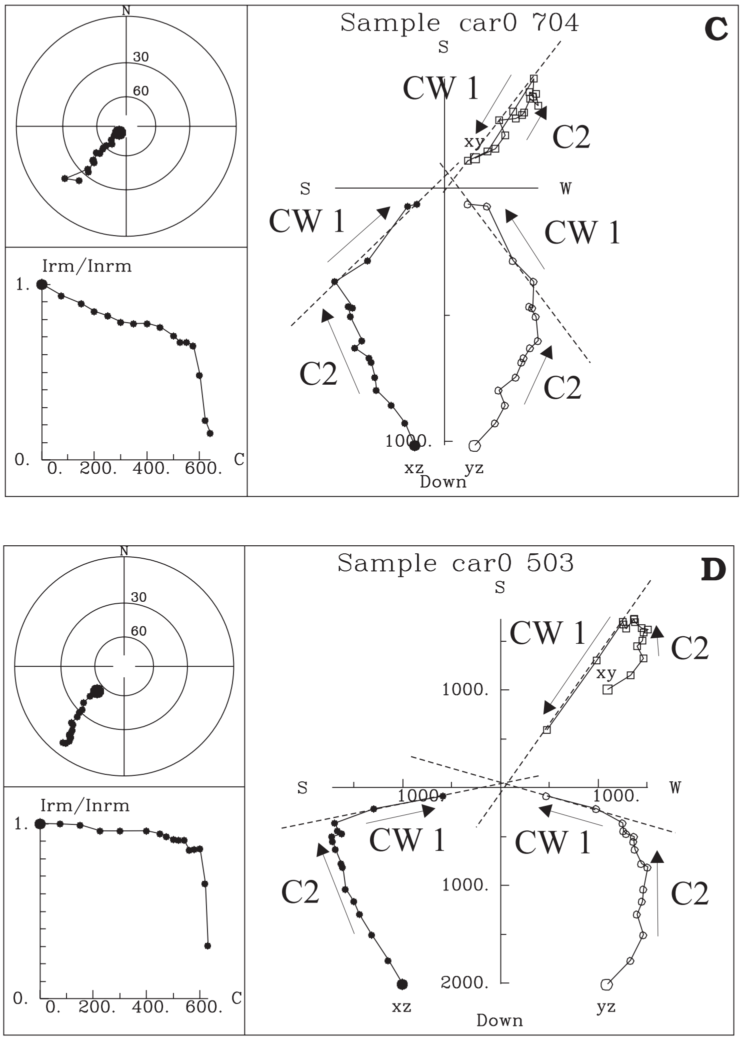


Fig. 4. Equal area, orthogonal (Zijderveld) projections and normalized intensity decay of induced remanent magnetization plots for selected specimens from the east (A, B) and the west (C, D) limb of the Hyrnefjellet Anticline; projections presented for *in situ* orientation; open/full symbols represent upper/lower hemisphere; squares/circles denote projections onto horizontal/vertical planes; units on the orthogonal plots are in uA/m; arrows indicate directions of selected NRM components; directions of high Tb additionally indicated by dashed lines.

diameter and 2.2 cm length were drilled. After cutting, three specimens with the highest value of initial intensity of magnetisation were chosen from each hand sample. They were subjected to stepwise thermal demagnetisation in order to investigate their natural remanent magnetisation (NRM) structure.

West limb of the Hyrnefjellet Anticline



For 36 specimens thermal demagnetisation was done using a Magnetic Minerals MM-1 furnace. The specimens were heated stepwise (in steps of 20–50°C) up to 670°C and cooled in a zero magnetic field. After each demagnetisation step, the remaining magnetization was measured using a 2G SQUID cryogenic magnetometer with a residual internal field below 3 nT and a noise level of about 5 mA/m. These laboratory instruments were operated inside Helmholz coils, reducing the ambient geomagnetic field by 95%. Measurements of magnetic susceptibility κ were performed on every specimen after each demagnetisation step, using a Czech low-field KLY-2 susceptibility bridge, since changes of κ are related to formation of new minerals in specimens during heating and may disturb their original NRM

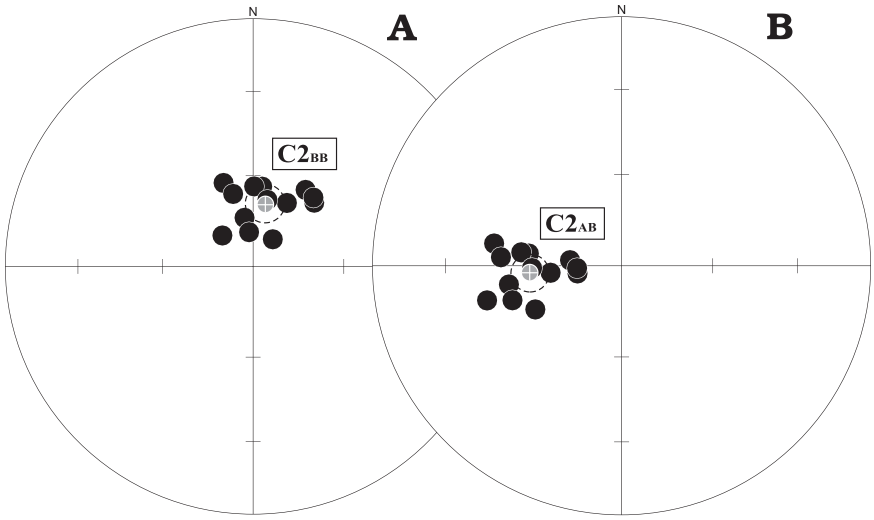


Fig. 5. Distribution of intermediate Tb NRM direction C2 of the Carboniferous specimens from the west limb of the Hyrnefjellet Anticline – equal area projections, lower hemisphere; A – *in situ*, B – after 100% tectonic correction; the mean direction of directional populations with their cones of α95% confidence are indicated by crossed symbols with dashed circles; NRM component symbol indexes: BB – before bedding correction, AB – after 100% tectonic correction.

structure. Specimens which revealed significant increase of κ, were eliminated from subsequent demagnetisations.

Palaeomagnetic Data Analysis (PCA) software by Lewandowski *et al.* (1997), employing principal component analysis (Kirschvink 1980), was used to calculate the characteristic NRM components (ChRM) from the demagnetisation data and to plot the demagnetisation diagrams. A ChRM was determined as a direction of the best fitted line to a minimum of three points with angular standard deviation (ASD) not exceeding 15°. Standard Fisher (1953) statistics has been used to calculate the characteristic mean direction for the ChRM populations.

Identification of magnetic minerals was done using the thermomagnetic analysis described by Kądziałko-Hofmokl and Kruczyk (1976). Small cylindrical cores (8 mm × 8 mm) of the investigated rock were first subjected to magnetization in a pulse magnetizer MMPM 10 in the field of 9 T to produce an induced isothermal remanent magnetization (IRM). After this step the cores were measured in a spinner magnetometer combined with a furnace. The specimens were heated up to 700°C, and the blocking temperature spectrum was plotted against decaying IRM.

Palaeomagnetic results

The thermomagnetic analysis identified hematite as the main magnetic carrier in the Carboniferous Hyrnefjellet Formation (with maximum Tb 670°C, see Fig. 3).

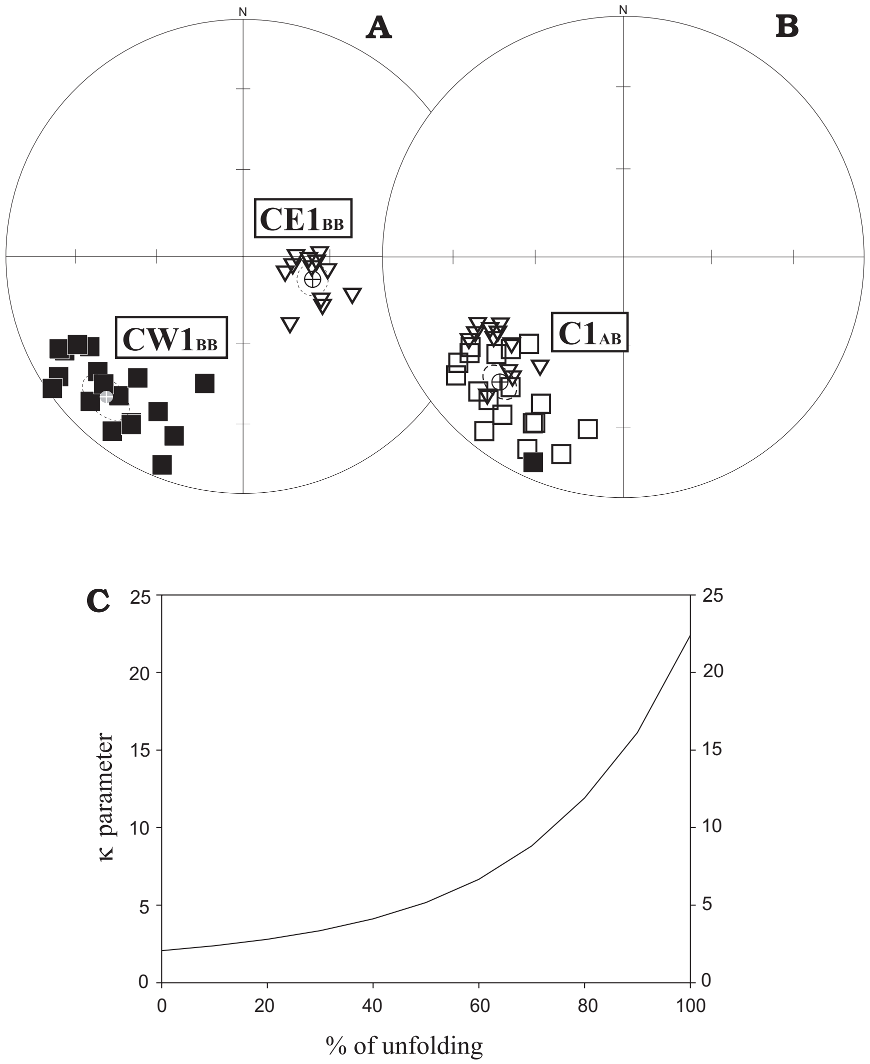


Fig. 6. Distribution of high Tb NRM direction C1 of the Carboniferous specimens from the west (CW1) and east limb (CE1) of the Hyrnefjellet Anticline – equal area projection; open/full symbols represent upper/lower hemisphere; A – *in situ*, B – after 100% tectonic correction; shown are the mean directions of NRM populations with their cones of α95% confidence; for other explanations see Fig. 5; C – palaeomagnetic fault test (Mc Fadden and Jones 1981) – κ parameter is plotted versus % of unfolding of the Hyrnefjellet Anticline.

The NRM structure in the two limbs of the Hyrnefjellet Anticline differs (Fig. 4). In the eastern limb, thermal demagnetisation up to 500– 550°C has not resulted in a decrease of the initial NRM intensity of the specimens. Above 550°C, the hard component, labelled C1, is separated, with Tb spectra reaching 650°C. In the western limb, the specimens acquired two components of NRM. An intermediate component, labelled C2, has been separated up to 550°C, and revealed a good grouping (for statistical parameters see Table 1). It is directed *in situ* to the N, with steep positive inclination (Fig. 5). After 100% tilt correction, the C2 component points westwards with moderate inclination (see discussion in the next chapter and Fig. 5). In contrast, the hard component (labelled C1) was separated in the temperature range above 550°C. NRM high Tb components from two limbs of the Hyrnefjellet Anticline (labelled CE1 and CW1 in the eastern and western limbs, respectively) pass the fold test *sensu* Mc Fadden and Jones (1981) – Fig. 6. This implies a prefolding origin of the component C1. The C1 component is directed toward SW with moderate negative inclination (Fig. 6).

Age of revealed palaeomagnetic directions

The folding of the Hyrnefjellet Formation has been entirely produced at the beginning of Palaeogene during Alpine tectonic events (Birkenmajer 1981, Dallman 1992), 250 Ma years after the sequence was deposited. This constrains the upper age limit for the component C1, since it is of prefolding origin. High Tb spectra above 575° indicate hematite as the carrier of the C1 component. Formation of the C1 hematite could be related to depositional oxic conditions during the sedimentation of the Hyrnefjellet Fm. (Birkenmajer 1964, 1984a). The palaeopole calculated for C1 falls exactly on the Carboniferous segment of the APWP for Baltica (Fig. 7). Thus, both sedimentologic and palaeomagnetic evidence suggests a primary origin of the C1 component. Consequently, it suggests that Svalbard has remained in the present day relative orientation with respect to Baltica since the Carboniferous.

Because the low/intermediate Tb C2 direction was determinated only in one limb of the Hyrnefjellet Anticline, a fold test for component C2 could not be applied. However, the component can be dated by comparison of the palaeopole calculated from the C2 direction with the APWP for Baltica, assuming that Svalbard was already consolidated with Baltica at the time when the C2 was acquired. The cone of 95% of coincidence of C2 palaeopole calculated for the present-day orientation of the beds lies in the vicinity of the Late Jurassic/Lower Cretaceous sector of APWP for Baltica (Fig. 7). Such an age of C2 cannot be accepted, since it would suggest at least a pre-Early Cretaceous age of deformation of the Hyrnefjellet Anticline, which is contradictory to geological evidence (Birkenmajer 1981, Dallman 1992). After 100% tectonic correction, the C2 paleopole is distant from the reference path (Fig. 7), implying significant tectonic rotation after aquisition of the C2 component. However, if only correction for the anticline axis tilt and correction for 10% of anticline limbs tilt are applied, the paleopole C2 falls into the Late Jurassic–Early Tertiary sectors of the reference path (Fig. 7). This may suggest that the C2 component was acquired before the anticline axis was tilted, and after an almost complete folding of the anticline limbs. Therefore the tilting of the axis was probably related to the final Alpine phases of the anticline deformation.

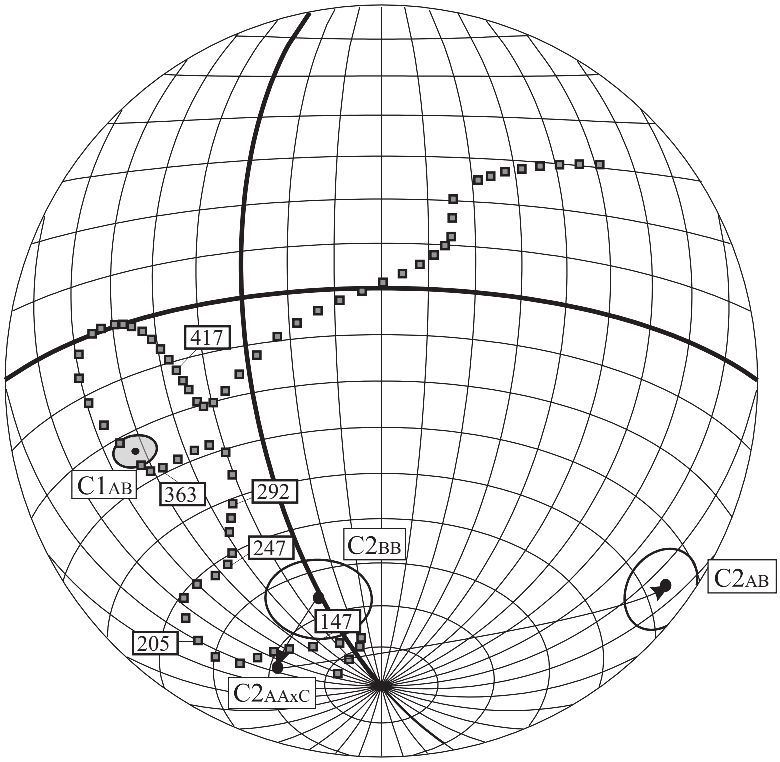


Fig. 7. The positions of palaeopoles obtained from the Carboniferous Hyrnrefjellet Fm. with their 95% confidence circles relatively to the APWP for Baltica-Schmidt projection (palaeopoles for APWP for Baltica compiled after Torsvik *et al.* 1992, Van der Voo 1993); ages of selected paleopoles are given in frames; paleopole symbol indexes: BB – before bedding correction, AB – after 100% bedding correction, AAxC – after tectonic correction for tilting of anticline axis; solid line arrows indicate the path of the C2 paleopole during tectonic correction if correction for tilting of the anticline axis is first applied.

Table 1

Palaeomagnetic results from Hyrnefjellet Formation – Hornsund area, southern Spitsbergen; abbreviations: N – number of independently oriented hand samples; n – number of measured cylindrical specimens used for the Fisher statistics; D – declination; I – inclination; κ – Fisherian precision parameter; α – half angle of a cone of 95% confidence; Φ/Λ – palaeopole latitude/longitude; dp/dm – half axes of paleopole oval of 95% confidence limit; plat – palaeolatitude.

Components	Position	N/n	D (°)	I (°)	κ	α (°)	Φ (°) N	Λ (°) E	dp (°)	dm (°)	plat (°)
CE1	*in situ*	6/12	107.2	–65.5	66.09	5.4	49.9	283.0	7.1	8.8	47.8
CW1		6/19	224.2	18.1	21.12	7.5	0.1	152.0	4	7.8	–9.4
C2		4/13	11.2	69.2	44.05	6.3	65.4	179.1	9.1	10.7	52.8
C1	100% tilt corrected	12/31	224.6	–27.9	22.40	5.6	23.3	147.7	3.4	6.1	14.2
C2		4/13	265.7	59.7	44.05	6.3	38.4	300.4	7.1	9.5	40.7

Conclusions

First results of a palaeomagnetic study performed on the Carboniferous Hyrnefjellet Formation in the Hornsund region (southern Spitsbergen) allow to determine two components of NRM labelled C1 and C2 (Table 1). The corresponding palaeopoles were compared with the reference APWP for Baltica (Fig. 7), with the following conclusions:

- The C1 direction is of prefolding, probably primary Middle/Late Carboniferous origin. The C1 paleopole falls into the Carboniferous sector of the APWP, supporting the hypothesis that Svalbard was part of Baltica already in the Carboniferous (*e.g.* Torsvik *et al.* 1985, Watts 1985, Jeleńska and Lewandowski 1986).
- The C2 direction is probably of synfolding origin and it was formed during the Tertiary Alpine Tectonic Events. It originated before tilting of the axis of the anticline and after an almost complete folding of its limbs. This suggests that tilting of the axis was associated with the final phases of the anticline deformation.

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References

BIRKENMAJER K. 1964. Devonian, Carboniferous and Permian formations of Hornsund, Vestspitsbergen. Studia Geologica Polonica 11: 47–123.

BIRKENMAJER K. 1972. Tertiary history of Spitsbergen and continental drift. Acta Geologica Polonica 22 (2): 193–213.

BIRKENMAJER K. 1975. Caledonides of Svalbard and plate tectonics. Bulletin of the Geological Society of Denmark 24: 1–19.

BIRKENMAJER K. 1977. Triassic sedimentary formations of the Hornsund area, Spitsbergen. Studia Geologica Polonica 51: 1–74.

BIRKENMAJER K. 1981. The geology of Svalbard, the western part of the Barents Sea, and the continental margin of Scandinavia. *In*: A.E.M. Nairn, M. Churkin and Stechli (eds), *The Ocean Basins and Margins 5*. Plenum Publishing Corporation New York; 265–329.

BIRKENMAJER K. 1984a. Mid-Carboniferous red beds at Hornsund, South Spitsbergen: their sedimentary environment and source area. Studia Geologica Polonica 80: 7–23.

BIRKENMAJER K. 1984b. Cyclic sedimentation in mixed alluvial to marginal-marine conditions: the Treskelodden Formation (?upper Carboniferous and Lower Permian). Studia Geologica Polonica 80: 25–46.

BIRKENMAJER K. 1990. Geology of the Hornsund area, Spitsbergen. Explanations to the map 1:75000 scale. University of Silesia, Katowice; 42 pp.

BULLARD E.C., EVERETT J.E. and SMITH A.G. 1965. The fit of the continents around the Atlantic. *In*: P.M.S. Blackett, E.C. Bullard and S.K. Runcorn (eds), A Symposium on Continental Drift. Philosophical Transactions of the Royal Society of London A 258: 41–51.

CRADDOCK C., HAUSER E.C., MAHER H.D., SUN A.Y. and GUO-QIANG Z. 1985. Tectonic evolution of the West Spitsbergen Fold Belt. Tectonophysics 114: 193–211.

DALLMAN W. K. 1992. Multiphase tectonic evolution of the Sørkapp-Hornsund mobile zone (Devonian, Carboniferous, Tertiary), Svalbard. Norsk Geologisk Tidsskrift 72/1: 49–66.

DÓRE A. G. 1991. The structural foundation and evolution of Mesozoic seaways between Europe and Arctic. Palaeogeography, Palaeoclimatology, Palaeoecology 87: 441–492.

FISHER R. 1953. Dispersion on a sphere. Proceedings of the Royal Astronomical Society A 217: 295–305.

GEE D.G. and PAGE L. 1994. Caledonian terrane assembly on Svalbard: new evidence from Ar/Ar dating in New Friesland. American Journal of Sciences 294: 1166–1186.

HARLAND W.B. (ed.) 1997. The Geology of Svalbard. Geological Society Memoir 17: 1–521.

HARLAND W.B. and WRIGHT N.J.R. 1979. Alternative hypothesis for the pre-Carboniferous evolution of Svalbard. Norsk Polarinstitutt Skrifter 167: 89–117.

JELEŃSKA M. 1985. Palaeomagnetism of Permo-Carboniferous sediments of Spitsbergen, Svalbard Archipelago. Acta Geophysica Polonica 33 (3): 279–298.

JELEŃSKA M. and LEWANDOWSKI M. 1986. A palaeomagnetic study of Devonian sandstone from Central Spitsbergen. Geophysical Journal of the Royal Astronomical Society 87: 617–632.

JELEŃSKA M. and VINCENZ S.A. 1987. Origin of the magnetization of Permo-Carboniferous sediments of Spitsbergen, Svalbard Archipelago. Earth and Planetary Science Letters 85: 173–182.

KĄDZIAŁKO-HOFMOKL M. and KRUCZYK J. 1976. Complete and partial self-reversal of natural remanent magnetization of basaltic rocks of Lower Silesia. Pure and Applied Geophysics 114: 207–213.

KIRSCHVINK J.L. 1980. The last-square line and plane and the analysis of palaeomagnetic data. Geophysical Journal of the Royal Astronomical Society 62: 699–718.

MANBY G.M., LYBERIS N., THIEDIG F. and CHOROWICZ J. 1994. Post-Caledonian tectonics along the Billefjorden fault zone: implications for the Arctic region. Geological Society of America Bulletin 105: 201–216.

MANBY G.M. and LYBERIS N. 1996. State of stress and tectonic evolution of the West Spitsbergen Fold Belt. Tectonophysics 267: 1–29.

MC FADDEN P.L. and JONES D.L. 1981. The fold test in paleomagnetism. Geophysical Journal of the Royal Astronomical Society 67: 53–58.

MÜLLER R.D. and SPIELHAGEN R.F. 1990. Evolution of the Central Tertiary Basin of Spitsbergen: towards a synthesis of sediment and plate tectonic history. Palaeogeography, Palaeoclimatology, Palaeoecology 80: 153–172.

NAWROCKI J. 1999. Paleomagnetism of Permian through Early Triassic Sequences in central Spitsbergen: implications for paleogeography. Earth and Planetary Science Letters 169: 59–70.

LEWANDOWSKI M., WERNER T. and NOWOŻYŃSKI K. 1997. PDA: a package of FORTRAN programs for palaeomagnetic data analysis. Program Manual. Institute of Geophysics Polish Academy of Sciences, Warsaw, Poland.

LYBERIS N. and MANBY G. 1993. The West Spitsbergen Fold Belt: the result of Late Cretaceous–Palaeocene Greenland-Svalbard convergence? Geological Journal 28: 125–136.

LYBERIS N. and MANBY G. 1999. Continental collision and lateral escape deformation in the lower and upper crust: An example from Caledonide Svalbard, Tectonics 18 (1): 40–63.

OHTA, Y. and DALLMAN W.K. (eds) 1999. Geological map of Svalbard 1:100000. Sheet B12G Torellbreen. Norsk Polarinstitutet Temahart no. 29.

ROWLEY D.B. and LOTTES A.L. 1988. Plate-kinematic reconstructions of the North Antarctic and Arctic: Late Jurassic to Present. Tectonophysics 155: 73–120.

SRIVASTAVA S.P. 1985. Evolution of the Eurasian Basin and its implications to the motion of Greenland along the Nares Strait. Tectonophysics 114: 29–53.

TARLING D.H. and HROUDA F. 1993. *The magnetic anisotropy of rocks*. Chapman and Hall. London; 217 pp.

TORSVIK T.H., LØVLIE R. and STURT B.A. 1985. Palaeomagnetic argument for a stationary Spitsbergen relative to the British Isles (Western Europe) since late Devonian and its bearing on North Atlantic reconstruction. Earth and Planetary Science Letters 75: 278–288.

TORSVIK T.H., SMERTHUS M., VAN DER VOO R., TRENCH A., ABRAHAMSEN N. and HALVORSEN E. 1992. Baltica. A synopsis of Vendian–Permian paleomagnetic data and their paleotectonic implications. Earth Science Reviews 33: 133–152.

VAN DER VOO R. 1993. *Paleomagnetism of the Atlantic, Tethys and Iapetus Oceans*. Cambridge University Press; 411 pp.

VINCENZ S.A., COSSACK D., DUDA S.J., BIRKENMAJER K., JELEŃSKA M., KĄDZIAŁKO-HOFMOKL M. and KRUCZYK J. 1981. Palaeomagnetism of some late Mesozoic dolerite sills of South Spitsbergen. Geophysical Journal of the Royal Astronomical Society 67: 599–614.

VINCENZ S.A., JELEŃSKA M., AIINEHSAZIAN K. and BIRKENMAJER K. 1984. Palaeomagnetism of some late Mesozoic dolerite sills of East Central Spitsbergen, Svalbard Archipelago. Geophysical Journal of the Royal Astronomical Society 78: 751–773.

WATTS D.R. 1985. Palaeomagnetism of the Lower Carboniferous Billefjorden Group, Spitsbergen. Geological Magazine 122: 383–388.

ZIEGLER P.A. 1988. Evolution of the Arctic-North Atlantic and the Western Tethys. Memoir of American Association of Petroleum Geology 43: 1–198.

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