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Palaeomagnetism and magnetostratigraphy of the Permian and Triassic of Spitsbergen: a review of progress and challenges

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Abstract

Permian and Triassic sediments from Svalbard provide a testing ground for evaluating concepts about the polarity and configuration of the geomagnetic field during the Palaeozoic–Mesozoic transition. This review examines existing palaeomagnetic and magnetostratigraphic data, and also re-examines the issue of partial remagnetization of these sediments. Permian and Triassic palaeomagnetic poles from Spitsbergen demonstrate a close similarity to the stable Europe apparent polar wander path. Magnetostratigraphy from the Gipsdalen and Tempelfjorden groups demonstrates the dominance of reverse polarity (the Permo-Carboniferous Reverse Superchron), with evidence for three normal magnetozones of short duration, one of which may provide a useful marker near the base of the Permian. The other two normal magnetozones in the middle and lower parts of the Kapp Starostin Formation are most likely to represent equivalent magnetozones in the Wordian and Capitanian (mid-Permian). Magnetostratigraphy of the Lower Triassic up to the lowest parts of the Upper Triassic in central and western Spitsbergen provides greater chronostratigraphic detail than has been available hitherto from biostratigraphy alone. This demonstrates the scale of a number of suspected hiatuses, and also hints at improved chronostratigraphic correlations between east and west Spitsbergen. Upper Triassic sediments provide the best palaeomagnetic properties, indicating that future magnetostratigraphic studies in this interval may improve chronostratigraphic understanding of this poorly dated interval. A persistent partial remagnetization affecting both Permian and Triassic sediments is not of a single origin. It may be both a Brunhes-age viscous remanence and a Palaeogene heating/burial-induced magnetization, or a fluid flow related remagnetization locally in western Spitsbergen. The remagnetization is often composite (Cenozoic plus older) in nature.

In addition to the drawback of their remote location, the Permian and Triassic rocks of Svalbard do not provide ideal and "classic" lithologies, such as volcanic and igneous rocks, pelagic limestones and red beds, for palaeomagnetic study. These are the main reasons these rocks have been overlooked for palaeomagnetic study until relatively recently. Nevertheless, the Permian and Triassic of Svalbard provide a potential testing ground for a number of significant issues in palaeomagnetism. First, they provide a largely undeformed marine sediment record through large parts of the Permian and Triassic (Mørk et al. 1992; Nakrem et al. 1992; Stemmerik 2000; Stemmerik & Worsley 2005), in contrast to sizeable parts of the Permian and Triassic world at lower palaeolatitudes, which are often continental red beds, or marine successions that were later involved in orogenesis. As such, the Svalbard successions provide key sections for unravelling the details of the polarity of the Earth's magnetic field (i.e., magnetostratigraphy) throughout the Permian and Triassic periods. Second, recent debates about the non-dipole (octapole) content of the longer term averaged geomagnetic field and its effect on apparent polar wander paths (APWP), and resulting conflicts of plate reconstructions, have heavily used data from rocks

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of Permian–Triassic age (Van der Voo & Torsvik 2001; Tauxe & Kent 2004; Kent & Tauxe 2005). These data are strongly biased towards studies on rocks from low to middle palaeolatitudes, whereas testing of long-term field models requires a spread of data through to high palaeolatitudes (Van der Voo & Torsvik 2001, 2004). The relatively well-dated Permian and Triassic rocks of the Arctic therefore provide a potential testing ground for these concepts.

The palaeomagnetic study of the Permian and Triassic rocks of Svalbard (Fig. 1) has a relatively short history, with all studies having been restricted to Spitsbergen. Jeleńska (1987) and Vincenz & Jeleńska (1985) were the first to attempt a study of the Spitsbergen Permian sediments, followed by Nawrocki (1999). In the late 1980s to mid-1990s several studies by a group based in Bergen were the first to attempt palaeomagnetic investigations of various parts of the Svalbard Triassic: these findings remain unpublished. The first fully published works on the Triassic are those of Nawrocki (1999) and Nawrocki & Grabowski (2000), along with a preliminary magnetostratigraphic summary of the Lower Triassic by Hounslow et al. (1996).

This review summarizes and evaluates published palaeomagnetic studies of the Permian–Triassic of Spitsbergen to gain an integrated view of the behaviour of the magnetic field during this interval. We also examine the issue of the partial remagnetization of these rocks (which is a recurring theme in most studies), using existing data as well as some unpublished data relating to our own studies of these rocks. We have also transferred the older lithostratigraphic nomenclature used by some of these authors onto the newer lithostratigraphy of Dallmann (1999).

Geological setting

The Permian and Triassic deposits of Svalbard (Fig. 1) are part of the extensive deposits on the northern passive margin of Pangaea, stretching from north-eastern Siberia in the east, through the Novaya Zemlya region into the Barents Sea, and on to the Sverdrup Basin in northern Canada (Doré 1991; Mørk et al. 1992; Stemmerik 2000; Stemmerik & Worsley 2005). The Permian and Triassic are largely marine rocks in Svalbard, although at other marginal locations on the northern Pangaean margin these interfinger with non-marine sediments (Mørk et al. 1992; Egorov & Mørk 2000; Stemmerik 2000). In western Spitsbergen the combined Permian and Triassic is on the order of 1700 m thick, which in central Spitsbergen thins to about 1400 m thick. The succession on Svalbard appears to represent most of the time span throughout the Permian and Triassic, except for hiatuses in parts of the mid-Permian, late Permian and at several points (mostly poorly understood) in the late Triassic (Fig. 2).

The Permian of Svalbard consists of limestones, dolomites and evaporites in the Gipsdalen Group, grading upwards into cherty limestones, and silicified shales and siltstones, in the Tempelfjorden Group (Fig. 2). In central Svalbard the Tempelfjorden Group often consists of sandy glauconitic and cherty limestones. The hiatus that characterizes the Permian–Triassic boundary and the late Permian is more extensive (i.e., continues into the Lower Triassic) in southern (e.g., Hornsund and Bellsund regions) and eastern (i.e., Edgeøya) Svalbard, whereas in western and central Spitsbergen the correlated Permian–Triassic boundary (i.e., the first occurrence of *Hindeous parvus*) is preserved in the base of the Vardebukta and Vikinghøgda formations (Wignall et al. 1997; Mørk, Dallmann et al. 1999; Mørk, Elvebakk et al. 1999; Hounslow, Peters et al. 2008). The Lower and Middle Triassic consists of shales, siltstones and sandstones organized into repeated coarsening-up cycles. These are more pronounced in western Spitsbergen, whereas in central and eastern Svalbard the succession is dominated by shales, often with organic matter contents of above 1% in the Spathian (late Olenekian) and Middle Triassic, along with phosphate-rich intervals in the Ladinian (Mørk, Elvebakk et al. 1999; Krajewski 2000). The Carnian (lower part of the Upper Triassic) on Svalbard (Tschermakfjellet and De Geerdalen formations; Fig. 2) displays a dramatic switch to an interval of deltaic and non-marine deposition. The Norian and last stage of the Triassic, the Rhaetian, is probably incomplete or highly condensed in comparison with the underlying parts of the Triassic and Permian (Fig. 2).

The successions in western Spitsbergen are segmented by open folding and thrusting: the consequence of transpression during the Palaeocene–Eocene, associated with the initial opening of the North Atlantic between Greenland and Svalbard (Braathen et al. 1999; Bergh & Grogan 2003), which often leads to moderate to steep bedding dips. The Permian and Triassic in central Spitsbergen, and the eastern Svalbard islands, are largely unaffected by this deformation, commonly having bedding dips of less than 5°. Thermal maturation of organic matter shows the least heating of the Permian and Triassic in central and eastern Svalbard (Bjorøy et al. 1978; Bjorøy et al. 2006).

Permian and Triassic palaeomagnetic poles

Rowley & Lottes (1988) initially considered Svalbard to be a separate microplate during the Mesozoic, in spite of earlier palaeomagnetic data from the Devonian and early

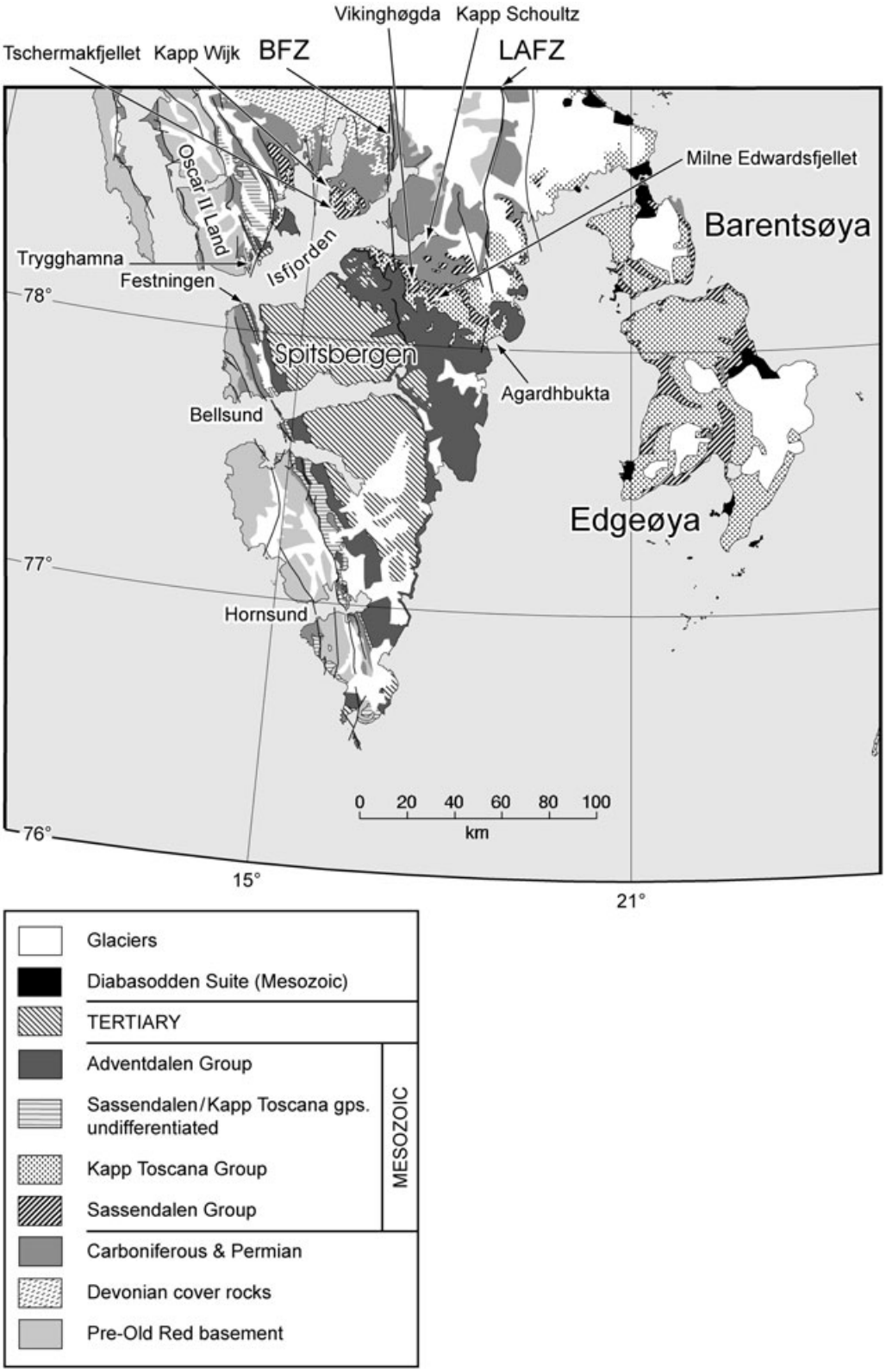

Fig. 1 Location map and simplified geology map of central and southern Svalbard (after Dallmann 1999). BFZ, Billefjorden Fault Zone; LAFZ, Lomfjorden–Argardbukta Fault Zone.

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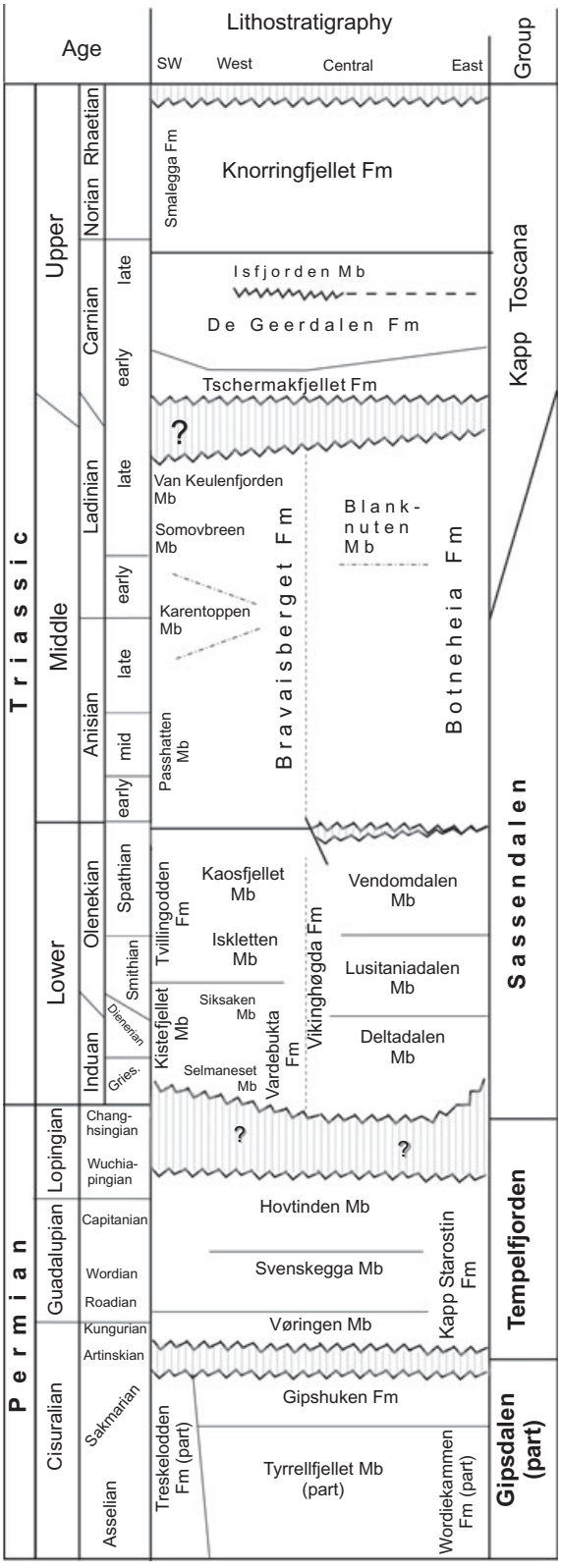

Fig. 2 Summary of the Permian and Triassic lithostratigraphy of Svalbard. Adapted from Dallmann (1999), Samuelsberg & Pickard (1999), Mørk, Dallmann et al. (1999) and Hounslow, Hu, Mørk, Vigran et al. (2007).

Carboniferous of Spitsbergen (Watts 1985; Torsvik et al. 1985; Jeleńska & Lewandowski 1986), which fall close to the Baltica APWP. Other virtual geomagnetic pole (VGP) data from the late Carboniferous–Permian, isolated by Vincenz & Jeleńska (1985) and Jeleńska (1987), appeared to deviate from that of the European APWP (Fig. 3a), which, in addition, had large directional uncertainty. Of the poles reported by Jeleńska & Vincenz (1985), those from the Festningen/Bellsund sections, from the lower part of the Kapp Starostin Formation (Fm.) and the Wordeikammen Fm., show significant (at 95% confidence) deviation from the Baltica APWP (Table 1). This deviation was originally explained as a result of the rotation of Spitsbergen in relation to Europe during the opening of the Labrador Sea and the Greenland–Norwegian Sea (Jeleńska 1987). However, the newest Carboniferous–Permian–Triassic palaeomagnetic data from the Isfjorden area supports the hypothesis that Spitsbergen has been an integral part of the Laurussia plate since this time (Nawrocki 1999), which is fully supported by the vast quantity of data now available from the Barents Sea, stemming from hydrocarbon exploration. The limited VGP data from the Gipsdalen and Tempelfjorden groups (Fig. 3; Table 1), isolated from the Kapp Schoultz, Trygghamna and Kapp Wijk sections (Nawrocki 1999), are statistically indistinguishable from the Permian part of the Laurussia APWP (Fig. 3a; Table 1). A closer relationship with the Laurussia APWP is shown by most of the Triassic VGP data, except for data from western Spitsbergen in the Trygghamna section (Fig. 3a; Table 1, pole ID 7).

Part of the apparent deviations from the APWP for the west Spitsbergen Permian–Triassic palaeopoles may relate to unrecognized vertical-axis rotations. Some results from western Spitsbergen clearly demonstrate some clockwise rotations of ca. 20–40° (Nakazawa et al. 1990; Michalski & Lewandowski 2004). However, the divergent Permian pole from the Lower part of the Kapp Starostin Fm. (Table 1, pole ID 3; Jeleńska & Vincenz 1985) cannot be explained by this mechanism, because of its anomalously steep inclination. Similar small vertical-axis rotations may also relate to local tectonic detachments in central Spitsbergen (Hounslow, Hu, Mørk, Vigran et al. 2007).

The Gipsdalen Group palaeomagnetic data of Nawrocki (1999) indicate that during this time, central Spitsbergen, being part of Laurussia, was located at about 27° N (Fig. 3b; Table 1). However, as has been suggested by Van der Voo & Torsvik (2001, 2004), the precise location of the late Palaeozoic–early Mesozoic palaeocontinents is subject to some 8° of latitudinal displacement if a purely geocentric axial dipole field model is used. The causes of this displacement are either an octapole contribution to the geomagnetic field or persistent sedimentary inclina-

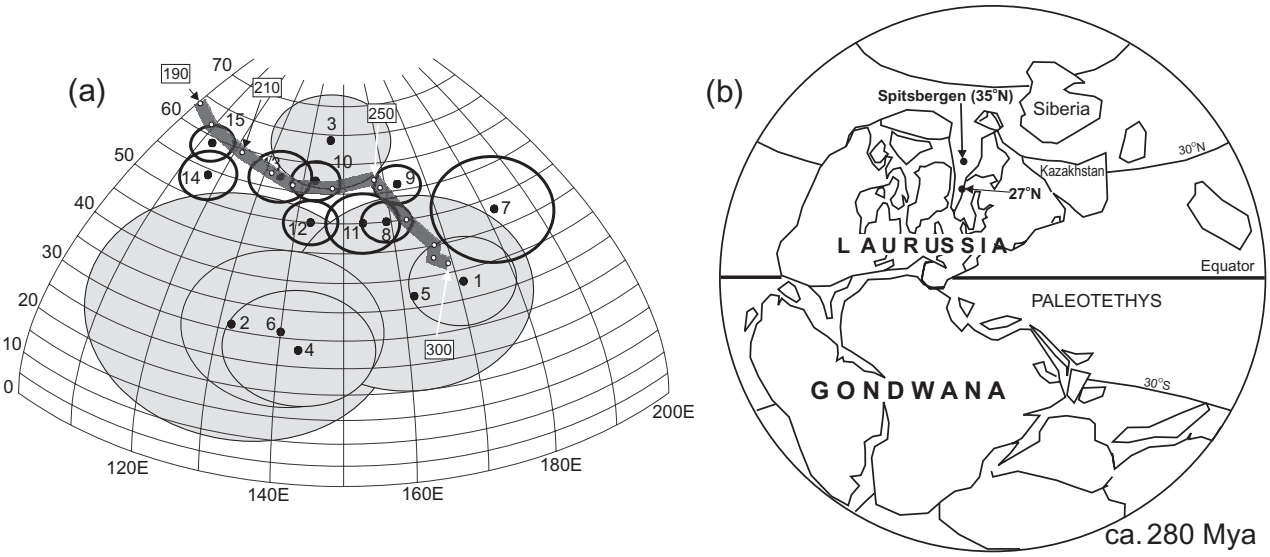

Fig. 3 (a) Late Carboniferous–Early Jurassic apparent polar wander path for stable Europe in 10-My increments (white dots), starting from 300 Mya (Torsvik & Cocks 2005), and palaeomagnetic poles isolated from the Permian and Triassic rocks of Spitsbergen. The pole numbers are the ID numbers in Table 1. The 95% confidence interval is shaded for the Permian poles, and Triassic poles have a thicker line defining the confidence cone. The time scale used is that of the palaeomagnetic database (see Table 1). (b) Palaeogeographic reconstructions of continents in the early Permian (after Van der Voo & Torsvik 2004). The location of Spitsbergen is shown according to the dipole model of the palaeomagnetic data at 27° N, and the octapole field model at 35° N.

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tion shallowing of the VGP data (Tauxe & Kent 2004; Tauxe 2005). Palaeogeographic reconstructions using the Pangaea A-type configuration for the Lower Permian (Fig. 3b) indicate ca. 8° of palaeolatitudinal difference between the projected location of Spitsbergen and the palaeomagnetic latitude obtained using the geocentric axial dipole hypothesis. Using these concepts, the refined palaeomagnetic data indicate that during the Lower Permian the true palaeolatitude of Spitsbergen was about 35° N, changing to 45° N near the Permian–Triassic boundary, and to about 55° N by the end of the Triassic.

The mineralogical origin of the magnetization in the Permian and Triassic rocks of Spitsbergen implicates magnetite or titanomagnetite as the most significant carrier, demonstrated by low-temperature properties and thermal demagnetization of isothermal remanent magnetization (Nawrocki 1999; Hounslow, Hu et al. 2008 [this issue]). The Permian rocks displaying primary components often show maximum unblocking temperatures of 450–500°C (Nawrocki 1999), which are partly disguised by thermal alteration at 420–440°C or at lower temperatures. In Triassic rocks, the magnetization process is quite complex in character, as can be seen by the associations between lithology groups, natural remanent magnetization (NRM) intensity and magnetic susceptibility (Fig. 4). In the Lower and Middle Triassic, enhanced NRM intensities are often associated with calcite and dolomite concretions and beds, which could indicate either better preservation of the magnetite in these lithologies (i.e., possibly they were protected from late sulphide diagenesis) or, perhaps, larger amounts of other magnetic minerals (possibly magnetic sulphides). Most of the clastic lithologies have broadly similar NRM intensities and magnetic susceptibilities, with values of NRM intensity often less than 1 mA m^{-1}. The clastic units in the Upper Triassic (Fig. 4a) are an exception. Either these have better preservation of magnetite or have a different sediment source (i.e., with more magnetite). We suspect that magnetic sulphides (possibly greigite) may make a contribution to the magnetization of some of the Permo-Triassic sediments (e.g., blocking temperatures near to 300°C in some specimens [Nawrocki 1999]), although positive proof of this is currently lacking. It is clear from low-temperature measurements that pyrrhotite is not present (Nawrocki 1999; Hounslow, Hu et al. 2008; Hounslow, Peters et al. 2008). In some Permian samples goethite appears to make a minor contribution to the natural remanence (Nawrocki 1999).

Problems of remagnetization

A persistent problem with the Permian and Triassic rocks on Spitsbergen is a partial to occasionally complete

Table 1 Summary of the mean palaeomagnetic pole data for the Permian and Triassic of Spitsbergen. The age boundaries used by Torsvik & Cocks (2005) and the palaeomagnetic database are 290 Mya for the Carboniferous/Permian, 251 Mya for the Permian/Triassic and 206 Mya for the Triassic/Jurassic boundaries.

		Mean direction					VGP				
Formation/Mb./Unit	Location	Dec.	Inc.	k[a]	α_{95}[b]	Nl[c]/Np[d]	Lat.[e]	Long.[f]	Ref.[g]	ID[h]	APWP"fit-age"[i] {γc/γo}
De Geerdalen Fm.[j]	Dalsnuten	66	71	24.4	3.1	63/27	59	113	1	15	203
Tschermakfjellet Fm.[j]	Dalsnuten	66	68	46.3	4.1	27/0	54	117	1	14	210
Top Botneheia Fm.	Milne Edwardsfjellet	50	68	125	4.3	10/0	57	134	1	13	223
Botneheia Fm.	Milne Edwardsfjellet	45	62	31.3	3.7	48/0	50	143	2	12	235
Vendomdalen Mb.	Milne Edwardsfjellet	36	60	36.3	5	24/0	50	154	2	11	265
Vendomdalen Mb.	Vikinghøgda	42	66	42.4	3.3	40/6	57	143	3	10	235
Lusitaniadalen Mb.	Vikinghøgda	26	64	24.5	3.2	28/53	56	163	3	9	260
Deltadalen Mb.[k]	Vikinghøgda	31	61	20.1	3.4	35/53	50	159	3	8	268
Vardebukta Fm.	Trygghamna	191	–55	39.3	8.9	8/0	48	182	4	7	280 {7.8/10.3}
Vindodden Limestone					14		31	140	5	6	—
Templefjorden Grp.	Trygghamna	209	–45	8.6	17	10/0	37	162	4	5	292
Upper Kapp Starostin Fm.	Festningen/Bellsund	47	36	12	10.5	117/0	28	143	6	4	292
Lower Kapp Starostin Fm.	Festningen/Bellsund	41	57	233	8.1	19/0	64	146	6	3	243 {7.0/7.8}
Wordiekammen Fm.	Festningen/Bellsund	56	43	12.9	22.3	40/0	31	132	6	2	230 {11/25}
Gipsdalen Grp.	Kapp Schoultz	199	–45	19.1	7.6	16/0	38	171	4	1	300

[a] Fisher precision parameter.
[b] Fisher 95% cone of confidence.
[c] Number of specimens with fitted lines used in determining the mean direction.
[d] Number of specimens with great circle planes used in determining the mean direction.
[e, f] The latitude and longitude of the mean virtual geomagnetic pole (VGP).
[g] References: 1, Hounslow, Hu, Mørk, Vigran et al. (2007); 2, Hounslow, Hu et al. (2008); 3, Hounslow, Peters et al. (2008); 4, Nawrocki (1999); 5, Jeleńska (1987); 6, Jeleńska & Vincenz (1985).
[h] Pole number in Fig. 3.
[i] The apparent polar wander path (APWP) fitted age is the closest age match (in My) to the Baltica APWP of Torsvik & Cocks (2005). Only those flagged with {γc/γo} are significantly different (at the 95% confidence level) to the APWP path using the comparison statistics of McFadden & McElhinney (1990), γc being the critical angle and γo the observed angular divergence.
[j] Probably vertically rotated on Palaeogene age decollément.
[k] Also includes samples from Kapp Starostin Fm.

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remagnetization, evident by an often dominant and steep, down-directed magnetization. This affects the rocks in western Spitsbergen, where the effects of the Palaeocene–Eocene tectonism are most clearly expressed, as well as in the flat-lying rocks in central Spitsbergen. Remagnetization is also a problem for the late Mesozoic igneous dykes and sills, which are common in various parts of Spitsbergen (Krumsiek et al. 1968; Briseid & Halvorsen 1974; Halvorsen 1972, 1989), which is perhaps indicative of a common origin of these remagnetizations.

Jeleńska (1987) first recognized the secondary nature of the steep magnetizations in Permian limestones. About 50% of Permian samples studied at the Trygghamna and Kapp Wijk sections (Fig. 1) are totally remagnetized (Nawrocki 1999). In these remagnetized Permian samples only a single distinct component with very steep, positive inclination (75–90°) was isolated. In spite of the extensive tests by Nawrocki (1999), there does not seem to be a distinctly different mineral that is responsible for the remagnetization, which also seems to reside in magnetite or titanomagnetite, like the primary Permian and Triassic magnetizations.

In the Trygghamna section in western Spitsbergen, some samples from a narrow fault zone also contained a strong remagnetization, but with a negative inclination (Table 2). The NRM intensities of these "fault-zone" samples were about 10 times larger than those partially and fully remagnetized samples outside of the fault zone (Nawrocki 1999). A substantial increase in magnetic susceptibility at temperatures of about 200–440°C (most often between 420 and 440°C) takes place in most Permian samples containing a primary component (Nawrocki 1999), which is not observed in these totally remagnetized fault-zone samples (Fig. 5). The increase of magnetic susceptibility in the non-remagnetized samples is mostly caused by pyrite alteration and oxidation during thermal demagnetization (sediment heating typically produces a variety of strongly magnetic oxides and sulphides; see e.g., Noltimier & Kopacz 1976; Novakova & Gendler 1995; Cairanne et al. 2004; Tudryn & Tucholka 2004). Some of the lower temperature alterations may result from clay alteration (e.g., Fig. 5c). Therefore, it is possible that alterations resulting from natural heating (hot fluids in the fault zone?) would produce new

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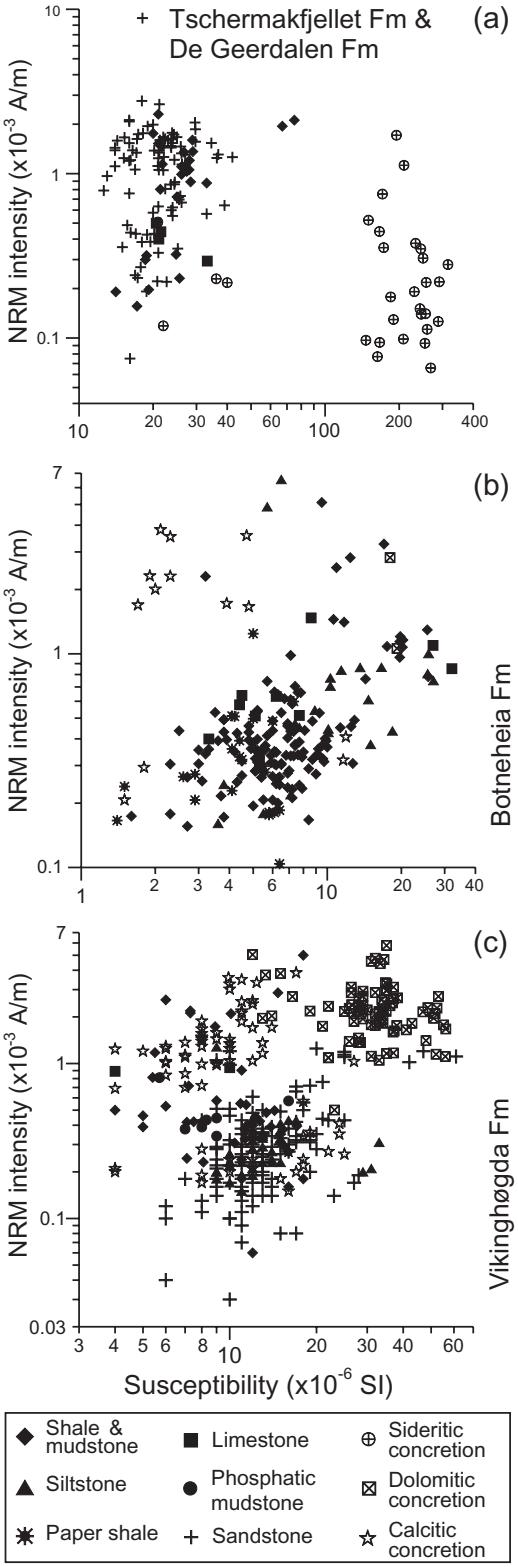

Fig. 4 Natural remanent magnetization (NRM) intensity and susceptibility properties of the Triassic of central Spitsbergen, subdivided according to formation and lithology. Data are from: (a) Hounslow, Hu, Mørk, Vigran et al. (2007) and Hounslow, Hu, Mørk, Weitschat et al. (2007); (b) Hounslow, Hu, Mørk, Vigran et al. (2007) and Hounslow, Hu et al. (2008); and (c) Hounslow, Hu et al. (2008) and Hounslow, Peters et al. (2008), but are presented in a different format.

magnetic minerals from pyrite, which would acquire a new chemical remanent magnetization (CRM), like that reproduced experimentally by Cairanne et al. (2004).

The anisotropy of magnetic susceptibility (AMS) of the samples containing a primary Permian component displayed conventional bedding perpendicular minimum susceptibility axes, unlike the AMS axes of the fault-zone remagnetized samples that have strongly scattered directions (Nawrocki 1999). This shows a lack of preferred orientation of the magnetic minerals that contribute to the AMS—as could be expected if these had grown from the alteration of cubic pyrite. Hence, it seems probable that both the AMS and the remagnetization (a CRM?) are both related to pyrite alteration through localized heating in the fault zone.

Some 15–30% of specimens from Triassic rocks in central Spitsbergen only contain this secondary overprint magnetization, with the remainder containing evidence of a Triassic magnetization, found either by conventional principle component line fitting or great circle trajectories (Fig. 6; Hounslow, Hu, Mørk, Vigran et al. 2007; Hounslow, Hu et al. 2008; Hounslow, Peters et al. 2008). There is evidence for a lithological preference for the remagnetization, with early diagenetic calcite concretions from the Lower Triassic (Deltadalen, Lusitaniadalen and Vendomdalen members) displaying the largest proportion (ca. 40%) of totally remagnetized specimens (Fig. 6). However, this is not the case for dolomitic and sideritic concretionary lithologies, which display lower rates (ca. 10%) of total remagnetization than the shale, siltstone and sandstone lithologies (Fig. 6). The reasons for these differences are as yet unclear.

Directional analysis of this secondary magnetization in interpreted Triassic reverse polarity specimens indicates that the secondary magnetization is deflected to the southwest (Fig. 7; Table 2), whereas the overprint directions in the Triassic normal polarity specimens are dominantly in the north-east quadrant (Table 2). As the means of the "reverse" overprint VGP directions are far from any Phanaerozoic palaeomagnetic poles (Fig. 7), it is probable that this component is a composite: a steeply down-directed remagnetization, with the addition of a small component of Triassic reverse. On the assumption that any secondary magnetization process will have affected both primary

Table 2 Summary of the mean directions for overprints from the Permian and Triassic of Spitsbergen (prior to bedding correction).

		Mean direction					VGP			
Formation/Mb. (polarity)	Location	Dec.	Inc.	k[a]	α_{95}[b]	Nl[c]	Lat.[d]	Long.[e]	Ref.[f]	ID[g]
De Geerdalen/Tsc. Fms. (R)	Dalsnuten	306	84	4.2	22.6	34	79	309	1	16
De Geerdalen/Tsc. Fms. (N)	Dalsnuten	8	84	11.8	5.5	62	88	92	1	15
top most Botneheia Fm. (N)	Milne Edwardsfjellet	36	82	66	6	10	81	114	1	14
Botneheia Fm (R)	Milne Edwardsfjellet	203	78	8.6	5.2	98	56	2	2	13
Botneheia Fm (N)	Milne Edwardsfjellet	17	83	22	3.3	86	86	127	2	12
Vendomdalen Mb. (R)	Milne Edwardsfjellet	270	75	7.3	12.1	23	60	309	2	11
Vendomdalen Mb. (N)	Milne Edwardsfjellet	8	81	23.3	4.7	41	84	175	2	10
Vendomdalen Mb. (R+N)	Vikinghøgda	296	68	13.8	9.4	19	55	276	3	9
Vendomdalen Mb. (N)	Vikinghøgda	303	73	16.2	10.2	15	63	273	3	8
Lusitaniadalen Mb. (R)	Vikinghøgda	232	85	9.2	5.8	50	71	353	3	7
Lusitaniadalen Mb. (N)	Vikinghøgda	15	84	14.3	4.5	73	87	102	3	6
Deltadalen Mb. (R)	Vikinghøgda	329	76	5.8	9	52	73	247	3	5
Deltadalen Mb. (N)	Vikinghøgda	57	85	13.4	7.3	31	80	70	3	4
Kapp Starostin Fm. (N)	Kapp Schoultz	30	81	49.9	3.1	42	80	132	4	3
Kapp Starostin Fm. (N)[h]	Kapp Schoultz	343	80	46.4	3.3	42	82	240	4	
Kapp Starostin Fm. (N)	Trygghamna	52	–3	30.5	8.9	10			4	2
Kapp Starostin Fm. (N)[h]	Trygghamna	0	78	48.2	7	10	79	199	4	
Kapp Starostin Fm. (R)	Trygghamna	239	–3	23.2	16.2	5			4	1
Kapp Starostin Fm. (R)[h]	Trygghamna	183	–77	76.4	8.8	5	78	193	4	

[a] Fisher precision parameter.
[b] Fisher 95% cone of confidence.
[c] Number of specimens with fitted lines used in determining the mean direction.
[d, e] The latitude and longitude of the mean virtual geomagnetic pole (VGP).
[f] References as given in Table 1.
[g] Pole number in Fig. 7.
[h] Overlying result after bedding correction.

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reverse and normal polarity samples equally, it seems likely that the overprint directions from Triassic normal polarity specimens may be equally composite in nature (Hounslow, Peters et al. 2008).

Possible origins of this secondary magnetization are: (a) heating events associated with the intrusion of the late Mesozoic dykes and sills of the High Arctic Large Igneous Province (HALIP), defined by Maher (2001); (b) heating and fluid migration associated with Palaeocene–Eocene transpression in western Spitsbergen; (c) a Brunhes-age viscous magnetization; and (d) Brunhes-age weathering events (e.g., permafrost formation and thawing?; Løvlie & Putkonen 1996).

The mean VGP directions of the overprints fall far from the cluster of poles associated with the primary directions of HALIP intrusions (Fig. 7), suggesting that it is unlikely that these intrusions have induced a large-scale remagnetization of Permian and Triassic rocks. Naturally, it is possible that this process may have occurred close to these intrusions.

The organic matter maturation in the Triassic clearly shows elevated values of maximum heating in western Spitsbergen, compared with central and eastern Svalbard (Bjorøy et al. 1978; Bjorøy et al. 2006). It seems probable that this enhanced organic matter maturation may be associated with deeper maximum burial (i.e., a higher maximum temperature) in western Spitsbergen, rather than widespread fluid migration in the low permeability mudrocks of the Triassic. In addition, the Triassic rocks from central Spitsbergen show no evidence that the coarser grained lithologies (sandstone and siltstones) are any more remagnetized than the shales (Fig. 6), which would suggest that wide-scale fluid migration as a process of remagnetization is not viable.

However, local hot fluid migration is a viable mechanism in western Spitsbergen, as shown by the above example of remagnetization from a fault zone in the Permian (Fig. 5). Nevertheless, considering that the Palaeocene–Eocene has a complex pattern of polarity changes, fluid flow or orogenic-related heating seems unable to fully account for widespread normal polarity remagnetizations. The mean pole positions of the Triassic "normal" overprints do not fall directly over the Palaeocene–Eocene (65–31 Mya) part of the APWP for Laurussia, but instead fall somewhat to the west (Fig. 7). Only one of these poles shows significant overlap with the APWP (Table 2, pole 10), although, considering the uncertainties in the APWP (in part expressed by the two APWP solutions in Fig. 7), some of these overprints could be considered as possible Palaeocene–Eocene

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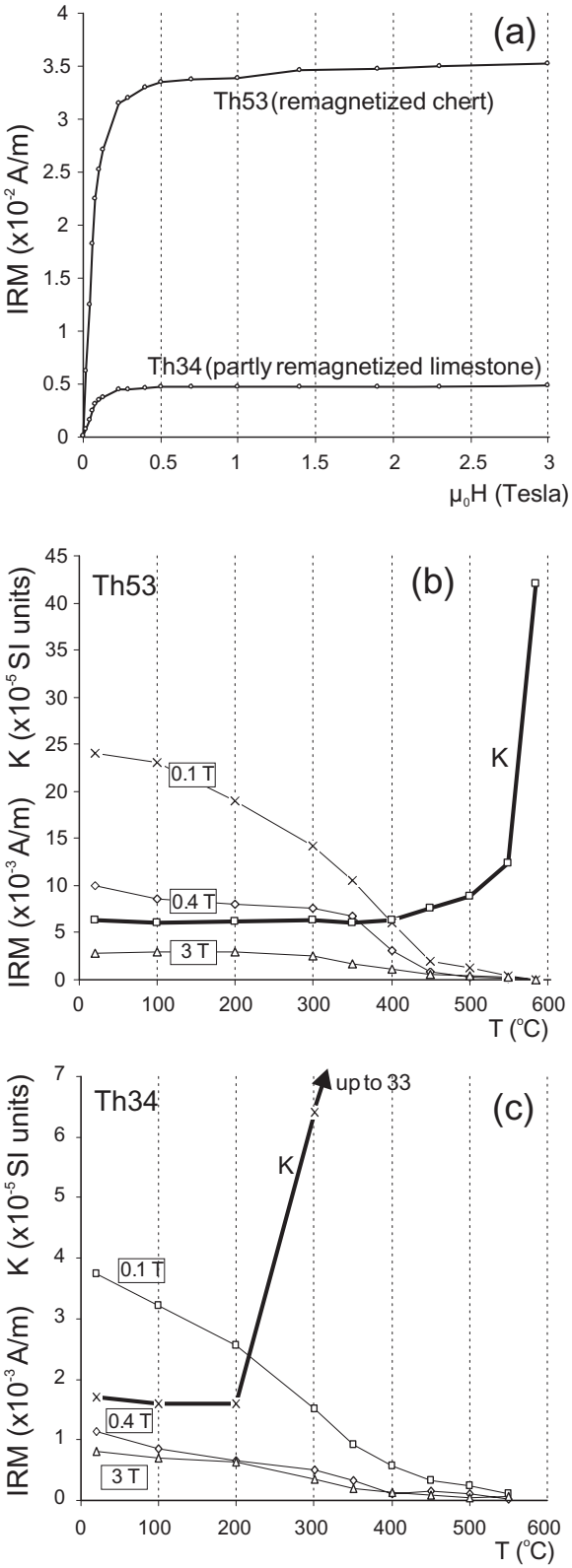

Fig. 5 (a) Isothermal remanent magnetization (IRM) acquisition curves of partly and totally remagnetized Permian samples from the Trygghamna section, and (b,c) thermal demagnetization of orthogonal-axis IRM curves prepared from the same samples (partly from Nawrocki 1999 and partly new data). *K* is the volume-specific susceptibility. The distinct blocking temperature at ca. 450°C, seen in (b), and to a lesser extent in (c), is typical of most Permian samples (Nawrocki 1999), and may result from titanomagnetite, a limited grain-size range of magnetite or maghaemite oxidation during heating.

remagnetizations. The Permian example above also demonstrates that these remagnetizations in western Spitsbergen are acquired after Palaeocene–Eocene folding. Also, in their study of HALIP igneous rocks, Vincenz et al. (1981) implicated Tertiary-age remagnetizations for both reverse and normal polarity magnetizations.

Brunhes-age viscous remagnetization has been evaluated as a viable mechanism in HALIP igneous rocks in western Spitsbergen (Sandal & Halvorsen 1973). Preliminary studies of viscous magnetization acquisition on the Triassic rocks also demonstrate that these rocks have the ability to acquire substantial viscous components (Fig. 8). This demonstrates that at least part of the remagnetization problem is associated with a Brunhes-age viscous magnetization, even in the dolomitic lithologies in the Lower Triassic, which have somewhat more stable palaeomagnetic behaviour than other rock types (Figs. 6, 8).

In conclusion, the remagnetization that is persistent in the Permian and Triassic rocks of Spitsbergen has several characteristics.

- The remagnetization is mostly younger than the Palaeocene–Eocene folding, although its direction is not easy to fully resolve because of demagnetization stability overlap with older magnetizations.
- Triassic sediments in central Spitsbergen show some lithological discrimination of remagnetization prevalence, which is not understood at this time.
- Bruhnes-age viscous magnetizations are in part responsible for the remagnetization in central Spitsbergen.
- Localized fluid migration along fault zones is a viable mechanism for remagnetization in western Spitsbergen.
- Palaeocene–Eocene orogensis and heating may have made a contribution to remagnetization in western Spitsbergen.

Magnetostratigraphy

The Permian polarity time scale

A dominantly reverse-polarity interval extends from the mid-Carboniferous to around the mid-Permian, the

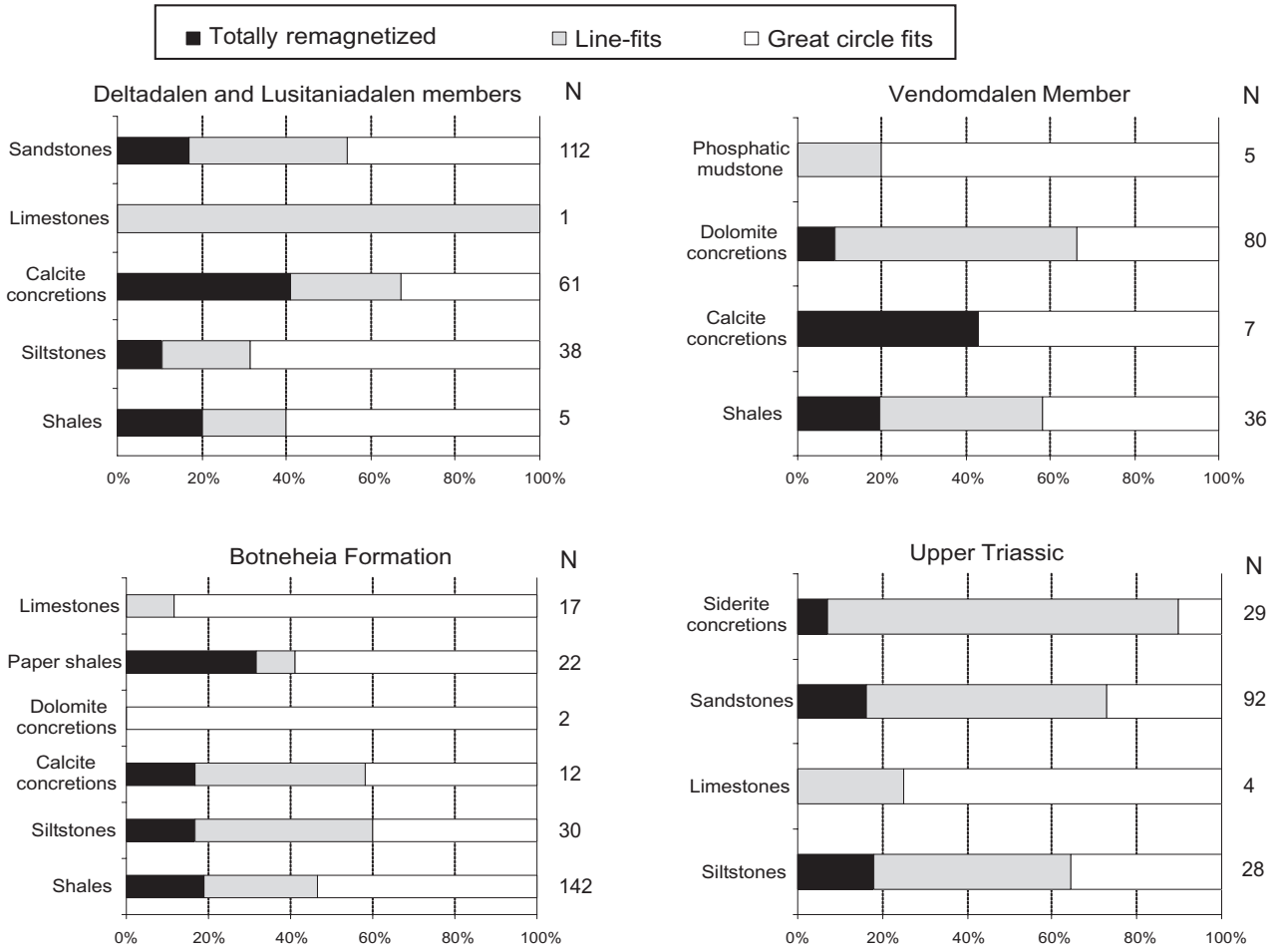

Fig. 6 Percentage subdivision of specimen magnetization characteristics for the Triassic of central Spitsbergen, subdivided according to formation and type of sample lithology. Line-fits: conventional principle component analysis derived from linear trajectory fitted-line to demagnetization data. Great circle fits: polarity interpreted according to great circle (remagnetization circle) trends (primary data from Hounslow, Hu, Mørk, Vigran et al. 2007; Hounslow, Hu et al. 2008; Hounslow, Peters et al. 2008; reformatted for this figure). *N* is the number of specimen data for each of the lithological categories.

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Permo-Carboniferous Reverse Superchron (PCRS), which is succeeded by an interval of normal and reverse polarity in the late Permian. However, the precise location of the top of the PCRS relative to the modern Permian stages is controversial (Gradstein et al. 2004; Menning et al. 2006; Steiner 2006). This controversy in part relates to how best to correlate the older Permian regional subdivisions with the modern stage subdivisions (Gialanella et al. 1997; Menning et al. 2006). It is also probable that relatively brief intervals of normal polarity occurred in the early parts of the mid-Permian, as the PCRS was ending, during the Wordian and Capitanian (Steiner 2006), so that there was probably not a "sudden end" to the PCRS. A robust solution to the Permian magnetostratigraphic time scale is hampered by the poor consistency of mid to late Permian magnetostratigraphic data from marine rocks with good biostratigraphic age control (Gallet et al. 2000; Steiner 2006). In contrast, data from poorly dated Russian platform red beds unequivocally locate the top of the PCRS in the Tatarian (Pechersky & Khramov 1973; Gialanella et al. 1997). In the most recent interpretations, the top of the PCRS is suggested to be near the base of the Capitanian (Gradstein et al. 2004; Menning et al. 2006), which is regarded as contemporaneous with the lower part of the normal magnetozones in the Russian Tatarian (Fig. 9; Menning et al. 2006). Differences in interpretation relate to the youngest age assigned to the Tatarian. An alternative analysis by Steiner (2006) suggests evidence for repeatable brief normal polarity magnetozones in the Wordian, which she suggests to be the top of the PCRS (Fig. 9).

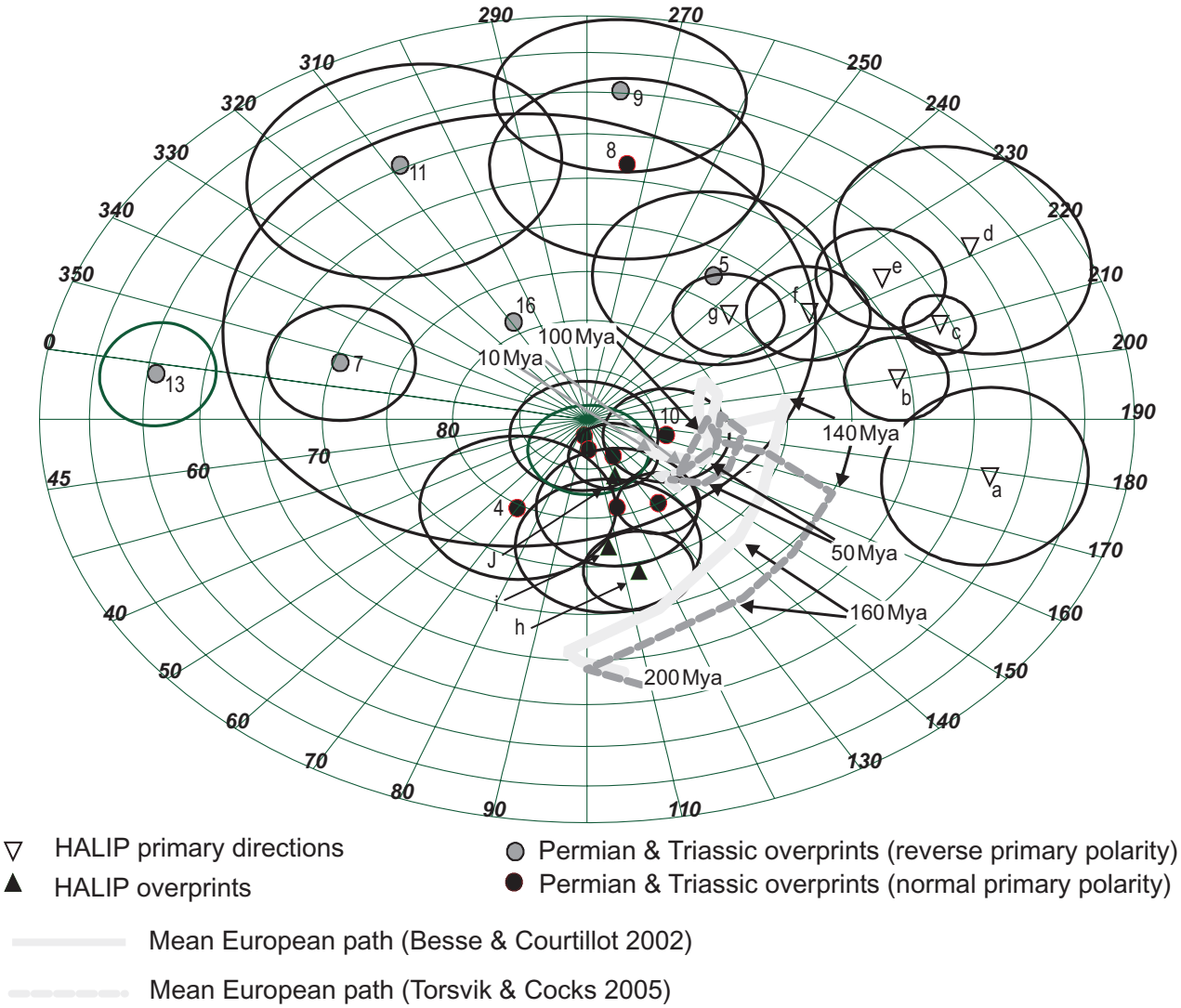

Fig. 7 Palaeopoles (and 95% confidence regions) from overprint magnetizations reported from Permian and Triassic formations from Spitsbergen, together with the palaeopoles (and 95% confidence regions) from the High Arctic large igneous province (HALIP; Maher 2001) of late Mesozoic age. Apparent polar wander paths (APWP) of the European plate (Besse & Courtillot 2002; Torsvik & Cocks 2005) are shown in grey. Most virtual geomagnetic poles (VGPs) are numbered with the ID from Table 2 (some have been omitted for clarity). HALIP primary and overprint poles are: a, Krumsiek et al. (1968); b, Halvorsen (1989); c, Briseid & Halvorsen (1974); d, Vincenz et al. (1984); e, Jeleńska & Vincenz (1985); f and h, Vincenz et al. (1981); g and i, Sandal & Halvorsen (1973); and j, Halvorsen (1972). The 0- and 5-Mya APWP poles are displaced by ca. 8° from the geocentric axial dipole model (i.e., +90°) because of the well-known "far-sidedness" of the palaeomagnetic data (Van der Voo & Torsvik 2004).

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Studies of the Permian on Spitsbergen

The palaeomagnetic studies of Jeleńska & Vincenz (1985) and Jeleńska (1987) covered the late Carboniferous Hymefjellet Fm., the latest Carboniferous–Lower Permian Treskelodden Fm. and the mid-Permian part of the Kapp Starostin Fm., and detected only normal polarity. Their results are clearly questionable, as they sampled intervals that correspond mostly to the PCRS, predominantly in western Spitsbergen, and mostly used alternating field demagnetization. They probably failed to fully separate the normal overprint magnetization from the Permian magnetization, so their extracted directions are probably composites, consisting of a normal overprint plus Permian reverse.

Modern magnetostratigraphic studies of the Permian on Spitsbergen have been undertaken by Nawrocki & Grabowski (2000) in order to try to recognize the upper boundary of the PCRS, and to try and establish the position of the first major overlying normal polarity interval,

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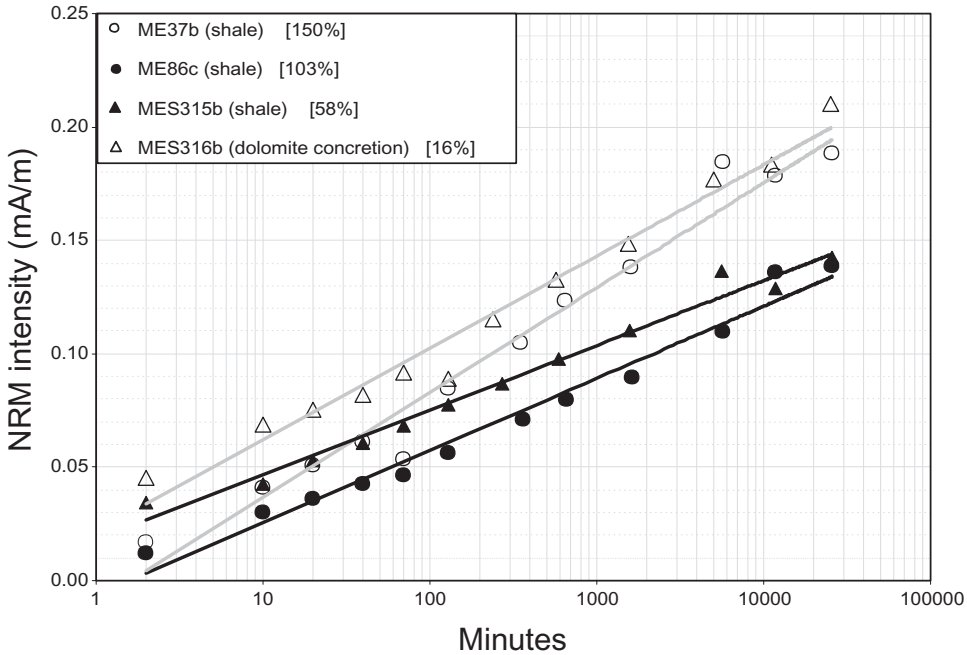

Fig. 8 Viscous remanent magnetization (VRM) acquisition acquired by four specimens (in a laboratory Earth magnetic field) over a period of 20 days, along with the fitted line through the intensity versus log (time) relationship. The initial starting state is measured after alternating field demagnetization at 100 mT (note that this has not entirely reduced all magnetization to zero). Values in brackets indicate the percentage of the non-demagnetized natural remanent magnetization (NRM) that, with acquisition at this rate, for 10 Ky, would be induced in the specimens.

in the mid to late Permian. Rocks from the Gipsdalen and Tempelfjorden groups were sampled by Nawrocki & Grabowski (2000) for magnetostratigraphy at Kapp Schoultz (Tempelfjorden, Fig. 1), Kapp Wijk (western Dicksonland, Fig. 1) and Trygghamna (western Spitsbergen). Nawrocki & Grabowski (2000) collected some 300 specimens, and in spite of numerous gaps in the magnetic polarity data for the sections (caused by complete remagnetization), these data do support a fragmentary magnetostratigraphy (Fig. 9). These samples are dominantly reverse polarity, but are interrupted by three limited-thickness normal polarity intervals: one within the base of the Tyrrellfjellet Member (Mb.), one in the lower parts of the Svenskegga Mb. and a probable third in the base of the Hovtinden Mb. (Fig. 9). As discussed previously, only 12% of the specimens possessed data suitable for robust conventional principle-component linear trajectory analysis (Nawrocki 1999), but some 38% of additional specimens displayed great circle trends, which could reliably be used to interpret the polarity. Nawrocki & Grabowski (2000) used a specimen data-quality classification, which we have used to display a composite magnetostratigraphy from each section (Fig. 9).

Reverse polarity in the Tyrellfjellet Mb. was interrupted by a normal magnetozone just below the level of *Palaeoaplysina* build-ups in the upper part of the Brucebyen Beds (data from Nawrocki & Grabowski 2000, mapped onto the modern lithostratigraphy). This magnetozone comprised two adjacent specimens (characteristic remanence directions in stratigraphic coordinates: declination/inclination = 348°/45°; 355°/48°), some 40 m above its base (Fig. 9). In sections in the Urals and Central Asia, in the top part of the Gzhelian (latest Carboniferous), there is a consistently detected normal magnetozone (Hramov [Khramov] & Davydov 1984; Davydov & Hramov [Khramov] 1991; Davydov & Leven 2003). In sections in Asia, a second normal magnetozone occurs in the basal Asselian (Khramov & Davydov 1993; Davydov & Leven 2003). Nilsson & Davydov (1997) have placed the Gzhelian–Asselian boundary within an interval near the top of the Brucebyen Beds and its transition into the overlying beds. This suggests that the tentative normal magnetozone in the Brucebyen Beds probably represents the equivalent of the late Gzhelian magnetozone identified by Khramov & Davydov (1993). The normal polarity interval in the Brucebyen Beds is only defined by two specimens, and is therefore somewhat tentative, but this magnetozone does demonstrate the potential for the more precise identification of the Carboniferous–Permian boundary in other sections in Svalbard.

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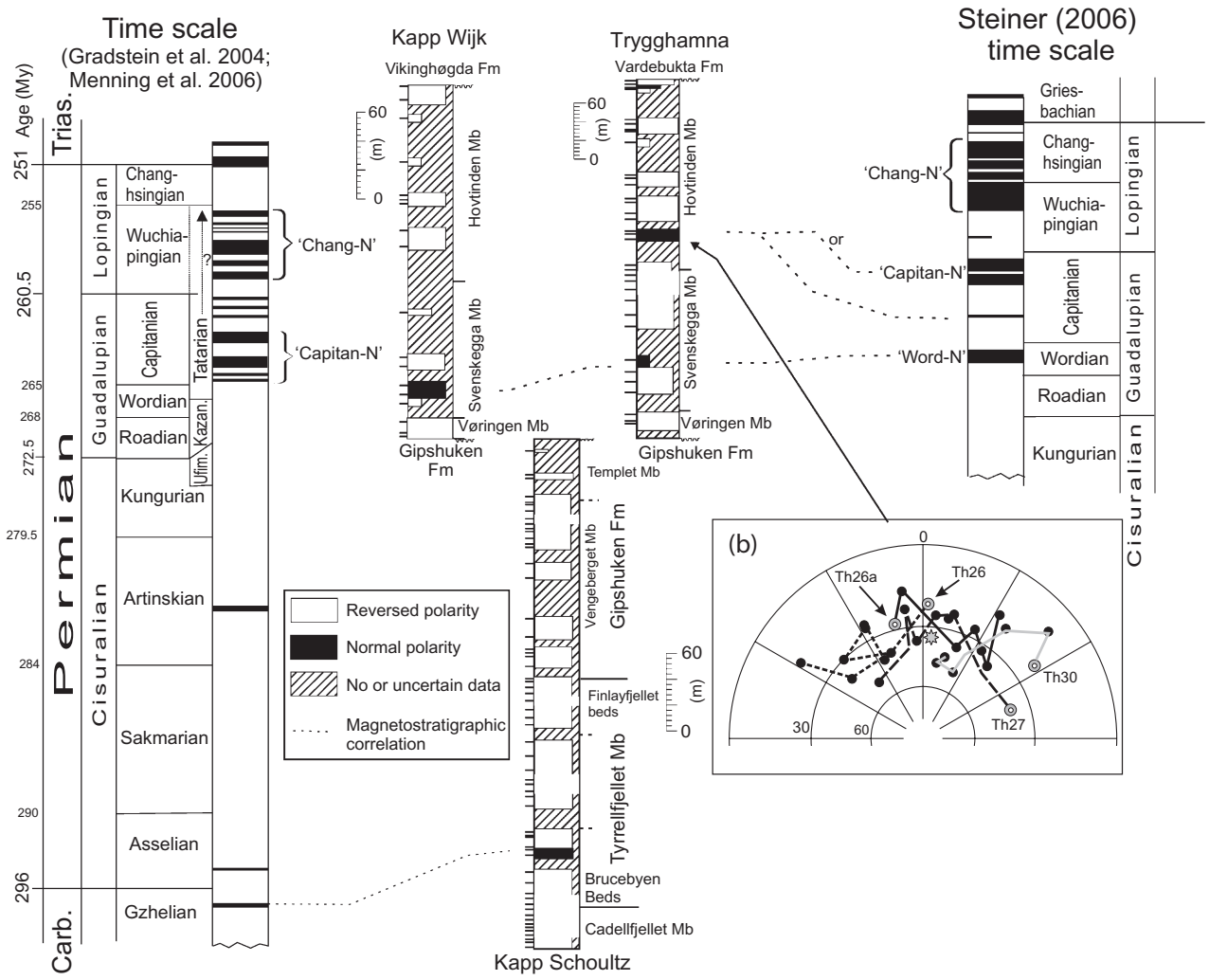

Fig. 9 Global magnetostratigraphic columns for the Permian (after Gradstein et al. 2004 and Steiner 2006), and their possible correlation with the magnetostratigraphy of the Kapp Wijk, Trygghamna and Kapp Schoultz sections of Nawrocki & Grabowski (2000). Magnetozone widths of one quarter indicate a single specimen, of poorer demagnetization quality, with no adjacent data; magnetozone widths of one half indicate a single specimen, of good demagnetization quality, with no adjacent data; magnetozone widths of three quarters indicate one or more adjacent specimens with poorer quality demagnetization data, of the same polarity; a full bar indicates one or more adjacent specimens, with good-quality demagnetization data, of the same polarity. Tick-marks adjacent to the left-hand side of the polarity columns indicate the sampling levels. Inset (b) shows the demagnetization paths of the four adjacent specimens from the normal magnetozone in the Hovtinden Mb. (Kapp Starostin Fm.). The round symbols in grey are the initial natural remanent magnetization (NRM) directions. Paths marked in black possess principle-component fitted-lines; paths marked in grey had no fitted-lines. The star marks the mean direction of the characteristic remanence of these four specimens.

Normal polarity was interpreted in three specimens in the lower part of the Svenskegga Mb.: two at Kapp Wijk (30 m from the base of the Kapp Starostin Fm; Fig. 9) and one at Trygghamna, which probably represents the equivalent normal magnetozone (Nawrocki & Grabowski 2000). This, like the lower normal magnetozone, was regarded as tentative because it was based on poorer quality data, in which polarity was determined using directional trends during demagnetization. However, this normal magnetozone compares favourably with Steiner's (2006) "Word-N" magnetozone (Fig. 9), which was identified in successions in North America and Transcaucasia.

The first fully reliable normal magnetozone appears in cherts from the base of the Hovtinden Mb. at Trygghamna (220 m above the base of the Kapp Starostin Fm.). This was based on three sample levels at 275, 278 and 283 m in the section, with three out of four specimens displaying linear-trajectory fitted-lines (Nawrocki & Grabowski 2000). These specimens yield a mean direction in stratigraphic coordinates of 8°/34° ($N = 4$, $k = 16$; Fig. 9). There

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is no confirmation of this magnetozone from the Kapp Wijk section (Fig. 9). This normal magnetozone probably represents one or another of the normal magnetozones in Steiner's (2006) Capitanian time scale. Reverse polarity seems to dominate the topmost part of the Kapp Starostin Fm. (Figs. 9, 10), which would suggest most of the Upper Permian (Lopingian) may be missing on Spitsbergen, consistent with some biostratigraphic interpretations (Nakazawa et al. 1990; Nakrem et al. 1992). Alternatively, it may be that the uppermost Kapp Starostin Fm. is earliest Lopingian in age, which is dominated by reverse polarity (Fig. 9) in Steiner's (2006) magnetostratigraphic time scale.

Some have suggested that the Kapp Starostin–Vardebukta Fm. boundary may be entirely conformable in western Spitsbergen (Wignall et al. 1997), which is at odds with both the biostratigraphy and magnetostratigraphy (Fig. 9). However, substantial parts of the Kapp Starostin Fm. have not allowed recovery of suitable magnetostratigraphic data to assess if substantive normal polarity magnetozones are present. Hence, a target for future studies of the Permian on Spitsbergen must be to find suitable sections in the Kapp Starostin Fm., perhaps in central Spitsbergen, that are not so extensively affected by the Cenozoic overprint.

Triassic magnetostratigraphy

The sediments of the Sassendalen Group began to be deposited during the latest Changhsingian (latest Permian). This is evident by the latest Permian palynofloral extinction event in central Spitsbergen (Mørk, Elvebakk et al. 1999), and by the associated organic carbon negative isotopic excursion (prior to the Permian–Triassic boundary; Yin et al. 2001), which occurs some 7 m above the base of the Vardebukta Fm in western Spitsbergen, in the Festningen section (Wignall et al. 1997).

Palaeomagnetic data from the Triassic of Spitsbergen (Hounslow, Hu, Mørk, Vigran et al. 2007; Hounslow, Hu et al. 2008; Hounslow, Peters et al. 2008) shows a greater proportion of specimens with linear-trajectory principle-component fitted lines than the Permian data (25% at Milne Edwardsfjellet, 36% at Vikinghøgda and 60% at Dalsnuten). This apparent difference from the Permian data of Nawrocki & Grabowski (2000) probably relates in part to differing demagnetization schemes, and magnetometers, as much as to differing intrinsic magnetic properties. The similarity to the Permian data is that most (except for the Upper Triassic at Dalsnuten) of the specimen polarity interpretations are based on great circle trends during demagnetization (Hounslow, Hu et al. 2008; Hounslow, Peters et al. 2008).

The magnetostratigraphy of the Spitsbergen Lower Triassic shows a reasonable degree of correspondence between the studies of Nawrocki & Grabowski (2000) and Hounslow, Peters et al. (2008). The correlations among the Trygghamna and Tschermakfjellet sections with wide sample spacing, and that at Vikinghøgda, with closer sample spacing, are, however, largely controlled by the lithostratigraphy (Fig. 10; Hounslow, Peters et al. 2008). The correlations between the Milne Edwardsfjellet and Vikinghøgda sections are additionally constrained with biostratigraphy (Hounslow, Peters et al. 2008).

The basal normal polarity that characterizes the lower part of the Griesbachian (Ogg & Steiner 1991; Gallet et al. 2000; Steiner 2006) is only clearly shown in the successions at Vikinghøgda (Fig. 10), whereas this interval was not apparently detected in the sections studied by Nawrocki & Grabowski (2000) at Trygghamna and Tschermakfjellet. The magnetostratigraphy demonstrates that the base of the Olenekian (defined by the first occurrence of the conodont *Neospathodus waageni*; Krystyn et al. 2007) probably occurs within the base part of the Lusitaniadalen Mb. (Hounslow, Peters et al. 2008). The top of the Selmaneset Mb. in western Spitsbergen may equate to a level near the top of the Deltadalen Mb. in central Spitsbergen (Fig. 10), as the *Promyalina*-bearing sandstone (the Brevassfjellet Bed) contains conodonts that are probably indicative of an interval in the early–mid-Dienerian (Nakrem et al. 2008 [this issue]). The overlying Siksaken Mb. contains conodonts indicating a later Dienerian age (Nakrem et al. 2008). These data, along with the lithostratigraphic correlation (Fig. 10), suggest that the Vardebukta Fm. of western Spitsbergen extends into the Olenekian (i.e., is equivalent to the Vh6r magnetozone; Fig. 10), rather than terminating near the Induan–Olenekian boundary.

The upper reverse polarity magnetozone in the Vendomdalen Mb. from Milne Edwardsfjellet (i.e., MF2r; Hounslow, Hu et al. 2008) appears to be the equivalent of the Tf5r magnetozone from Tschermakfjellet (Fig. 10). This reverse magnetozone appears to be absent at Vikinghøgda, because of probable erosion prior to the deposition of the Botneheia Fm., and because of the absence of the lowest part of the Botneheia Fm. at Vikinghøgda (Hounslow, Peters et al. 2008). The immediately underlying reverse magnetozone in the Vendomdalen Mb. (i.e., Tf4r, Vh8n.2r and MF2n.2r; Fig. 10), although represented by a single sampling level in all three sections appears confirmed in all three sections (Fig. 10).

The challenge remaining in the Lower Triassic is to extract a more detailed magnetostratigraphy from western Spitsbergen, to better understand the relationship between the lithostratigraphic boundaries in western Spitsbergen and those now defined in central Spitsbergen

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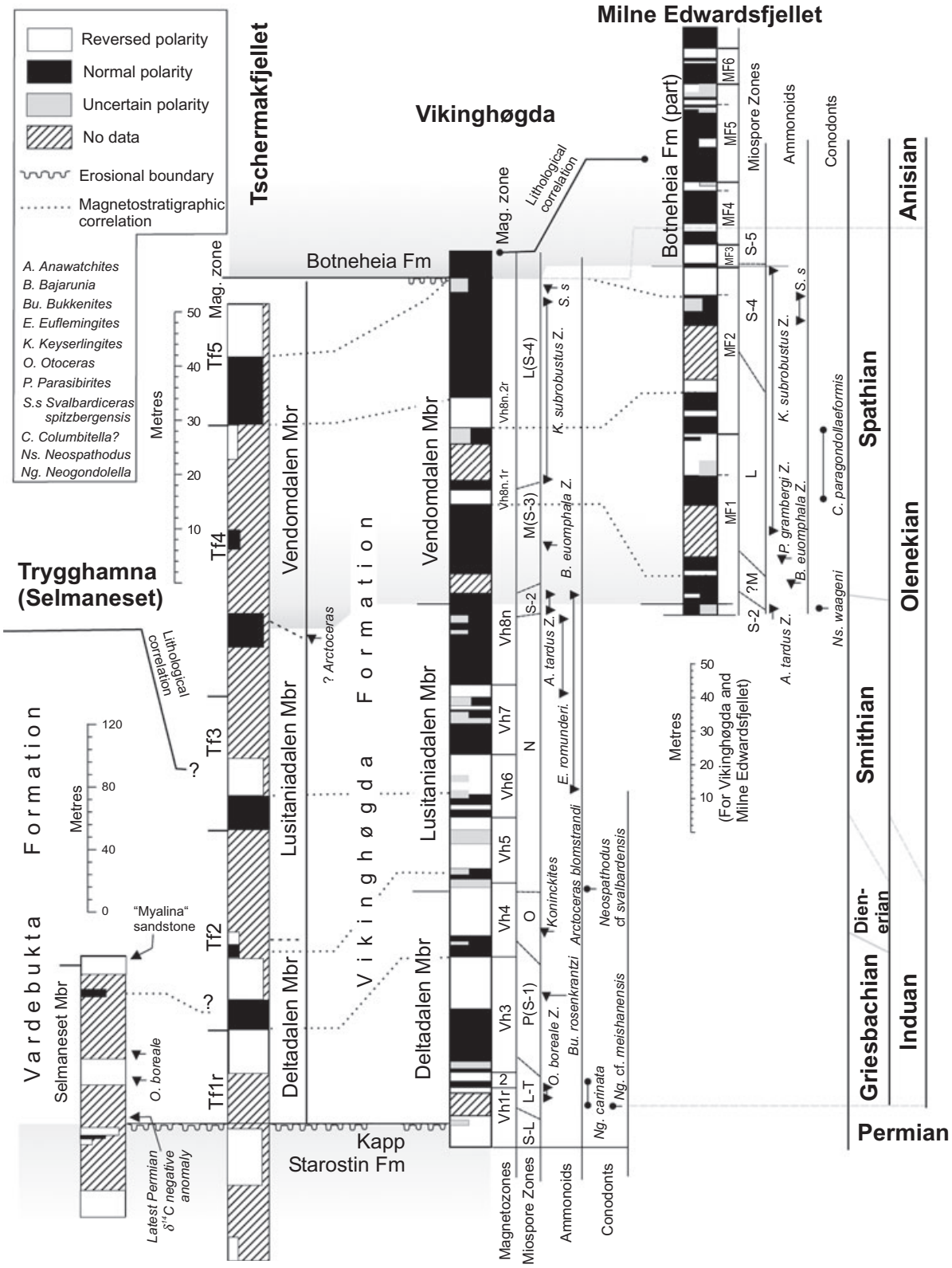

Fig. 10 Summary of the Lower Triassic magnetostratigraphy and biostratigraphy from Spitsbergen. Tschermakfjellet and Trygghamna section from Nawrocki & Grabowski (2000), re-drawn according to the magnetozone criteria in Fig. 9, and using the modern lithostratigraphy; Vikinghøgda section from Hounslow, Peters et al. (2008); Milne Edwardsfjellet section from Hounslow, Hu et al. (2008). The Vikinghøgda–Tschermakfjellet intersection magnetostratigraphic correlations are speculative, and are largely dictated by the lithostratigraphy. Section locations are indicated in Fig. 1.

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by Mørk, Dallmann et al. (1999). In combination with Ogg & Steiner's (1991) magnetostratigraphic data from the Sverdrup Basin, Spitsbergen is likely to be the key area in the world for defining the Lower Triassic magnetic polarity time scale (Hounslow, Peters et al. 2008).

The biomagnetostratigraphy of the Middle and Upper Triassic has been detailed by Hounslow, Hu, Mørk, Weitschat et al. (2007) and Hounslow, Hu et al. (2008) from Vendomdalen in central Spitsbergen, supported by ammonoid, palynology and conodont data. The work on the Middle Triassic shows a close similarity to published works on the Tethyan Middle Triassic, suggesting, as hinted at by the ammonoids (Weitschat & Dagys 1989; Hounslow, Hu, Mørk, Vigran et al. 2007), that the upper part of the Ladinian is missing (Fig. 11). The key point of the Middle Triassic work from Spitsbergen is that this validates the pattern of polarity changes through the Anisian, suggested by other workers from lower palaeolatitudes (Nawrocki & Szulc 2000; Muttoni et al. 2000), adding detail particularly in the lower part of the Anisian. It also demonstrates the much reduced sedimentation rate in central Spitsbergen during the late Anisian, and its transition into the early Ladinian.

There is currently only a rudimentary knowledge of the Upper Triassic magnetostratigraphy on Spitsbergen, which is only well defined in the Tschermakfjellet Fm. and in the lower part of the De Geerdalen Fm. in the Vendomdalen area, through what appears to be mostly the Carnian (Hounslow, Hu, Mørk, Weitschat et al. 2007). In terms of palaeomagnetic behaviour, the Upper Triassic probably provides the best palaeomagnetic properties in the whole of the Spitsbergen Permian–Triassic, as only about 15% of samples are dominated by the Cenozoic overprint (Fig. 6). The upper Carnian to latest Triassic has been intensely studied for magnetostratigraphy in other areas of the world, so understanding of the polarity pattern during this interval is good. This is advantageous for further magnetostratigraphic studies in Svalbard, as this interval is the most poorly characterized in terms of age control in the whole of the Permian–Triassic of the archipelago.

Conclusions

- The Permian–Triassic palaeomagnetic data generally confirm the Baltica/European credentials of the Spitsbergen apparent polar wander path.
- The persistent overprint magnetization, which in part plagues palaeomagnetic studies of the Permian and Triassic, is a post-folding remagnetization. Its age may vary from Tertiary to Holocene. It is not likely to be of one single origin, but may be viscosity or weathering related, or locally in western Spitsbergen it may be of fluid-flow origin. The often strong overlap of this remagnetization component with the primary Permian and Triassic magnetizations is the primary reason that only small to moderate proportions of specimens are characterized by classic linear trajectory demagnetization data.
- A tentative normal magnetozone in the base of the Tyrrellfjellet Mb. (Gipsdalen Group) provides a good marker for the close proximity of the Carboniferous–Permian boundary. Together with a second normal magnetozone in the lowermost Permian, known from other areas at this level, this may help constrain correlations at this level in future studies.
- Two normal magnetozones, one in the base of the Svenskegga Mb. (Kapp Starostin Fm.) and a second in the lower part of the Hovtinden Mb. (Kapp Starostin Fm.), are probable equivalents to the Wordian and Capitanian magnetozones identified by Steiner (2006) from other sections of this age. The younger of these magnetozones is strongly supported by multiple specimens on multiple horizons, and is not substantially affected by remagnetization. The upper parts of the Kapp Starostin Fm. are a key target for future magnetostratigraphic work on Spitsbergen to refine the mid- to late Permian chronostratigraphy on Svalbard.
- The biomagnetostratigraphy through the Lower Triassic on Spitsbergen probably provides the key area in the world for the robust construction of the magnetic polarity time scale over this interval.
- Newer time scales for the Triassic have some 28 of the 51 My of Triassic time now occupied by the Upper Triassic. This fact makes it crucially important to better understand the detailed sequence and chronostratigraphy of the Svalbard Upper Triassic. This can be supported by the detailed data available from magnetostratigraphic studies.

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Atle Mørk provided some useful discussion on the Lower Triassic in western Spitsbergen. Simon Chew helped draft the figures. The Triassic sample data presented was

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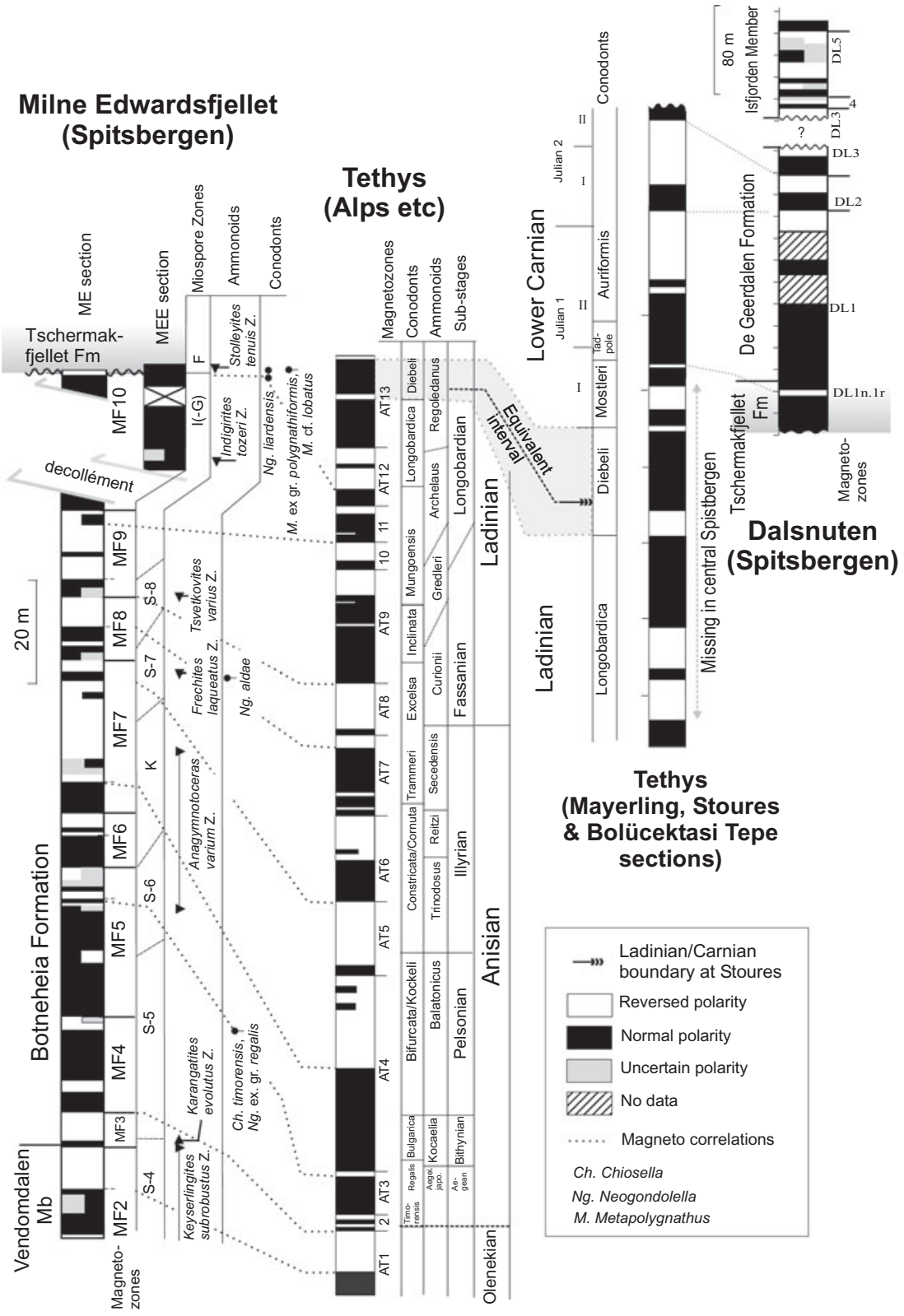

Fig. 11 Summary of the Middle and Upper Triassic magnetostratigraphy of central Svalbard. Milne Edwardsfjellet section (from Hounslow, Hu, Mørk, Vigran et al. 2007; Hounslow, Hu et al. 2008); Dalsnuten section data from Hounslow, Hu, Mørk, Vigran et al. (2007). Section locations are indicated in Fig. 1. Tethys (Alps) column after Muttoni et al. (2000), and references in Hounslow, Peters et al. (2008). Tethys (Mayerling, Stoures, Bolücektasi Tepe) from Gallet et al. (1992), Broglio Loriga et al. (1999), Gallet et al. (1994), as compiled in Hounslow, Hu, Mørk, Vigran et al. (2007).

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References

Bergh S.G. & Grogan P. 2003. Tertiary structure of the Sørkapp–Hornsund region, south Spitsbergen, and implications for the offshore southern extension of the fold-thrust belt. *Norwegian Journal of Geology 83*, 43–60.

Besse J. & Courtillot V. 2002. Apparent and true polar wander and the geometry of the geomagnetic field over the last 200 Myr. *Journal of Geophysical Research—Solid Earth 107*, doi:10.1029/2000JB000050.

Bjorøy M., Hall P.B. & Mørk A. 2006. Triassic hydrocarbon source rocks on Svalbard and in the Barents Sea. In H.A. Nakrem & A. Mørk (eds.): *Boreal Triassic 2006. Longyerbyen, Svalbard, 16–19 August 2006. NGF Abstracts and Proceedings of the Geological Society of Norway 3*, 42–55.

Bjorøy M., Vigran J.O. & Rønningsland T.M. 1978. *Source rock evaluation of Mesozoic shales from Svalbard. IKU Open Report 160/1/78*. Trondheim: Continental Shelf Institute.

Braathen A., Andresen A., Hansen A.-I., Bergvik A., Bergh S., Karlsen F. & Maher Jr. H. 1999. Kinematics of the Isfjorden–Ymerbukta Fault Zone: a dextral oblique-thrust ramp in the Tertiary fold-thrust belt of Spitsbergen. *Norsk Geologisk Tidsskrift 79*, 227–239.

Briseid E. & Halvorsen E. 1974. The primary magnetic remanence of a dolerite sill from northeast Spitsbergen. *Physics of the Earth and Planetary Interiors 9*, 45–50.

Broglio Loriga C., Gianolla P., Franco Laghi G., Lowrie W., Manfrin S., Mastandrea A., Mietto P., Muttoni G., Neri C., Posenato R., Rechichi M., Rettori R., Roghi G., Cirilli S., De Zanche V. & Di Bari D. 1999. The Prati di Stuores/Stuores Wiesen section (Dolomites, Italy): a candidate Global Stratotype Section and Point for the base of the Carnian Stage. *Rivista Italiana di Paleontologia e Stratigrafia 105*, 37–78.

Cairanne G., Aubourg C., Pozzi J.-P., Moreau M.-G., Decamps T. & Marolleau G. 2004. Laboratory chemical remanent magnetization in a natural claystone: a record of two magnetic polarities. *Geophysical Journal International 159*, 909–916.

Dallmann W.K. (ed.) 1999. *Lithostratigraphic lexicon of Svalbard. Upper Palaeozoic to Quaternary bedrock. Review and recommendations for nomenclature use*. Tromsø Norwegian Polar Institute.

Davydov V.I. & Hramov [Khramov] A.N. 1991. Paleomagnetizm verhnego karbona i nizhnej permi Kara'atyra (Ju. Fergana) i problemy korreljacii razrezov giperzony Kiama. (Palaeomagnetism of the Upper Carboniferous and Lower Permian in the Karachatyr region [southern Ferhgana] and the problems of correlation of the Kiaman hyperzone.) In A.N. Hramov (ed.): *Paleomagnetizm i paleogeodinamika territorii SSSR. (Palaeomagnetism and palaeogeodynamics of the territory of USSR.) Transactions of the VNIGRI*. Pp. 45–53. Leningrad: All Russia Petroleum Research Exploration Institute.

Davydov V.I. & Leven A.N. 2003. Correlation of Upper Carboniferous (Pennsylvanian) and Lower Permian (Cisuralian) marine deposits of the Peri-Tethys. *Palaeogeography Palaeoclimtology Palaeoecology 196*, 39–57.

Doré A.G. 1991. The structural foundation and evolution of Mesozoic seaways between Europe and the Arctic Sea. *Palaeogeography Palaeoclimatology Palaeoecology 87*, 441–492.

Egorov A.Y. & Mørk A. 2000. The east Siberian and Svalbard Triassic successions and their sequence stratigraphical relationships. In G.H. Bachmann & I. Lerche (eds.): *Epicontinental Triassic. Vol. III. Zentralblatt für Geologie und Paläontologie Teil 1*. Pp. 1377–1430. Stuttgart: E. Schweizerbart'sche Verlagsbuchhandlung.

Gallet Y., Besse J., Krystyn L. & Marcoux J. 1992. Magnetostratigraphy of the late Triassic Boucektasi Tepe section (south western Turkey): implications for changes in magnetic reversal frequency. *Physics of the Earth Planetary Interior 93*, 273–282.

Gallet Y., Besse J., Krystyn L., Theveniant H. & Marcoux J. 1994. Magnetostratigraphy of the Mayerling section (Austria) and Erebkolu Merzarlik (Turkey) section: improvement of the Carnian (late Triassic) magnetic polarity time scale. *Earth Planetary Science Letters 125*, 173–191.

Gallet Y., Krystyn L., Besse J., Saidi A. & Ricou L-E. 2000. New constraints on the Upper Permian and Lower Triassic geomagnetic polarity timescale from the Abadeh section (central Iran). *Journal of Geophysical Research—Solid Earth 105*, 2805–2815.

Gialanella P.R., Heller F., Haag M., Nurgaliev D., Borisov A., Burov B., Jasonov P., Khasanov D., Ibragimov S. & Zharkov I. 1997. Late Permian magnetostratigraphy on the Eastern Russian Platform. *Geologie en Mijnbouw 76*, 145–154.

Gradstein F., Ogg J. & Smith A. 2004. *A geologic time scale 2004*. Cambridge: Cambridge University Press.

Halvorsen E. 1972. A palaeomagnetic study of two volcanic formations from northern Spitsbergen. *Norsk Polarinstitutt Årbok 1970*, 70–75.

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Halvorsen E. 1989. A palaeomagnetic pole position of Late Jurassic/Early Cretaceous dolerites from Hinlopenstretet, Svalbard, and its tectonic implications. *Earth Planetary Science Letters 94*, 398–408.

Hounslow M.W., Hu M., Mørk A., Vigran J.O., Weitschat W. & Orchard M.J. 2007. Magneto-biostratigraphy of the lower part of the Kapp Toscana Group (Carnian), Vendomdalen, central Spitsbergen, Arctic Norway. *Journal of the Geological Society, London 164*, 581–597.

Hounslow M.W., Hu M., Mørk A., Weitschat W., Vigran J.O., Karloukovski V. &. Orchard M.J. 2007. Intercalibration of Boreal and Tethyan time scales: the magneto-biostratigraphy of the Botneheia Formation (Middle Triassic) and the late Early Triassic, Svalbard (Arctic Norway). *New Mexico Museum of Natural History and Science Bulletin 41*, 68–70.

Hounslow M.W., Hu M., Mørk A., Weitschat W., Vigran J.O., Karloukovski V. &. Orchard M.J. 2008. Intercalibration of Boreal and Tethyan time scales: the magneto-biostratigraphy of the Middle Triassic and the latest Early Triassic from Spitsbergen, Arctic Norway. *Polar Research 27*, 469–490.

Hounslow M.W., Mørk A., Peters C. & Weitschat W. 1996. Boreal Lower Triassic magnetostratigraphy from Deltadalen, central Svalbard. *Albertiana 17*, 3–10.

Hounslow M.W., Peters C., Mørk A., Weitschat W. & Vigran J.O. 2008. Magneto-biostratigraphy of the Vikinghøgda Formation, Svalbard (Arctic Norway) and the geomagnetic polarity timescale for the Lower Triassic. *Geological Society of America Bulletin 120*, 1305–1325.

Hramov [Khramov] A.N. & Davydov V.I. 1984. Paleomagnetizm nekotoryh verhnekamennougol'nyh i nizhnepermskih tolšč juga SSSR i problema struktury giperzony Kiama. (Palaeomagnetism of some Upper Carboniferous and Lower Permian layers in the south of the USSR and the problems of the structure of the Kiaman hyperzone.) In A.N. Hramov (ed.): *Paleomagnitnye metody v stratigrafii. (Paleomagnetic methods in stratigraphy.) Transactions of the VNIGRI*. Pp. 55–73. Leningrad: All Russia Petroleum Research Exploration Institute.

Jeleńska M. 1987. Aspects of pre-Tertiary palaeomagnetism of Spitsbergen and their tectonic implications. *Tectonophysics 139*, 99–106.

Jeleńska M. & Lewandowski M. 1986. A palaeomagnetic study of Devonian sandstone from central Spitsbergen. *Geophysics Journal of the Royal Astronomical Society 87*, 617–632.

Jeleńska M. & Vincenz S.A. 1985. Origin of the magnetization of Permo-Carboniferous sediments of Spitsbergen, Svalbard Archipelago. *Earth Planetary Science Letters 85*, 173–182.

Kent D.V. & Tauxe L. 2005. Corrected late Triassic latitudes for continents adjacent to the North Atlantic. *Science 307*, 240–244.

Khramov A.N. & Davydov V.I. 1993. Results of palaeomagnetic investigations. *Permian system: guides to geological excursions in the Uralian type localities. Occasional Publication ESRI, New Series 10*, 34–42. Columbia, SC: Earth Sciences and Resources Institute, University of South Carolina.

Krajewski K.P. 2000. Phosphorus concentration and organic carbon preservation in the Blanknuten Member (Botneheia Formation, Middle Triassic), Sassenfjorden, Spitsbergen. *Studia Geologica Polonica 116*, 139–173.

Krumsiek K., Nagel J. & Nairn A.E.M. 1968. Record of palaeomagnetic measurements on some igneous rocks from the Isfjorden region, Spitsbergen. *Norsk Polarinstitutt Årbok 1966*, 76–83.

Krystyn L., Bhargava O.N. & Richoz S. 2007. A candidate GSSP for the base of the Olenekian Stage: mud at Pin Valley; district Lahul & Spiti, Hamachal Pradesh (western Himalaya), India. *Albertiana 35*, 5–29.

Løvlie R. & Putkonen J. 1996. Dating of thaw depths in permafrost terrain by the palaeomagnetic method: experimental acquisition of a freezing remanent magnetization. *Geophysical Journal International 125*, 850–856.

Maher H.D. Jr. 2001. Manifestations of the Cretacous High Arctic large igneous province in Svalbard. *Journal of Geology 109*, 91–104.

McFadden P.L. & McElhinny M.W. 1990. Classification of the reversal test in paleomagnetism. *Geophysical Journal International 103*, 725–729.

Menning M., Davydov V.I., Devuyst F.-X., Forke H.C., Grunt T.A., Hance L., Heckel P.H., Izokh N.G., Jin Y.-G., Jones P.J., Kotlyar G.V., Kozur H.W., Nemyrovska T.I., Schneider J.W., Wang X.-D., Weddige K., Weyer D., Work D.M., Alekseev A.S. & Chuvashov B.I. 2006. Global time scale and regional stratigraphic reference scales of central and west Europe, east Europe, Tethys, south China, and North America as used in the Devonian–Carboniferous–Permian Correlation Chart 2003 (DCP 2003). *Palaeogeography Palaeoclimatology Palaeoecology 240*, 318–372.

Michalski K. & Lewandowski M. 2004. Palaeomagnetic results from the Middle Carboniferous rocks of the Hornsund region, southern Spitsbergen: preliminary report. *Polish Polar Research 25*, 169–182.

Mørk A., Dallmann W.K., Dypvik H., Johannessen E.P., Larssen G.B., Nagy J., Nøttvedt A., Olaussen S., Pčelina T.M. & Worsley D. 1999. Mesozoic lithostratigraphy. In W.K. Dallmann (ed.): *Lithostratigraphic lexicon of Svalbard. Upper Palaeozoic to Quaternary bedrock. Review and recommendations for nomenclature use*. Pp. 127–214. Tromsø: Norwegian Polar Institute.

Mørk A., Elvebakk G., Forsberg A.W, Hounslow M.W., Nakrem H.A., Vigran J.O. & Weitschat W. 1999. The type section of the Vikinghøgda Formation: a new Lower Triassic unit in central and eastern Svalbard. *Polar Research 18*, 51–82.

Mørk A., Vigran J.O., Korchinskaya M.V., Pchelina T.M., Fefilova L.A., Vavilov M.N. & Weitschat W. 1992. Triassic rocks in Svalbard, the Arctic Soviet islands and the

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Barents Shelf: bearing on their correlations. In T.O. Vorren et al. (eds.): *Arctic geology and petroleum potential: proceedings of the Norwegian Petroleum Society Conference, 15–17 August 1990, Tromsø, Norway*. Pp. 457–479. Amsterdam: Elsevier.

Muttoni G., Gaetani M., Budurov K., Zagorchev I., Trifonova E., Ivanova D., Petrunova L. & Lowrie W. 2000. Middle Triassic palaeomagnetic data from northern Bulgaria: constraints on Tethyan magnetostratigraphy and palaeogeography. *Palaeogeography Palaeoclimatology Palaeoecology 160*, 223–237.

Nakazawa K., Suzuki H., Kumon F. & Winsnes T.S. 1990. Scientific results of the Japanese Geological Expedition to Svalbard 1986. In T. Tatsumi (ed.): *The Japanese Scientific Expedition to Svalbard 1983–1988*. Pp. 179–214. Tokyo: Kyoikusha Press.

Nakrem H.A., Nilsson I. & Mangerud G. 1992. Permian biostratigraphy of Svalbard (Arctic Norway)—a review. *International Geological Review 34*, 933–959.

Nakrem H.A. & Orchard M.J., Weitschat W., Hounslow M.W., Beatty T. & Mork A. 2008. Triassic conodonts from Svalbard and their Boreal correlations. *Polar Research 27*, 523–539.

Nawrocki J. 1999. Palaeomagnetism of Permian through Early Triassic sequences in central Spitsbergen: implications for palaeogeography. *Earth and Planetary Science Letters 169*, 59–70.

Nawrocki J. & Grabowski J. 2000. Palaeomagnetism of Permian through Early Triassic sequences in central Spitsbergen: contribution to magnetostratigraphy. *Geological Quarterly 44*, 109–117.

Nawrocki J. & Szulc J. 2000. The Middle Triassic magnetostratigraphy from the Peri-Tethys basin in Poland. *Earth Planetary Science Letters 182*, 77–92.

Nilsson I. & Davydov V.I. 1997. Fusulinid biostratigraphy in the Upper Carboniferous (Gzelian) and Lower Permian (Asseslian–Sakmarian) successions of Spitsbergen, Arctic Norway. *Permophiles 30*, 18–24.

Noltimier H. & Kopacz M. 1976. Thermomagnetic study of coal and associated roof shale. *IEEE Transactions on Magnetics 12*, 528–531.

Novakova A.A. & Gendler T.S. 1995. Metastable structural–magnetic transformations in sulphides in the course of oxidation. *Journal of Radioanalytical and Nuclear Chemistry 190*, 363–368.

Ogg J.G. & Steiner M.B. 1991. Early Triassic polarity time-scale: integration of magnetostratigraphy, ammonite zontationzonation and sequence stratigraphy from stratotype sections (Canadian Arctic Archipelago). *Earth and Planetary Science Letters 107*, 69–89.

Pechersky D.M. & Khramov A.N. 1973. Mesozoic palaeomagnetic scale of the USSR. *Nature 244*, 499–501.

Rowley D.B. & Lottes A.L. 1988. Plate-kinematic reconstructions of the North Atlantic and Arctic: late Jurassic to present. *Tectonophysics 155*, 73–120.

Samuelsberg T.J. & Pickard N.A.H. 1999. Upper Carboniferous to Lower Permian transgressive regressive sequences of central Spitsbergen, Arctic Norway. *Geological Journal 34*, 393–411.

Sandal S.T & Halvorsen E. 1973. Late Mesozoic palaeomagnetism from Spitsbergen: implications for continental drift in the Arctic. *Physics of the Earth and Planetary Interiors 7*, 125–132.

Steiner M.B. 2006. The magnetic polarity timescale across the Permian–Triassic boundary. In S.G. Lucas et al. (eds.): *Non-marine Permian biostratigraphy and biochronology. Geological Society Special Publication 265*. Pp. 15–38. London: The Geological Society.

Stemmerik L. 2000. Late Palaeozoic evolution of the North Atlantic margin of Pangaea. *Palaeogeography Palaeoclimatology Palaeoecology 161*, 95–126.

Stemmerik L. & Worsley D. 2005. 30 years on—Arctic Upper Palaeozoic stratigraphy, depositional evolution and hydrocarbon prospectivity. *Norwegian Journal of Geology 85*, 151–168.

Tauxe L. 2005. Inclination flattening and the geocentric axial dipole hypothesis. *Earth and Planetary Science Letters 233*, 247–261.

Tauxe L. & Kent D.V. 2004. A simplified statistical model for the geomagnetic field and the detection of shallow bias in palaeomagnetic inclinations: was the ancient magnetic field dipolar? In J.E.T. Channell et al. (eds.): *Timescales of the palaeomagnetic field*. Pp. 101–116. Washington, DC: American Geophysical Union.

Torsvik T.H. & Cocks L.R.M. 2005. Norway in space and time: a centennial cavalcade. *Norwegian Journal of Geology 85*, 73–86.

Torsvik T.H., Løvlie R. & Sturt B.A. 1985. Palaeomagnetic argument for stationary Spitsbergen relative to the British Isles (western Europe) since the late Devonian and its bearing on North Atlantic reconstruction. *Earth Planetary Science Letters 75*, 278–288.

Tudryn A. & Tucholka P. 2004. Magnetic monitoring of thermal alteration for natural pyrite and greigite. *Acta Geophysica Polonica 52*, 509–520.

Van der Voo R. & Torsvik T.H. 2001. Evidence for late Palaeozoic and Mesozoic non-dipole fields provides an explanation for the Pangaea reconstruction problems. *Earth and Planetary Science Letters 187*, 71–81.

Van der Voo R. & Torsvik T.H. 2004. The quality of the European Permo-Triassic palaeopoles and its impact on Pangaea reconstructions. In J.E.T. Channell et al. (eds.): *Timescales of the palaeomagnetic field*. Pp. 29–42. Washington, D.C.: American Geophysical Union.

Vincenz S.A., Cossak D., Duda S.J., Birkenmajer K., Jeleńska M., Kadzialko-Hofmokl M. & Kruczyk J. 1981. Palaeomagnetism of some late Mesozoic dolerite dykes of south Spitsbergen. *Geophysics Journal of the Royal Astronomical Society 67*, 599–614.

Vincenz S.A. & Jeleńska M. 1985. Palaeomagnetic investigations of Mesozoic and Palaeozoic rocks from Svalbard. *Tectonophysics 114*, 163–180.

Vincenz S.A., Jelenska M., Auehsazian K. & Birkenmajer K. 1984. Palaeomagnetism of some late Mesozic dolerite

sill of eastern central Spitsbergen; palaeomagnetic implications. *Geophysics 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.

Weitschat W. & Dagys A.S. 1989. Triassic biostratigraphy of Svalbard and a comparison with NE-Siberia. *Mitteilungen Geologisch–Paläontologisches Institut Universität Hamburg 68*, 179–213.

Wignall P.B., Morante R. & Newton R. 1997. The Permo–Triassic transition in Spitsbergen: $\delta^{13}C_{org}$ chemostratigraphy, Fe and S geochemistry, facies, fauna and trace fossils. *Geological Magazine 135*, 47–62.

Yin H., Zhang K., Tong J., Yang Z. & Wu S. 2001. The Global Stratotype Section and Point (GSSP) of the Permian–Triassic boundary. *Episodes 24*, 102–114.

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