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Early Proterozoic palaeomagnetic data from the Pechenga Zone (north-west Russia) and their bearing on Early Proterozoic palaeogeography

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SUMMARY

An Early Proterozoic palaeomagnetic signature (*c.* 2125 Ma), verified by a positive conglomerate test, is recorded in the Kuetsyarvi Formation, Pechenga Group (north-west Russia), but the majority of the palaeomagnetic directions observed in the Pechenga Group lithologies reflect a low-grade remagnetization event probably linked with the Late Precambrian Baikalian Orogeny which affected north-west Russia and northern Norway. Secondary pyrrhotite is the dominant remanence carrier in the uppermost formations of the Pechenga Group.

Palaeomagnetic poles from the Kuetsyarvi Formation differ somewhat or partially overlap with coeval palaeomagnetic poles from other tectonomagmatic provinces in northern Fennoscandia, but it is premature at this stage to speculate on intraplate movements during the Early Proterozoic. Besides, the Kuetsyarvi Formation probably developed during an early phase of intracontinental rifting along the northern margin of Fennoscandia, similar to the present-day East African rift. Hence younger intercontinental rifting, possible seafloor-spreading and subsequent convergence would remain undetected by our palaeomagnetic data. Palaeolatitude estimates from the Kuetsyarvi Formation suggest that the Pechenga region was located in latitudes of around 20° to 30° during the 2100–2200 Ma interval. These low-latitude estimates are supported by the sedimentary record in the Pechenga region which is characterized by red beds and evaporites.

Comparison of Fennoscandian palaeomagnetic poles with coeval poles from the Slave and Superior cratons (Laurentia) questions previously publicized supercontinental configurations. A close relationship between Fennoscandia and Early Proterozoic Laurentian Provinces is conceivable from palaeomagnetic data, but, given the lack of longitudinal control as well as the choice of hemisphere, such postulates are tentative at best on purely palaeomagnetic grounds.

Key words: Early Proterozoic, Fennoscandia, north-west Russia, palaeogeography, palaeomagnetism, Pechenga Zone.

INTRODUCTION

The Fennoscandian Shield comprises several Archean and Proterozoic tectono-magmatic provinces, but palaeomagnetic data have not yet demonstrated intraplate movements similar to those proposed for the Canadian Shield (Irving, Davidson & McGlynn 1984; Symons 1991). This lack of intraplate motion could be an artefact of data quality, inadequate data coverage from coeval tectonic provinces, or merely be due to the magnitude of the intraplate movements being below the power of palaeomagnetic resolution (*cf.* Pesonen *et al.* 1989; Elming *et al.* 1993).

In order to augment the Precambrian palaeomagnetic data base for Fennoscandia, which contains few reliable Pre-Svecofennian (>1850 Ma) palaeomagnetic poles, we present the first Early Proterozoic palaeomagnetic data from the Pechenga Zone, Kola Peninsula (north-west Russia; Fig. 1). This zone forms part of the Polmak–Pasvik–Pechenga–

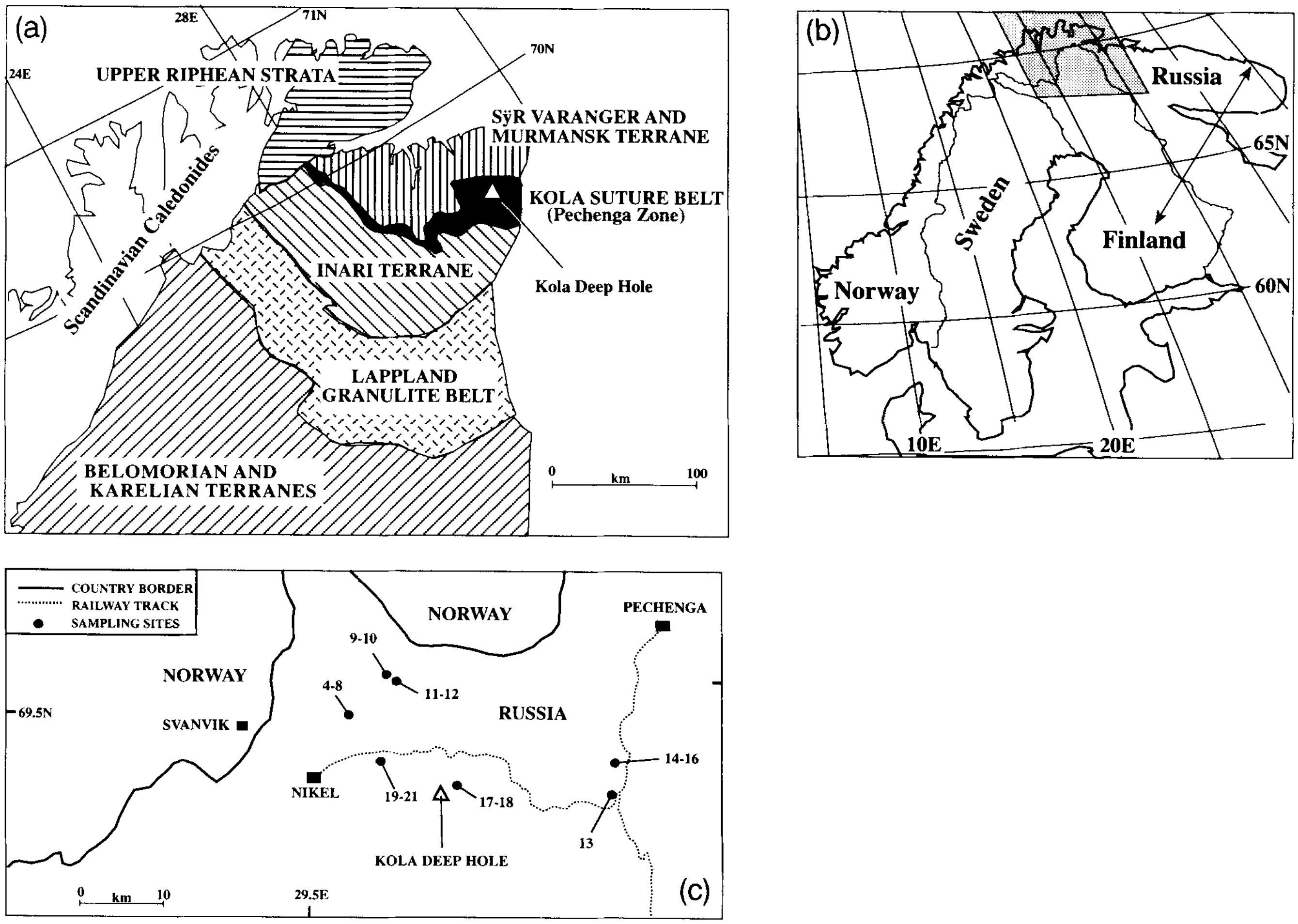

Figure 1. (a) Tectonic province map for northern Scandinavia and north-west Russia (simplified from Berthelsen 1992). (b) Geographic map of Scandinavia and north-west Russia, with the area covered in (a) shaded. (c) Palaeomagnetic sampling sites within the Pechanga Zone.

Imadra/Varzuga-Ust'Ponoy Greenstone Belt (PV Greenstone Belt) which is renowned for its Ni–Cu deposits and the Kola Superdeep Drill Hole (Melezhik & Sturt 1994).

The PV Greenstone Belt consists of a remarkably complete volcano-sedimentary sequence that developed between 2500 Ma and 1800 Ma. The PV Greenstone Belt has been depicted as an intracontinental rift (e.g. Zagorodny, Predovsky & Radchenko 1982; Predovsky *et al.* 1987; Melezhik 1988), and Melezhik & Sturt (1994) have proposed the following three-stage model for its development:

(1) an intracontinental rift stage (2500–2100 Ma), characterized by lacustrine, red-coloured evaporites associated with alkaline volcanism, that is comparable with the present-day Afar Triangle and East African rift;

(2) a transitional stage from intracontinental to intercontinental rifting (2100–1970 Ma) with possible short-lived spreading caused by a mantle plume that resembles a present-day Red Sea type environment;

(3) a collision-related stage (1970–1850 Ma) marked by boninites, high-Al_2O_3 andesites and TiO_2-rich picrites which was followed by the Svecofennian orogeny at *c.* 1850–1700 Ma.

The PV Greenstone Belt has also been referred to as the Kola Suture Belt (Berthelsen & Marker 1986), marking the boundary between the Sørvaranger and Murmansk Terranes to the north and the Inari Terrane to the south (Fig. 1a). In this mobilistic synthesis, the latter terrane along with the Lappland Granulite Belt and the Belomorian and Karelian Terranes (Fig. 1a), all of Archean age, were supposedly amalgamated during the Kola–Karelian Orogen (2000–1900 Ma; *cf.* review in Windley 1992).

SAMPLING AND LOCAL GEOLOGY

The present study includes 18 palaeomagnetic sampling sites (Table 1; not sequentially listed) from the Pechenga Zone. All sites are located in the vicinity of the city of Nikel and the Kola Superdeep Drill Hole (Fig. 1c). The metamorphic grade within the PV Greenstone Belt varies from prehnite–pumpellyite to amphibolite facies (Belyaev *et al.* 1977) with the central parts of the Pechenga Zone being the least metamorphosed (Melezhik & Sturt 1994). Our sampling was confined to this central zone.

Early Proterozoic basement, including a layered gabbro-norite intrusion dated at 2453 ± 42 Ma (^{147}Sm–^{144}Nd; Bakushin *et al* 1990), was sampled at sites 14–16. The basement is overlain by the Pechenga Group, which consists of a cyclic arrangement of sedimentary and volcanic

Table 1. Sampling details of the northern Pechenga region (S_0 = bedding/layering; right-hand convention) together with site-means of the natural remanent intensity (NRM), median destructive alternating field (M_D) and remanence coercive force (H_{CR}). Approximate ages in Ga. Sites are listed in descending stratigraphic order. Mean geographic sampling location: 69.5°N, 29.5°E.

Site	Rock-Type	Formation/Age	S_o	NRM (mA/m)	M_D (mT)	H_{CR} (mT)
18	Andesite	Pil'guyarvi/1.9	131/40	77		
17	Andesite	Pil'guyarvi/1.9	131/40	197	5	15
	1970±5Ma (U-Pb-Zircon), 1955±43Ma (Pb-Pb) & 1990±66Ma (Sm-Nd) - Hanski et al. 1990					
21	Andesite	Kolasyoki/2.0	088/5	284		
19	Andesite	Kolasyoki/2.0	088/5	299		
20	Pillow Basalt/Andesite	Kolasyoki/2.0	066/20	152	8	30
	1990±55Ma, 1960±66Ma, 1980±72Ma, 1980±150Ma (Pb-Pb); 1970±110Ma (Sm-Nd)-Mitrofanov et al. 1991).					
6	Andesite	Kuetsyarvi/2.1	043//30	47	3	25
5	Andesite	Kuetsyarvi/2.1	043/30	9	4	50
	2125Ma (Melshik; pers. com.)					
4	Conglomerate	Kuetsyarvi/2.15	048/30			
7	Volcanoclastics	Kuetsyarvi/2.15	043/30	776	6	60
8	Pillow Basalt	Kuetsyarvi/2.15	043/30	751		
11	Red & pink sandstone	Kuetsyarvi/2.2	104/40	37	130	>70
12	Red sandstone	Kuetsyarvi/2.2	104/40	16	22	>60
9	Amygdaloidal basalt	Akhmalahti/2.3	113/50	4	12	
10	Amygdaloidal basalt	Akhmalahti/2.3	113/50	1	9	
	2330±38Ma (Rb/Sr)-Balashov et al. 1990.					
13	Basal conglomerate	Akhmalahti/2.3	113/50	2		
16	Layered Gabbro	Basement/2.45	353/80	4	28	
15	Layered Gabbro	Basement/2.45	353/80	8	35	55
14	Layered Gabbro	Basement/2.45	353/80	0.5		
	2453±42Ma (Sm-Nd)-Bakushkin et al. 1990					

formations (Fig. 2) whose total stratigraphic thickness approaches 12 km. The Pechenga Group consists of a classic greenstone belt sequence that commences with sedimentary deposition, often separated by non-depositional unconformities, and culminates with extensive volcanism (Melezhik & Sturt 1994). The Pechenga Group is subdivided into four lithostratigraphic formations, namely the Akhmalahti, Kuetsyarvi, Kolasyoki and Pil'guyarvi Formations (Fig. 2).

The Akhmalahti Formation starts with basal fluviatile polymict conglomerates (site 13) and sandstones capped by subaerial amygdaloidal basaltic andesites with komatiitic affinities (sites 9 and 10; Melezhik & Sturt 1994). The basaltic andesites are dated at 2330 ± 38 Ma (Rb–Sr; Balashov *et al.* 1990).

No published geochronologic data exist for the Kuetsyarvi Formation, but Melezhik (private communciation 1994) quotes an age of 2125 Ma from the volcanics. The base of the Kuetsyarvi Formation includes red and pink sandstones (sites 11 and 12), which are capped by alkaline volcanics (sites 5, 6 and 8) with a pronounced sodic trend and high enrichment in TiO_2. Alkaline volcanics are represented by subaerial amygdaloidal, columnar trachybasalts, trachyandesites, trachydacites, mungerites and albitophyres with subordinate alkaline picrites (Melezhik & Sturt 1994). A distinct break within the alkaline volcanics is marked by volcanoclastics (site 7), conglomerates (site 4) or cold mudflow deposits.

The Kolasyoki Formation (sites 19–21), submarine basalts and andesites, is dated between 1990 Ma and 1960 Ma (*cf.* Table 1). Volcanic and sedimentary rocks from the overlying Pil'guyarvi Formation (sites 17 and 18) are distinctly different from the older sequences. The Pil'guyarvi Formation, dated between 1970 Ma and 1955 Ma (*cf.* Table 1), contains an association of tholeiitic basalts and 'black shales' with basaltic and picritic tuffs. The rhyolitic lavas contain numerous xenoliths of granites and granitoid gneisses derived from the Archean basement. These lower crustal xenoliths led Melezhik & Sturt (1994) to conclude that the volcanics (*c.* 1990–1970 Ma) developed through continental crust beneath the Pechenga Zone. The Pechenga Group is overlain by the South Pechenga Group but is separated from it by an orogenic unconformity (Fig. 2).

PALAEOMAGNETIC RESULTS

The natural remanent magnetization (NRM) was measured with a 2G superconducting magnetometer at the University of Michigan. The stability of NRM for a total of 238 samples was tested by stepwise thermal demagnetization and/or alternating-field (AF) demagnetization. In general, samples yielded cleaner demagnetization trajectories using stepwise thermal demagnetization. Characteristic remanence components were calculated using least-squares algorithms. Site-mean values for NRM intensity, median destructive fields and remanence coercivity forces for selected sites are listed in Table 1. Sites 14 (layered gabbro, basement) and 13 (basal conglomerate, Akhmalati Formation) were magnetically unstable, probably as a result of viscous behaviour.

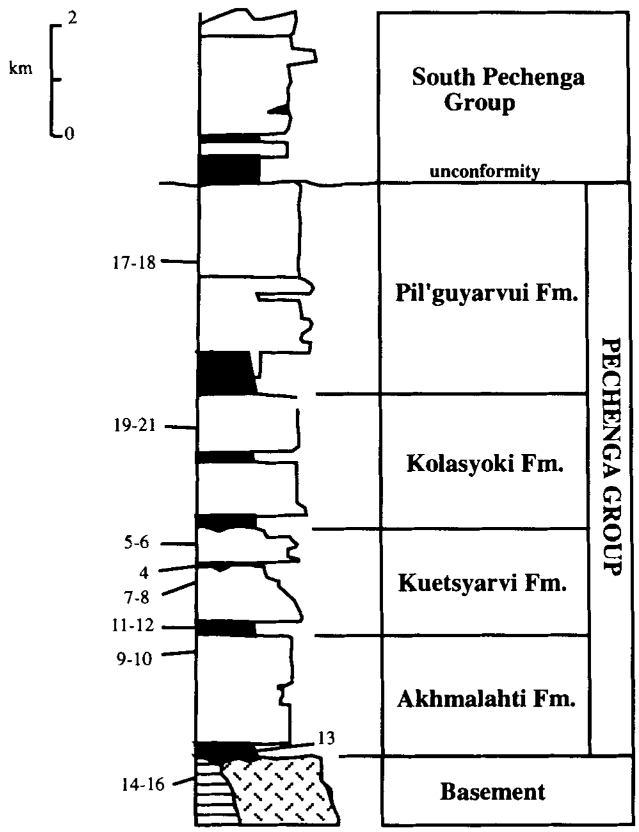

Figure 2. Stratigraphic units in the Pechenga Group and the stratigraphic positions of palaeomagnetic sampling sites. Black (white) ornaments represent sediments (volcanics).

These sites were rejected for further analysis. Demagnetization results are described (see below) in *in situ* coordinates.

Basement (*c.* 2450 Ma) and Akhmalahti Formation (*c.* 2300 Ma)

Layered gabbro samples from sites 15 and 16 (basement) are variably serpentinized and yield low NRM intensities in the 0.5–8 mA m^{-1} range. All samples are dominated by steeply downward magnetization with a northerly declination (Figs 3a and b). Discrete unblocking between 525 °C and 570 °C (Fig. 3a), median destructive AF fields around 28–35 millitesla (mT) and isothermal remanent magnetization (IRM) saturation fields of *c.* 0.2 tesla (T) (Fig. 4a) suggest magnetite or titanium-poor titanomagnetite as the primary remanence carrier.

Basaltic samples from the overlying Akhmalahti Formation are also dominated by a steep northerly component, but in addition we recognize a north-easterly and shallow-dipping magnetization at temperatures above 400–450 °C (Figs 3c and d). Component identification, however, often proved difficult due to a somewhat irregular viscous behaviour, and directional stability in these samples was not observed at temperatures above 540 °C.

Kuetsyarvi Formation (*c.* 2100–2200 Ma)

Samples from andesites and pillow basalts at sites 5, 6 and 8 are dominated by two magnetization components. Both components have shallow, mostly downward dipping inclinations, and westerly or north-westerly declinations (Figs 5 and 6). Except for site 5, the angular difference between the low–intermediate and high unblocking temperature components is usually less than 10 degrees of arc (Fig. 5; *cf.* sites 6 and 8). High unblocking components are typically identified above 525–540 °C and directional stability was retained up to 575 °C. This behaviour suggests that magnetite or titanium-poor titanomagnetite is the primary remanence carrier. The median destructive field and remanence coercivity force is typically in the 3–4 mT and 25–50 mT range, respectively. IRM curves show saturation in fields of 0.3 T (Fig. 4b).

The demagnetization behaviour for one volcanoclastic site (site 7) differs from the extrusive sites. Samples from this site are dominated by low–intermediate unblocking components that are steeply dipping, but a shallowly inclined magnetization with a north-westerly declination is recorded above 600–620 °C (Figs 5 and 6). The high unblocking component, carried by haematite, is generally more northerly directed than that of the majority of the extrusive sites but compared favourably with high unblocking components from site 5. The low unblocking component resembles the direction isolated at sites 15 and 16 (basement) and low unblocking components from site 9 (*cf.* Figs 3 and 6).

Samples in pink and red sandstones (sites 11 and 12) from the lowermost part of the Kuetsyarvi Formation are dominated by steep northerly magnetizations carried by haematite (Fig. 7). In many cases, there is clear evidence for an underlying and more shallow component similar to that of the volcanoclastic samples from site 7. This shallow component was only clearly isolated in three samples (site 11; Fig. 7). The remaining samples demonstrated viscous behaviour at elevated temperatures (above 650°C). IRM curves from sites 11 and 12 are not saturated in the maximum available field of 1.25 T, suggestive of haematite (Fig. 4c).

Pil'guyarvi and Kolasyoki (*c.* 1970–1980 Ma) Formations

All samples from these two youngest volcanic formations are dominated by low unblocking components ($T_{b,\max}$ 300–350 °C) with easterly declinations and steeply downward inclinations (Figs 8 and 9). In some instances this component appears to be the only component (Fig. 8c). More commonly, a high unblocking component is clearly present since the low unblocking component is not decaying towards the origin of the vector plots. This high unblocking component was not clearly isolated because of viscous behaviour at elevated temperatures. The low unblocking component is likely to be carried by multidomain pyrrhotite, as suggested by the T_b spectra, low median destructive fields (*c.* 5–8 mT), low remanence coercive forces (15–30 mT) and IRM saturation at fields of the order of 0.2–0.3 T (Fig. 4d). The Pil'guyarvi Formation is renowned for its Ni–Cu deposits and iron sulphide mineralization. The iron sulphides are principally pyrite and pyrrhotite where the pyrrhotite is a secondary low-grade metamorphic phase replacing pyrite (Abzalov, Both & Brewer 1993). This secondary pyrrhotite apparently carried more than 90 per cent of the total NRM in our samples.

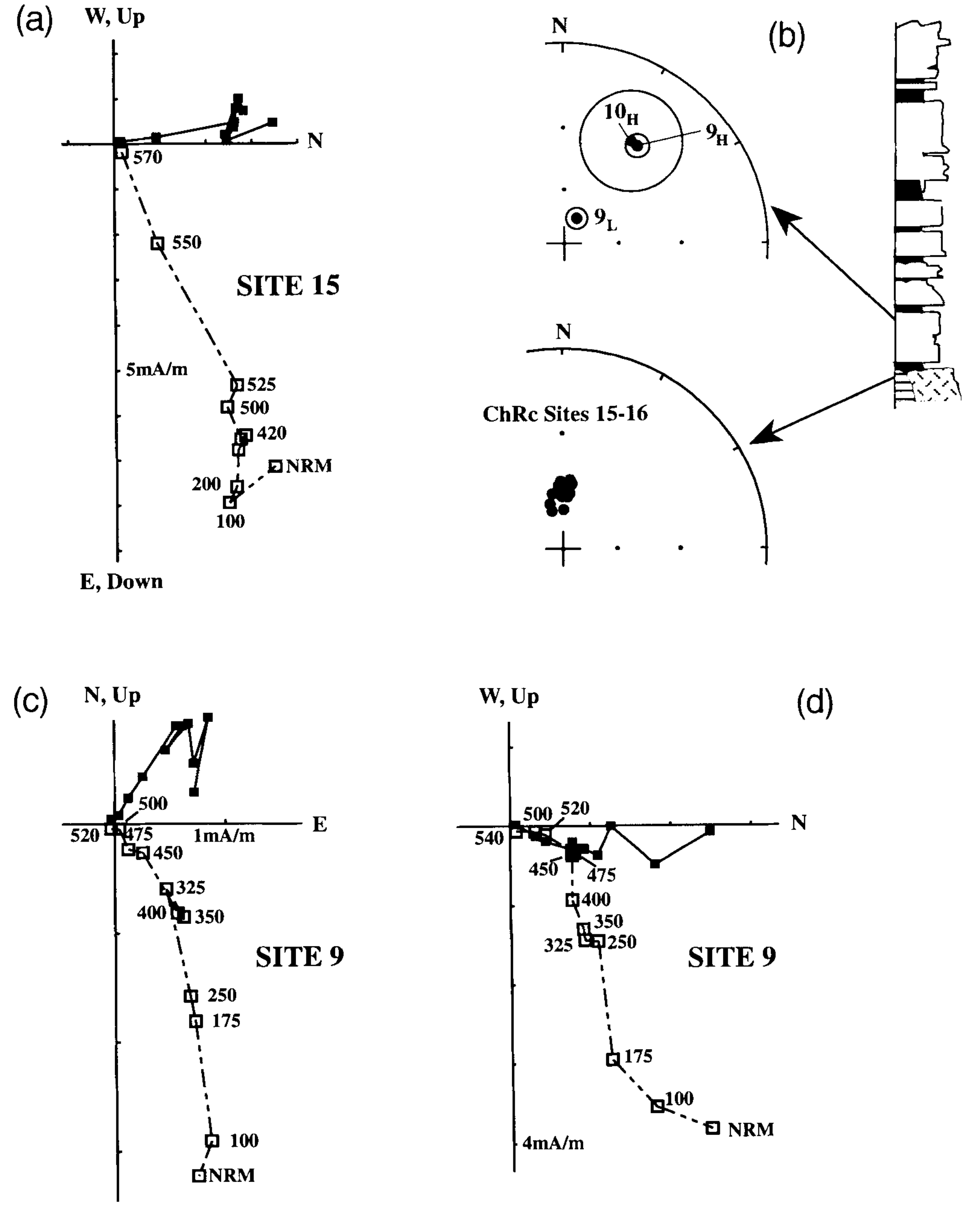

Figure 3. Typical examples of thermal demagnetization of samples from the basement (a) and the overlying Akhmalahti Formation (c–d). In the orthogonal vector diagrams, points in the horizontal (vertical) plane are plotted as closed (open) symbols. Characteristic remanence components from sites 15 and 16 and site-means with 95 per cent oval confidences for sites 9 and 10 are shown in (b). In the stereoplots, downward (upward) inclinations are plotted as solid (open) symbols.

DIRECTIONAL ANALYSIS AND FIELD TESTS

Directional data, unblocking spectra and field tests suggest that the directional data can be divided into two major component groups (Tables 2 and 3). We call these components A and B and interpret them as 'primary' and 'secondary' components, respectively.

Component B

Steeply downward and northerly directed components (denoted B1) are observed in the gabbro samples from the basement (sites 15 and 16) and the overlying Akhmalahti (site 9) and Kuetsyarvi Formations (sites 7, 11 and 12). B1 is either 'univectorial' (sites 15, 16 and 12) or constitutes the lower-intermediate unblocking temperature range (sites 7, 9 and 11) when co-existing with the A component. B1 is found in rocks covering an age span of approximately 250 Ma which, along with a statistically negative fold-test at the 95 per cent confidence level, suggests a secondary post-folding origin (Fig. 10a).

Sites 17–21, spanning an age range of c. 50 Ma, are also characterized by steeply downward magnetizations that are carried by secondary pyrrhotite, but with more easterly declinations (denoted B2). This component is also assumed

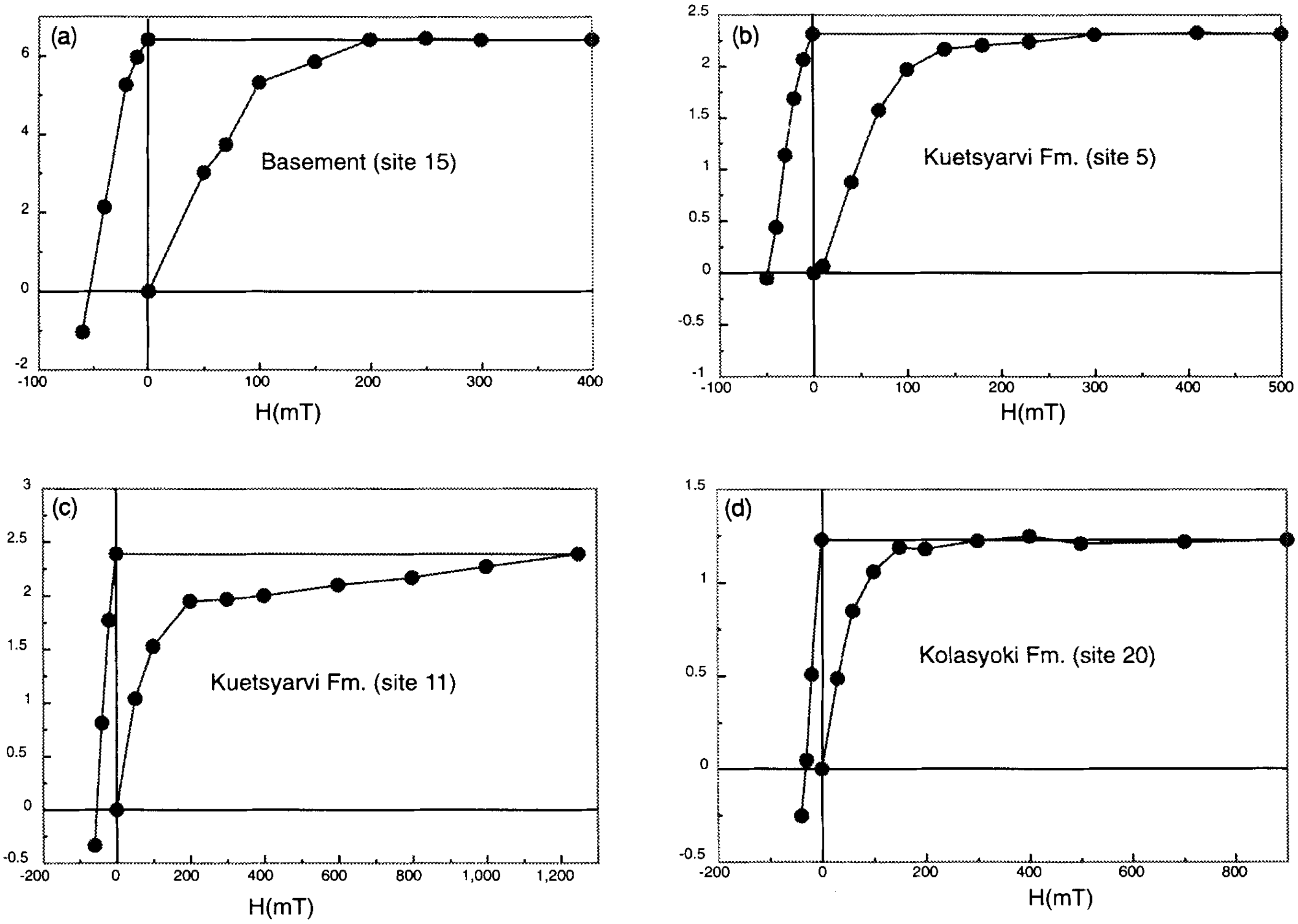

Figure 4. Typical isothermal remanent magnetization (IRM) acquisition and backfield curves.

to be secondary, but a local fold-test (Fig. 9) did not prove significantly negative at the 95 per cent confidence level. *In situ* site-means are well removed from the local field direction (008°/77°) which suggests that it is not a present-day viscous remanent magnetization (VRM) component.

A combination of components B1 and B2 yields a statistically negative fold-test (Fig. 10), but we are as yet uncertain whether they represent a single, or a multistage, secondary overprint. We notice that B1 *in situ* site-means plot close to the present field direction, but high-stability 'single-component' remanences carried by haematite (site 12) seemingly do not resemble a present-day type VRM.

Component A

Possible 'primary' components are only found within the Akhmalahti and Kuetsyarvi Formations. Component A (*in situ*) is always shallower than component B, and, when they co-exist in the same sample, component A always occupies the higher unblocking spectra. Within the Kuetsyarvi Formation, volcanoclastics (site 7) and pink and red sediments (sites 11 and 12) are always contaminated by the B component, whereas andesitic and basaltic samples (sites 5, 6 and 8) carry the A component in both the lower-intermediate (A2) and high unblocking (A3) spectra. A total of eight basaltic and volcanoclastic boulders were sampled from an intraformational conglomerate at site 4. High unblocking components, often carried by haematite, from all boulders are internally consistent but they differ between boulders (Fig. 11). This clearly suggests a positive conglomerate test for the A component. We further suggest that the angular difference between the low (A2) and high unblocking (A3) components, exclusively observed in the extrusive sites (sites 5, 6 and 8), originates from secular variation during initial cooling and/or delayed cooling/partial reheating caused by the extrusion of successive younger lava flows.

A fold-test for the Kuetsyarvi Formation (A2–A4) or for a combination of the Kuetsyarvi and Akhmalahti Formations (A1) is inconclusive at the 95 per cent confidence level (Fig. 10b). Conversely, if component A is primary, a positive fold-test that combines palaeomagnetic data spanning approximately 200 Ma (A1–A4), or alternatively 100 Ma (A2–A4), is suspicious unless no apparent polar wander (APW) occurred during these time intervals. We do note that the site-mean data are converging upon unfolding, and, given the positive conglomerate test, we submit that the angular difference between directions at 100 per cent unfolding may represent APW.

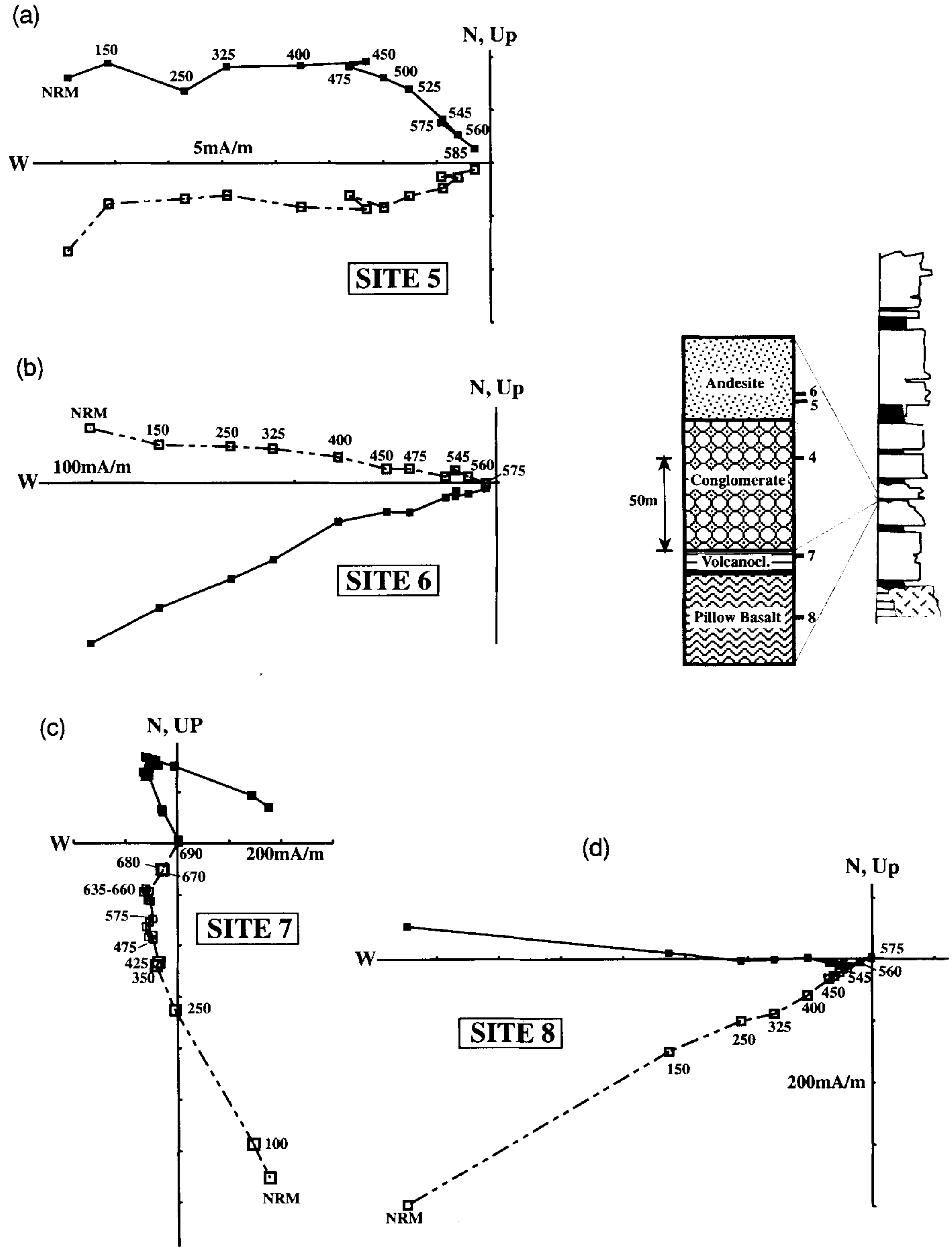

Figure 5. Thermal demagnetization diagrams from the Kuetsyarvi Formation. Stratigraphic positions of sampling sites are indicated in the diagram to the right.

PALAEOMAGNETIC POLES AND AGE OF REMANENCE

Primary data

We consider that an average of the low–intermediate (A2) and high unblocking (A3) components from sites 5–8 (mean age 2125 Ma), or alternatively, combined with site-mean data from site 11 (mean age 2150 Ma), represents a reliable estimate of an Early Proterozoic palaeofield direction (Table 3). A primary palaeomagnetic signature for the Kuetsyarvi Formation is supported by the positive conglomerate test (site 4), although we admit that the palaeomagnetic stability for the intraformational boulders is often an order of magnitude better than their parent sedimentary and volcanic

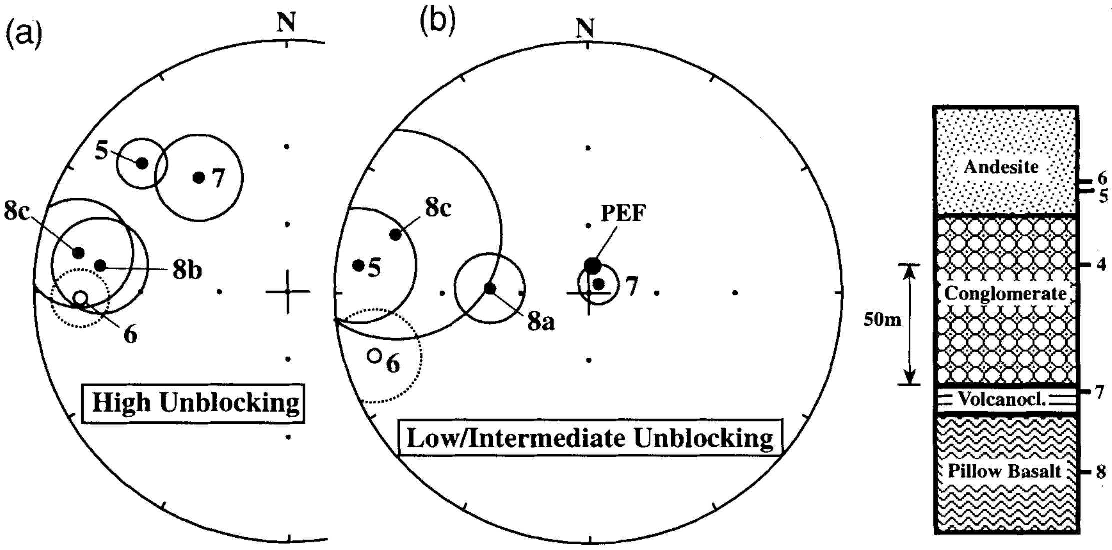

Figure 6. Distribution of characteristic remanence components (site-means with 95 per cent confidence circles) for the Kuetsyarvi Formation (PEF = present Earth's field at the sampling site).

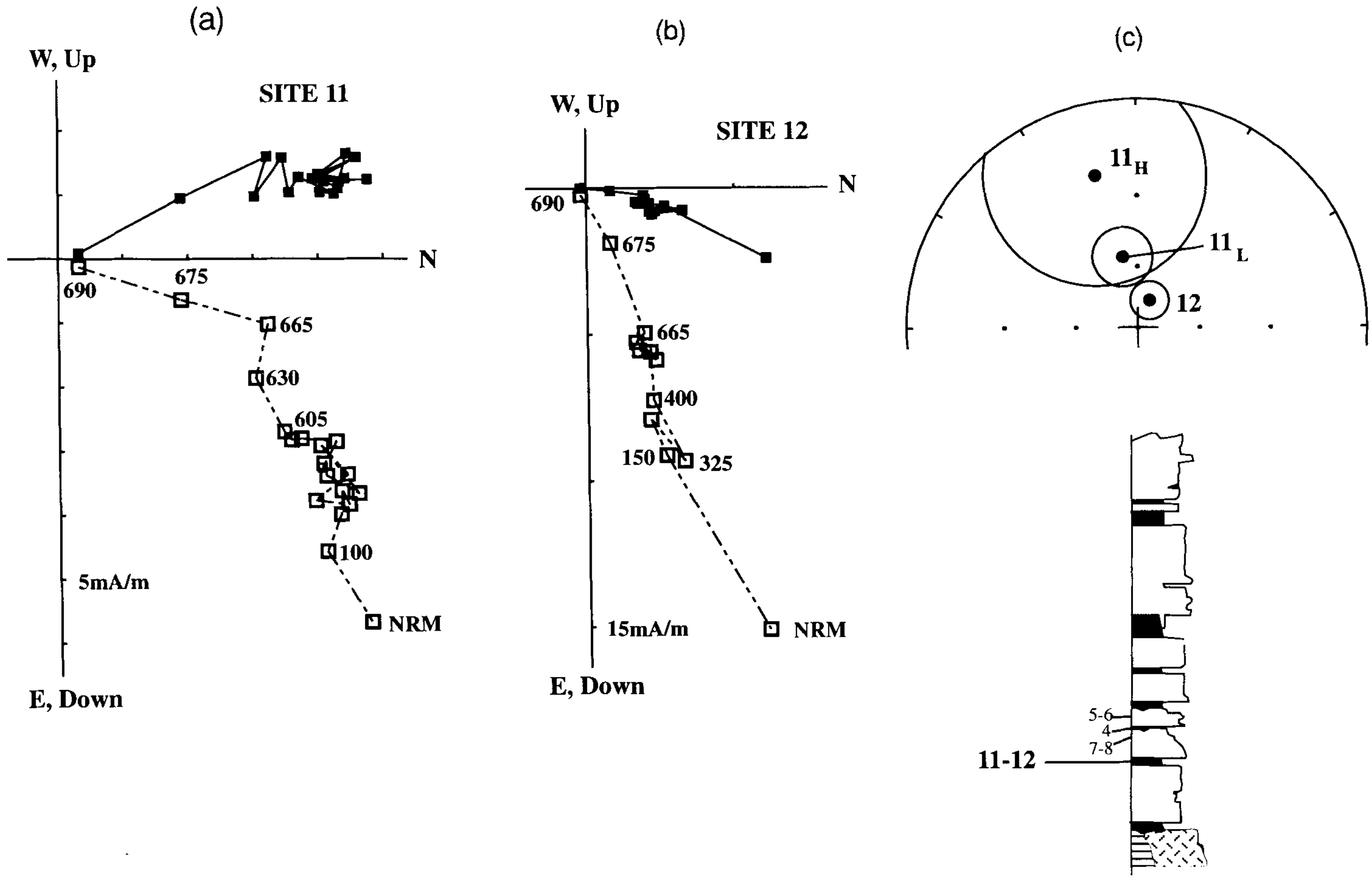

Figure 7. Thermal demagnetization of samples from the basal sediments of the Kuetsyarvi Formation together with the site-mean direction for site 12 and high-unblocking (H) and low-unblocking (L) site-means for site 11.

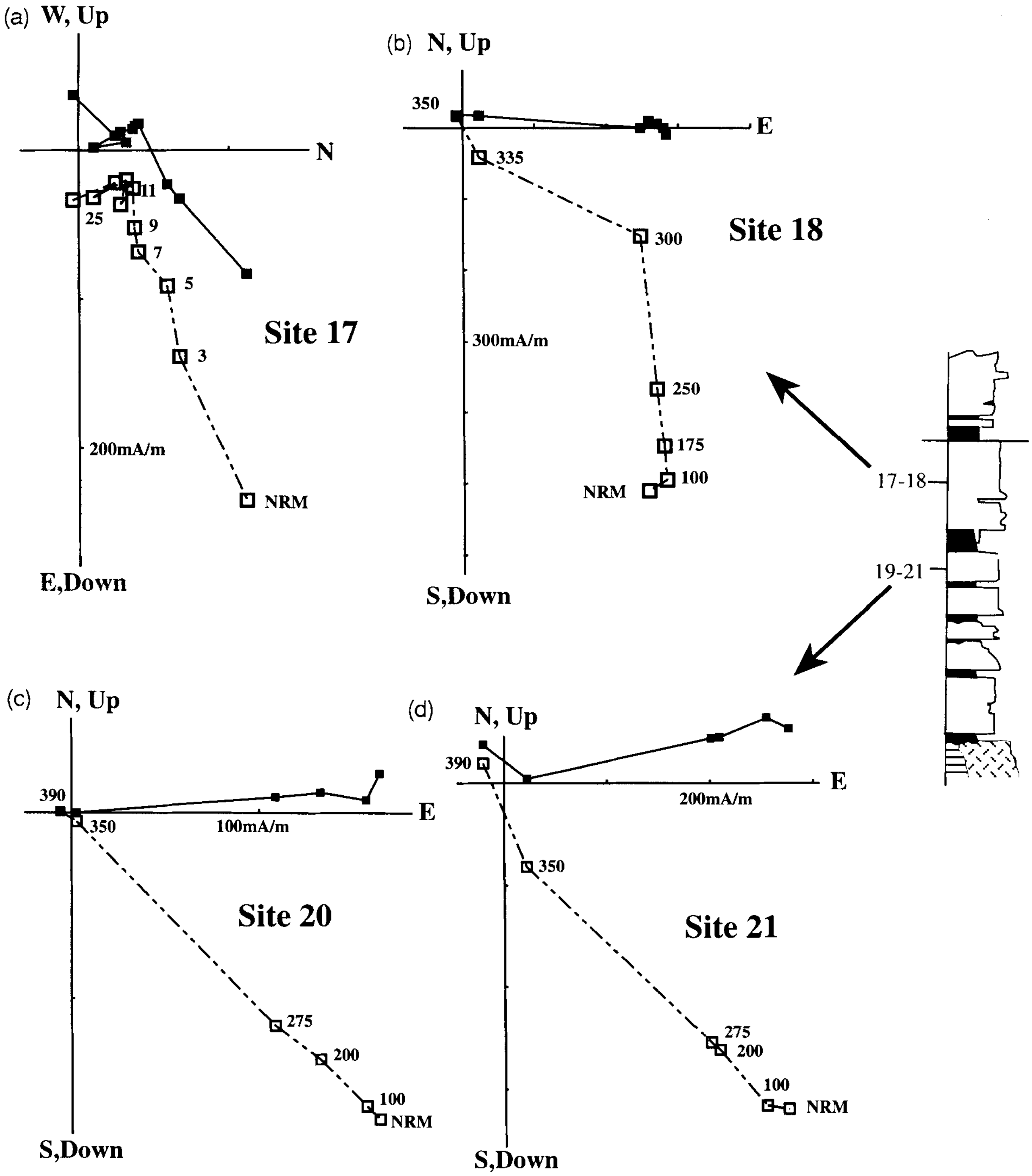

Figure 8. Alternating field (a) and thermal (b–d) demagnetization of samples from the Kolasyoki and Pil'guyarvui Formations. Alternating field values in mT.

samples. The palaeomagnetic pole, calculated using the A2 and A3 components from the Kuetsyarvi Formation, falls at 22.8°N, 298.3°E ($\delta p = 5°$, $\delta m = 8.5°$). This pole is compared with a recent compilation of palaeomagnetic poles from Fennoscandia by Elming *et al.* (1993); it is evident that our pole for the Kuetsyarvi Formation corresponds favourably with their 2120 Ma grand mean pole (Fig. 12). The path of Elming *et al.* (1993) is, however, constrained by only two palaeomagnetic studies: one in the Karelia subprovince of northern Finland (*c.* 2100 Ma layered intrusions; Mertanen *et al.* 1989); and the other from the Muezerskaja gabbro–diabase dykes in northern Russia (*c.* 2140 Ma; Gooskova & Krasnova 1990). Palaeomagnetic poles from these two regions differ substantially, but we note that the palaeomagnetic pole derived from the Kuetsyarvi Formation plots in the area between (mean of A2–A3), or overlaps (mean of A2–A4) with, these poles.

Secondary data

The B components (B1 and B2) have completely overprinted the original magnetic signature within the two

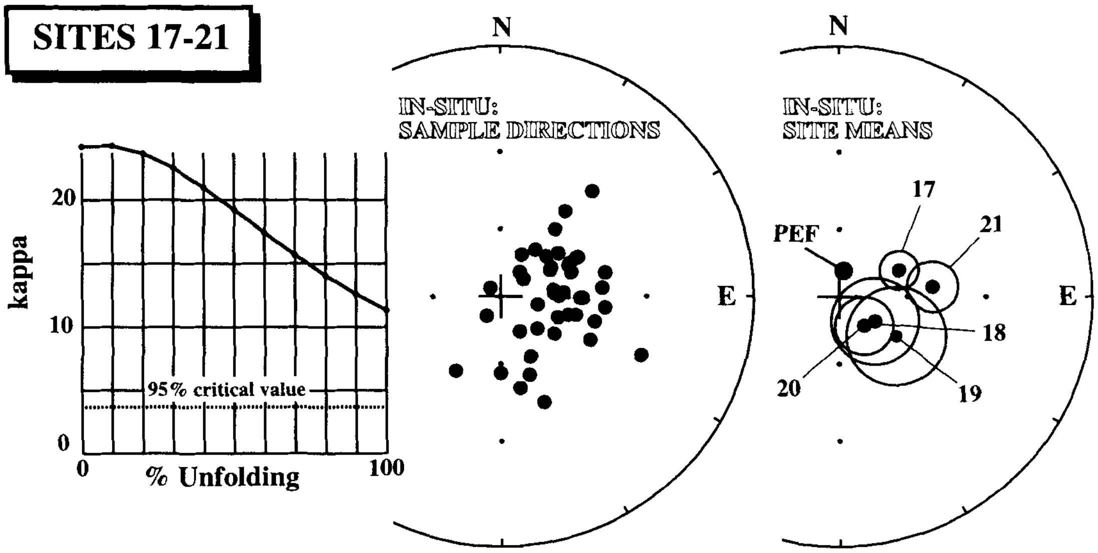

Figure 9. Distribution of *in situ* characteristic remanence directions (sample and site-level) from the Kolasyoki and Pil'guyarvui Formations. The diagram to the left shows the variation in the statistical precision parameter kappa as a function of incremental unfolding (site-means).

Table 2. Palaeomagnetic results—site-means.

Site	Rock Type	T_b	Dec_I	Inc_I	α_{95}	k	N	Dec_C	Inc_C	Component
Basement (c. 2.45Ma)										
15	Gabbro	**H**	359.4	59.5	4.2	148.5	9	52.6	5.4	B1
16	Gabbro	**H**	357.4	58.9	3.8	209.1	8	51.8	6.3	B1
Akhmalahti Fm. (c. 2.3 Ba)										
9	Basalt	L	026.3	74.1	5.9	47.0	14	201.4	55.9	B1
		H	037.0	27.7	4.9	41.1	22	70.5	27.7	**A1**
10	Basalt	**H**	033.4	27.5	20.6	20.9	4	60.7	74.8	**A1**
Kuetsyarvi Formation (c. 2.1-2.2 Ba)										
6	Andesite	**H**	268.2	-11.4	7.8	31.8	12	268.4	10.2	**A2**
		L	253.5	-7.3	11.8	62.0	4	253.3	8.1	**A3**
5	Andesite	**H**	311.7	15.2	7.1	42.7	11	311.2	45.2	**A2**
		L	276.9	5.3	14.0	16.6	8	270.9	28.8	**A3**
4	Conglomerate		'RANDOM DIRECTIONS'				25			
7	Volcanoclastics	**H**	322.6	30.6	14.7	13.2	9	329.6	59.9	**A2**
		L	48.1	84.0	9.0	30.0	10	121.3	58.9	B1
8a	Pillow Basalt	L	272.7	47.4	13.6	82.9	3	233.2	63.6	**A3**
8b	Pillow Basalt	**H**	278.0	16.6	13.8	31.8	5	267.3	39.8	**A2**
8c	Pillow Basalt	**H**	280.5	10.1	14.3	22.8	6	273.0	34.5	**A2**
		L	287.0	13.1	27.9	20.6	3	279.5	39.3	**A3**
11	Pink Sandstone	**H**	344.9	20.9	34.7	13.7	3	325.1	52.9	**A4**
		L	348.3	55.0	13.5	84.8	3	256.3	73.7	B1
12	Red Sandstone	**H**	023.1	75.4	9.4	22.2	12	188.7	64.3	B1
Pil'guyarvi Fm. and Kolasyoki Fm. (c. 1.97-1.98 Ba)										
18	Andesite	L	125.3	70.6	19.0	9.5	8	191.4	48.1	B2
17	Andesite	L	66.1	61.2	8.2	32.3	11	179.3	72.1	B2
21	Andesite	L	83.7	49.5	10.1	26.9	9	89.6	49.6	B2
19	Andesite	L	125.4	59.4	20.6	9.6	7	131.5	56.2	B2
20	Andesite/P.B	L	140.2	72.7	12.8	17.2	9	148.3	53.1	B2

T_b=Thermal unblocking spectra:**H**=High, L=Low/Intermediate; Dec_I/Inc_I=Mean *in-situ* declination/inclination; α_{95}=radius of 95 percent confidence circle; k=precision parameter (Fisher 1953); N=number of samples; Dec_C/Inc_C=Mean corrected declination/inclination; P.B.=pillow basalt..

Table 3. Overall mean directions and palaeomagnetic poles.

Component A:

	Age	Dec_I	Inc_I	α_{95}	k	N	Dec_C	Inc_C	VGP (Corrected) Plat	Plong	(dp/dm)
Akhmalahti Fm.											
A1	(2.3)	036.4	27.6	4.7	37.9	26	069.0	73.4			
Kuetsyarvi Fm.											
A2	(2.1-2.15)	292.5	11.2	8.7	7.3	43	286.8	38.8			
A3	(2.1-2.15)	272.5	10.8	11.6	9.8	18	264.0	32.4			
A2+A3	(2.1-2.15)	286.4	11.2	7.2	7.4	61	279.5	37.4	**N22.8**	**E298.3**	**(5.0/8.5)**
A4	(2.2)	344.9	20.9	34.7	13.7	3	325.1	52.9			
A2-A4	(2.1-2.2)	289	15	19.9	6.8	10#	278	41	**N24.7**	**E300.8**	**(13.0/21.4)**
							α_{95}=17.6, k=8.5				

Component B:

	Dec_I	Inc_I	α_{95}	k	N	Dec_C	Inc_C	VGP (In-situ) Plat	Plong	(dp/dm)
Basement, Akhmalahti & Kuetsyarvi Fm.										
B1	004	69	11.2	36.9	6#	93	69	N72.9	E201.2	(16.2/19.0)
						α_{95}=53.3, k=2.5*				
Pil'guyarvi & Kolasyoki Fm.										
B2	103	65	15.9	24.2	5#	146	61	N39.1	E088.5	(20.7/25.7)
						α_{95}=23.5, k=11.5				
Combined										
B1+B2	051	75	13.2	12.8	11#	125	67	**N68.4**	**E114.8**	**(22.0/24.1)**
						α_{95}=26.1, k=4.0*				

N=samples (#=number of sites);*=statistcal negative fold-test at the 95% confidence level; VGP=Virtual Geomagnetic Pole; Plat/Plong=Pole latititude/longitude; dp/dm=semi-axes of the 95 percent confidence ovals. Cf. Table 2 for additional legend

youngest formations of the Pechenga Group, i.e. the Pil'guyarvi and Kolasyoki (*c.* 1970–1980 Ma) Formations, as well as within the Early Proterozoic basement tested at sites 14–16. These magnetic overprints are distinct from palaeomagnetic directions expected from Kola-Karelian or Svecofennian (*c.* 1700–1850 Ma) resetting. Conversely, these secondary palaeomagnetic components, B2 or a combined mean of B1 and B2, compare favourably with palaeomagnetic overprints (620–570 Ma; dated from authigenic secondary growth of illites) recorded in Upper Riphean sediments from the Kola Peninsula and with primary components identified from Vendian dykes (*c.* 546–580 Ma; K/Ar and $^{40}Ar/^{39}Ar$ mineral ages) in the same region (Torsvik, Roberts & Siedlecka 1995). We suggest that the B components may have resulted from a low-grade Late Precambrian (Vendian) remagnetization event.

COMPARISON WITH PALAEOMAGNETIC POLES FROM LAURENTIA

The Kola Peninsula 2125 Ma pole can be compared to similar-age poles from cratonic provinces in Laurentia in an effort to test hypothesized continental reconstructions. A sequence of well-dated poles from the greater Superior Province of Laurentia defines an apparent polar wander path (APWP) from 2219 to 2114 Ma (Fig. 13; Table 4). Two palaeomagnetic results from the Slave Province of Laurentia yield a consistent pole for that craton at 2186 Ma (Fig. 13, Table 4) which is distinct from the Superior Province mean pole. This is not surprising as both Hoffman (1988) and Symons (1991) propose that the Slave and Superior Provinces were only later amalgamated, between 1910 and 1790 Ma during the Trans-Hudson orogenic event. The Svecofennian orogen slightly post-dates the Trans-Hudson orogeny, but Hoffman (1988) suggests that the Svecofennian orogenic event may have its counterparts in Laurentia. Gower & Owen (1984) propose that the Fennoscandian and Laurentian regions were amalgamated in a Bullard, Everitt & Smith (1965) fit by the end of the Svecofennian orogeny at least. While our Kola Peninsula 2125 Ma palaeomagnetic pole does not directly allow us to test the hypothesis of Gower & Owen (1984), we can rotate our pole according to Bullard *et al.* (1965) which shows the Fennoscandian and Superior cratons were probably not joined at 2125 Ma (Fig. 13). The coincidence of our 2125 Ma pole and the 2186 Ma poles from the Slave Craton using the Bullard *et al.* (1965) fit is difficult to assess given the 60 Ma difference in ages. Also the Bullard *et al.* (1965) fit, accounting for the Tertiary opening of the North Atlantic, has little applicability for pre-Silurian palaeogeographic reconstructions given the known disparate tectonic drift-histories for Baltica and the Slave Craton as part of Laurentia during Late Precambrian

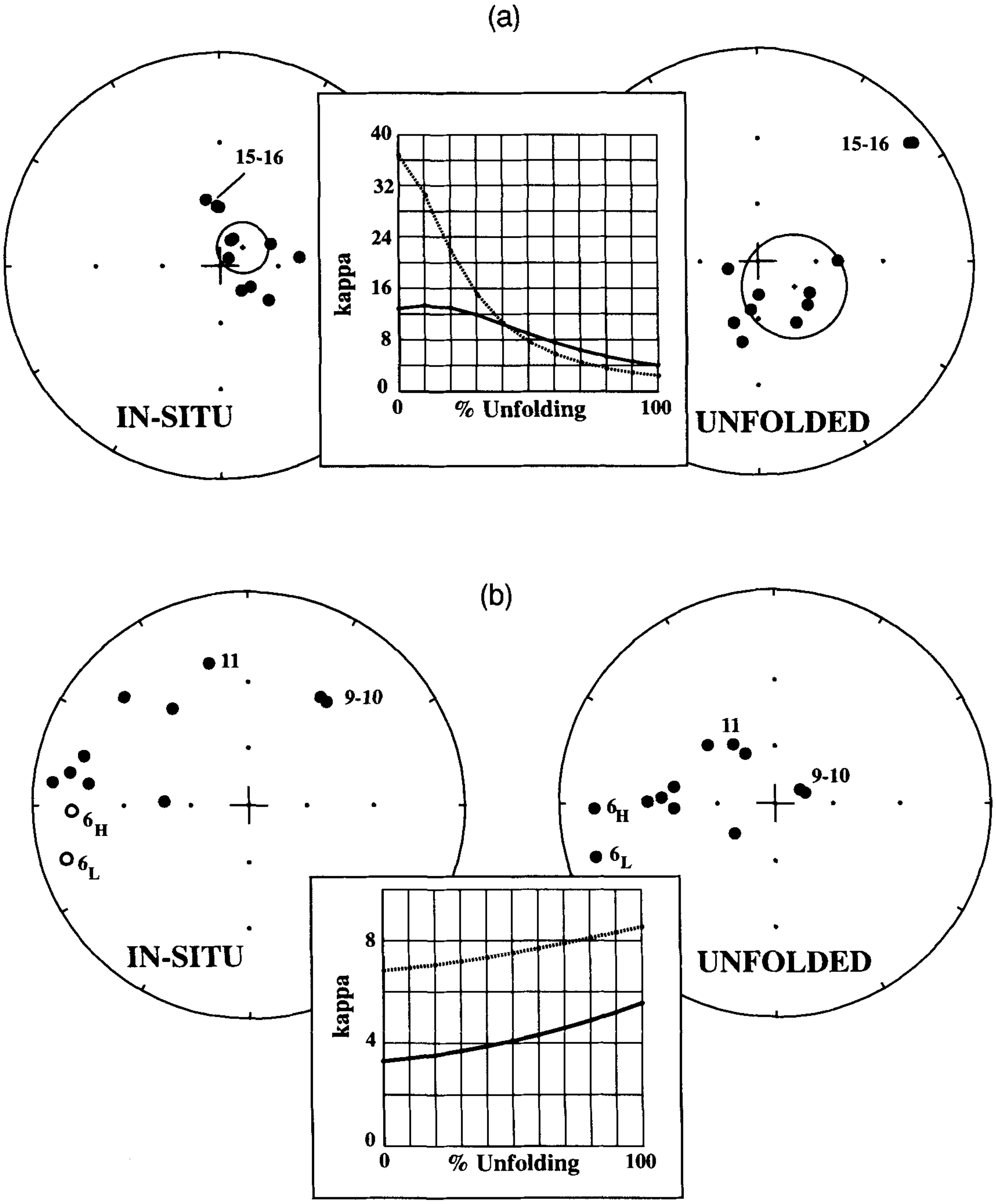

Figure 10. (a) Incremental unfolding test for the steeply inclined B1 components recorded from sites 15, 16, 9, 7 and 11–12 (*cf.* Table 2). The change in precision parameter kappa is indicated for B1 sites (stippled line) and for a combination of all B (B1 + B2) sites (solid line). Both tests are statistically negative at the 95 per cent confidence level (note that the negative test results from the directional data from sites 15 and 16). (b) Incremental unfolding test, combining all the A components (solid line; *cf.* Table 2) or excluding the directional data from sites 9 and 10 (stippled line). None of the combinations is statistically significant at the 95 per cent confidence level. Note, however, that corrected site-means define a directional swath from steep inclinations, associated with older stratigraphic units (e.g. sites 9, 10 and 11), to shallow inclinations recorded in younger units (e.g. site 6). This may relate to apparent polar wander (APW).

and Early Palaeozoic times (Torsvik *et al.* 1992; Meert, Van der Voo & Payne 1994a). It is interesting to note, however, that when younger (1725–1880 Ma) Svecofennian poles from Fennoscandia are rotated according to a Bullard *et al.* (1965) fit they conform to coeval poles from Superior and Slave from *c.* 1750 Ma, which can be taken as evidence that these provinces were close to Fennoscandia at that time (Fig. 14).

Piper (1987) has also suggested Early Proterozoic links between Fennoscandia and Laurentia in his supercontinental reconstruction based on an analysis of the global palaeomagnetic data set (Fig. 15a). According to his reconstruction, the global configuration of continents was valid from 2800 to 1100 Ma. Thus, coeval palaeomagnetic poles from the various cratonic nuclei would be required to conform to a single APWP when rotated into his

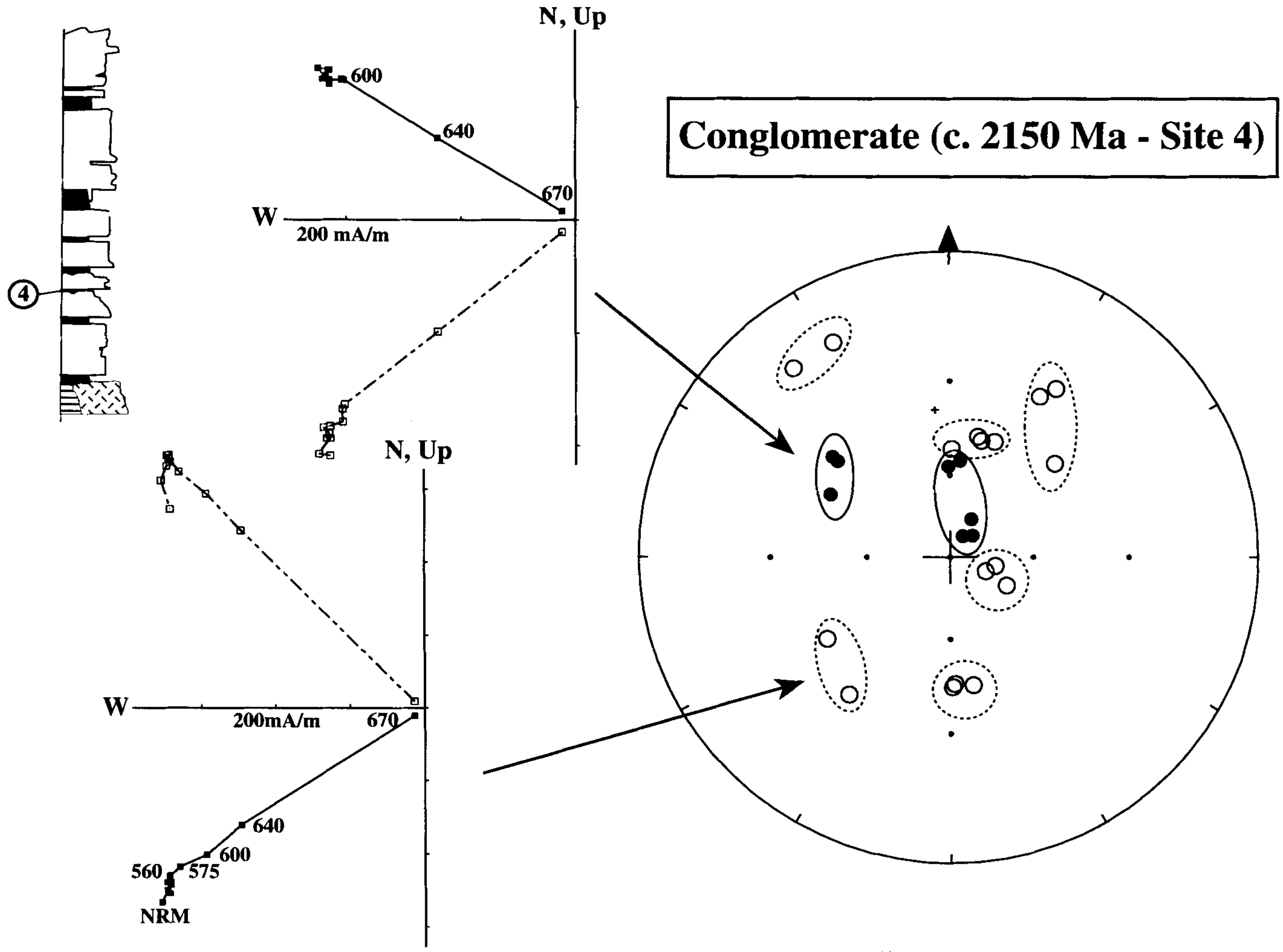

Figure 11. Examples of thermal demagnetization of conglomerate clasts from site 4 (Kuetsyarvi Formation) with the distribution of characteristic remanence components from individual boulders encircled.

reconstruction. This conclusion was challenged for the Late Proterozoic by Van der Voo & Meert (1991) and Meert *et al.* (1994b, 1995) on the basis of palaeomagnetic data from Africa. The Kola Peninsula palaeomagnetic pole, when rotated according to Piper (1987), falls significantly away from the 2125 Ma segment of his APWP (Fig. 13). Our data indicate that Piper's (1987) configuration is not valid at 2125 Ma and, when combined with the inconsistencies in his reconstruction demonstrated from the African data, this supercontinental configuration is at best doubtful.

CONCLUSIONS

Palaeomagnetic data from the Early Proterozoic Pechenga Group yield two main magnetization components, components A and B. B is secondary and probably related to a low-grade, Late Precambrian (Vendian), remagnetization event associated with the Baikalian Orogeny which affected the Kola (northern Russia) and Varanger (northern Norway) Peninsulas (*cf.* Torsvik *et al.* 1995).

The most reliable 'primary' component (A) is recorded within the Kuetsyarvi Formation (2100–2200 Ma). Its 'primary' nature is verified by a positive conglomerate test and a directional convergence upon unfolding. Palaeomagnetic poles from the Kuetsyarvi Formation, Kola Province, differ somewhat (A2–A3) or partly overlap (A2–A4) with coeval palaeomagnetic poles from other tectonomagmatic provinces in northern Fennoscandia (Fig. 12), but it is premature at this stage to speculate on any substantial intraplate movements between Fennoscandian tectonomagmatic provinces or terranes during the Early Proterozoic. Besides, the Kuetsyarvi Formation is characterized by lacustrine red beds, evaporites and alkaline volcanics, and was probably developed during an early phase of intracontinental rifting along the northern margin of Fennoscandia (Meleshik & Sturt 1994), similar to the present-day East African rift. Hence younger intercontinenal rifting, possible seafloor-spreading and the subsequent convergence could remain undetected from our palaeomagnetic data.

Palaeolatitude estimates from the Kuetsyarvi Formation and coeval palaeomagnetic data from northern Finland (Karelia) and north-west Russia suggest that the Pechenga region was located at latitudes around 20°–30° during the 2.1–2.2 Ga interval (Figs 15b and c). These subtropical latitude estimates are supported by the sedimentary record

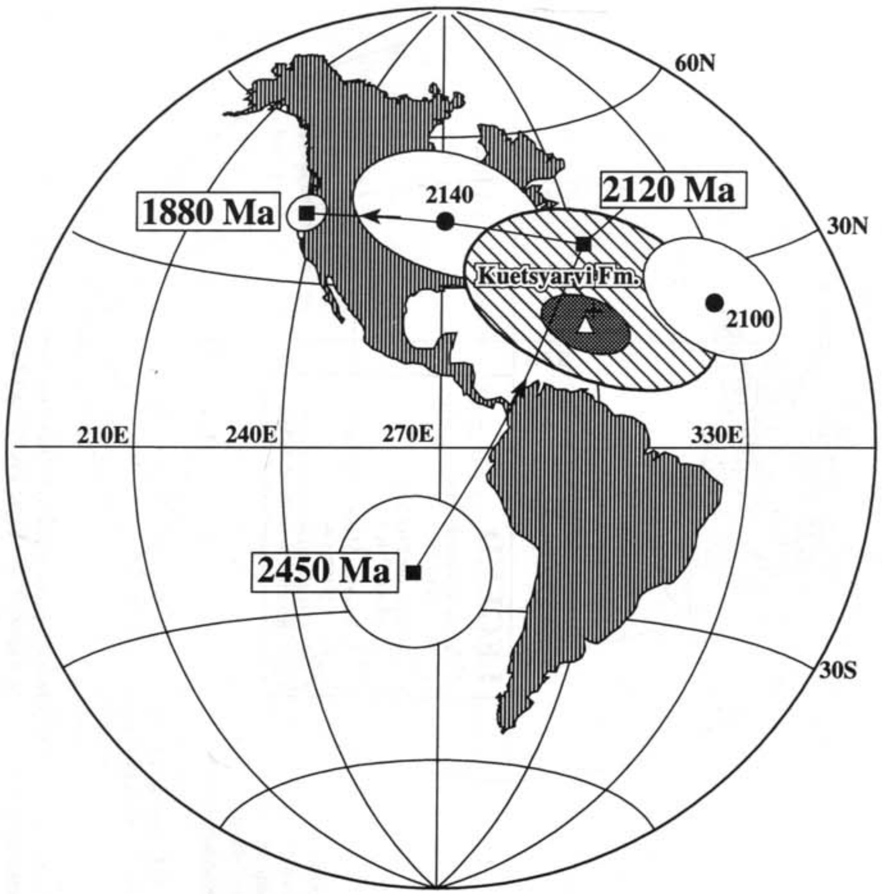

Figure 12. Palaeomagnetic poles from the Kuetsyarvi Formation (A2 + A3, small shaded confidence oval, or A2–A4, large hatched confidence oval; *cf.* Table 3) plotted together with a suggested APW path for Fennoscandia (Elming *et al.* 1993) and two Early Proterozoic palaeomagnetic poles from northern Finland (2100 Ma pole) and northern Russia (2140 Ma pole).

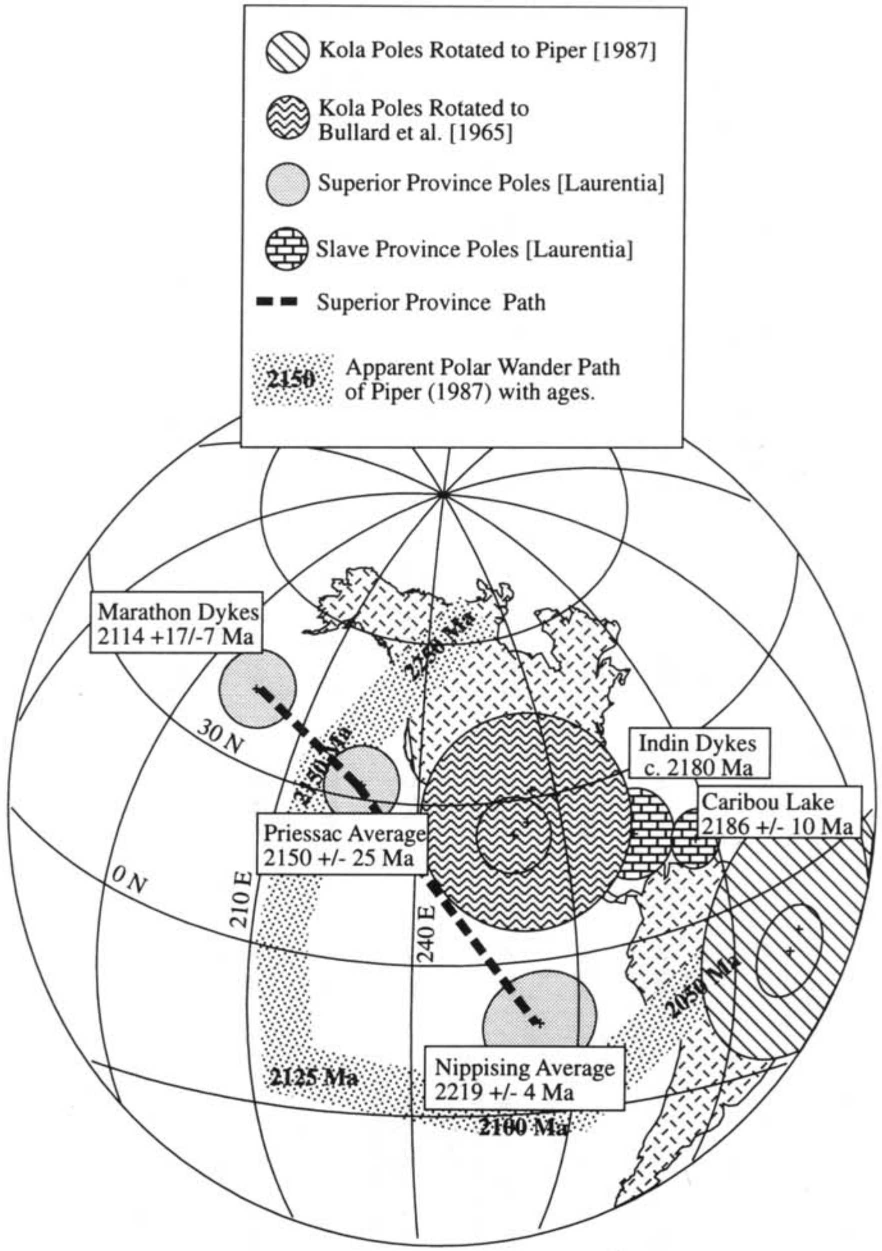

Figure 13. Palaeomagnetic poles from the Superior and Slave Provinces (Table 4) along with the Kola poles (*cf.* Fig. 12 and Table 3) rotated according to the supercontinent fit of Piper (1987) or the Bullard *et al.* (1965) fit. The Superior Province APW path and the APW path suggested by Piper (1987) are indicated.

Table 4. Palaeomagnetic poles from the Superior and Slave Provinces.

Pole Name	Pole Latitude	Pole Longitude	Age of Pole	Reference(s)
Nippising Average (Superior Province) [N=10]	-12° N	263° E	2219 ± 4 Ma	Compiled from Global Paleomagnetic database of Lock and McElhinny, 1991
Caribou Lake Pole (Slave Province)	14° N	296° E	2186 ± 10 Ma	Irving et al., 1984
Indin Dykes (Slave Province)	19° N	284° E	c. 2180 Ma	McGlynn and Irving, 1975
Priessac Average (Superior Province) [N=5]	32° N	227° E	2150 ± 25 Ma	Compiled from Global Paleomagnetic database of Lock and McElhinny, 1991
Marathon Dykes (Superior Province)	43° N	196° E	2114 +17/-7 Ma	Halls et al., 1994
Slave-Rae-Hearne Mean Pole	02° S	262° E	1850 ± 30 Ma	Symons, 1991
Superior Province Mean Pole	38° N	290° E	1850 ± 30 Ma	Symons, 1991
Slave-Superior Combined Mean Pole	45° N	167° E	1725 ± 50 Ma	Compiled from Global Palaeomagnetic database of Lock and McElhinny, 1991

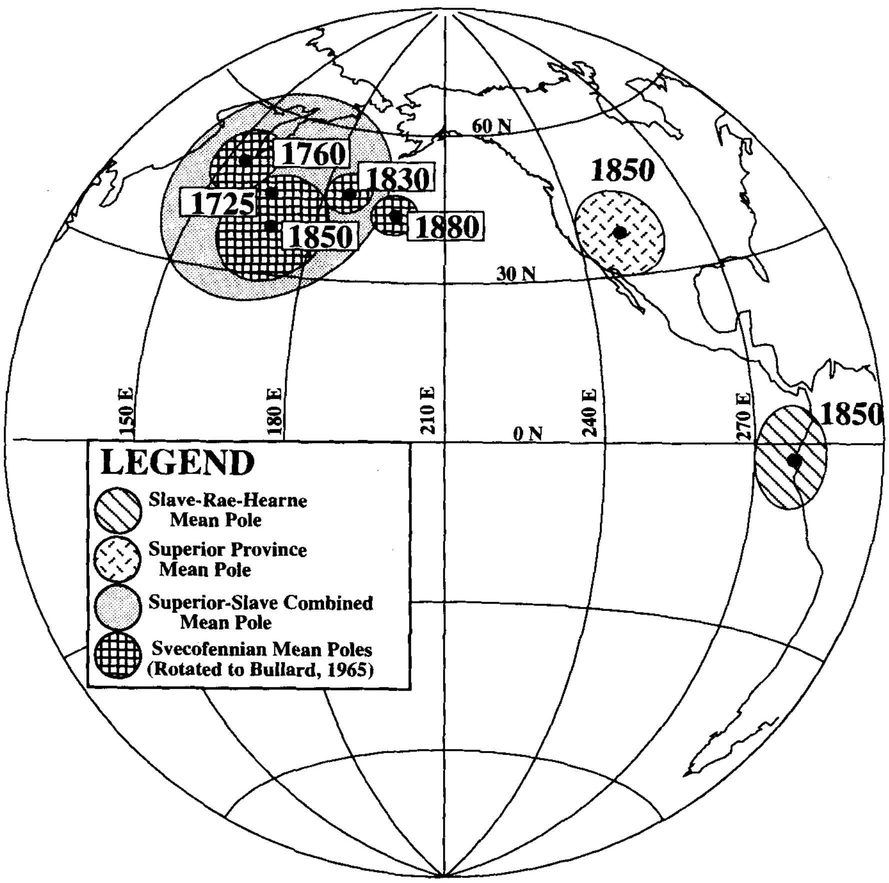

Figure 14. Comparison of Svecofennian poles from Fennoscandia (mean poles listed in Elming *et al.* 1993; Bullard *et al.* 1965 fit) and coeval palaeomagnetic mean poles for the Superior and Slave Provinces (Table 4).

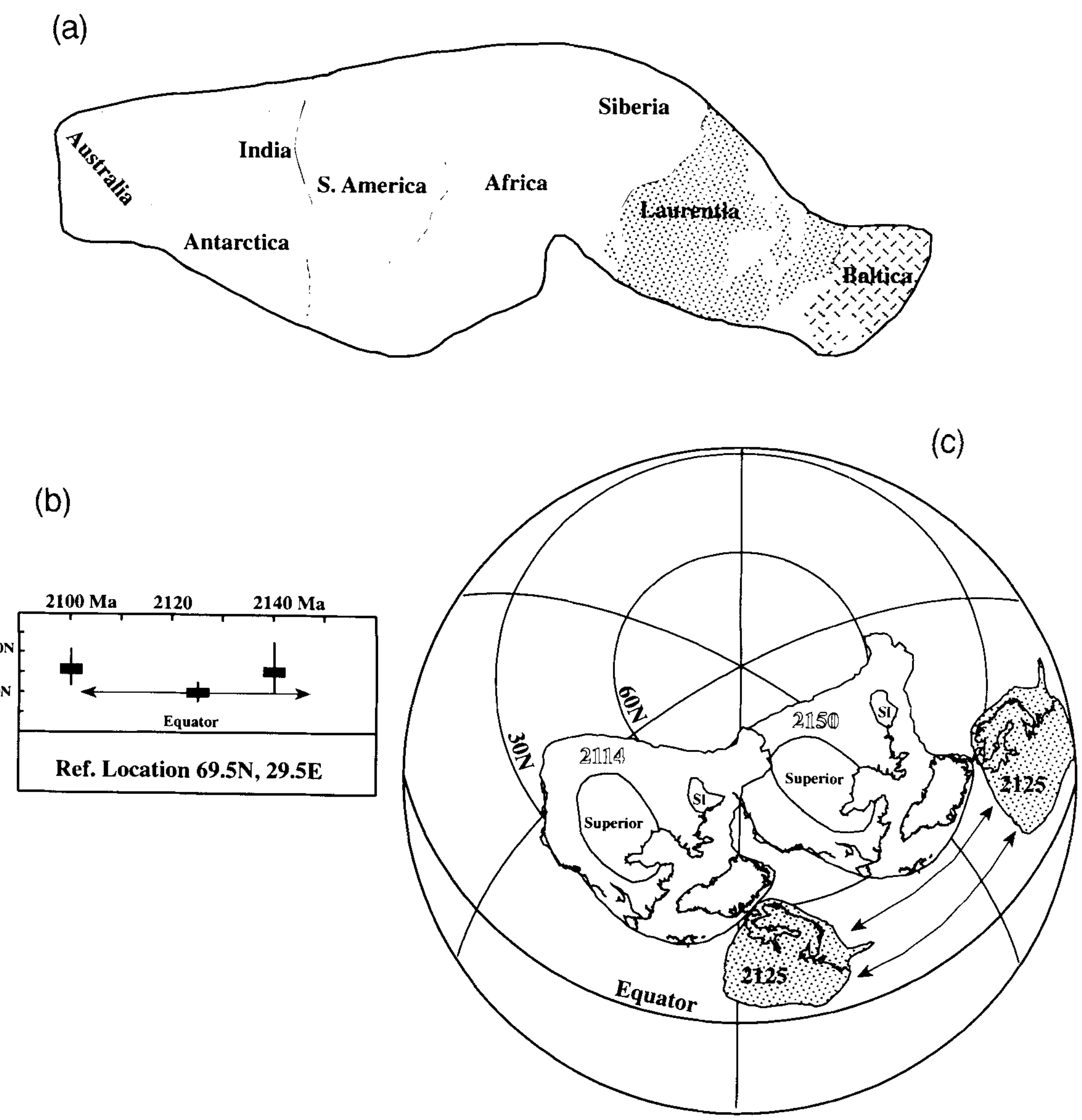

Figure 15. (a) Supercontinent configuration considered valid by Piper (1987) from 2200 Ma to 1100 Ma. (b) Palaeolatitudes for Fennoscandia estimated from the Kola pole (A2–A4) and similarly aged poles from northern Finland (2100 Ma) and northern Russia (2140 Ma). (c) A plausible close fit between Fennoscandia (using the Kola pole) and Laurentia (using the Superior Province poles; Table 4), but highly speculative given the lack of palaeologitudinal and hemispheric control. The reconstruction is made on the assumption that the poles illustrated in Fig. 14 (Tables 3 and 4) are palaeomagnetic *northpoles*.

in the Pechenga region which is characterized by red beds and evaporites.

Comparison of our palaeomagnetic pole with coeval poles from the Slave and Superior cratons (Fig. 14) demonstrates that the supercontinental configuration of Piper (1987; Fig. 15a) is not valid at 2125 Ma. A close but different fit between Baltica and Laurentia is conceivable from the available palaeomagnetic data (Fig. 15c), but given the lack of longitudinal control as well as the choice of hemisphere (northern or southern) such a reconstruction is speculative at best.

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