Magnetic Susceptibility Ellipsoids in Nagssugtoqidian and Archaean rocks in South-East Greenland

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Measurements of magnetic susceptibility have been carried out on Precambrian rocks in south-east Greenland in the Nagssugtoqidian mobile belt from Ammassalik northwards to its boundary with the Archaean craton, and slightly beyond. Directions of Maximum susceptibility are the best defined, and are as follows: Ammassalik: Declination = 3º, Inclination = 40º,α_{95} = 7º; Nagssugtoqidian/ Archaean "boundary": Declination = 311º, Inclination = 62º,α_{95} = 10º; area enclosing post-tectonic plutons: Declination = 194º, Inclination = 87º, α_{95} = 17º. The boundary is invisible to the directions of Maximum susceptibility.

A shear zone near the boundary has been studied in detail. The Maximum directions of the samples are tightly grouped and lie in the plane of the zone, whilst the Intermediate directions rotate about the Maximum direction as the zone is approached, until they lie in its plane. Such rotation is widespread in the boundary area.

A plate tectonic explanation for the Maxima from the boundary and from Ammassalik is proposed as follows: the Maximum direction from the boundary is attributed to subduction and collision of the Archaean plate arriving from the north-east, followed by a vertical component imprinted by the emplacement of the plutons. The Maximum direction at Ammassalik is due to overriding Archaean crust coming from the north.

Anisotropy of magnetic susceptibility is useful in detecting shear zones and rock fabric when these are not apparent in the field or hand specimen.

Key Words. Greenland, Nagssugtoqidian, Archaean, Magnetic Anisotropy, Shear Zones collision.

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Geological Setting

The Precambrian rocks of south-east Greenland were described by Andrews et al. (1973) who identified a section between about 64º and 66º N, which, they asserted, is a continuation of the Nagssugtoqidian mobile belt of west Greenland. In 1976 the Geological Survey of Greenland (GGU, since renamed The Geological Survey of Denmark and Greenland, GEUS) mounted an expedition in the motor cutter "Tycho Brahe" to map the extension of this belt to the north. At its northernmost extremity an area of granulite facies rocks was reported (Bridgwater et al. 1977), which was subsequently recognised as Archaean craton by Bridgwater & Myers (1979), who regarded Nagssugtoqidian effects there as mild. These authors perceived the boundary between the Archaean craton and the Nagssugtoqidian belt as sharp but later work suggested that it is diffuse (Chadwick et al. 1989; Dawes et al. 1989). The long period of Nagssugtoqidian deformation had been divided into two main phases (Bridgwater et al. 1977) although Bridgwater & Myers (1979) considered that there was, after all, no intervening period of crustal stability but, rather, a continuous series of events.

The expedition initially worked near Ammassalik (Fig. 1) to articulate with earlier work there (Wright et al. 1973). Ammassalik is centred on an intrusive body, some 600 km^2 in area, known as the Ammassalik charnockite complex. This massive body retains primary igneous features and was emplaced "just before or possibly during the youngest phase of Nagssugtoqidian deformation" (Bridgwater & Myers

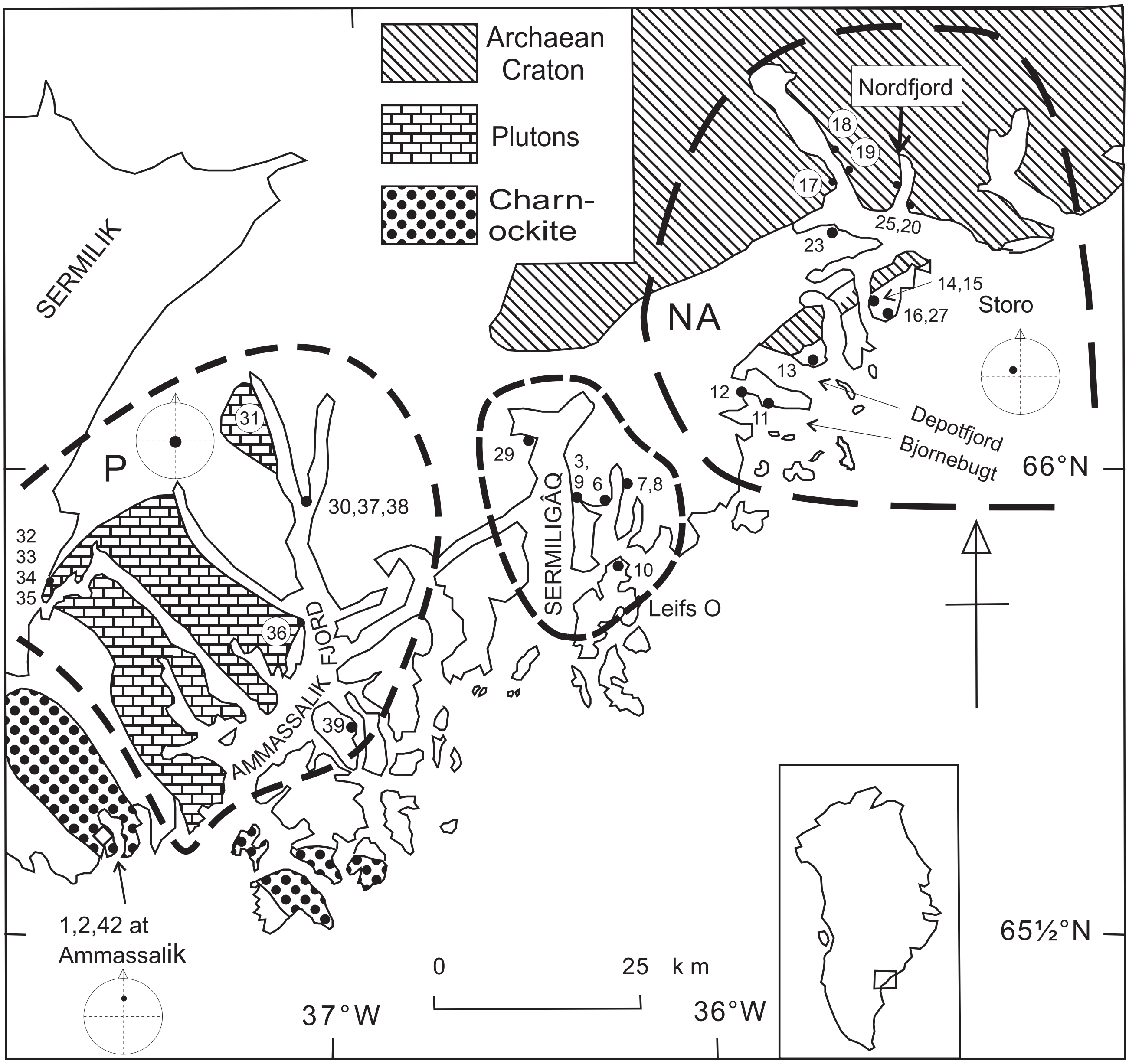


Fig. 1. Map of region studied by the 1976 expedition, after Bridgwater & Myers (1979), showing sites sampled in the present study, in four areas. The miniature stereograms indicate the mean directions of Maximum susceptibility; the smaller the dot the more precisely is the direction known.

1979). It is associated with continental collision and is thus analogous to the Sisimiut charnockite on the west coast (van Gool et al. 2002). Some 20 km north-east of Ammassalik there lies an area of post-tectonic plutons, of about the same extent. All these rock bodies were described by Bridgwater & Myers (1979), who cited ages as follows:

Archaean craton: 2,800 Ma
Nagssugtoqidian deformation: 2,700–1,900 Ma
Ammassalik charnockite: 1,900 Ma
Post-tectonic plutons: 1,580–1,550 Ma.

These authors regarded a Rb-Sr whole rock age on south Storo of 2,635 (±55) Ma (Pedersen & Bridgwater 1979) as a good estimate of the beginning of the Nagssugtoqidian metamorphism, and they noted a peak of thermal activity at 2,600 Ma. A precise age of emplacement for the Ammassalik complex was later obtained at 1,886 (±2) Ma by Hansen & Kalsbeek (1989), but it underwent metamorphism until 1773 (±22) Ma, or later (Kalsbeek & Taylor 1989). It therefore follows that the Nagssugtoqidian metamorphism ended between about 1,750 and 1,580 Ma.

In this paper there will be frequent references to the Nagssugtoqidan/Archaean boundary. This is the border in Fig. 1 between the hatched and white areas of land within the area NA (ignoring the outcrops of Archaean material). This border will sometimes be called simply "the boundary".

The present author was invited to participate in the expedition to perform palaeomagnetic work in the region (Beckmann 1977,1979,1983), which also included Tertiary dykes (Beckmann 1982). The Ammassalik complex yielded results of exceptional precision (Beckmann 1983). Upon completion of the palaeomagnetic work, it occurred to him to determine the anisotropy of magnetic susceptibility (AMS) ellipsoids of all the Precambrian samples. The results are presented in this paper, which expands the unpublished report he submitted to GGU in 1977.

Magnetic Susceptibility

Preamble

When a magnetic field is applied to a substance its initial magnetisation is proportional to the field. The constant of proportionality is known as the "magnetic susceptibility", which is thus a measure of the ease with which the substance can be magnetised. In rocks, the susceptibility varies with direction because they are anisotropic. A direction can be established in which the susceptibility is a maximum, another in which it is a minimum, and a third, orthogonal to the other two, in which it has intermediate susceptibility. These three directions form a triad in which the values ($k_{max,}$ $k_{int,}$ k_{min}) form the semi-axes of the susceptibility ellipsoid. It is common practice to define ratios as follows, analogous to those of the strain ellipsoid:

$P_1 = k_{max} / k_{int}$ = lineation (L)
$P_2 = k_{max} / k_{min}$ = anisotropy factor (An)
$P_3 = k_{int} / k_{min}$ = foliation (F)
$P_3/P_1 = (k_{int})^2 / k_{max}\, k_{min}$ = eccentricity (E).

E is important for recognising the shape of the ellipsoid. If $E < 1$ the lineation dominates and so the ellipsoid is prolate, and if k_{min} and k_{int} are nearly equal it is cigar-shaped. If $E > 1$ foliation dominates, and so the ellipsoid is oblate, and if k_{int} is close to k_{max} the ellipsoid is disk-shaped.

There are two applications of AMS to the study of rocks:

1. Palaeomagnetism:

When a rock acquires magnetism, it does so ideally in the direction of the ambient field but, in practice, the direction is deflected on account of anisotropy. The expected deflections were calculated by Uyeda et al. (1962) in a study which predicted that they would be smaller than had been generally assumed, and subsequently justified the application of palaeomagnetism to metamorphic rocks in the 1970's, e.g. Beckmann (1976). Sampling was even done in a shear zone in west Greenland; in this case there was an attempt to correct for the deflections by incorporating the AMS ellipsoids (Beckmann et al. 1977).

2. Petrofabric analysis:

The present paper deals only with this application. Graham (1954) was the first to suggest the application of AMS to structural problems. He demonstrated that the direction of Maximum susceptibility in ferromagnetic grains was parallel to their length. Many authors have since made the same point. The speed of modern machines renders the method particularly appealing, but, even now, this tool has not been fully exploited, especially in metamorphic rocks.

Much work was done on slates, for example Fuller (1963) and Singh et al. (1975). Wood et al. (1976) proved that the finite strain ellipsoids coincided with the AMS ellipsoids in slates.

Khan (1962) studied thin sections of a dyke and demonstrated that the AMS is due to the orientation of the magnetite grains. Khan obtained striking results from Precambrian dykes and gneisses from the Lewisian of north-west Scotland, which yielded well-grouped principal directions of AMS. The ellipsoids were oblate with maximum/intermediate planes parallel to the visible foliation and the maximum direction parallel to the visible lineation. Khan also showed that the directions from Scourian and Laxfordian sites (Sutton & Watson 1951) were different, implying that directions are reset by metamorphism.

Khan subjected some rocks to temperatures up to 700ºC and to high pressures, and sometimes both together. He found no changes in the orientations of the AMS ellipsoids. Consequently, he stressed that AMS orientations are a fundamental property of rocks, which would not be altered as long as there were no melting or shearing. Khan's results are seminal to the present paper.

In west Greenland Beckmann et al. (1976) noticed that in Nordre Stromfjord the axes of the AMS ellipsoid generally coincided with the strain ellipsoid. In contrast, a subtler situation exists near Sisimiut (formerly Holsteinsborg) on the mountain Kaellingehaetten which has had such a complex metamorphic history that the tectonic fabric is locally devoid of a linear element. On the other hand there does exist a linear component in the magnetic fabric. Moreover, the AMS axes correspond to those of the strain ellipsoid for rocks a few km to the south which have been strongly affected by later Nagssugtoqidian deformation. The authors concluded that the determination of AMS ellipsoids offered a sensitive means of ascertaining the direction of the last deformation in a metamorphic terrain, in accordance with the prediction of Khan (1962).

Later in this paper particular importance will be attached to the Maximum direction of AMS. Intuitively, this is the direction of stretching of rocks. However, if rocks had been fluid, a rolling motion can be envisaged. Jeffery (1922) investigated mathematically the orientation of prolate spheroidal particles in a flowing liquid. He predicted that they would align themselves with their long axes normal to both the velocity and to the direction of its maximum gradient. Khan (1962) found some support for this prediction in lavas and gabbros. In the present paper, the two styles for the Maximum AMS direction will be called the "stretching" and "rolling" modes. Evidently, research on the rolling mode has been carried out on rocks which had been liquid. However, it might also occur in solid rocks, which, in a metamorphic terrain, could behave like a very viscous liquid over the millions of years during which changes occur.

Ellwood (1978) studied lavas further, and again found support for the rolling prediction, although he noted that the effect depended on the physical circumstances. Indeed, the relationship between AMS directions and petrofabric is more complex than realised in early papers on this subject. Rochette et al. (1992) made a theoretical study of influences on AMS directions, which they illustrated particularly with their work on dykes from the Oman ophiolite. They pointed out that research on AMS directions has usually rested upon three assumptions:

1. The AMS ellipsoid is coaxial with the petrofabric ellipsoid
2. The shape of the AMS ellipsoid is directly related to the rock fabric
3. AMS directions are not influenced by the natural remanent magnetisation (NRM).

These authors proved that these assumptions are not always justified. Sometimes rocks exhibit an "inverse" fabric in which the principal AMS directions swap with the "normal" directions. This effect can be caused by the bulk of the minerals in the rock, the matrix, which is normally regarded as non-magnetic but which becomes temporarily slightly magnetised during the measuring processes.

Rochette et al. (1992) demonstrated, in the Oman dykes, three sets of directions, and a miscellaneous set. Such experiments emphasise how difficult it is to correlate AMS directions with flow directions. (These authors were aware of the "rolling" possibility, first noticed by Khan (1962), but did not find it in these dykes).

It was mentioned at the beginning of this section that AMS affects the direction of NRM. Is the reverse true? Rochette et al. (1992) found that there is indeed a linkage but that the following factors reduce its importance:

Thermal, or tumbling alternating field (AF) demagnetisation
Low intensity of NRM (implying well separated magnetic grains)
High values of anisotropy.

An attempt will be made in the Discussion section to relate the warnings of Rochette et al. (1992) to the rocks of the present study.

Analytical Methods

The principal directions and magnitudes of the AMS components were measured with the Complete Results Anisotropy Delineator (CRAD). The magnitudes were corrected using the formulae of Hrouda et al. (1983). The CRAD was invented by L. Molyneux and M.J. Gross, of this Department, and described by Collinson (1983).

The statistics applied to directions are those of Fisher (1953). These feature **k**, commonly known as the precision parameter, which is a measure of the precision of grouping, and α_{95}, which is the semi-angle of the cone of 95% confidence about the mean direction. These statistics apply to circularly symmetrical distributions of directions. It will be seen that the distributions in this paper are not circular. Nevertheless, α_{95} has been found to be a useful and realistic measure of error. Precedents for the application of Fisher statistics to AMS directions were set by Khan (1962) and Fuller (1963).

Magnetic susceptibility is like a vector in that it has direction and size but the direction is double-ended. It is usual to assume that it has the same value in one direction as the opposite. Hence a decision has to be made as to which end to choose. Consider, say, the Maximum directions for a site. The simplest case occurs when they are well-grouped and away from the horizontal; then simply choose the

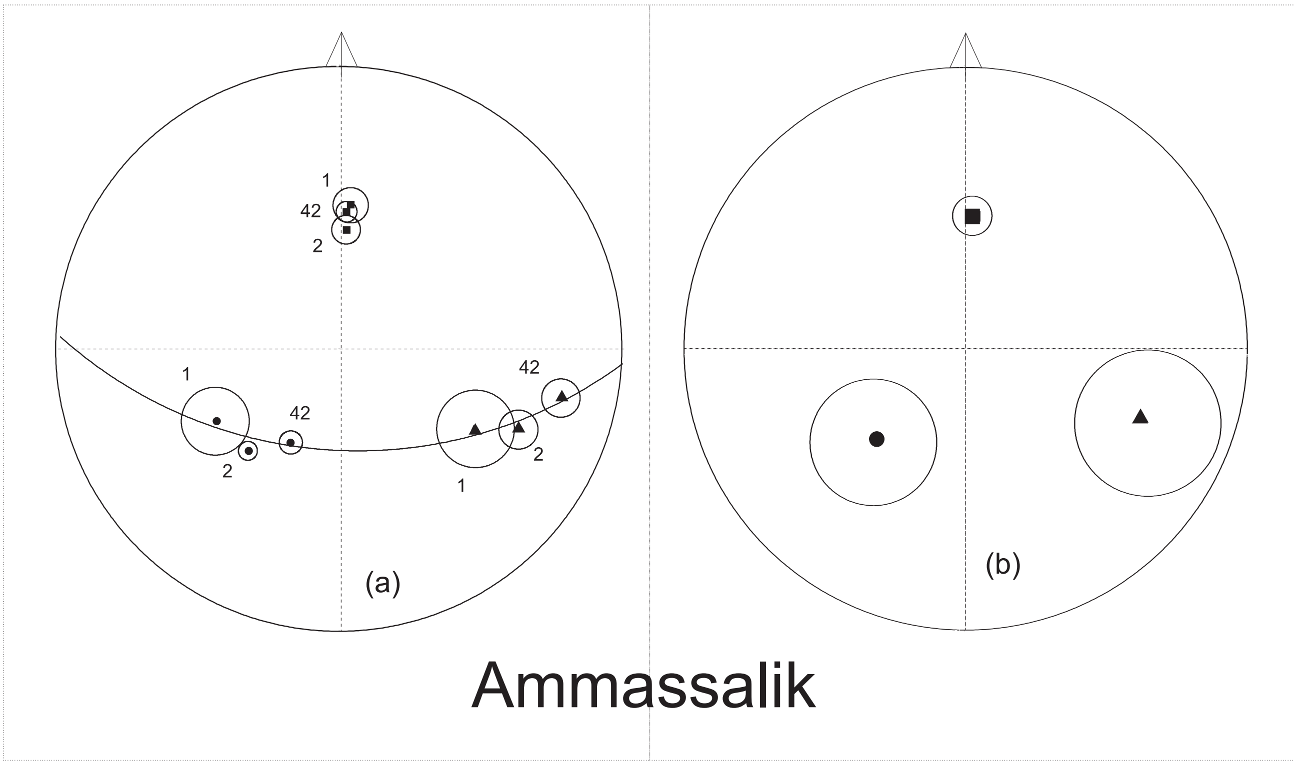


Fig. 2. Directions of the axes of magnetic susceptibility ellipsoids at Ammassalik:
[■ = Maximum, ▲ = Intermediate, ● = Minimum]
(a). Mean directions of the principal axes from the three sites, in relation to the locus of points orthogonal to the mean of the mean Maximum directions.
(b). Means of the mean directions.

downward inclinations. In other cases, choose all the downward inclinations and form their mean. Then note the angle between the Maximum of the first sample and this mean; if it is greater than a right angle reverse it, and so on through all the samples. Form a new mean and repeat the process until no further changes are required. If the final mean has negative inclination reverse it. These calculations are done in company with the other two principal directions. The angles between the three means are noted at the end; when there is compact grouping, these are often within one or two degrees of 90º (although they are not required to be orthogonal).

Notes: All stereograms in this paper are in Wulff (equal angle) projection. Filled squares, triangles, and circles denote Maximum, Intermediate, and Minimum directions respectively, following Khan (1962). Phrases like "directions of Maximum magnetic susceptibility" will be shortened to "Maximum directions".

Field Work

The procedures used to obtain the rocks in this collection have already been described (Beckmann 1983).

The charnockite complex was sampled at three sites in Ammassalik harbour. Two of these were of garnetiferous granulite, 0.7 km apart (sites 1 & 2), whilst the third was a norite (42). On average, 17 samples were taken from each site.

Thirteen sites were sampled in the vicinity of the Nagssugtoqidian/Archaean boundary, all lying within 30 km of it. Eight of these were within Nagssugtoqidian rocks whilst five were in the Archaean craton (Fig. 1, area NA). The average number of samples per site was 18.

Ten sites were chosen from area P (Fig. 1), surrounding the plutonic complex. One of the sites was a granite (32) and three were from gneisses close to a granite contact (33,34,35). Site 31 was a norite within a small outcrop of plutons. More granites would have been sampled but their hardness was an inhibiting factor in view of the short time available for sam-

TABLE 1. Susceptibility Results from Ammassalik

Site	Samples	Axis	DEC	INC	k	α_{95}	L	An	F	E
1	20						1.10	1.20	1.09	0.99
		Max	4	36	34	5.7				
		Int	121	33	8	12.0				
		Min	240	36	10	10.9				
2	21						1.10	1.28	1.17	1.07
		Max	2	44	43	4.9				
		Int	115	21	36	5.4				
		Min	222	38	106	3.1				
42	11						1.12	1.23	1.10	0.98
		Max	2	38	181	3.4				
		Int	103	13	92	4.8				
		Min	208	49	124	4.1				
Mean Max			3	40	354	6.6				
Mean Int			112	23	39	20.0				
Mean Min			225	42	35	21.1				

Note: L, An, F, E in Tables 1, 2, & 3 denote mean values at a site for Lineation, Anisotropy, Foliation, & Eccentricity, respectively.

pling. Approximately 12 samples were taken from each site.

Seven sites were sampled in the Sermiligâq area, at about 20 samples per site.

Results

The Main Results

At Ammassalik the principal directions are well-grouped, especially the Maximum directions, whose means are close to each other (Fig. 2, and Table 1).

In area NA (Fig. 1) the Maximum directions are the easiest to interpret on account of their grouping. The sites from the Nagssugtoqidian area form a group with similar Maximum directions to those from the Archaean craton (Fig. 3). Thus no change is apparent upon crossing the boundary, and so the 13 sites may be regarded as a single group (Fig. 3 & Table 2). On the other hand, the Intermediate and Minimum directions of individual samples are generally poorly-grouped and tend to "swing" along the arc which is orthogonal to the mean Maximum direction, for example site 18 (Fig. 4). Site 11 is the sole exception in area NA (Fig. 4). Such swinging behaviour occurs between sites, as well as between samples within a particular site, as illustrated by plotting the mean Intermediate and Minimum directions

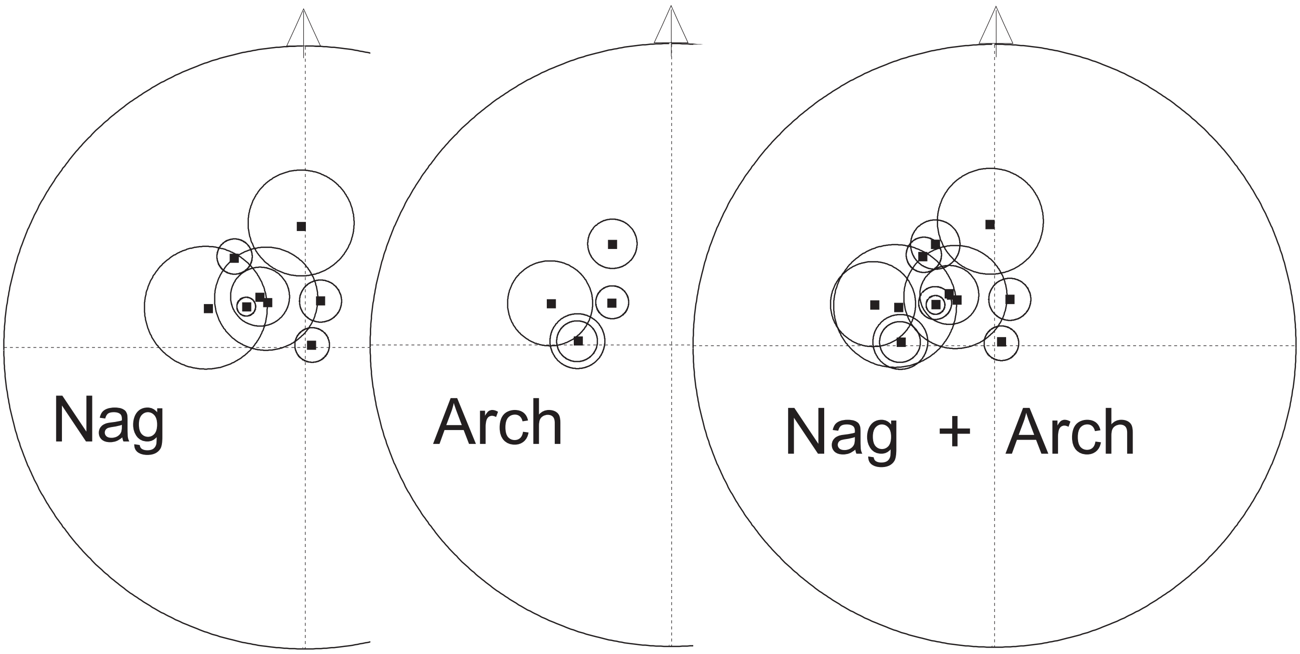


Fig. 3. Mean Maximum directions of the sites near the Nagssugtoqidian/Archaean boundary (area NA).

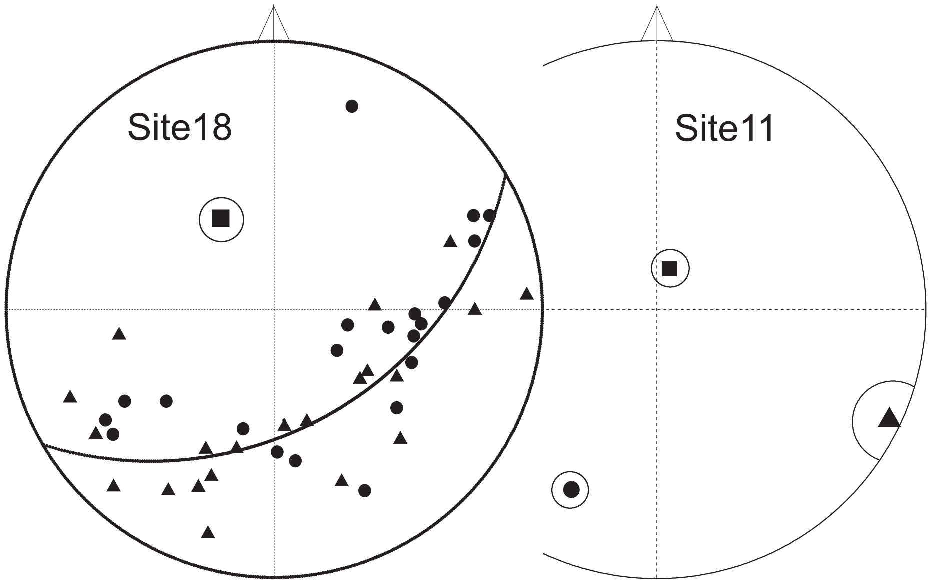


Fig. 4. Site 18: Mean Maximum direction, and the Intermediate and Minimum directions of individual samples, in relation to the locus of points orthogonal to the mean Maximum. Site 11: Mean directions of its principal directions.

Table 2: Details of Sites near NAG/Archaean boundary

Site	Samples	Locality	Rock Type	Max-DEC	Susc INC	k	α_{95}	L	An	F	E
Archaean:											
17	22	Kangertivatsiaq/ Sangmilik	Granulite Gneiss	272	55	20	7.1	1.06	1.12	1.06	1.00
18	21	Kangertivatsiaq	Granulite Gneiss	330	48	16	8.1	1.18	1.26	1.07	0.92
19	21	Kangertivatsiaq	Granulite Gneiss	289	44	6	13.7	1.09	1.20	1.10	1.01
20	21	Nordfjord	Gneiss & Quartzite Granulite	272	55	12	9.5	1.20	1.32	1.10	0.92
25	*3	Nordfjord	Pseudo-tachylite	306	63	437	5.9	1.06	1.08	1.02	0.96
NAG:											
11	21	Bjornebugt	Banded Gneiss	18	72	18	7.8	1.12	1.64	1.47	1.32
12	21	Bjornebugt	Dyke Amphibolite	70	87	24	6.6	1.07	1.13	1.06	0.99
13	20	Depotfjord	Dyke Amphibolite	322	48	32	5.9	1.07	1.10	1.03	0.96
14	21	South Storo	Gneissified granite	358	46	4	17.1	1.08	1.24	1.15	1.06
15	21	South Storo	Granite+ gneiss	321	67	4	18.7	1.09	1.19	1.09	1.01
16	12	South Storo	Dyke Amphibolite	318	64	18	10.6	1.12	1.22	1.08	0.97
23	11	Sangmilik	Granulite Gneiss	292	52	6	20.6	1.09	1.22	1.12	1.02
27	£6	South Storo	Shear Zone	305	63	394	3.4	1.32	1.83	1.39	1.06

* 10 samples collected. £ 7 samples collected.

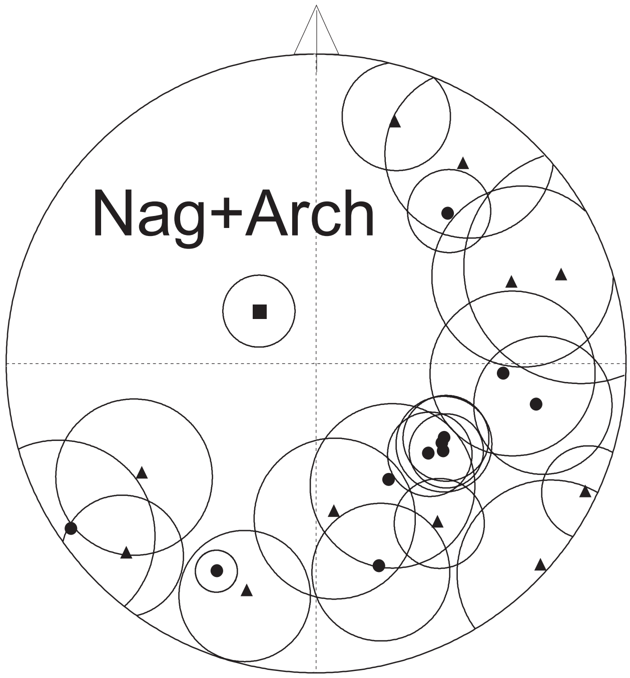


Fig. 5. Area NA: 11 of the 13 sites: Mean of the mean Maxima in relation to the mean Intermediate and Minimum directions of the individual sites.

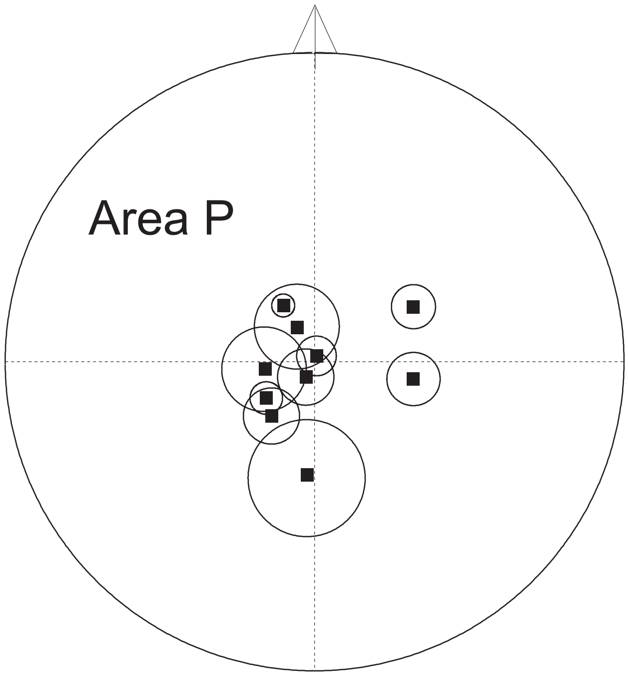


Fig. 6. Mean Maxima of the ten sites in area P which contains the post-tectonic plutons.

Table 3: Details of the Remaining Sites

Site	Sam- ples		Locality	Rock Type	Max- DEC	Susc INC	k	α_{95}	L	An	F	E
Plutonic area:												
	30	12	Tasilaq	Dyke Amphibolite	210	83	18	10.4	1.03	1.05	1.02	0.99
	31	12	Qingorssuaq	Norite	262	72	9	15.2	1.06	1.14	1.07	1.02
	32	12	Tiniteqilâq	Granite	333	76	9	15.4	1.12	1.15	1.03	0.93
	33	12	Island:Ingmik- êrtorajik	Banded Banded	184	50	6	18.9	1.03	1.12	1.08	1.05
	34	13	Island:Ingmik- êrtorajik	Banded Gneiss	218	65	18	9.9	1.06	1.21	1.14	1.08
	35	12	Ingmik- êrtorajik	Gneiss	233	68	57	5.8	1.08	1.18	1.10	1.03
	36	13	Pig Island, byKungmiut	Gneiss	331	66	105	4.1	1.04	1.23	1.18	1.14
	37	12	Tasilaq	Gneiss	61	50	37	7.2	1.07	1.20	1.13	1.06
	38	11	Tasilaq	Gneiss	100	54	27	8.9	1.19	1.68	1.41	1.19
	39	12	Nîaliqkap- ikâsâ	Norite	18	88	36	7.3	1.04	1.06	1.01	0.97
Sermiligâq:												
	3	21	Ilivtiartiq	Amphibolite Gneiss	49	54	19	7.4	1.11	1.25	1.13	1.02
	6	21	Kangertivart- ikajik	Dyke Amphibolite	304	74	5	16.9	1.05	1.16	1.10	1.05
	7	20	Kangertivart- ikajik	Augen Gneiss	359	70	5	15.3	1.07	1.23	1.15	1.07
	8	12	Kangertivart- ikajik	Dyke Amphibolite	3	37	38	7.1	1.11	1.19	1.07	0.96
	9	21	Ilivtiartiq	Gneiss	7	44	3	23.4	1.12	1.25	1.11	1.00
	10	22	Leifs O: Sarfaq Pynt	Banded Gneiss	35	10	7	12.6	1.08	1.26	1.17	1.09
	29	22	Sermiligaq: Nûgârtik	Gneiss acid + basic	14	68	40	4.9	1.06	1.24	1.17	1.10

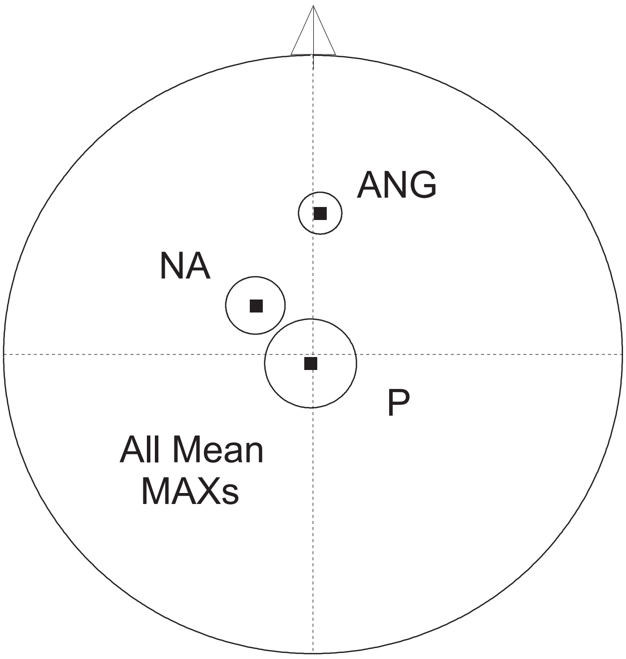


Fig. 7. Summary stereogram for the mean Maxima from three areas.

of 11 of the 13 sites (Fig. 5). (Sites 25 and 27 have been excluded because their Intermediate and Minimum mean directions are not significant at the level of 95% confidence (Irving 1964, p. 63)).

In area P the Intermediate and Minimum directions vary greatly. However, in the Maxima, some consistency is apparent, yet again (Fig. 6), so that it is reasonable to calculate the mean direction of these means, which is practically vertical.

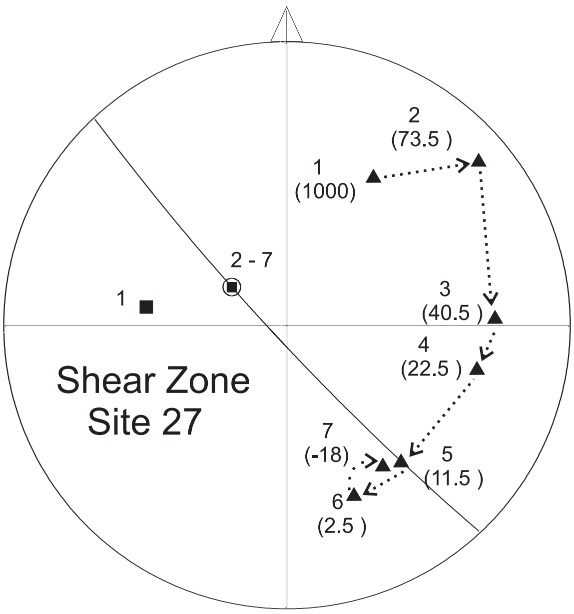
The mean directions of the Maxima from each of the areas above are depicted in Fig. 7, each surrounded by its circle of 95% confidence.

The sites near Sermiligâq display such a variety of directions (Table 3) that it is not realistic to generalise about them.

Results from Particular Sites

Shear Zone

Site 27 is a shear zone in the gneisses of south Storo. Its strike is 137º, it is nearly vertical, and is 25 cm wide. Seven cores were drilled at measured distances from the north-eastern margin. The first was ten metres from it, the next four were within one metre of it, and one was at the margin, whilst the seventh was inside the shear zone.



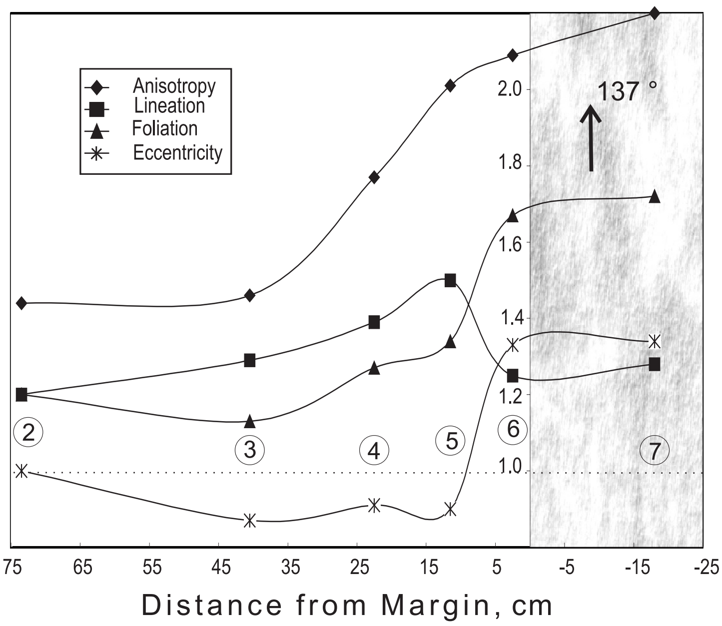


Fig. 8. Site 27: Left: Precise mean Maximum of samples influenced by this shear zone, (with the Maximum for a sample uninfluenced by it), in relation to their Intermediate directions as the shear zone is approached. Numbers in brackets are distances from the nearer margin of the zone. The solid arc is the plane containing the mean Maximum direction and the strike of the shear zone. Right: Behaviour of the susceptibility ratios upon approach to the shear zone (shaded). Numbers in circles are sample numbers.

Table 4. Summary of Maximum Susceptibility directions

Area	Sites	Dec	Inc	k	α_{95}
NA	13	311	62	17	10.3
Ammass	3	3	40	354	6.6
P	10	194	87	9	16.9

The Maximum directions from samples 2 to 7 are so nearly parallel that they cannot be distinguished on a stereogram. Their mean direction is illustrated in Fig. 8, left. The direction from sample 1 is remote from that direction; it is therefore not particularly influenced by the shear zone. The study of the zone will therefore be confined to samples 2 to 7.

The Intermediate directions of the samples rotate in an arcuate manner as the shear zone is approached; that for sample 5 lies in the plane of the shear zone, whilst 7 is very close to it. Sample 6 "overshoots" the plane. This behaviour is probably associated with a change in the iron oxides from "ilmenomagnetites" in rocks ten metres from the shear zone to hydrated ferric oxides and haematite in the shear and immediate country rocks (D. Bridgwater, personal communication, 1979). Evidence for such changes comes from falling values of the mean susceptibility as the margin is approached down to sample 6 which has only 7% of that in sample 3 (nevertheless sample 7 has a value close to sample 3).

Pseudotachylite

Site 25 is a pseudotachylite; it is a member of a swarm on the west coast of Nordfjord, in the Archaean craton. They are within and parallel to a several hundred metre wide retrogressed ductile shear zone bordered by granulite facies rocks (Bridgwater et al. 1977). This particular pseudotachylite is a few cm wide and strikes at 140º. Palaeomagnetic analysis had proved that it is of similar magnetic age to the gneisses in the Nordfjord region (Beckmann 1983).

Ten samples were taken from this feature; they are nearly isotropic. The lineation is hardly greater than unity, so that it is generally not meaningful to quote Maximum susceptibility directions. However, three

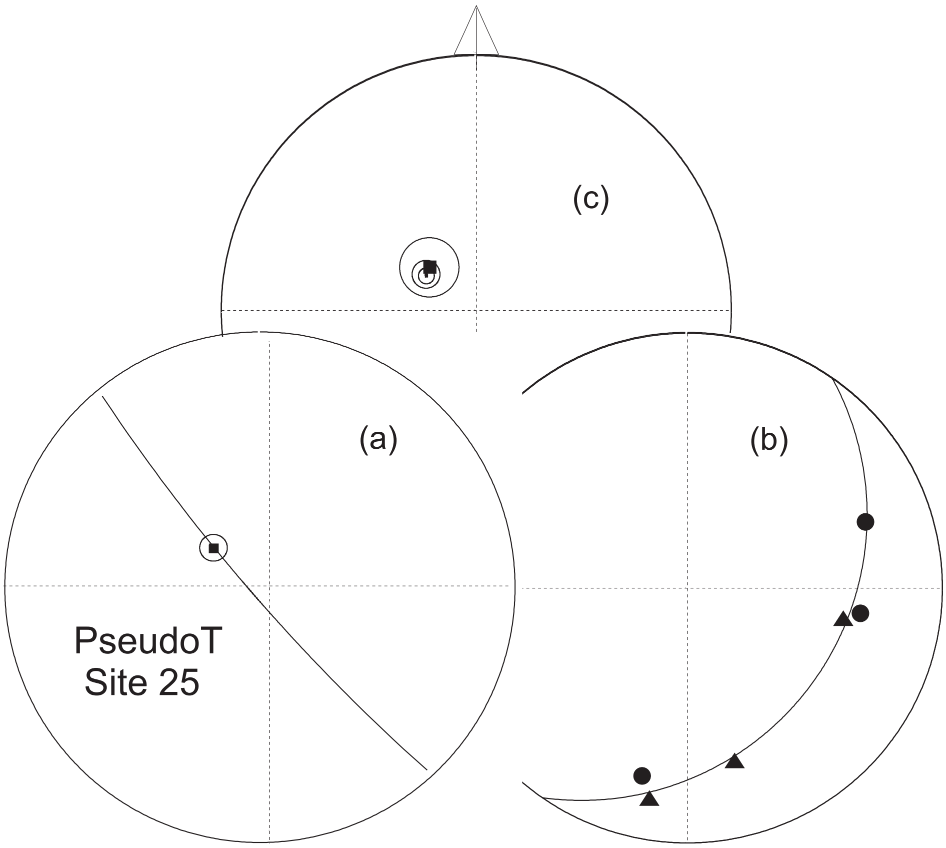


Fig. 9. (a) Mean Maximum direction from the pseudotachylite (site 25) and the plane containing this direction and the strike of this feature. (b) Intermediate and Minimum directions of its samples in relation to the locus of points orthogonal to the mean Maximum. (c) Mean Maxima from sites 25 & 27 and the mean of mean Maxima from the remaining 11 sites in area NA.

of the samples have average lineation greater than the other seven, namely 1.06 compared with 1.02, and they are the only prolate ones. These three samples have yielded practically parallel Maximum directions, whose mean is indistinguishable from that of the shear zone (27). The plane containing this mean direction and the strike of the pseudotachylite (Fig. 9a) is indistinguishable from that of the shear zone (27, Fig. 8, left). The Intermediate and Minimum directions display swinging behaviour (Fig. 9b) like that seen in the shear zone. The mean Maximum directions for the shear zone (27) and the pseudotachylite (25) are plotted in relation to the mean Maximum direction of the other 11 sites in area NA (Fig. 9c).

Site 13
This is a dyke amphibolite which was sampled with the late David Bridgwater, who noted that it is garnet-bearing and undeformed, within country rock in granulite facies. Nevertheless, some deformation is implicit in the magnetic fabric which has a well-defined Maximum direction (Table 2). We sampled normally to the dyke margin, from 5 cm to 35 metres, but no systematic variation of directions with distance has been found.

Site 35
This site is of particular interest. The first six samples from this gneiss were in an area of folds, whereas the second six were not. In spite of this difference

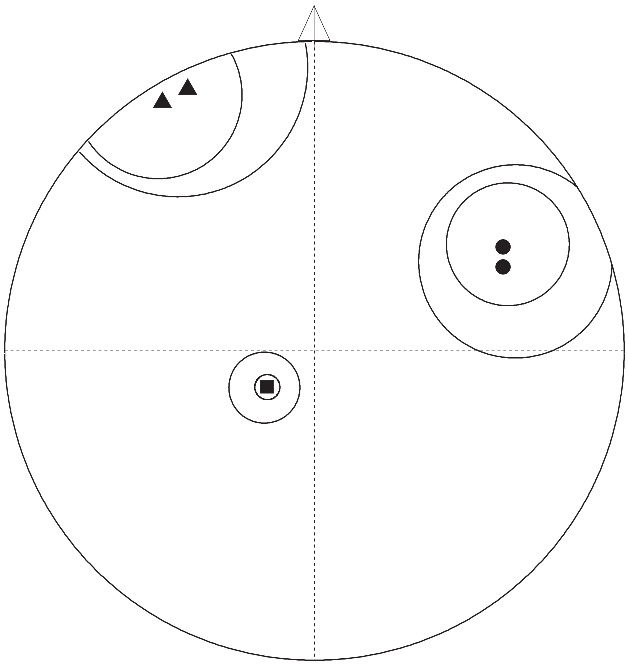


Fig. 10. Fold test on site 35.

their principal axes of magnetic susceptibility are indistinguishable (Fig. 10). Therefore these directions were imposed after the folding. (This test is analogous to the "fold test" in palaeomagnetism).

Discussion

The shear zone, site 27, formed at the beginning of the Nagssugtoqidian metamorphism, in view of the age of two adjacent shear zones, namely 2,660 (±180) Ma (Pedersen & Bridgwater 1979). However, such shear zones were probably reactivated much later (Chadwick & Vasudev 1989). If so, this would be another example of the persistence of tectonic lineaments near structural boundaries for hundreds of millions of years (Bridgwater et al. 1973; Watterson 1975). It is now suggested that the transparency of the Nagssugtoqidian/Archaean boundary to AMS was caused by overprinting late in the Nagssugtoqidian metamorphism. This would imply that Nagssugtoqidian events in the Archaean were more widespread than had been recognised by Bridgwater & Myers (1979). This point of view was reinforced by Chadwick et al. (1989), who concluded that the boundary is not sharp but, rather, a zone as much as 100 km wide.

The "swinging" behaviour of the Intermediate directions as the shear zone (27) is approached offers an explanation of this phenomenon in site 18, and other sites, which may therefore also have been situated in shear zones. The implication is that shear zones in this part of south-east Greenland are abundant. This suspicion is supported by geological evidence from south Storo, where the shear belts vary in width between several hundred metres and less than one metre (Bridgwater 1979), and a shear belt hundreds of metres wide in Nordfjord (Bridgwater et al. 1977).

The shear zone (27) and pseudotachylite (25) strike north-west/south-east. This strike looks the same as for the boundary from aeromagnetic data (Verhoof et al. 1996, depicted in van Gool et al. 2002, Fig. 6), implying that these features may be associated with continental collision, like the Nordre Stromfjord shear zone on the west coast (van Gool et al. 2002, Figs. 3 & 4). There are indications of collision of two Archaean blocks from geochronology in the Ammassalik area (Kalsbeek & Taylor 1989).

There is geological evidence about the sense of movement of the shear zones in area NA. The appearance in the field of the shear zone (27) indicates that the shearing movement had been dextral, in accord with three other shear zones in the locality

(Bridgwater 1979). Site 27 had experienced north-side-down movement (see Fig. 8, left), in common with shear zones in Nordfjord (Bridgwater et al. 1977). Three shear zones adjacent to site 27 trending 130º/V are 10–20 cm wide; within one metre of their margins the mineral fabric is intensified and rotated to become parallel to the central zones (Pedersen & Bridgwater 1979). Rotation about the Maximum susceptibility axis of the shear zone (27), and the other sites in Area NA, would correspond to the "rolling" mode mentioned in the "Magnetic Susceptibility" section of this paper.

The suggestion of continental collision can be taken further with the AMS results, but the steep inclination of the Maximum direction from area NA presents a problem because rolling would be expected to be horizontal. However, this Maximum direction could be regarded as a combination of a horizontal component striking north-west/south-east and a vertical one. This strike is to be expected if oceanic crust were subducting towards the south-west, causing a rolling motion in the receiving rocks anticlockwise about a horizontal axis directed to the south-east. (Indeed, the sense of subduction should be underneath the mobile belt on the basis of the convexity of the aeromagnetic boundary, as proposed for the west coast by van Gool et al. (2002)). The vertical component of the Maximum direction could have been imposed later. A reservation with this model is that it violates the proposition that AMS directions correspond to the last metamorphic event. However, the model could be sustained if the vertical component had been the response to stretching rather than metamorphism.

This rolling regime accords with the subduction and collision model of van Gool et al. (2002) for west Greenland when the curvature of the aeromagnetic boundary is taken into account. In their Fig. 5, panel 3, progress of the Disko (Ilulissat) craton is seen towards the North Atlantic craton, with subduction of oceanic crust, followed by collision as it arrives from the WNW (panel 4) causing peak metamorphism, whilst the thrust arrows can be interpreted as a rolling motion anticlockwise about a horizontal axis directed ENE, which is the same sense as that now proposed for east Greenland.

The area P, consisting of Nagssugtoqidian gneisses surrounding the plutons, has yielded a mean Maximum direction which is practically vertical. This direction was probably established as the emerging plutons exerted upward stresses. Comparison of Fig. 3, right and Fig. 6 shows overlapping, implying that the directions from area NA have been influenced by the emplacement of the plutons. Thus the vertical component from the plutons would provide the vertical component postulated after the rolling in area NA. Moreover, it would have been a stretching imposed in non-metamorphic conditions because the Nagssugtoqidian metamorphism had ceased by that time.

The Maximum direction identified at Ammassalik, namely north and 40º downwards, can be explained by Archaean crust overriding the mobile belt (Bridgwater 1979; Chadwick & Vasudev 1989; Dawes et al. 1989), with a stretching effect which would have expressed itself as a north to south lineation, ie the direction of the Maximum in AMS terms, in "stretching" mode. Such a hypothesis would nearly fit the observation of Bridgwater and Myers (1979), at the southern margin of the mobile belt, of linear fabrics in younger Nagssugtoqidian shear planes plunging at 20º–30º to the north.

Two of the declinations identified in the present investigation, from the Nagssugtoqidian/Archaean boundary and from Ammassalik (311º and 3º, respectively), recall a remark in Andrews et al. (1973): "Strong linear fabrics developed in these [shear] belts, plunging to the north-west and north". These authors even refer to interference patterns between the two sets of directions. These two declinations are also reminiscent of those mentioned by van Gool et al. (2002) for the Nagssugtoqidian of east Greenland: "The structural grain shows a consistent ESE structural trend and south-directed thrusts exist throughout the orogen" (bearing in mind that a particular direction in AMS is equivalent to its opposite owing to double-end-edness). The present paper supplements the declinations of these authors with inclinations, giving directions.

No reason suggests itself for the lack of an outcome for the Sermiligâq area. The default explanation is that this is an area of diverse local disturbances which prevented consistent directions from being established, a possibility which accords with the lack of meaningful palaeomagnetic results in this area (Beckmann 1983), indicating that these magnetic records have been largely lost.

The precise mean Maximum directions at Ammassalik (Table 1) recall the precision of the palaeomagnetic results here (Beckmann 1983), particularly for the two garnetiferous granulite sites, whose directions of magnetisation are very close to each other. Perhaps the robustness of these magnetic records is associated with the massive character of these rocks.

The deductions from the principal AMS directions are at risk in view of the caveats of Rochette et al. (1992). It is assumed that the AMS directions of the present study arise from multi-domain magnetite. But have they been affected by a contribution from the matrix? This question is answered by considering the area NA. This contains a great variety of rock types (Table 2), with a corresponding variety of matrices, and yet they have a common Maximum direction, and common "swinging" behaviour (except site 11). Any contribution from the matrices is therefore unlikely because such contributions would be different from each other. In detail, the mineralogy of the shear zone (27) changes drastically as the margin is approached (Bridgwater 1979) whilst the Maximum direction remains constant (even for specimen 6 in the margin itself, and specimen 7 within the shear).

The rocks of this study are favourable to there being just weak linkage between AMS and NRM thus:

(i) low intensity of NRM and high values of anisotropy compared with basaltic rocks, such as those studied by Rochette et al. (1992),
(ii) previous demagnetisation, especially tumbling AF.

This collection had been treated by tumbling AF demagnetisation in one site, and thermal for the remainder (Beckmann 1983). The AF site was site 1 at Ammassalik, whereas sites 2 & 42 there had been treated thermally (subject to checking that no chemical changes had occurred). Nevertheless, the Maximum directions are practically parallel (Fig. 2); if there had been a linkage the two methods would have manifested a link in different ways.

"Inverse" fabrics have not been noticed in the present rocks; indeed Rochette et al. (1992) recorded other authors who had concluded that multi-domain magnetite yields "normal" AMS fabric. Above all, it needs to be said that Rochette et al. (1992) did not consider metamorphic rocks, and so their reservations may not, in any case, apply to this study.

Dansk Resumé

Målinger af anisotropien i den magnetiske susceptibilitet (AMS) er blevet udført på Prækambriske bjergarter i Sydøstgrønland i området fra det Nagssugtoqidiske mobile bælte ved Ammassalik og imod Nord til lidt forbi grænsen af det Arkæiske Kraton. Retningerne af den maksimale susceptibilitet er de bedst definerede, og er som følger: Ammassalik: Dec = 3°, Inc = 40°, α_{95} = 7°; Nagssugtoqidiske Arkæiske"grænse": Dec = 311°, Inc = 62°, α_{95} = 10°; Arealet med post-tektoniske plutoner: Dec = 194°, Inc = 87°, α_{95} = 17°. En shearzone nær grænsen er blevet detailleret undersøgt. Maksimums-retningerne af prøverne er vel grupperede og falder i shearzonens plan, mens de intermediære retninger drejer omkring maksimumsretningen når man nærmer sig shearzonen, indtil de ligger i dens plan. En sådan drejning er almindelig i grænseområdet.

En pladetektonisk forklaring for de maksimale retninger i grænseområdet og fra Ammassalik foreslås som følger: Maksimumsretningen fra grænseområdet tilskrives subduktion og kollision af den Arkæiske plade kommende fra nordøst, efterfulgt af en vertikal komponent, som overprintes ved plutonernes intrusion. Maksimumsretningen ved Ammassalik skyldes overridende Arkæisk skorpe der kommer fra nord.

Conclusions

The Maximum directions are summarised in Table 4 and Fig. 7, and depicted according to their areas in Fig. 1. The directions from the three areas are significantly different from each other, at the 95% confidence level, implying differences in the times at which these directions were established. The horizontal part of the direction from the area NA is probably older than that from Ammassalik because the Ammassalik area stabilised later (Chadwick & Vasudev 1989; Kalsbeek & Taylor 1989). This order of events agrees with that established palaeomagnetically (Beckmann 1983). The direction from area P is probably the youngest.

The discovery of "swinging" behaviour in a shear zone has demonstrated that AMS would be useful in detecting shear zones, even when they are not apparent in the field. Moreover, fabric has been recognised in rocks in which it is invisible in hand sample. The advocacy of Graham (1954) of AMS as "an unexploited petrofabric indicator" is thus upheld.

An interpretation of the AMS results has been made in terms of a plate tectonic model for the Archaean/Nagssugtoqidian boundary which is similar to that of van Gool et al. (2002) for the west coast of Greenland. Clearly, the present author's solution is speculative but he hopes that it will provide a basis for discussion, and that the data presented in this paper will prove helpful in any further work on the plate tectonic history of the Precambrian rocks of south-east Greenland.

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