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Palaeomagnetism of 935 Ma mafic dykes in southern Sweden and implications for the Sveconorwegian Loop

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SUMMARY

New palaeomagnetic results for the 935 Ma Göteborg-Slussen mafic dykes in southern Sweden provide a well-dated high-quality palaeomagnetic pole for Early Neoproterozoic Baltica. New U-Pb geochronological data for several palaeomagnetically studied mafic intrusions yield three additional well-dated palaeopoles and one virtual geomagnetic pole. This set of dated poles suggests minimal drift of Baltica in moderate latitudes between ~965 and 915 Ma. They also support the hypothesis of a post-900 Ma regional remagnetization event in SW Sweden and SW Norway. The positions of three distinct clusters of ~1100 to 850 Ma palaeopoles suggest a clockwise time progression of the Baltica apparent polar wander path (the Sveconorwegian Loop) during this time interval. New well-dated palaeomagnetic poles for ~970 to 900 Ma from Laurentia are required to verify the palaeogeographic reconstructions of Baltica and Laurentia.

Key words: Baltica, mafic dykes, palaeomagnetism, Sveconorwegian, Sweden.

1 INTRODUCTION

Early Neoproterozoic mafic intrusions are widespread in southern Sweden and southern Norway, and have been subjected to intensive palaeomagnetic studies (e.g. Abrahamsen 1974; Poorter 1975; Patchett & Bylund 1977; Stearn & Piper 1984; Bylund 1985, 1992; Pisarevsky & Bylund 1998; Walderhaug *et al.* 1999; Bylund & Pisarevsky 2002; Brown & McEnroe 2004). These studies provided most of the palaeopoles for Early Neoproterozoic Baltica (Pisarevsky 2005). The majority are from dolerite dykes of the Protogine Zone and the Blekinge-Dalarna Dolerites in southern Sweden (Patchett & Bylund 1977; Bylund 1992; Bylund & Elming 1992). They are good quality results, but poorly dated. Ages of 1000 to 880 Ma were estimated by Sm-Nd (Johansson & Johansson 1990) and Rb-Sr (Patchett 1978) methods. Bylund (1992) reported that almost all of these poles can be separated into two major groups: medium- to high-latitude 'A' poles and equatorial 'B' poles. Consequently, it was suggested that the apparent polar wander path (APWP) for Baltica forms a loop termed the Sveconorwegian Loop (Patchett & Bylund 1977). This loop is broadly similar to the coeval 'Grenville Loop' in the Laurentian APWP (e.g. Hyodo & Dunlop 1993; Weil *et al.* 1998). The similarity between APWPs for two continents provides palaeomagnetic evidence for the existence of a Late Mesoproterozoic–Early Neoproterozoic connection between Baltica and Laurentia (see Pisarevsky *et al.* 2003, for overview). However, the exact shape, timing, and age progression of the Grenville and Sveconorwegian loops are still a matter of debate (e.g. Weil *et al.* 1998; Pisarevsky & Bylund 1998; Walderhaug *et al.* 1999; McElhinny & McFadden 2000). Several recent publications provide new precise ages for some mafic intrusions in southern Sweden (Scherstén *et al.* 2000; Söderlund *et al.* 2002, 2004; Hellström *et al.* 2004). In particular, Hellström *et al.* (2004) reported a new U-Pb baddeleyite age of 935 ± 3 Ma for the Tuve dyke in the Göteborg area. A preliminary palaeomagnetic study of ten samples from this dyke was reported by Abrahamsen (1974). Despite its good quality, this result has not usually been included in plate tectonic reconstructions due to imprecise dating of the dykes (until the publication of Hellström *et al.* 2004) and the small number of samples. The Slussen dyke of the same swarm was also studied palaeomagnetically in the Bredfjället area ~60 km north of Göteborg (Pisarevsky & Bylund 1998).

The main aim of this study was to resample the Tuve dyke and other Göteborg dykes and to obtain a high-quality, well-dated palaeopole. We also reconsider some other previously poorly dated Early Neoproterozoic palaeomagnetic results in light of new geochronological data and discuss the problem of the Sveconorwegian Loop.

2 GEOLOGY AND SAMPLING

The 1.1 to 0.9 Ga Sveconorwegian orogen, along the SW margin of the Fennoscandian Shield (Fig. 1), is thought to be a continuation of the Grenville orogen in Laurentia, and formed from the collision of Laurentia, Baltica, and Amazonia during the amalgamation of the Rodinia supercontinent (e.g. Hoffman 1991; Park

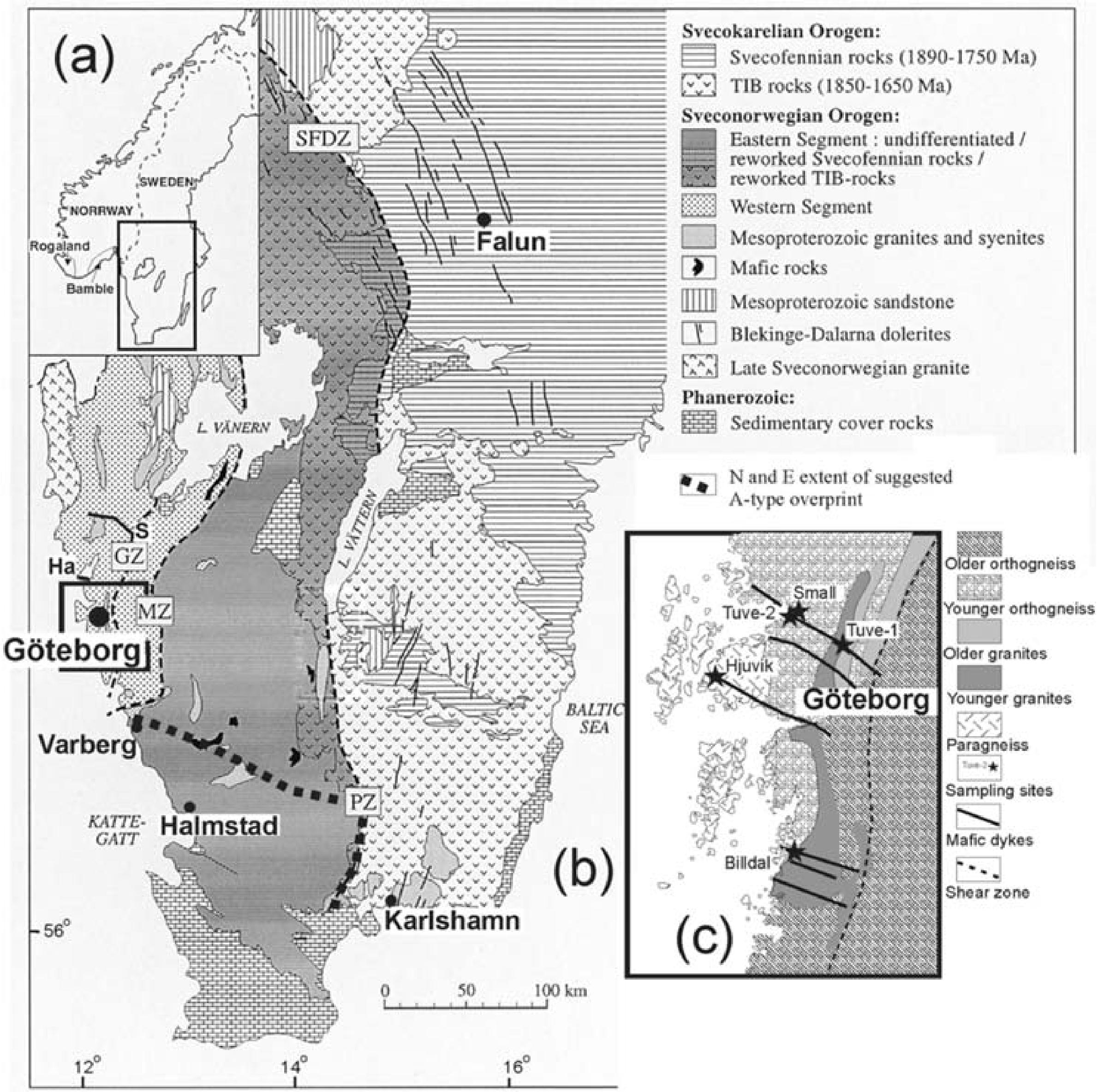

Figure 1. (a) Location of the studied area. (b) Geological map of southern Sweden and Norway, showing mafic intrusions and sampling sites. MZ, Mylonite Zone; GZ, Göta Älv Zone; PZ, Protogine Zone; SFDZ, Sveconorwegian Frontal Deformation Zone; S, Slussen dyke; Ha, Hakefjorden Complex. (c) Dykes in the area around Goteborg and sampling sites. Individual dykes referred to in the text are labelled.

1992; Starmer 1996; Pisarevsky *et al.* 2003). The eastern margin of the Sveconorwegian orogen is delimited by the Sveconorwegian Frontal Deformation Zone (SFDZ) usually referred to as the Protogine Zone south of the Lake Vättern (Fig. 1). Another major shear zone, termed the Mylonite Zone divides the Swedish part of the Sveconorwegian orogen (Andersson *et al.* 2002) into the 1.85 to 1.65 Ga orthogneisses of the Transscandinavian Igneous Belt affiliation of the Eastern Segment, and the 1.64 to 1.58 Ga calc-alkaline paragneisses and orthogneisses of the Western Segment (Fig. 1).

The final stage (∼1000 to 900 Ma) of the Sveconorwegian orogeny is marked by voluminous magmatism that accompanied post-collisional extension, terrane exhumation, and orogenic collapse (e.g. Romer & Smeds 1996). Mafic dyke swarms formed an important part of this magmatic event. East of the Protogine Zone is the ∼700 km long N- to NNW trending Blekinge-Dalarna Dolerites swarm (fig. 1; Solyom *et al.* 1992). Some dykes of the Protogine Zone may also belong to this swarm (Johansson & Johansson 1990; Solyom *et al.* 1992). These dykes were intensively studied palaeomagnetically by Patchett & Bylund (1977), and Bylund (1985, 1992). Until recently their age has been considered to be between 1000 and 880 Ma based on Sm-Nd and Rb-Sr data (Johansson & Johansson 1990; Patchett 1978). Recent U-Pb baddeleyite data (Söderlund *et al.* 2005) indicate dyke emplacement between 935 and 978 Ma.

There are numerous mafic intrusions in the Western Segment, including twenty WNW- to W-trending subvertical Göteborg dykes (Hellström *et al.* 2004) (Fig. 1). Unfortunately, many of these dykes traced by geophysical data are not accessible for palaeomagnetic sampling due to the absence of outcrops and/or location in highly urbanized areas. In particular, we did not find any accessible outcrops of the dyke situated between the sampled Tuve and Hjuvik dykes, and spotted only one small outcrop in the Billdall area (Fig. 1c).

There are also mafic dykes north of Göteborg, west of the Göta Älv Shear Zone (Fig. 1), which are believed to be of the same age based on similar geochemistry and field relationships (Hellström *et al.* 2004). The largest of these dykes, the Slussen dyke, was studied palaeomagnetically (Pisarevsky & Bylund 1998). Hellström *et al.* (2004) describe these dykes as 'post-kinematic' owing to their discordance to all ductile structures in the country rocks, their unaltered primary mineralogy, and undeformed igneous intergranular texture. Christoffel *et al.* (1999) described similar post-kinematic mafic dykes in the western part of the Eastern Segment, in the Varberg–Halmstad region.

Hellström *et al.* (2004) obtained a U-Pb baddeleyite age of 935 ± 3 Ma for the largest Tuve dyke of the Göteborg swarm. Abrahamsen (1974) studied 10 samples from this dyke palaeomagnetically and demonstrated that it possessed a stable remanence carried by magnetite of 'Late Sveconorwegian' (900 to 800 Ma) age. This palaeopole, however, has not been widely used in tectonic applications for three reasons. First, results from a single dyke provide a single spot reading of the Earth's magnetic field, and are not likely to have averaged palaeosecular variation (PSV). Second, the age of the Tuve dyke was unknown until publication of the Hellström *et al.* (2004) U-Pb result. Third, ten samples is an insufficient number for a reliable pole (McElhinny & McFadden 2000). In 2004, we revisited the Göteborg area and obtained a new collection of oriented blocks from several dykes. We resampled the Tuve dyke in two outcrops (Fig. 1). The first (Tuve-1, 57°46′49″N, 11° 49′52″E) is in a small road cut of the Bärby–Skra Bro road ∼3 km from Bärby, where the northern contact (∼2 m wide) of the Tuve dyke with country gneiss is exposed. The second outcrop (Tuve-2, 57°47′01″N, 11°48′45″E) is ∼3 km NNW of Björlanda Church on the coast, in the same location described by Abrahamsen (1974). The thickness of the exposed part of the dyke here is about 100 m and the southern contact is accessible. We have also sampled a thin (∼15 cm) dolerite dyke ∼150 m north of this outcrop, which we refer to as the Small dyke. In addition, we sampled two other dykes from the same swarm, Hjuvik (∼30 m road cut 8 km south of the Tuve dyke, 57°42′43″N, 11°43′28″E) and Billdal (two small islands ∼10 to 20 m each near the shore, 20 km south of the Tuve dyke, 57°33′45″N, 11°55′39″E). Sixty-five block samples were collected, using both sun and magnetic compasses for sample orientation. Two to six cylindrical specimens (25 mm diameter) were drilled from each block.

3 ANALYTICAL TECHNIQUES

Samples were analysed in the palaeomagnetic laboratory of Lund University (Sweden) and in the Tectonics Special Research Centre at the University of Western Australia. Magnetic remanence at both laboratories was measured using 2G cryogenic magnetometers. Several specimens were subjected to stepwise thermal demagnetization, up to 600°–650°C, using Schonstedt TSD-1 and Magnetic Measurements TD2 furnaces. All other specimens were subjected to progressive alternating field (AF) demagnetization using a 2G600 automated degaussing system up to 160 mT. Magnetic susceptibility was measured with a MS2 susceptibility meter. Curie temperatures (T_c) were estimated by observing variations of low-field magnetic susceptibility with temperature in a MS2WF furnace.

4 RESULTS

Characteristic components of natural remanent magnetization (ChRM) were isolated using a least-squares algorithm (Torsvik 1986), combined with analysis of stereograms. Fisher (1953) statistics were used for calculations.

4.1 Tuve dyke

Both thermal and AF demagnetizations of all samples revealed a single stable remanence component carried by magnetite. After removal of a low-stability, randomly oriented overprint from most samples, all samples exhibit an SE-directed, downwards magnetization (Figs 2a, b and 3a). This agrees with Abrahamsen (1974), who employed microscopic and rock-magnetic studies of the dyke to infer that single-domain (SD) magnetite formed by deuteric alteration shortly after the solidification of the magma. The natural remanent magnetization (NRM) intensities are between 0.6 and 5.3 A m^{-1}. Thermomagnetic curves (low-field magnetic susceptibility versus temperature) show Hopkinson peaks close to 580°C (Fig. 4a), confirming the presence of fine-grained single-domain magnetite (Schmidt 1993). The relatively high coercivity of these dolerites also indicates that SD magnetite is the carrier of the most stable part of remanence—typically up to 160 mT was required for the AF-demagnetization (Fig. 2b). SD magnetite is highly stable palaeomagnetically, and must be heated close to 580°C to reset its remanence (e.g. Pullaiah *et al.* 1975; Walton 1980). However, because the dyke is post-kinematic (Hellström *et al.* 2004) and not metamorphosed, such reheating is very unlikely. Collectively, these observations argue strongly in favour of the magnetization of the dyke being primary. The mean palaeomagnetic direction is $D = 122.2°, I = 53.7°, k = 91.2, \alpha_{95} = 3.2°$ with a palaeopole of 14.0°S, 237.9°E. The result is close to that of Abrahamsen (1974), showing a 2°–3° shallower inclination, which can be explained by our use of higher AF fields (160 mT versus 60 mT used by Abrahamsen 1974).

Because the contacts of the Tuve dyke with country gneiss are exposed, we have applied a baked contact test. Baked gneiss sampled within 1–20 cm from the dyke margin yield the remanence direction of $D = 114°, I = 53°, \alpha_{95} = 6°$, close to those of the dyke (Table 1), consistent with remagnetization of the baked rocks during the dyke emplacement. However, we could not conduct a full test, because all gneisses sampled farther from the contact are either magnetically unstable, or show random remanence direction. This may be a regional characteristic of the country rocks, because a similar soft remanence with dispersed directions in the nearby Kungälv gneiss was reported by Poorter (1975).

4.2 Small dyke

Three block samples (ten specimens) from this fine-grained dyke exhibit magnetic properties similar to those of the Tuve dyke. NRM intensity is between 2.3 and 3.6 A m^{-1}. Hopkinson peaks in thermomagnetic curves are very distinct (Fig. 4b). The remanence is single component and carried by SD magnetite (Figs 2c and d), and is likely to be primary. Its direction ($D = 124.5°, I = 54.6°, k = 281.0, \alpha_{95} = 7.4°$) is close to remanence of the Tuve dyke (Fig. 3b; Table 1).

4.3 Hjuvik dyke

Unlike the Tuve dyke, the Hjuvik dyke is poorly exposed. We found only a single small (∼20 m) outcrop on Road 155 between Vedskär and Dalen (Fig. 1). Only 12 of 18 samples carry a stable remanence. NRM intensities are much lower than in Tuve dyke, between 50 and

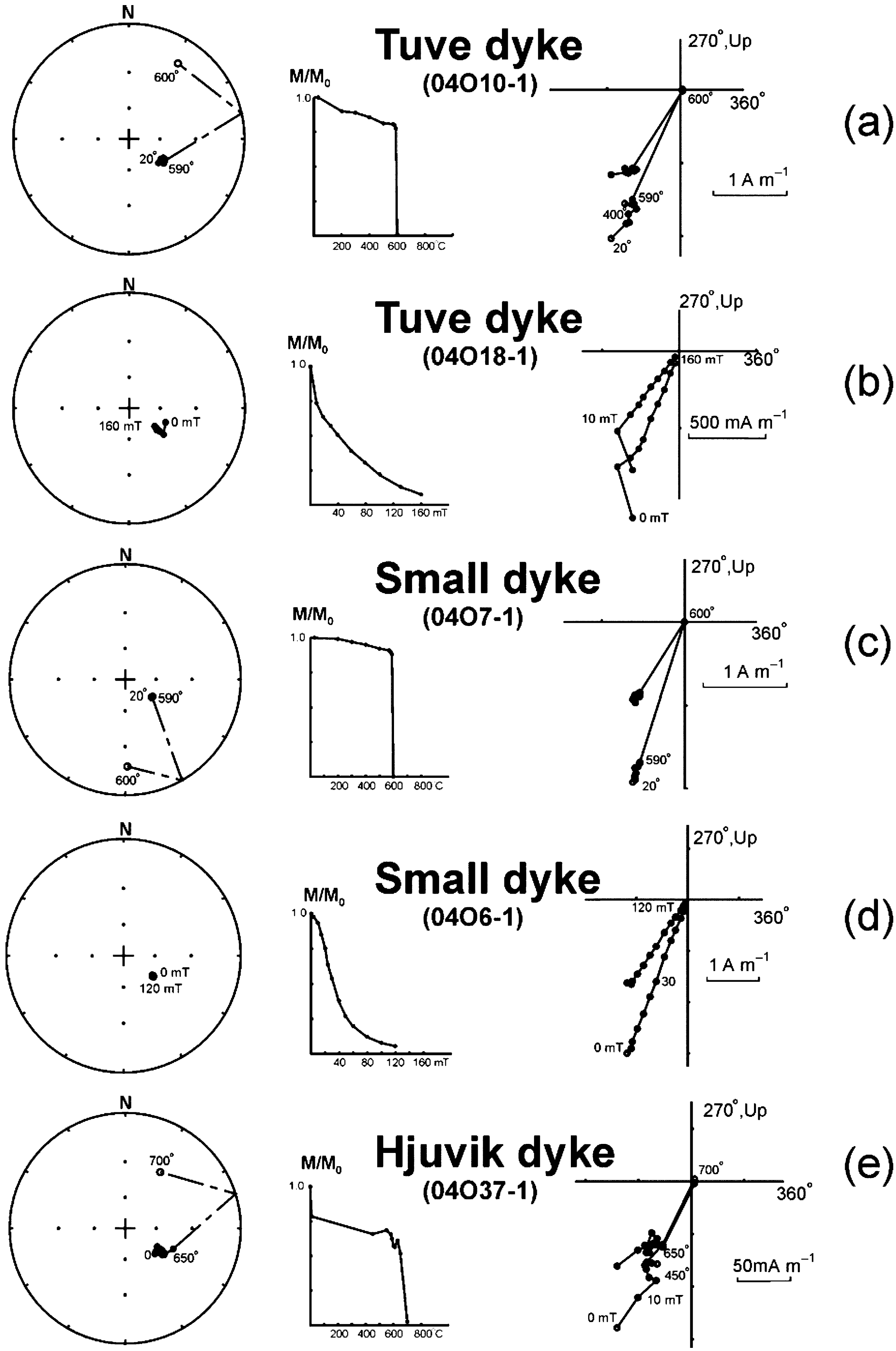

Figure 2. Stereoplots and examples of demagnetization behaviour for studied dykes. In orthogonal plots, open (closed) symbols show magnetization vector endpoints in the vertical (horizontal) plane; curves show changes in intensity during demagnetization. Stereoplots show upwards (downwards) pointing palaeomagnetic directions with open (closed) symbols.

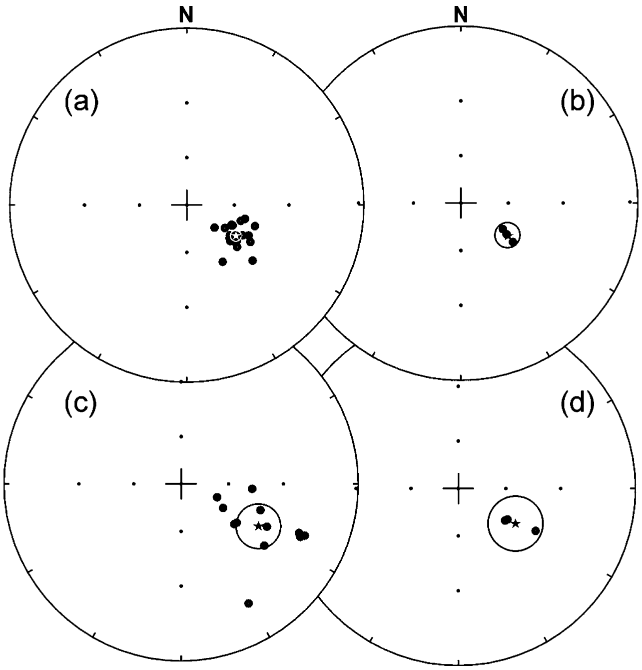

Figure 3. Stereoplots of the directions and mean directions of ChRM from: (a) Tuve dyke; (b) Small dyke; (c) Hjuvik dyke; (d) dyke means. Mean directions are shown with stars surrounded by α_{95} error circles.

500 mA m^{-1}, and the thermomagnetic curve is also very different (Fig. 4c). Some unblocking temperatures exceed 600°C (Fig. 2e), but the coercivity is lower than in the Tuve and Small dykes. Twelve samples yield an imprecise mean direction of $D = 118.8°$, $I = 37.1°, k = 15.2, \alpha_{95} = 11.5°$ (Fig. 3c), which is slightly shallower than those in the Tuve and Small dykes (Table 1).

4.4 Billdal dyke

This dyke is exposed on two small islands near the coast (Fig. 1). Despite indications of SD magnetite in thermomagnetic curves (Fig. 4d), no stable remanence was isolated in this dyke. The remanence is of low coercivity, with NRM intensities between 10 and 20 A m^{-1}, and highly dispersed. No useful palaeomagnetic information was obtained. The location of this outcrop together with the rock magnetic characteristics suggest lightning strikes related IRM as a possible contamination factor.

5 SVECONORWEGIAN PALAEOPOLES FROM SOUTHERN SWEDEN

Most 'Sveconorwegian' palaeomagnetic data for Baltica were obtained from mafic intrusions in southern Sweden (Abrahamsen 1974; Poorter 1975; Patchett & Bylund 1977; Stearn & Piper 1984; Bylund 1992; Pisarevsky & Bylund 1998; Bylund & Pisarevsky 2002) and southern Norway (Poorter 1972, 1975; Stearn & Piper 1984; Walderhaug *et al.* 1999 and references therein; Brown & McEnroe 2004). Owing to the lack of precise geochronology, palaeomagnetic results for individual intrusions were commonly grouped on the basis of their remanence directions, or virtual geomagnetic poles (VGPs). This was probably the best approach in that situation, but it did not include any consideration of PSV, which could cause additional error in the estimation of the pole position, especially from small intrusions, because the difference between VGPs and palaeomagnetic poles might be as much as 15°–25°, or

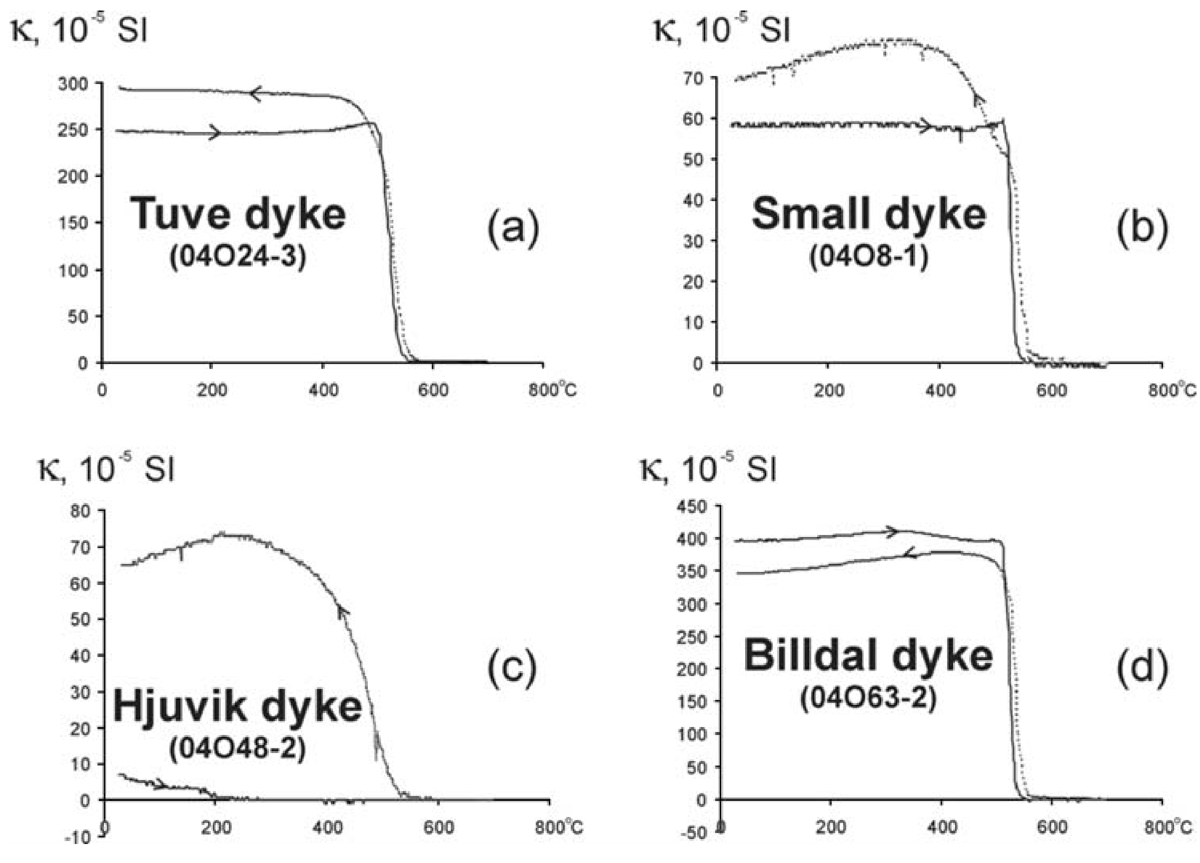

Figure 4. Thermomagnetic curves (magnetic susceptibility versus temperature). Solid lines—heating curves, dotted lines—cooling curves.

Table 1. Mean palaeomagnetic directions from mafic dykes of the Göteborg area.

Dyke	B/N/n	Slat (°N)	Slong (°E)	Decl. (°)	Incl. (°)	k	α_{95} (°)	Plat (°N)	Plong (°E)	D_p (°)	D_m (°)
Tuve	2/23[a]/53	57.8	11.8	122.2	53.7	91.2	3.2	−14.0	237.9	3.1	4.5
Small	1/3[a]/10	57.8	11.8	124.5	54.6	281.0	7.4	−13.9	235.8	7.4	10.4
Hjuvik	1/12[a]/21	57.7	11.7	118.8	37.1	15.2	11.5	−3.3	246.9	7.9	13.5
3 dykes	3[a]/38/84	57.7	11.8	121.5	48.5	65.3	15.4	−10.0	240.7	13.3	20.2
Slussen	1/6[a]/11	58.2	12.2	300.9	−26.5	34.7	11.5	3.2	248.5	6.8	12.5
4 dykes	5[a]/44/95							−7.0	242.4	$A_{95} = 12.0$	

B/N/n, number of sites/samples/specimens; Slat, Slong, locality coordinates; Decl, Incl., sample mean declination, inclination; k, precision parameter of Fisher (1953); α_{95}, semi-angle of the 95 per cent cone of confidence; Plat, Plong, latitude, longitude of palaeopole; D_p, D_m, semi-axes of the 95 per cent cone of confidence about the mean pole.
*Level of statistics.

even larger if a geomagnetic excursion occurred (e.g. McElhinny & McFadden 2000). Recent precise U-Pb ages for some of these intrusions (Scherstén *et al.* 2000; Söderlund *et al.* 2002, 2004; Hellström *et al.* 2004) permit data from individually dated dyke swarms to be averaged, rather than data from individual dykes having similar remanence directions. This reduces uncertainty due to PSV and yields more reliable palaeopoles. In the following paragraphs we reassess those precisely re-dated Sveconorwegian palaeopoles (Table 2).

5.1 Göteborg-Slussen dykes (pole G)

Hellström *et al.* (2004) suggested that other NW- to W- trending mafic dykes in the Western Segment are likely to be similar in age to the Göteborg dykes, and in particular that the Slussen dyke (60 km north of Göteborg) is similar to the Göteborg dykes in field relationships and geochemistry. Pisarevsky & Bylund (1998) reported palaeomagnetic results for the Slussen dyke (in Bredfjället); the Slussen palaeopole is similar to that for the Göteborg dykes (Table 1), but not identical. The difference can be attributed to PSV for individual dykes of slightly different ages. Because the Slussen dyke is magnetized in the opposite polarity to the other dykes (Table 1), we conclude that, collectively, the dykes were emplaced over a sufficient length of time to have encompassed at least one reversal of the Earth's magnetic field. Hence, these four dykes provide a mean pole which has better averaged PSV (Table 1) than the previously published result of Abrahamsen (1974). The dykes show no evidence of local rotations since their emplacement, and we consider this pole to be tectonically coherent with Baltica at 935 Ma.

Table 2. Sveconorwegian palaeopoles.

Pole	Intrusions	Age (Ma)	Plat (°N)	Plong (°E)	D_p (°)	D_m (°)	Reference
B	Bamble intrusions (mean)	1100–1040	3	217	15	15	in: Brown & McEnroe (2004); Torsvik & Eide (1998)
L	Laanila dykes	1042 ± 50	−2	212	13	21	Mertanen *et al.* (1996)
N	Nilstorp (1 dyke)	966 ± 2	9	239	6	11	Patchett & Bylund (1977); Söderlund *et al.* (2004)
K	Karlshamn-Fäjö (5 dykes)	946–954	2	242	30	30	Patchett & Bylund (1977); Söderlund *et al.* (2004)
	(4 dykes)		*13*	*247*	*16*	*16*	
D	Dalarna (4 dykes)	946 ± 1	5	239	15	15	Bylund (1992); Söderlund *et al.* (2005)
G	Göteborg-Slussen (4 dykes)	935 ± 3	−7	242	12	12	This study
Ha	Hakefjorden	916 ± 11	5	249	3	5	Stearn & Piper (1984); Scherstén *et al.* (2000)
Hu	Hunnedalen (4 dykes)	≤848	−41	222	10	11	Walderhaug *et al.* (1999)
	Egersund anorthosite	929–932	−44	214	4	4	Stearn & Piper (1984); Torsvik & Eide (1998)
	Egersund-Ogna anorthosite	∼900	−42	200	9	9	Brown & McEnroe (2004)
	Pyätteryd amphibolite	933–945	−43	214	11	11	Pisarevsky & Bylund (1998) Wang *et al.* (1996)
	Känna gneiss	948–974	−50	225	17	17	"
	Gällared amphibolite	956 ?	−46	214	19	19	Pisarevsky & Bylund (1998); Möller & Söderlund (1997)
	Gällared granite-gneiss	980–990	−44	224	6	6	"

5.2 Karlshamn dykes (pole K)

Patchett & Bylund (1977) studied five mafic dykes in the southmost area of Blekinge-Dalarna Dolerites, near Karlshamn (Fig. 1). The primary nature of their remanence was supported by the study of a baked xenolite of the country red sandstone, which has similar directions of magnetization. Both polarities are present. At the time of their study the K-Ar ages of these dykes, as well as ages of all other Blekinge-Dalarna dykes, were loosely constrained between ∼800 and 1000 Ma. Recently, three of these dykes (Karlshamn, Bräkne-Hoby, and Fäjo) were dated with the U-Pb baddeleyite method at 954 to 946 Ma (Söderlund *et al.* 2004, 2005). Four of the five dykes studied by Patchett & Bylund (1977) have directions that are well grouped, but the Karlshamn dyke has an anomalously steep downward remanence. This could reflect secular variation, or an excursion of the geomagnetic field. Table 2 contains both the calculated mean poles (with and without the Karlshamn dyke).

5.3 Nilstorp dyke (pole N)

The Nilstorp dyke in central Blekinge-Dalarna area was studied palaeomagnetically by Patchett & Bylund (1977) and has a recent U-Pb baddeleyite age of 966 ± 2 Ma (Söderlund *et al.* 2005). The primary origin of its remanence is supported by a positive baked contact test. Although this pole is included in Table 2 and Fig. 5, it is based on a single dyke and is therefore a VGP.

5.4 Dalarna dykes (pole D)

Bylund & Elming (1992) reported coherent palaeomagnetic directions from a swarm of parallel dykes in the Dalarna area north of Falun (Fig. 1). One dyke was dated recently at 946 ± 1 Ma by U-Pb baddeleyite (Söderlund *et al.* 2005). The mean palaeopole for four dykes (entries 1–4 in the Table 1 of Bylund & Elming 1992) is shown in Fig. 5 and in Table 2.

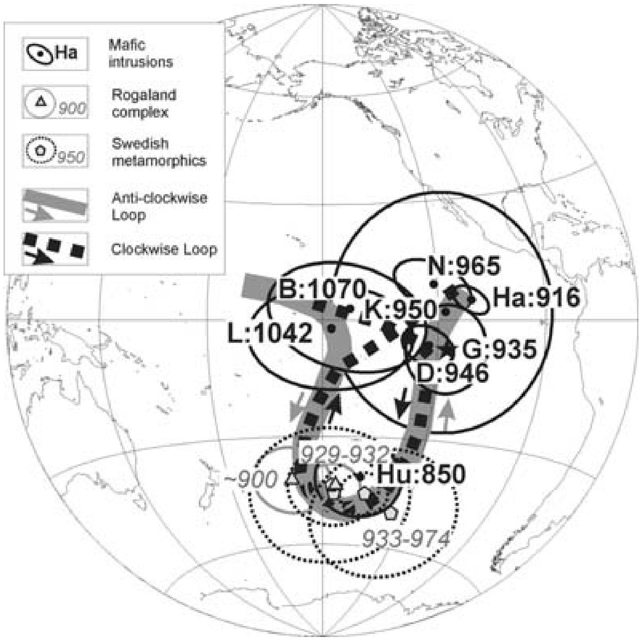

Figure 5. Sveconorwegian palaeomagnetic poles from Baltica. Pole letters correspond to entries in Table 2. Ages are in Ma. Solid grey and dashed black grey lines represent alternative versions of the Sveconorwegian Loop with arrows indicating age progression.

5.5 Hakefjorden Complex (pole Ha)

Stearn & Piper (1984) reported a palaeomagnetic study of the Hakefjorden Complex in the Älgön and Brattön islands north of Göteborg. Recently Scherstén *et al.* (2000) published a 916 ± 11 Ma U-Pb zircon age for granitic back-veining intruding the complex, and interpreted it the age of intrusion of the mafic magma. The Hakefjorden Complex is a ca. 5 km by 1 km, norite–anorthosite intrusion (Årebäck & Stigh 2000) and its cooling process was probably relatively slow. Stearn & Piper (1984) sampled a full transect of the body and determined a palaeopole (Fig. 5, Table 2) that to some extent probably averages out PSV.

5.6 Hunnedalen dykes (pole Hu)

Several palaeomagnetic studies (summarized by Walderhaug *et al.* 1999; Brown & McEnroe 2004) of the 929–932 Ma Rogaland anorthosites and related rocks in southwestern Norway have also revealed only a steep upward remanence. Walderhaug *et al.* (1999) noted that all rocks in the Sveconorwegian domain of SW Norway have an almost identical steep upward magnetization, similar to the A-type directions of Bylund (1992). The Hunnedalen dykes have an 848 ± 29 Ma ^{39}Ar-^{40}Ar biotite age, and similar palaeomagnetic directions and polarity (Table 2). This prompted Walderhaug *et al.* (1999) to propose that a short-lived, post-900 Ma metamorphic or hydrothermal event caused the complete remagnetization of all rocks in the area.

6 DISCUSSION

6.1 Remagnetization event?

Bylund (1992) showed that all studied dolerite dykes (about twenty) of the Protogine Zone south of ∼57°N possess similar steep upwards remanence directions, and corresponding A-type, high-latitude palaeopoles. All are of the same magnetic polarity, exactly as in ∼930 Ma rocks in SW Norway. North of 57°N, as well as in the area of the Blekinge-Dalarna Dolerites, steep palaeomagnetic directions occur more rarely, the dominant remanence (type B) being more shallow and bipolar to the NW and SE. Pisarevsky & Bylund (1998) studied ∼950 Ma metamorphic rocks of the Eastern Segment in southern Sweden, and also found only steep upwards A-type directions. The area of exclusive occurrence of A-type directions is outlined in Fig. 1 by a thick dotted line. B-type directions dominate north and east of this line, although some A-directions are also present. Interestingly, and unlike results from the south-west areas, A-directions with both polarities are found.

The apparent similarity of the single-polarity A-type remanence in mafic intrusions and ∼950 Ma metamorphic rocks of SW Sweden, ∼930 Ma anorthosites in SW Norway, and ∼850 Ma Hunnedalen dykes could be explained by negligible polar wander between 950 and 850 Ma. However, new ∼916–965 Ma palaeopoles discussed here yield B-type remanence and equatorial palaeopoles (Fig. 5, Table 2). The Göteborg-Slussen mafic dykes are coeval with SW Norwegian anorthosites (Rogaland Complex), but also yield B-type remanence. Consequently, we prefer to explain the A-type magnetization as an overprint acquired during a single remagnetization event, as was suggested by Walderhaug *et al.* (1999). The Hunnedalen dykes are probably slightly older than their 848 Ma biotite age, as suggested by Walderhaug *et al.* (1999). The main problem for this explanation is an apparent lack of any evidence for a large-scale thermal or hydrothermal event at 900 to 850 Ma in

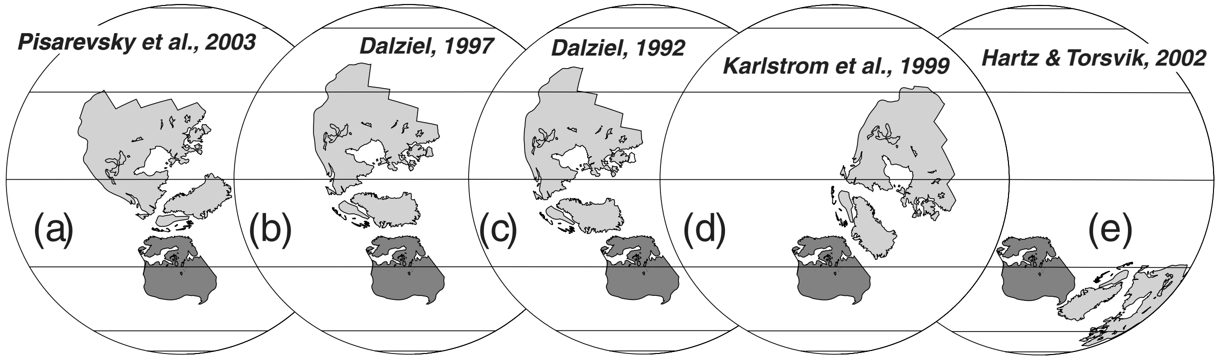

Figure 6. The palaeoposition of Baltica at ~935 Ma and various reconstructions of Baltica and Laurentia.

SW Sweden. Several studies in the Eastern Segment indicate that the Sveconorwegian metamorphic peak in this area was reached by 960 to 950 Ma, and was followed by post-orogenic collapse, crustal extension, and emplacement of the Blekinge-Dalarna Dolerites at 965 to 935 Ma. Also at ~950 Ma, post-tectonic granite and pegmatite dykes were emplaced; these are the youngest Precambrian intrusions in the Eastern Segment (Wang *et al.* 1996; Möller & Söderlund 1997; Möller 1998; Andersson *et al.* 1999; Söderlund *et al.* 2002, 2004). The youngest ^{39}Ar-^{40}Ar (hornblende) age in this area is ~915 Ma (Page *et al.* 1996). At present there are no ages around 850 Ma reported from the Sveconorwegian of SW Sweden, so it is not clear what could cause the resetting of magnetite- and haematite-based remanence in rocks of Eastern Segment and Protogine Zone (Bylund 1992; Pisarevsky & Bylund 1998). We may guess that some kind of low temperature chemical remagnetization took place, as it happened in the Appalachians (e.g. McCabe & Elmore 1989), but much more interdisciplinary studies are necessary to approach this problem.

6.2 The Sveconorwegian Loop

New palaeomagnetic data presented in this paper, combined with new geochronological data that constrain the ages of previous, reliable palaeomagnetic results, have significant implications for the Fennoscandian APWP and the Sveconorwegian Loop.

The palaeopoles from Swedish mafic intrusions (Table 2) with ages from 965 to 916 Ma are similar (Fig. 5), implying that Baltica was located at ~30° latitude, and underwent minimal drift during this interval. We realize that the 966 Ma Nilstorp result is from a single dyke and thus is unlikely to have averaged PSV. Other poles provide better averaging of PSV, however, more well-dated palaeomagnetic data are highly desirable.

In view of the suggestion of the <900 Ma major remagnetization event in SW Sweden and SW Norway, we can subdivide palaeopoles into three distinct clusters at 1100 to 1040 Ma, 965 to 915 Ma, and <900 Ma (Fig. 5), suggesting that the Baltica APWP indeed forms a loop. The 965 to 915 Ma group is located at ~30° east of the ~1100 to 1040 Ma group, implying a clockwise age progression within this loop. The age of the 'younger' end of the loop (i.e. the time when Baltica returned from polar to moderate latitudes) is unclear.

There is general agreement that Laurentia and Baltica were part of the Late Mesoproterozoic to Early Neoproterozoic supercontinent Rodinia (e.g. Hoffman 1991; Dalziel 1997; Weil *et al.* 1998; Pisarevsky *et al.* 2003). The presence of nearly coeval loops for the Laurentian and Baltican APWPs is evidence in support of their incorporation in a single supercontinent. However, the present palaeomagnetic database for ~1000 to 800 Ma is insufficient to delineate the exact shapes of these loops and to provide, for direct comparison, precisely dated coeval poles from both continents. As a result, several different Laurentia-Baltica reconstructions can be accommodated (Fig. 6). Geological constraints for these reconstructions and their implications is discussed by Cawood & Pisarevsky (2006). Our new results, together with our re-assessment of previous reliable results, in light of new geochronological data, provide several potential key poles for Baltica.

The shape and age progression of the Laurentian APWP for ~1000 to 800 Ma (the 'Grenville Loop') is also debated (Hyodo & Dunlop 1993; Weil *et al.* 1998; Alvarez & Dunlop 1998; McElhinny & McFadden 2000; Pisarevsky *et al.* 2003; Meert & Torsvik 2003). Most Laurentian poles for this time interval are either from metamorphic rocks with ambiguous ages of magnetization (e.g. Buchan & Dunlop 1976; Warnock *et al.* 2000), or from sedimentary rocks of imprecisely known age (e.g. Weil *et al.* 2003). New palaeomagnetic data from well-dated ~970 to 900 Ma Laurentian rocks are required to verify the Laurentia-Baltica reconstruction within Rodinia.

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