SVERIGES GEOLOGISKA UNDERSÖKNING

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F. G. MULDER

PALEOMAGNETIC RESEARCH IN SOME PARTS OF CENTRAL AND SOUTHERN SWEDEN

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F. G. Mulder
Paleomagnetisch Laboratorium 'Fort Hoofddijk', de Uithof, Utrecht, Nederland

C. DAVIDSONS BOKTRYCKERI AB, VÄXJÖ 1971

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SUMMARY

Samples of several rock types with different ages were collected in the central and southern part of Sweden for paleomagnetic research.

Investigations of the Precambrian rock samples from the Gothian Dala porphyries and granites of Dalarna (central Sweden), the Jotnian basalts and the late Jotnian dolerites showed that some of these rock samples contained a characteristic magnetization acquired in Lower Paleozoic times (Caledonian orogeny), whilst other rock samples contained only a viscous magnetization.

Various Gothian hyperite-dolerite dykes (1550 ±100 m.y.) of southern Sweden gave consistent normal and reversed remanent magnetic directions. Their NRM is assumed to be original. The pole position belonging to the average direction for individual dykes is 134° W and 12° S (46° E and 12° N). The intensity of the NRM in the samples of these dykes indicated that the earth magnetic dipole moment during the two polarity periods was 0.9 and 1.8 $\times 10^{25}$ gauss. cm^3, respectively.

The Ordovician limestone samples from Västergötland revealed magnetizations similar to those in the dolerite samples from the overlying sills. It is most probable that these limestones have acquired their present magnetization during the intrusion of the sills.

The intensity of the remanent magnetization in the Ordovician limestone samples collected on Öland was too weak to give reliable results.

Dolerite sills in eastern and western Västergötland revealed magnetizations with pole positions at 174° E, 31° N and at 166° E, 38° N, respectively. Age determinations performed on the samples of both sills gave an age of 282 ±5 m.y. and place the time of intrusions in the Upper Carboniferous.

Samples from various dolerite dykes in Skåne revealed similar magnetizations. The pole position belonging to the average magnetic direction of these dykes is 174° E and 37° N.

Ancient field intensity studies on the samples of the dolerite sills and on the samples of the dolerite dykes showed that the earth magnetic dipole moment during both intrusions was 1.2 $\times 10^{25}$ gauss. cm^3. The similarity of the paleomagnetic directions indicates that the Skåne dykes were intruded during the same period as the Västergötland sills, thus in the Upper Carboniferous. The average pole position of the dolerites of both regions is 171° E and 35° N, which is in good agreement with other paleomagnetic studies of Upper Carboniferous rocks of Europe.

1. INTRODUCTION

The geomagnetic field can in a first approximation be described as a dipole field. The dynamo theories of the geomagnetic field predict and the results from paleomagnetic studies have shown, that averaged over periods of several thousands of years, the virtual dipole axis coincides with the rotation axis of the earth. Deviations are attributed to secular variations. On account of the secular variation, the direction of the earth magnetic field fluctuates approximately 10° to 20° around the average field direction.

At present the virtual dipole axis makes an angle of $11\,{}^{1}/_{2}^{\circ}$ with the rotation axis of the earth.

In the geomagnetic dipole field there is a simple relation between the local field direction and the pole position. The declination points to the pole and the polar distance (Q) can be calculated from the lokal inclination (I) by $\text{cotg}\ Q = {}^{1}/_{2}\ \text{tg}I$.

Most rocks contain minor amounts of iron oxides and sulfides, which (accessory) minerals have magnetic properties. Because of several kinds of processes it is possible that the magnetic minerals obtain a Natural Remanent Magnitization (NRM) in a preferential direction. This preferential direction in the rocks often represents the geomagnetic field direction at the moment of rock formation. In oriented rock samples it is thus often possible to detect the direction of the earth magnetic field at the place of sampling during the rock formation and hence the position of the ancient geomagnetic pole.

Besides the secular variation there is evidence for apparent polar wandering and/or continental drift.

The movement of the pole relative to a paleogeographic area, which movement can be observed over long time sequences, is called apparent polar wandering. This apparent polar wandering might be partly or entirely a consequence of continental drift.

Paleomagnetic pole positions for the geological past of stable Europe are fairly scarce. Only for the late Paleozoic and the Tertiary periods sufficient consistent paleomagnetic data are available. These paleomagnetic data show an apparent polar wandering path from the western Pacific towards the present geographical north. Since suitable rocks are lacky in the European Mesozoic, any details of this apparent polar wandering path are absent. Also the extension of the European apparent polar wandering path in the early Paleozoic is highly disputed. Paleomagnetic data of the Precambrian of the European area are practically absent. In order to get more information about the apparent polar wandering path of 'stable' Europe in the Precambrian and in the Paleozoic, paleomagnetic investigations were made on oriented samples, which were collected from some formations in the central and southern part of Sweden.

Since at the Baltic shield early Paleozoic as well as late Precambrian rocks are found tectonically undisturbed, this region looked very suitable for a paleomagnetic research about these older periods.

As far as of interest for the present study, the following main periods may be distinguished in the geologic history of the Baltic shield:

Upper-Carboniferous/Permian magmatism (intrusion of sills and dykes; magmatism of the Oslo Graben)	280– 260 m.y.
Caledonian orogenic cycle (Cambro-Ordovician geosynclinal sedimentation and Caledonian orogeny)	600– 380 m.y.
Sveconorwegian (Dalslandian) event (magmatism and metamorphism)	1100– 900 m.y.
Jotnian period (denudation; sedimentation; basalt and dolerite magmatism)	± 1200 m.y.
Gothian magmatic event (Dala and Trysil porphyries and granites; intrusion of hyperite-dolerites)	1500–1600 m.y.
Svecofennian orogenic cycle	± 2300–1750 m.y.

The investigated rock samples were collected in the following areas:

1) Dalarna	Precambrian in- and extrusives
2) Skåne, Småland and Värmland	Precambrian hyperite-dolerite dykes
3) Västergötland and Öland	Ordovician limestones
4) Västergötland	Paleozoic dolerite sills
5) Skåne	Paleozoic dolerite dykes

2. GEOLOGY AND SAMPLING LOCALITIES

2.1. Precambrian rocks from Dalarna

2.1.1. LOWER AND UPPER DALA SERIES

Dalarna is the old name of Kopparberg county, situated in the central part of Sweden. The whole area is overlain by a glacial cover. Only in road cuttings and along rivers are the rocks locally exposed. The basement rocks in Dalarna belong to the Svecofennian cycle (2300–1750 m.y.). They are separated from the overlying volcanic series by a period of denudation. These Dala volcanics consist mainly of porphyries. From one bed to another they show great variations. The porphyries alternate with beds of clastic materials, such as tuff, volcanic conglomerate and sandstones (Digerberg rocks). The Dala series have originated through repeated volcanic eruptions flowing out over a large area. Extensive microscopic studies (Hjelmqvist, 1966) reveal the stratigraphic sequence of the Dala series as listed in table 1. In the porphyries Hjelmqvist has

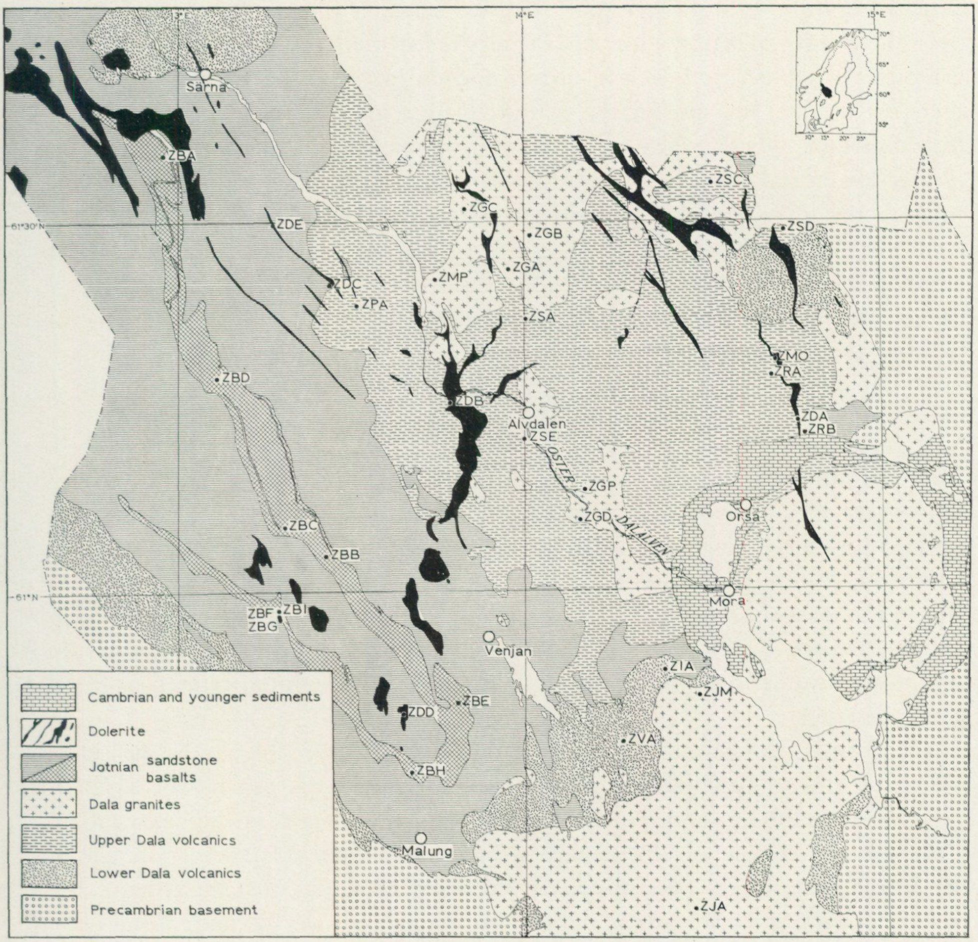

Fig. 1. Geological sketch map and location of the sampling sites of the rocks collected in Dalarna (simplified after Hjelmqvist, 1964)

distinguished a Lower and an Upper Dala series. The Lower Dala series are characterized by porphyries with small quartz phenocrysts, which distinguish them from those of the Upper Dala series.

In the Upper Dala porphyries we find mainly feldspar phenocrysts and no quartz phenocrysts. Although sometimes an ash flow structure is well developed (schlieric porphyry), in most of the porphyries it is hard to see owing to the numerous phenocrysts.

2.1.2. DALA GRANITES

The rocks of the Lower and Upper Dala series are intruded by the Dala granites. Several types of granites can be distinguished. The Garberg granite (a Rapakivi-like granite) is a massive rock with red feldspar phenocrysts, which often have the border of white albite characteristic for the Rapakivi type. The Siljan granite is a reddish rock rich in quartz and the white Järna granite is poor in quartz. Rutten (1966) postulated that the Dala granites have no normal batholitic character, but represent rheo-ignimbritic masses related to the extrusions of the Lower and Upper Dala porphyries.

Since the intercalated Digerberg rocks (the layered sequences of the Dala series) are undeformed tectonically, it is concluded that the Dala porphyries and the Dala granites are also not tilted since their deposition.

Age measurements (Chapter 3.) reveal an age of 1570 ±40 m.y. for the intrusion of the granites.

2.1.3. JOTNIAN BASALTS

After the deposition of the Dala volcanics and the 'intrusion' of the Dala granites there was a period of strong denudation. The products of weathering provided material for the Jotnian sandstones, which now cover the Sub-Jotnian peneplain in the western part of Dalarna. In the northwest (of Dalarna) and in the west (in Norway) the Jotnian rocks are overthrusted by large Caledonian nappes. Cross-bedding, ripple marks and raindrop impressions are common in the sandstones. The sandstones may thus be interpretated as flood plane deposits.

The Jotnian sandstones are undeformed tectonically. The sandstone series is divided into an upper and a lower section by a series of basalts (Öje basalts). This series comprises several basalt flows, with a total thickness of at least 100 m.

At some places the basalts display pronounced pillow structures. The age of the Jotnian basalts, as determined by the K-Ar method, must be at least 931 m.y. However, since this method gave too young ages for the underlying Dala rocks, it is probable that the basalts are older than 931 m.y. (Chapter 3.)

2.1.4. LATE JOTNIAN OR YOUNGER DOLERITES

Both the older Dala porphyries and granites and the Jotnian sediments and basalts have been intruded by dolerite dykes and sills.

The exact age of the dolerite intrusions is unknown; but since the dolerites have not intruded the Paleozoic sediments (as shown in Fig. 1. in the region near locality ZRB), it is concluded that they have a pre-Paleozoic and perhaps late-Jotnian age.

One type, the Åsby dolerite, is a rather coarse-grained ophitic dolerite. A finer-grained dolerite is called the Särna dolerite. This type of dolerite has the same composition as the Åsby dolerite. It has, however, a micropoikilitic texture of large pyroxene areas with scattered small grains of olivine or olivine pseudomorphs.

Table 1. Stratigraphic sequence, mainly as given by Hjelmqvist (1964, 1966)

Jotnian or younger intrusives		Dolerite of the Åsby and Särna type Monzonite
Jotnian extrusives and sediments		Sandstone Öje basalts Sandstone, conglomerate and breccia
Sub-Jotnian	Dala granites	Dala granites of the Garberg, Siljan and Järna type Syenite Gabbro and diorite
	Upper Dala series	Bredvad porphyry Porphyry rich in phenocrysts Digerberg rocks (tuff, agglomerate, sandstone and conglomerate) Schlieric porphyry (ignimbrite) Andesite Porphyrite (grey and red)
	Lower Dala series	Quartz porphyry Porphyry rich in phenocrysts Schlieric porphyry, tuff (ignimbrite) Agglomerate Venjan porphyrite Porphyrite Quartzite, conglomerate, arkose

The Åsby dolerite dykes with a roughly northwest-southeast orientation frequently pass into a monzonitic type.

Oriented hand samples were collected from 11 sites of the Dala porphyries (63 samples), from 7 sites of the Dala granites (40 samples), from 9 sites of the Jotnian basalts (48 samples) and from 6 sites of the late Jotnian or younger dolerites (31 samples).

The sampling localities, each coded with three letters, are shown in Fig. 1. In each locality five to six samples were collected.

Apart from the samples collected for paleomagnetic investigations, samples for radiometric age determinations were collected in several of the same outcrops. In the sampling list these sites are marked with an *.

Sampling list:

1) A. Jotnian or younger intrusives
    a) Dolerites of the Åsby and the Särna type
        ZDA 1–5 exposed in the river Ämån 1 km N of Storstupet
        ZDB 1–5 exposed in the river Ugsiån 0.5 km S of Älvdalsåsen
        ZDC 1–5 road cutting at Bunkris
        ZDD 1–5 at the foot of the Lybergsgnupen
        ZDE 1–5 road cutting 2 km S of Glysjön
    b) Monzonite
        ZMO 1–6 road cutting 1 km S of Emådalen

B. Jotnian extrusives. Öje diabase (basalts)
ZBA 1–5 road cutting at Siavallen
ZBB 1–6 road cutting E of Gussjösätern
*ZBC 1–6 road cutting NE of Transtrand
ZBD 1–6 road cutting between Horrmund and Lövnäs
*ZBE 1–5 road cutting at Venjansåsen
ZBF 1–5 cliff W of Torgåsmon
ZBG 1–5 cliff W of Torgåsmon
ZBH 1–5 road cutting N of Momyckelberget
*ZBI 1–5 exposed in the river Feman NW of Torgåsmon

2) Dala granites
a) Granites of the Garberg type
ZGA 1–6 road cutting N of Älvdalen at Gumpertsberget
ZGB 1–6 road cutting between Jöllen and Kräckelbäcken
ZGC 1–6 road cutting at Mossiberg
*ZGD 1–6 road cutting N of Oxberg

b) Granites of the red Siljan type
ZJM 1–5 road cutting at Gesundaberget

c) Järna granite
ZJA 1–6 road cutting E of Dala Järna at Säljberget

d) Syenite
ZMP 1–5 road cutting NE of Trängslet

3) Upper Dala series
a) Bredvad porphyry
*ZPA 1–6 exposed in the river Gryvelån at Kälkstupet

b) Porphyry rich in Phenocrysts
*ZSA 1–6 road cutting at Jöllen N of Älvdalen
ZSB 1–5 road cutting at Tansöborg N of Noppikoski
ZSC 1–5 at the top of Paljokkaberget
*ZSD 1–5 near the bridge over the Oreälven at Älvho
ZSE 1–6 road cutting at Kötilla S of Älvdalen

c) Grey porphyrite
*ZGP 1–6 old porphyrite quarry at Blyberget

d) Red porphyrite
ZRA 1–5 road cutting S of Emådalen
ZRB 1–6 exposed in the river Ämån at Storstupet

4) Lower Dala series
a) Schlieric porphyry (ignimbrite)
ZIA 1–7 at the top of Leksberget

b) Venjan porphyrite
ZVA 1–6 at Säxberget S of Vimo.

2.2. Precambrian hyperite-dolerite dykes from the 'schistosity zone' in Skåne, Småland and Värmland

The Pre-Gothian rocks in the western part and the Gothian rocks in the eastern part of southern Sweden are separated by a 29 km wide mylonitic belt. This belt, called the 'schistosity zone' or the 'fracture zone', can be followed over a long distance from Skåne north over lake Vättern and further to the northwest into Norway.

The original rocks in this zone (in the southern part gneisses and in the northern part granites) are completely altered into schistose rock types. In this zone unaltered hyperite-dolerites and syenites are found intruding along the nearly vertically dipping schistosity planes.

The age relation of the rocks at both sides of the fracture zone is somewhat complex. Geological field evidences (Magnusson, 1965) have shown that the metamorphism of the Pre-Gothian rocks west of the schistosity zone is older then the Gothian rocks east of the schistosity zone. These Gothian rocks consist of granites and volcanics. Age determinations on these non-metamorphic rocks with the K-Ar method (Polkanov and Gerling, 1960) gave ages ranging between 1660 and 1420 m.y.

The Pre-Gothian rocks west of the schistosity zone consist of several types of gneisses. Age determinations on these gneisses with the K-Ar method (Polkanov and Gerling, 1960) gave unexpectedly low ages ranging between 1130 and 920 m.y.

Obviously, these ages for the Pre-Gothian rocks represent rejuvenation in Sveconorwegian (Dalslandian) time (1100–900 m.y.)

This apparent contradiction can be explained by accepting the following series of events since the Gothian magmatic event:

1) A sinking of the present Pre-Gothian area in the (Late) Gothian.
2) The intrusion of hyperite-dolerites and syenites along the faults in the schistosity zone.
3) A rejuvenation of the Pre-Gothian rocks, while they were deeply buried during the Sveconorwegian (Dalslandian) period.
4) A post-Sveconorwegian rise of the present Pre-Gothian area.
5) A peneplanization of southern Sweden in the late Precambrian.

As will be discussed in Chapter 3, the age determinations performed on the samples of five hyperite-dolerite dykes showed two groups of ages. It is assumed that the younger ages (about 800–900 m.y.) reflect the inprint of the Sveconorwegian event and that the older age of 1550 ± 100 m.y. represents the time of intrusion of the dolerite dykes in the schistosity zone. This is in accordance with the age determination of the Vaggeryd syenite, which has a minimum age of 1270 m.y. (Magnusson, 1960).

Oriented core samples were collected from six different hyperite-dolerite dykes. In one locality (Hägghult quarry) 50 samples in total were collected,

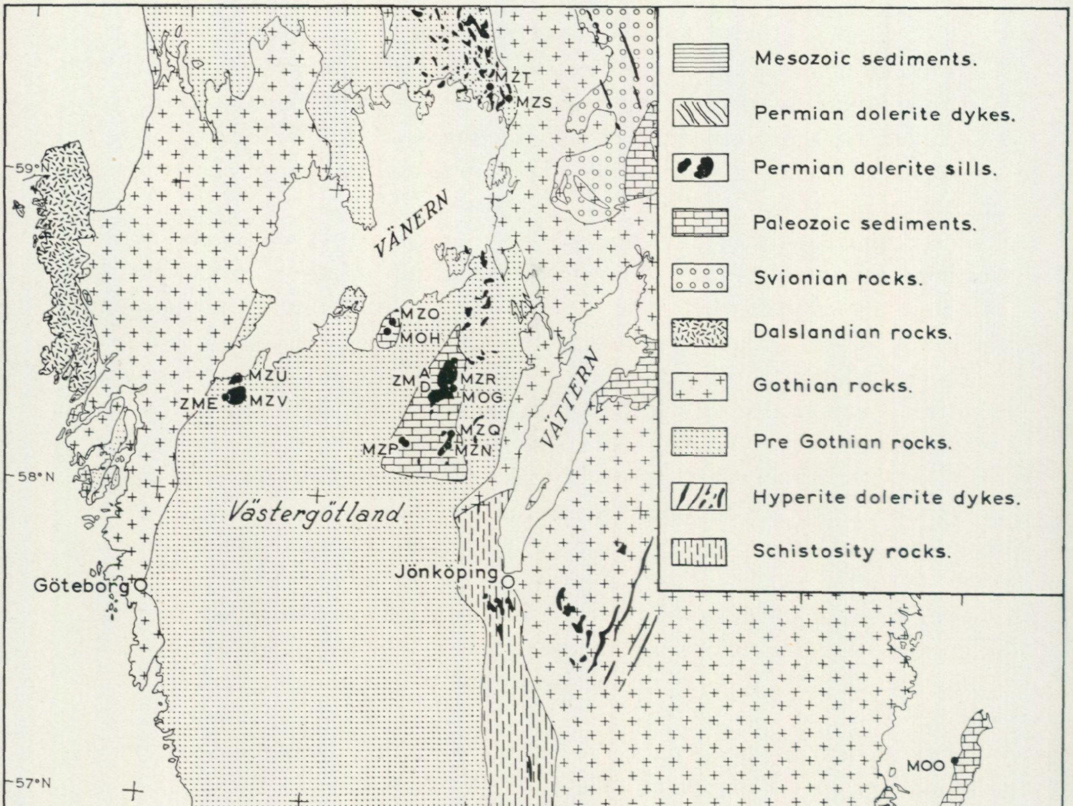

Fig. 2. Geological sketch map and location of the sampling sites of the rocks collected in southern Sweden (after Magnusson and collaborators, 1960)

each 70 cm across a single dyke, to test whether the direction of the NRM in the samples shows a symmetrical spreading across the dyke.

Sampling list (the location of the sites is shown in Fig. 2)

MZI	1–50	dolerite quarry E of Hägghult.
MZK	1–5	road cutting 6 km N of Osby.
MZL	1–5	road cutting at Målaskog.
MZM	1–5	dolerite quarry at Hjortsjö.
MZS	1–5	road cutting 6 km NW of Kristinehamn.
MZT	1–5	road cutting 14 km NW of Kristinehamn.

2.3. Ordovician limestones from Västergötland and Öland
and
2.4. Paleozoic dolerites from Västergötland

Southern Sweden was base levelled into a peneplain during the late Precambrian. Over this peneplain Cambro-Silurian sediments were deposited, which still are in a practically flat-lying position. These sediments are preserved in some localities in Västergötland thanks to the protection of large caps of dolerite. The dolerites intruded the Silurian shales as sills during the uppermost Carboniferous (Chapter 3.)

The Cambro-Silurian sediments, with their dolerite cap, rise now as table mountains over the Precambrian peneplain and its cover of Quaternary glacial sediments.

The stratigraphic sequence of the Paleozoic rocks in Västergötland as given by Thorslund (1960) and as shown in Fig. 3 is:

dolerite (max. 50 m)
Silurian shales (max. 55 m.)
Ordovician limestones, mudstones and shales (max. 115 m)
Cambrian Sandstones and shales (max. 60 m)

Several types of Cambrian sandstones occur; clayey sandstone, pure quartz sandstone, and phosphoritic sandstone rich in glauconite. The top of the Cambrian sediments is formed by alum shales with bituminous limestones. Pilot

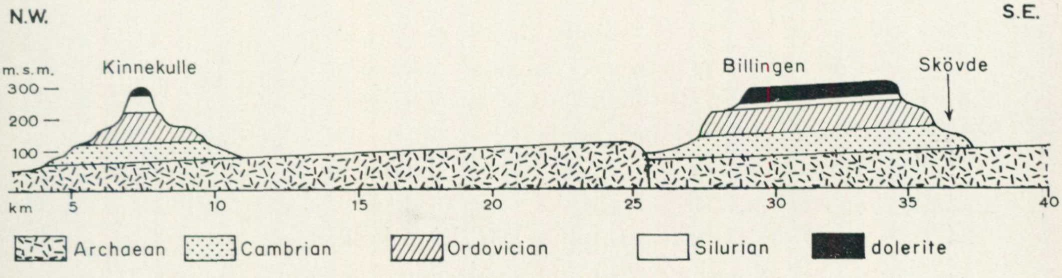

Fig. 3. NW–SE section through Västergötland (after Thorslund in Magnusson and collaborators, 1960)

samples of the sandstones have shown that the rocks are unsuitable for paleomagnetic research.

The Lower and Middle Ordovician is represented by red limestones and the Upper Ordovician by mudstones and shales. The repeated interruptions in sedimentation in all of the sections point to their epicontinental nature and deposition in shallow water. In two localities oriented hand samples of the Ordovician red limestones were collected. The distance between the dolerite sill contact and the sampling site is about 40 m for Mt. Billingen and about 80 m for Mt. Kinnekulle.

The maximum thickness of the Silurian shales is 55 m. The sediments (shales) shows effects of heating due to the intrusion of the dolerite sills.

In the eastern part of Västergötland the dolerites have intruded the Silurian sediments horizontally. In the western part (Mts. Halleberg and Hunneberg) the dolerites cut obliquely through the lower Paleozoic sediments.

The main constituents of the doleritic rocks, which show an ophitic texture, are titanaugite and labradorite, with minor amounts of olivine, biotite, chlorite and quartz.

The dolerites from the sills in the western part contain more quartz than the dolerites from the sills in the eastern part of Västergötland.

Core samples as well as handsamples were collected from these dolerite sills.

In Öland only Ordovician rocks are exposed. In essentials the same sequence of strata is found in boreholes in Öland as in Västergötland (Thorslund, 1960). In Horns Udde (northwest Öland) oriented limestone samples were collected with the intention to compare their NRM direction with that found in the Ordovician limestone samples from Västergötland.

Sampling list (the location of the sites is shown in Fig. 2.).

Ordovician limestones 2.3.

ZMF	1–6	Gullhögen limestone quarry W of Skövde (Mt. Billingen)
MOG	1–12	
MOH	1–5	Limestone quarry at Hällekis (Mt. Kinnekulle)
MOO	1–22	coastal cliff N of Horns Udde (Öland)

Paleozoic dolerites 2.4.

ZMA	1–6	and MZR 1–18 dolerite quarry at Skövde	All at Mt. Billingen
ZMB	1–6	road cutting between Lerdala and Skövde	
ZMC	1–6	road cutting between Skövde and Varnhem	
ZMD	1–6	road cutting E of Lerdala	
MZN	1–16	road cutting between Falköping and Tidaholm (Mt. Gerumsberget)	
MZO	1–5	SW of Hällekis on top of Mt. Kinnekulle	
MZP	1–6	NW of Falköping on top of Mt. Mösseberg	
MZQ	1–6	Ne of Falköping on top of Mt. Varvsberget	

MZU 1–12 road cutting NE of Trollhättan (Mt. Halleberg)
ZME 1–6 and MZV 1–15 both road cutting E of Trollhättan (Mt. Hunneberg)

Samples for radiometric age determinations were collected in the dolerite quarry at Skövde (Mt. Billingen) and in a road cutting E of Trollhättan (Mt. Hunneberg).

2.5. Paleozoic dolerites from Skåne (southern Sweden)

Paleozoic rocks occur in large areas of southern Sweden. In the early Paleozoic southern Sweden (Skåne) formed the northern extension of the middle European sedimentary basin. In this basin Cambrian, Ordovician and Silurian sediments were deposited (Thorslund, 1960). The Lower-Cambrian series (thickness ±200 m) consist mainly of sandstones and quartzites and the Upper-Cambrian series of alum shales, limestones and mudstones. Over the Ordovician shales (thickness ±100 m) are lying Silurian shales with a maximum thickness of 1000 m.

After an upheavel in late Silurian time, Skåne was situated between the Precambrian shield (in the north) and the European sedimentary basin (in the south).

Owing to differential movements of various blocks, locally very different rates in sedimentation and erosion occurred. Therefore, in some blocks lower-Paleozoic rocks are well preserved and the Mesozoic sediments reach a maximum thickness, whereas in other places the erosion has exposed the Precambrian basement.

The main faults in Skåne have a NW–SE orientation. Along these faults several dolerite dykes have intruded (Fig. 2). The dykes intruded the Silurian but not the Mesozoic sediments. Their age must therefore be post Silurian and pre Mesozoic (Hjelmqvist, 1936). As discussed in Chapter 7, our paleomagnetic data prove that the dykes have intruded in Upper Carboniferous time.

Oriented core samples were collected in nine sites of six different dolerite dykes.

Sampling list (the location of the sites is shown in Fig. 2):

MZA 1–5 quartzite quarry at Hedeberga (southern dolerite dyke)
MZB 1–5 quartzite quarry at Hedeberga (northern dolerite dyke)
MZC 1–6 dolerite dyke in the quartzite quarry at Dalby
MZD 1–5 dolerite dyke in the quartzite quarry 2 km E of Dalby
MZE 1–6 northern border
MZF 1–6 middle part } of the dolerite dyke in the quarry at Rönnarp
MZG 1–4 southern border
MZH 1–6 exposed along the coast 3 km S of Simrishamn

3. GEOCHRONOLOGICAL INVESTIGATIONS

As mentioned already in Chapter 2, samples for radiometric age determinations were collected from the Dala porphyries and granites, the Jotnian basalts, the hyperite-dolerite dykes, and Paleozoic dolerite sills. The age determinations were carried out at the 'ZWO Laboratory for Isotope Geology' at Amsterdam (Priem et al., 1968)*).

Dating was done according to the ^{87}Rb–^{87}Sr and the ^{40}K–^{40}Ar methods.

Since radiogenic argon is fairly easy lost from the rocks under conditions of metamorphism, the ages measured with the K–Ar method are often minimum ages. Mostly they show the time of latest rejuvenation of the rocks.

1) Precambrian rocks from Dalarna.

a) Four samples from the Precambrian Upper Dala porphyries (Bredvad porphyry and the porphyry rich in phenocrysts) and one sample of the Dala granites were dated according to both the Rb–Sr and the K–Ar methods.

Within the limits of error, Rb–Sr dating gave the same age for the Upper Dala porphyries as for the Dala granites of the Garberg type. This means that there can have been only a relatively short time interval between the extrusion of the porphyries and the intrusion of the granites. The isochron age of this magmatism is 1570 ± 40 m.y. (Priem et al., 1970); this event may be designated as Gothian.

K–Ar determinations on the same samples, however, show younger ages, between 921 and 605 m.y. (Table 2). It may be concluded that these rocks have lost radiogenic argon in younger times, probably due to the Sveconorwegian and/or Caledonian events.

b) Four Jotnian basalt samples, collected at different localities, were dated with the K–Ar method. The ages range between 931 and 745 m.y. (Table 2).

From this large spread and since the K–Ar ages of the underlying porphyries and granites have also been influenced by later events it is concluded that the K–Ar ages of the Jotnian basalts are due to rejuvenations. The ages determined may in part represent the imprint of the Sveconorwegian event, while possibly also some loss of radiogenic argon occurred during the Caledonian orogeny.

It is therefore concluded that the extrusion age of the Jotnian basalts must be older than 930 m.y.

2) Precambrian hyperite-dolerite dykes from southern Sweden.

Samples from five hyperite-dolerite dykes intruding the schistosity zone were dated with the K–Ar method. The determinations on samples from three

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*) Additional Rb-Sr measurements on the Dala porphyries and granites and the corresponding rocks in the Trysil area, eastern Norway, were made by Priem et al., (1970) and Welin and Lundqvist (1970). The isochron age of these rocks is 1570 ± 40 m.y.

Table 2. Locations of the sampling sites and measured ages

Rock type	Sampling site	Sample series	K-Ar ages in m.y.	Rb-Sr ages in m.y.
Jotnian basalt	Torgåsmon, 70 km W of Mora	ZBI	931 ±28	
Jotnian basalt	N of Sälen, 72 km WNW of Mora		873 ±45	
Jotnian basalt	Transtrand, 65 km WNW of Mora	ZBC	745 ±25	
Jotnian basalt	Venjansåsen, 40 km WSW of Mora	ZBE	873 ±45	
Upper Dala porphyry	Kälkstupen, 65 km NW of Mora	ZPA	605 ±30	isochron age: 1570 ±40 m.y. Priem et al. (1970)
Upper Dala porphyry	Jöllen, 42 km NNW of Mora	ZSA	701 ±35	
Upper Dala porphyry	Älvho, 59 km NW of Mora	ZSD	806 ±40	
Upper Dala porphyry	Blyberget, 29 km NW of Mora	ZGP	921 ±45	
Dala granite	N of Oxberg, 21 km NW of Mora	ZGD	736 ±36	
Hyperite-dolerite	E of Hägghult	MZI	838 ±25	
Hyperite-dolerite	between Osby and Älmhult, NNE of Osby	MZK	781 ±25	
Hyperite-dolerite	Hjortsjö, 10 km NW of Alvesta	MZM	1573 ±50	
Hyperite-dolerite	6 km NW of Kristinehamn (Värmland)	MZS	1516 ±50	
Hyperite-dolerite	Målaskog, 20 km E of Ljungby	MZL	886 ±45	
dolerite (sill)	Billingen, 3 km NNW of Skövde	ZMA+MZR	287 ±15	
dolerite (sill)	Hunneberg, 13 km ENE of Trollhättan	ZME	279 ± 8	

dykes yielded ages of about 800–900 m.y., whereas the samples of two other dykes have an average age of 1550 ±100 m.y. (Table 2). As discussed in Chapter 2, the higher age of 1550 ±100 m.y. may be assumed to represent the date of intrusion of the dykes, whereas the ages in the 800–900 m.y. range reflect the imprint of Sveconorwegian rejuvenation.

3) Paleozoic dolerite sills from Västergötland.

Samples from the sill which now forms the top of Mt. Billingen and from the sill which now forms the top of Mt. Hunneberg were dated according to the K–Ar method. The ages are 275 ±15 m.y. and 279 ±8 m.y., resp. According to the Geological Society Phanerozoic time scale (1964) these ages place the time of intrusion approximately at the Carboniferous-Permian boundary.

4. SAMPLING PROCEDURES, MEASURING TECHNIQUES AND ANALYSING METHODS

4.1. Introduction

Measurement of the magnetization of rock samples show two different magnetic quantities, namely the induced and the remanent magnetization. The induced magnetization (M) is dependent on the susceptibility ($\varkappa$) and on the ambient field (H) and would be absent when the field is removed ($M = \varkappa H$). The total magnetization left in a zero field is defined as the remanent magnetization. The remanent magnetization in rocks is determined by the properties of the atoms, domains and mineral grains.

a) In the atoms the electrons have a magnetic moment due to the orbital motion and due to the electron spin. In most materials there is no remanent net effect of the magnetic moments. When a field is applied, there is in such materials no more than small scale induced magnetism. This magnetism is due to paramagnetic or diamagnetic properties of the materials.

b) In materials with ferrimagnetic or antiferromagnetic minerals the moments of adjoining atoms interact together They form 'domains' with a diameter of the order of 10^{-6} cm in which these interactions develop an ordered alignment of the individual atomic magnetic moments. The interaction of the atomic moments is dependent on the temperature and on the strength of the field applied. Above the Curie temperature no interaction results and the materials are paramagnetic.

c) Dependent on the size of the magnetic minerals, individual grains and crystals may contain one or more domains.

Spontaneous ferrimagnetic or antiferromagnetic magnetizations appear by cooling through the Curie points. With further cooling this spontaneous magnetization will remain in the rocks and increases in intensity and in coercive force. The magnetization acquired in this way is called Thermo Remanent Magnetization (TRM).

The NRM in sediments and in metamorphic rocks is often thought to be the effect of chemical processes at temperatures below the Curie temperatures. The direction of these magnetizations are representative for the ambient field during these chemical processes. This kind of magnetization is called 'Chemical Remanent Magnetization' (CRM).

Another type of magnetization of sediments is obtained by the deposition of particles with remanent magnetic moments in sediments. These particles are erosion products of older magnetic minerals. Statistically the magnetic moments of minerals will be aligned in the sediments along the ambient field. However, dependent on the size of the magnetic particles and the process of sedimentation, it is possible that the moments of magnetizations are systematically different from the ambient field due to the influence of the layering, compaction, flow etc. Together these moments form the 'Depositional Remanent Magnetization' (DRM).

Over longer time-spans the intensity of the NRM may be altered by viscous magnetic effects. These are due to thermal agitations occurring during the geological history. So, even at temperatures below the Curie temperature, the thermal energy is sufficiently high to change magnetizations of domains into lower energy levels. The decay of the original magnetization is called viscous demagnetization or viscous decay. Due to the same thermal agitations a new magnetization may be acquired if a magnetic field is present. This new magnetization is called 'Viscous Remanent Magnetization' (VRM).

The VRM is normally rather soft and although it is built up since the genesis of the rocks, it is mostly directed parallel to the direction of the geomagnetic field at the collecting locality. It might even be partly parallel to the direction of the ambient field during storage in the laboratory.

4.2. Sampling procedures

For the measurement of a NRM direction in a rock it is necessary to collect oriented samples. For statistical reasons at least six samples must be taken in each sampling locality (Doell and Cox, 1967). Both hand samples and core samples were collected for this study. Each hand sample was oriented in situ, by marking and measuring the strike direction of a horizontal line, and the dip of a flat surface. Only after orienting was the sample detached from the rocks. In the laboratory each hand sample is sawn into an equidimensional form and cast in oriented position in cubes of plaster of paris or paraffine.

The core samples were collected with a portable drilling equipment (Doell and Cox, 1967). Before the core was detached, the drill direction was scratched on the core as a line. The dip of this line and the azimuth of this line was measured.

The length of the cores varied from 5 to 10 cm and the diameter was 2.5 cm. In the laboratory the cores are sawn into cylinders with a length of 2.2 cm; so it was possible to get 2 or 3 specimens from each sample.

The orientation of the samples were determined with a magnetic compass or with a sun compass. Since the corrections for the variation of the present magnetic field in Sweden were less than one degree in the period 1964–1967, no corrections in the magnetic orientation were necessary.

4.3. Measuring techniques

In this study it is assumed that the magnetic particles in the rock samples are uniformely distributed. If the form of the rock sample is isotropic the magnetic moment of the whole rock may be thought to be that of a dipole in the rock's center. The method of measuring and computation is based on this assumption. The magnetic measurements were all made by measuring the magnetic components along three orthogonal axes with astatic magnetometers. The magnetic measurements on the hand samples were made while the samples were cast in oriented positions in cubes of paraffine or plaster of paris. Thus the components measured along the three cube axes represent the N–S, E–W and the vertical component of magnetization in the rock sample. In this case the direction and intensity of the total NRM could easily be calculated from the three principal components. The core samples were measured, whilst fitted in plastic cubes, with the drill direction in a fixed position. For these core samples the direction of magnetization is calculated by a transformation of axes dependent on the drill direction (Klootwijk, 1967).

For the description of the astatic magnetometers and the measuring technique reference is made to As (1960).

From the magnetic measurements the following information about the magnetic properties of the rock samples could be calculated:

1) the direction of the NRM (expressed by declination and inclination)
2) the intensity of the NRM pro volume unit (J/cm^3)
3) the intensity of the induced magnetism (M/cm^3)
4) the susceptibility $K = \frac{M}{H_z}$ ($H_z = 0.44$ Oe; the intensity of the vertical component of the present geomagnetic field in the Utrecht laboratory)
5) the ratio between the remanent intensity and the induced intensity

$$Q = \frac{J/cm^3}{M/cm^3}$$

The values of these five parameters indicated whether further research by demagnetizing techniques was worth while.

4.4. Analysing methods

In paleomagnetic work the stability of NRM in rocks is of decisive importance. The NRM will normally be composed of one or more magnetizations, which often have different stability ranges. These stability ranges can be tested in the laboratory by measuring their resistance to alternating fields or to heat treatments.

1) Alternating fields.

The NRM in most of our rock samples were analysed by treating the samples stepwise in increasing alternating fields. A description of such an alternating field demagnetizing apparatus has been given, for instance, by As (1967).

The apparatus produces fields up to 3000 Oe peak value. During each demagnetization step the magnetic domains with a coercive force less than the force produced by the alternating field are directed in both directions along the field axis. During the slow decrease of the intensity of the alternating field they become fixed in these two opposite directions and thereby cancel each other out. The alternating field has a maximum action on the domains which have a magnetic moment parallel to the applied field. Therefore the best results in demagnetization would thus be obtained by treating the samples in all directions. This is experimentally possible by tumbling the sample. In practice however, it was found that tumbling of the samples in alternating fields gave bad results. Much better results were obtained by demagnetizing the sample along three perpendicular axes.

2) Thermal demagnetization.

For thermal demagnetization a furnace was built, which will be described in Chapter 6. In the furnace some of our samples were treated in stepwise increasing temperatures and cooled again to room temperature. Heating and cooling took place in a zero field within a set of Helmholtzcoils. The remaining part of the NRM after each heating and cooling cycle was measured. The principle of thermal demagnetization is that in a zero field the magnetic direction of the domains with a blocking temperature less than the applied temperature take up random orientations upon cooling.

Graphical projection of the results will help in analysing the magnetic measurements. In this study the change of the NRM vector of the sample during the demagnetization procedure is given in an orthogonal axes system by plotting the projections of the end point of this NRM vector on the horizontal plane (determined by the N–S and the E–W axis) and on a vertical plane (determined by the vertical axis and either the N–S or the E–W axis).

The results of alternating field and thermal demagnetization procedures projected in this manner show the changes in both intensity and in direction.

As described in the following Chapter the NRM in our rock samples was composed of a viscous magnetization and a stable magnetization. This stable magnetization may represent the geomagnetic field during the formation of the rock, but may as well represent a period of stable (re)magnetization occurring at some time in the later history of the rock.

The most stable magnetic direction in each sample is determined by testing the sample in alternating fields and/or thermally. From this 'cleaned' direction in each of the samples the average magnetic site direction is calculated. In the calculations unit weight is given to each sample. The accuracy of the average magnetic site direction is expressed by Fisher's (1953) best estimate (k) and cone of confidence (α_{95}). The mean direction of rocks of similar age is computed from the site directions by giving unit weight to each site direction. From this average site direction (after a possible tectonical correction) the paleomagnetic pole position is calculated.

5. MAGNETIC MEASUREMENTS

5.1. Precambrian rocks from Dalarna

1) From the Dala series in Dalarna 103 samples were collected in 18 localities. As to its magnetization this collection can be divided in three groups, namely: a) samples from 13 localities with a soft viscous magnetization, b) samples from 3 localities with a hard magnetization directed along the present geomagnetic field direction and c) samples from 2 localities with a rather hard magnetization with a direction different from the present geomagnetic field direction.

a) This group comprised the Venjan porphyrite (ZVA) of the Lower Dala series; samples from one locality of the red porphyrites (ZRA), some of the series of the porphyries rich in phenocrysts (ZSA, ZSD and ZSE) and the Bredvad porphyry (ZPA) of the Upper Dala series and all the samples of the Dala granites (ZGA-ZGD, ZJM, ZJA and ZMP). The initial measurements revealed for the NRM intensities varying between 10^{-4} and 10^{-6} emu/cm^3 and directions close to the direction of the present geomagnetic field at the place of sampling. The induced magnetization in these samples was in the order of 10^{-3} emu/cm^3. Testing of the samples in alternating fields showed that the greater part of the magnetization was eliminated after treatment in alternating fields of 200 or 300 Oe peak value (samples ZMP 3 and ZGD 2 in Fig. 4). The soft character and the direction along the present geomagnetic field point to viscous properties of this magnetization. The intensity of the magnetization left in the samples after treatment in alternating fields of 300 Oe was in some of our samples still measurable. The induced magnetism, however, was in general much higher. Small anisotropic properties in the induced magnetism will then show up in the measurements. So, the smaller the Q-value ($\frac{R}{M}$) the less reliable

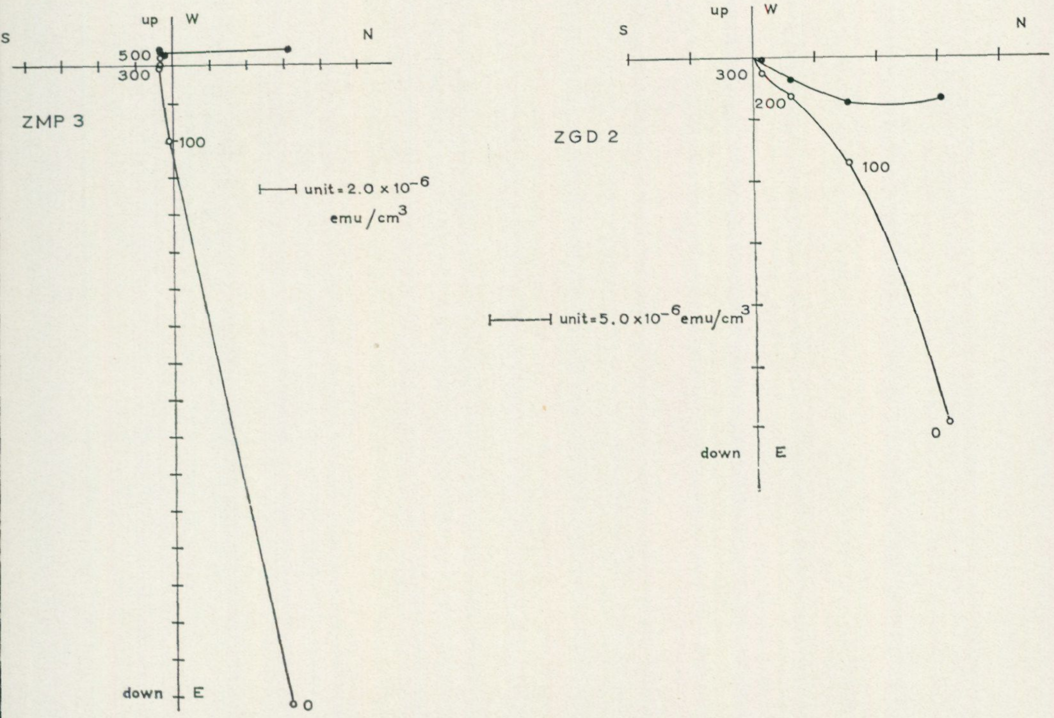


Fig. 4. Demagnetization diagrams of a sample of the Dala syenites (ZMP 3) and of a sample of the Dala granites (ZGD 2), showing the soft character of the magnetization in these rock types. The end point of the NRM vector is projected in the horizontal plane (determined by the N–S and the E–W axes) in dots and on a vertical plane (determined by the vertical axis and either the N–S or the E–W axis) in circles. The numbers represent the Oe values.

the measurements become. Consequently further analysing after the elimination of the viscous magnetizations did not lead to reliable results.

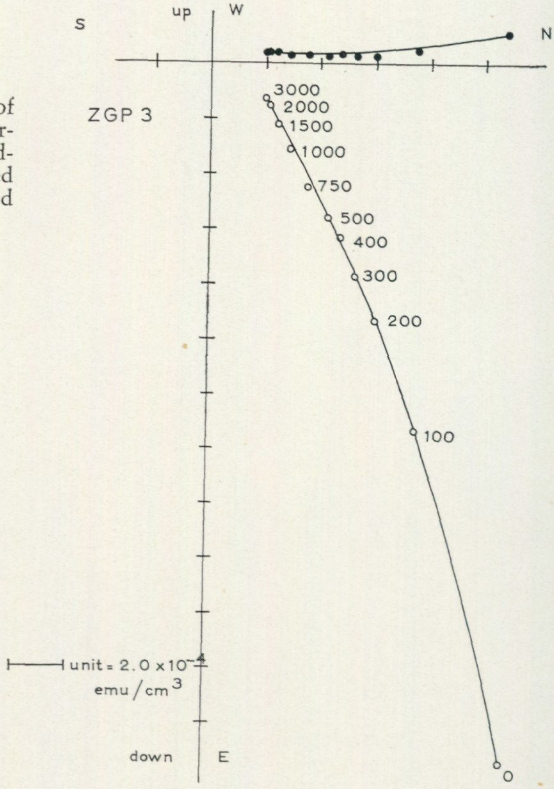
b) Samples of the Lower Dala schlieric porphyry and of the Upper Dala red and grey porphyrites showed harder magnetizations.

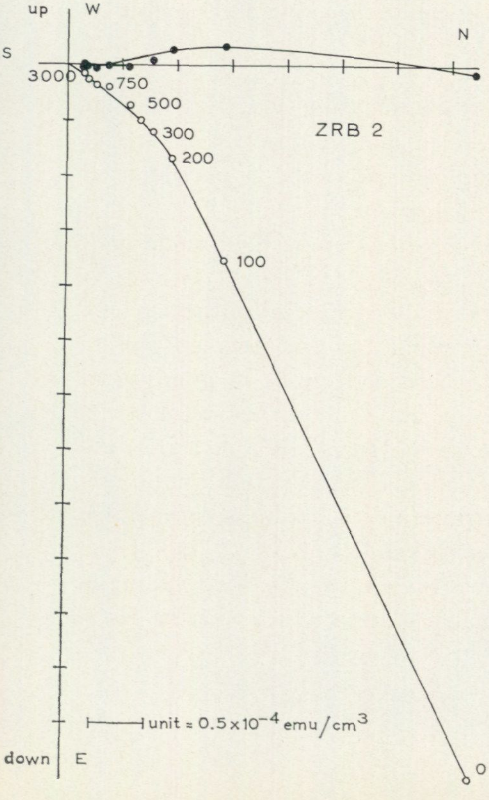
The initial NRM directions all pointed more or less along the present geomagnetic field.

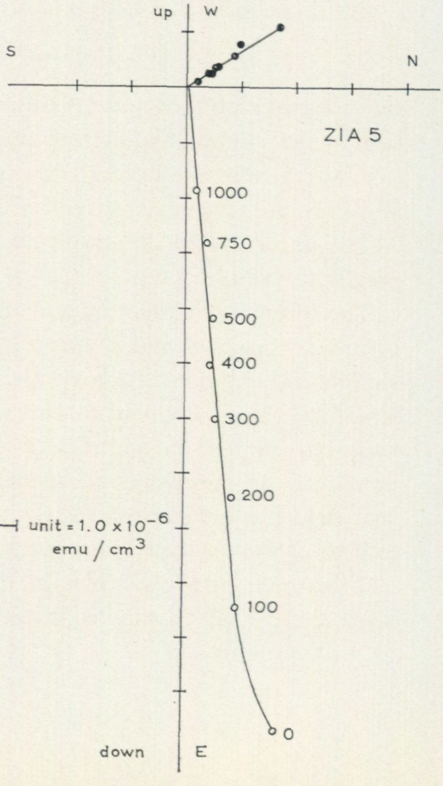
The intensity of the magnetization was about 10^{-5} emu/cm^3 in the schlieric porphyry samples and about 10^{-3} emu/cm^3 in the red and grey porphyrite samples. Demagnetization of the samples showed a decrease in intensity of 40–75 % after treatment in alternating fields of 200 Oe. Further stepwise demagnetization of the samples of the schlieric porphyries (ZIA 5 in Fig. 5) did not bring out another component of magnetization. The induction by the present field has evidently resulted in a magnetization of a hardness comparable to that of the primary magnetization in other rocks.

Treatment of the samples of the red and grey porphyrites (Fig. 5 samples ZRB 2 and ZGP 3) showed a decrease of magnetization which was the resul-

Fig. 5. Demagnetization diagrams of samples of the Lower Dala schlieric porphyries (ZIA 5), of the Upper Dala Bredvad porphyries (ZGP 3) and of the Red porphyries (ZRB 2). Projection method as in Fig. 4.







tant of a magnetization with a roughly northern declination and steep inclination and a magnetization with a northern declination and a rather low inclination. The magnetization with a rather high inclination probably represents a stable recent (re)magnetization, while the magnetization with a low inclination represents a more primary magnetization (Chapter 7 a Lower Paleozoic magnetization). Since the hardness ranges of the two different magnetizations overlap each other, the direction remained after application of alternating fields of 3000 Oe must be considered as non-representative for either of the two magnetizations. Thermal treatment of the samples did not yield better results.

c) Only the samples collected in two localities of the Upper Dala porphyries rich in phenocrysts (ZSA and ZSD) have an initial NRM direction different from the present geomagnetic field direction. The intensity of the NRM in these samples was about 10^{-5} emu/cm^3. Treatment of the samples in alternating fields (Fig. 6 sample ZSD 5) showed a small viscous component of magnetization, which was eliminated by treatment in 200 Oe and further stepwise demagnetization up to 3000 Oe showed only one stable component of magnetization. The within site dispersion of these stable magnetization proved to be small. The average magnetic site directions of these two localities are listed in Table 3 and are shown in Fig. 7. The average direction of both series was declination 17° and inclination –9°.

2) Jotnian basalt samples (48) were collected in 9 localities. Initial magnetic measurements showed that the NRM intensities varied between 10^{-3} and 10^{-6} emu/cm^3.

The samples with the lowest intensities (10^{-5}–10^{-6} emu/cm^3 and the lowest Q-values (0.1–0.4) were more or less weathered (ZBD, ZBF, ZBH and ZBI series).

The initial magnetic directions were all along the present geomagnetic field. Demagnetization of these samples revealed only viscous magnetizations which were eliminated in fields of 300 Oe.

The samples with intensities of about 10^{-4} emu/cm^3 and Q-values of about 0.9 had the same initial magnetic directions. Demagnetization in alternating fields of the samples of these series (ZBE and ZBG) showed a rather hard magnetization which was eliminated in fields of 3000 Oe. The direction of this magnetization was parallel to that of the present magnetic field.

Only the magnetization in the samples of two series (ZBB and ZBC) had an initial magnetization different from that of the present field. The NRM intensities in these samples were approximately 10^{-3} emu/cm^3, the susceptibility 0.0002 and the Q-value 1.2. Demagnetization of the samples in alternating fields showed a weak viscous magnetization eliminated in alternating fields of 300 Oe and a more stable magnetization. In Fig. 6 the demagnetization curve of the Jotnian basalt sample (ZBB 2) is shown. From the stable magnetization in each of the samples the average magnetic site direction was cal-

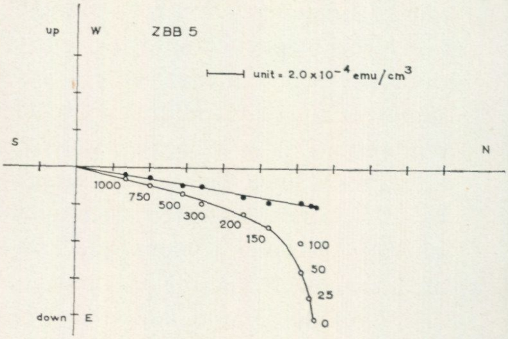
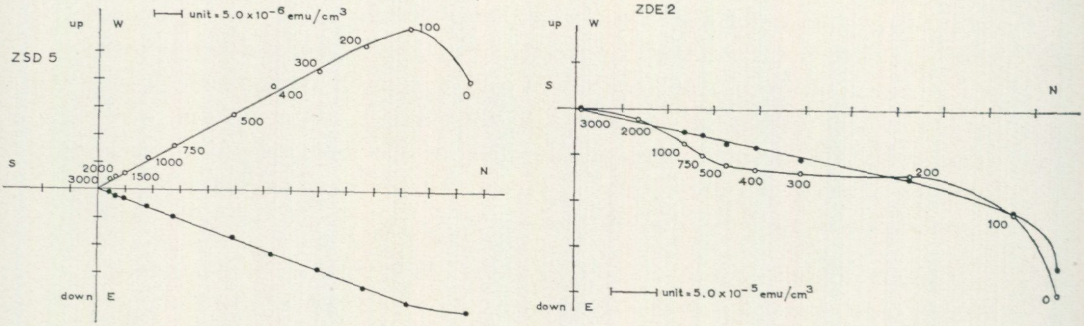


Fig. 6. Demagnetization diagrams of samples of the Upper Dala porphyry rich in phenocrysts (ZSD 5), the Jotnian basalts (ZBB 5) and the late Jotnian dolerites (ZDE 2). Projection method as in Fig. 4.



culated. These directions are declination 8°, inclination +8° and declination 6° and inclination +4°, respectively (Fig. 7 and Table 3).

3) From the six late Jotnian or younger dolerite dykes, listed at the end of Chapter 2.1, 31 dolerite samples were collected. Preliminary magnetic measurements revealed that the samples of two series were unusable for further research. The NRM directions in these samples (ZDE and ZMO series) were highly scattered and the intensity of the NRM in these samples was in the order of 10^{-6} emu/cm^3.

Demagnetization of these samples both in alternating fields and thermally showed that the NRM was due to viscous magnetism.

The samples of the other series (ZDA, ZDC, ZDD, ZDE) all contained a NRM with intensities in the order of 10^{-3} emu/cm^3 and susceptibilities in the order of 0.005. The initial directions of the NRM were quite different from the present geomagnetic field direction and the initial directions in the samples from the same locality were fairly similar. The samples of these series were all treated in alternating fields. As shown in Fig. 6 (ZDE 2) a weak viscous component of the total NRM was eliminated after treatment in 300 Oe peak

Table 3. Average directions, Fisher's best estimates (k) and cone of confidences (α_{95}) of the rocks collected in Dalarna

Rock type	series Number	decl.	incl.	α_{95}	k
Sub-Jotnian Dala porphyries	ZSA 6	14°	0°	9°	61
	ZSD 5	20°	– 18°	6°	140
	average	17°	– 9°		
Jotnian basalts	ZBB 6	8°	+ 8°	5°	195
	ZBC 5	6°	+ 4°	7°	130
	average	7°	+ 6°		
late Jotnian or younger dolerites	ZDA 5	28°	+ 4°	7°	138
	ZDC 4	340°	– 5°	17°	38
	ZDD 5	31°	– 42°	10°	62
	ZDE 5	21°	+15°	6°	148
	average	14°	– 9°		

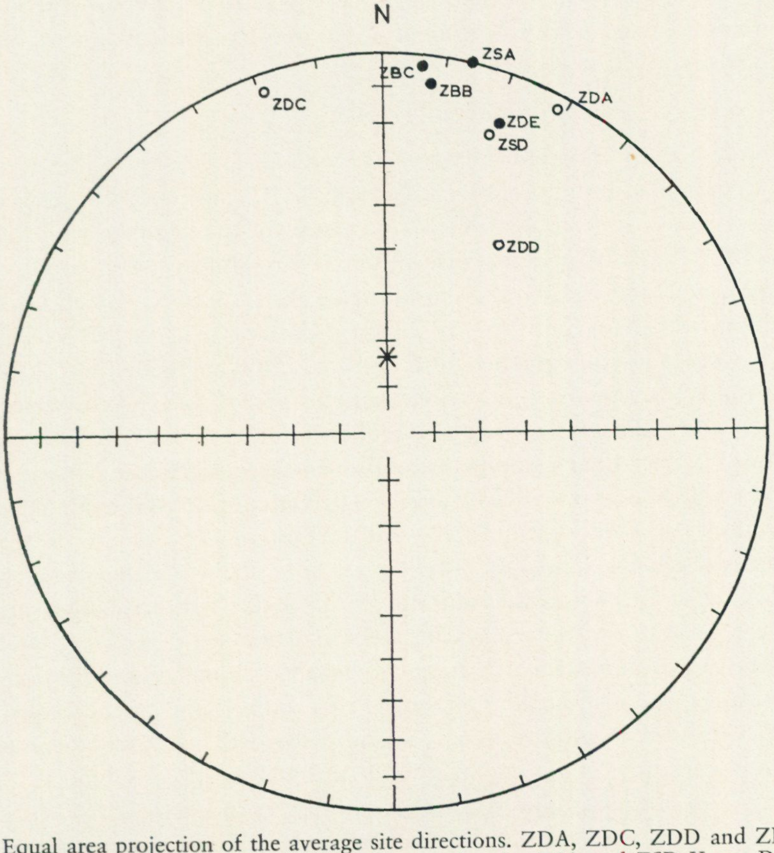


Fig. 7. Equal area projection of the average site directions. ZDA, ZDC, ZDD and ZDE Late Jotnian or younger dolerites. ZBB and ZBC Jotnian basalts. ZSA and ZSD Upper Dala porphyries rich in phenocrysts. Directions pointing up in open circles, pointing down in full dots.

value. The remaining magnetization was rather hard. Demagnetization of the other samples showed the same hardness distribution of the NRM. The 'cleaned' NRM directions in samples belonging to the same series were almost identical. The average direction of the magnetization in the samples of each series is listed in Table 3 and is shown in Fig. 7. Since the age of the dolerite intrusions is unknown, the differences in the direction of the magnetization remain unexplained.

5.2. Precambrian hyperite-dolerites from southern Sweden

Hyperite-dolerite samples were collected from six different dykes, that have intruded the schistosity zone. Preliminary magnetic measurements showed that the weathered rocks from the road cutting 12 km northwest of Karlshamn (MZT series) were unusable for paleomagnetic studies. The NRM intensities in these samples were in the order of 10^{-6} emu/cm^3 and the susceptibility was about 0.003. The initial NRM directions in the samples of the other series, although scattered in the samples from some sites, were all different from the present field direction in Sweden. Since the magnetic properties of the samples of the various dykes showed differences, the results of the magnetic measurements are discussed separately.

MZI series

In the quarry at Hägghult 50 samples were collected across the dyke, each 70 cm apart. The initial directions of the NRM in the samples showed a rather good concentration. The NRM intensities in the samples were approximately 10^{-3} emu/cm^3 and the susceptibility was about 0.003. Some samples were subjected stepwise to alternating fields up to 3000 Oe peak value. The alternating field demagnetization procedure showed that the NRM was composed by a soft viscous magnetization and a stable magnetization. The weak viscous magnetization was eliminated in fields of 200 Oe and the more stable magnetization did hardly change in direction by further stepwise demagnetization (Fig. 9). The other samples were all treated in alternating fields of 500, 700 and 1000 Oe peak value. The average direction of the stable magnetization of all samples was declination 327° and inclination –75°.

When cooling, the flanks of a dyke cool first. So, when they cool through the blocking temperatures the material in the flanks will acquire its magnetization earlier than the material in the middle of the dyke. If during cooling of a dyke the direction of the earth magnetic field has changed (secular variation), this will be reproduced in the samples. On the other hand, if there is no symmetrical variation of the magnetic direction, this will mean, a) there was no significant variation of the geomagnetic field during the cooling, or, b) the magnetization of the samples was due to influences in later periods. A thermal magnetization by reheating of an area will induce variations in the magnetic directions in samples situated at various distances from the cooling surface.

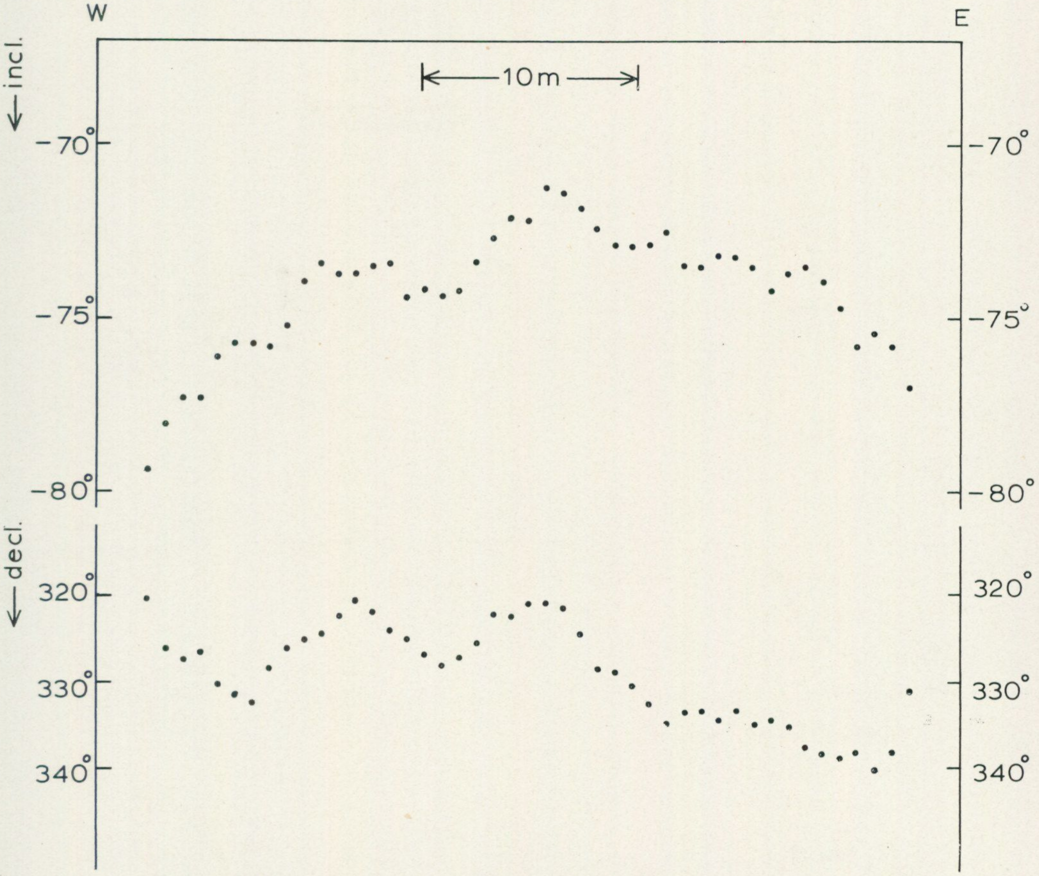


Fig. 8. Section through the dolerite dyke at Hägghult, representing the variation of the inclination (upper plot) and the variation of the declination (lower plot).

In general the magnetic variations in a vertically intruded dyke will be symmetric with regard of the middle of the dyke.

The 50 samples of the Hägghult quarry were collected to test whether there is such a symmetrical variation of the magnetic direction in this dyke. For this purpose the average magnetic direction of each six succeeding samples was calculated. The inclination and the declination with regard of the place of sampling in the dyke is plotted in Fig. 8. This figure shows a rather symmetrical distribution of the variation of the inclination with respect to the middle of the dyke. In the declination, however, there is no symmetric variation. Since the vertical component of the magnetization (sin I) represents about 80 % and the horizontal component about 20 % (cos I) of the magnetization, a fluctuation of one degree in the inclination will be equivalent to four degrees variation in the declination. So, in Fig. 8 the vertical axis of the inclination is four times enlarged.

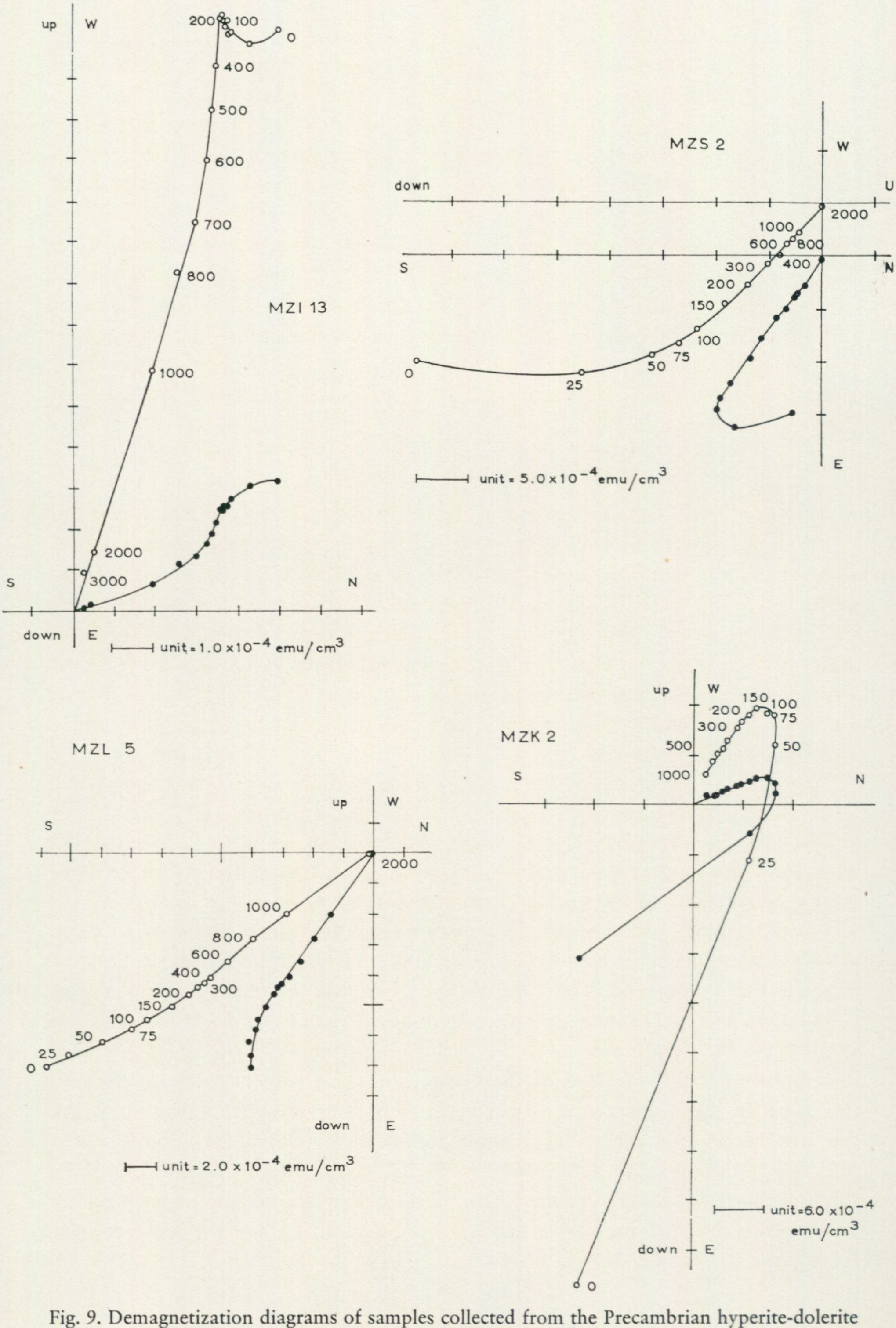


Fig. 9. Demagnetization diagrams of samples collected from the Precambrian hyperite-dolerite dykes. Projection method as in Fig. 4.

MZK series and MZM series

The samples of these series were collected in the road cutting 6 km north of Osby and in the dolerite quarry at Hjortsjö, respectively.

The within site dispersion of the initial directions in these samples was rather high. Also the NRM intensities varied over a wide range (10^{-4}–10^{-3} emu/cm^{6}). Demagnetization of the samples showed that the scattering was due to large viscous magnetizations. These magnetizations could be eliminated in fields of 200 Oe. The viscous magnetizations represented in some of the samples 80 % of the original NRM intensities. The directions of the viscous magnetizations were highly scattered and responsible for the scatter of the initial directions of the NRM. Further stepwise demagnetization did yield no other component of magnetization then a rather hard one (MZK 2 in Fig. 9). The average magnetic directions were calculated from these magnetizations and are listed in Table 4 and shown in Fig. 10.

MZL and MZS series

The samples of these series were collected in road cuttings at Målaskog and northwest of Kristinehamn, respectively. The magnetic properties in the samples of both series were almost similar. The intensities of the NRM were in the order of 10^{-3} emu/cm^{3} and the susceptibilities were in the order of 0.005. The initial directions were in good agreement with each other. Pilot samples of both series were treated stepwise in alternating fields up to 2000 Oe. In Fig. 9 the demagnetization curves of the samples MZL 5 and MZS 2 are shown. They show that the NRM was composed of a weak viscous magnetization and a more stable magnetization.

The average directions of the samples of each series were respectively decl. 124°, incl. +51° and decl. 128°, incl. +39° (Table 4 and Fig. 10).

The average directions were in rather good agreement with each other; but the age determinations showed great variations (Chapter 3). As shown, the direction of the magnetizations in the samples of both series was nearly the opposite of that in the samples of the other hyperite-dolerite dykes.

Table 4. Average magnetic directions, Fisher's best estimates (k) and cone of confidences (α_{95}) of the Precambrian hyperite-dolerites collected in southern Sweden

locality	series	N	decl.	incl.	k	α_{95}
Hägghult	MZI	50	327°	−75°	338	1°
Osby	MZK	5	337°	−53°	163	6°
Målaskog	MZL	5	124°	+51°	1892	2°
Hjortsjö	MZM	5	322°	−72°	1372	2°
Kristinehamn	MZS	5	128°	+39°	117	7°

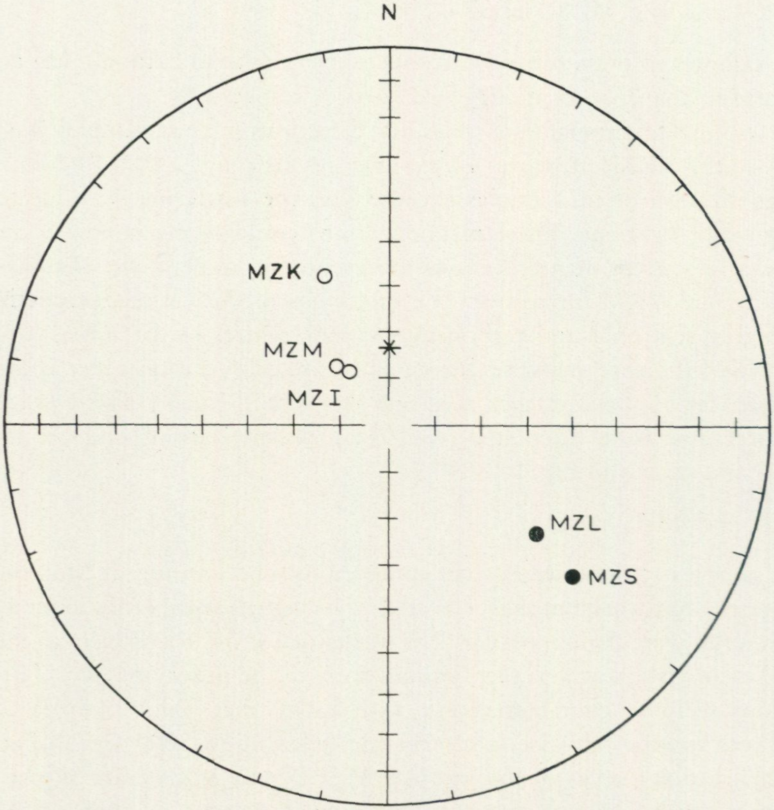


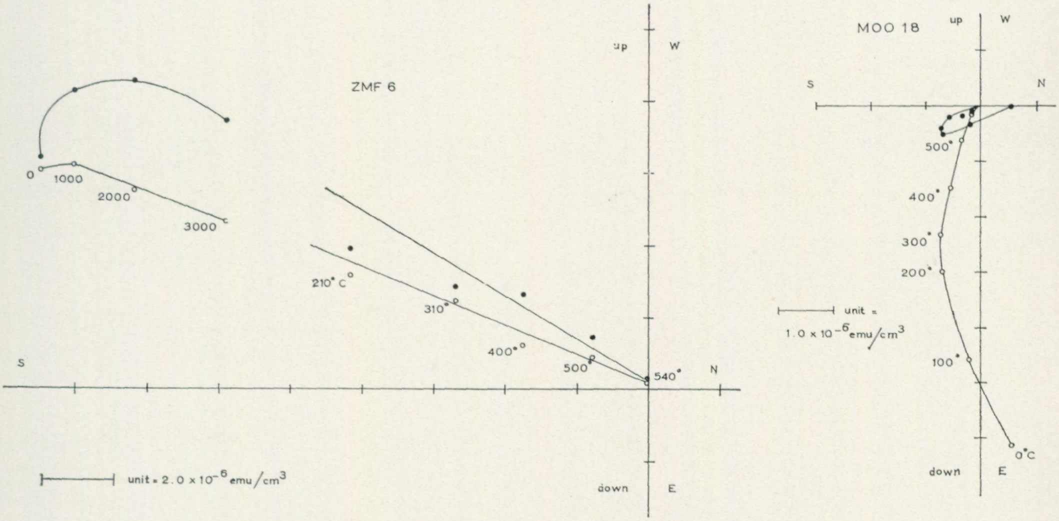
Fig. 10. Equal area projection of the average site directions of the samples collected from the hyperite-dolerite dykes. Directions pointing up in open circles, pointing down in full dots.

5.3. Ordovician limestones from Västergötland and Öland

In Västergötland oriented hand samples were collected in two localities of the Ordovician reddish limestones.

Preliminary magnetic measurements revealed that the NRM in the samples had rather high intensities (10^{-5} emu/cm^3). Treatment of the samples in alternating fields showed a small secondary magnetization and a stable magnetization which slightly decreased in alternating fields up to 3000 Oe. Thermal treatment in 200° C of the same sample showed already a further decrease of the NRM than was reached after treatment in 3000 Oe (Fig. 11).

The direction of the cleaned NRM in the samples was almost the same as the direction of the NRM in the dolerite samples of the overlying dolerite sills (declination = 198° and inclination = –4°). Formerly is was supposed (Mulder, 1966) that the time span between the deposition of the Ordovician limestones and the intrusion of the dolerites was relatively short. Age measure-



Fi. 11. Demagnetization diagrams of the limestone samples collected in Västergötland (ZMF 6) and on Öland (MOO 18).

ments have shown, however, that the sills intruded in the Upper-Carboniferous, and since very likely the paleomagnetic direction during the Ordovician was perceptibly different from those directions during the Upper Carboniferous, it is concluded that the NRM in the Ordovician limestones is caused by the intrusion of the overlying dolerites.

To test this conclusion, samples were collected from the Ordovician limestones of Öland. The intensities of the NRM in these samples were much lower (10^{-6}–10^{-7} emu/cm^3) than the NRM intensities in the Ordovician limestones from Västergötland. Samples with the highest intensities were tested both in alternating fields and thermally (Fig. 11 sample MOO 18). The remaining part of the NRM after cleaning showed such low intensities that the detection of reliable earlier magnetizations was impossible. Anyhow, it is clear that the magnetic properties of the limestones in Öland are different from that of the limestones in Västergötland.

5.4. Paleozoic rocks from Västergötland

From the dolerite sills which have once intruded the Silurian limestones and are now found as protective caps in Västergötland, hand samples and core samples both were collected. In eastern Västergötland the samples were collected from the mountains Billingen, Gerumsberget, Kinnekulle, Mösseberg and Varvsberget and in western Västergötland from the Hunneberg and the Halleberg. No indications for multiple intrusions exist on each mountain, only

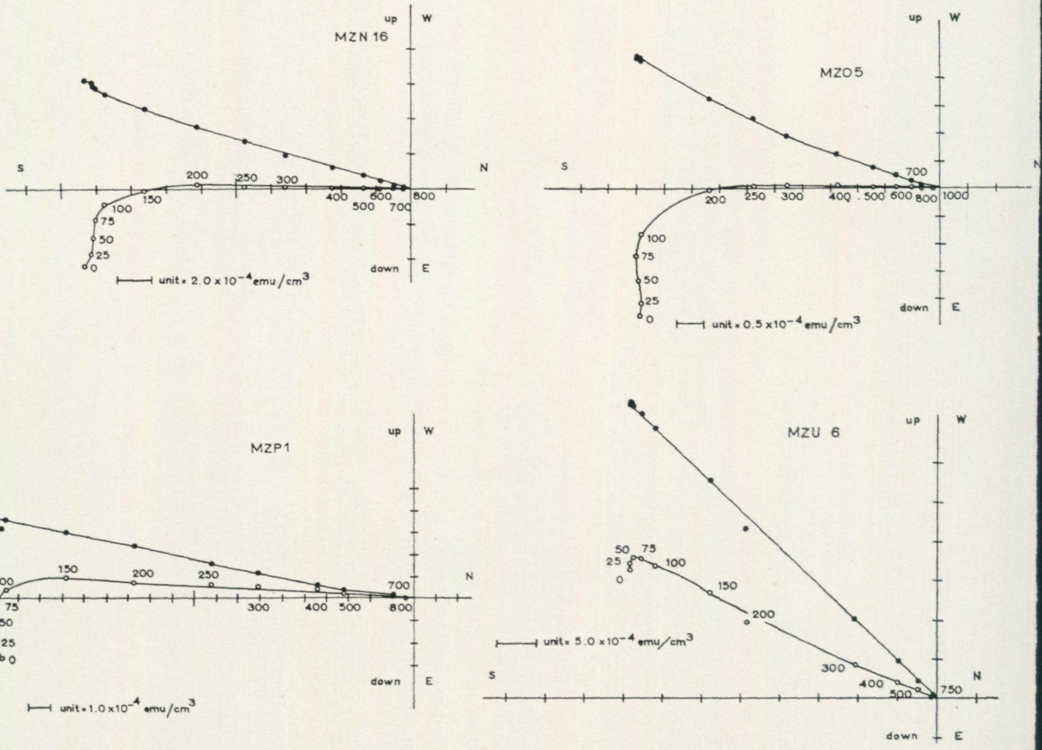


Fig. 12. Demagnetization diagrams of the dolerite samples collected from the sills in E Västergötland (MZN 16, MZO 5 and MZP 1) and in W Västergötland (MZU 6). Projection method as in Fig. 4.

Table 5

mountain	average NRM intensities	average susceptibilities
Billingen	1.7×10^{-3}	0.0020
Gerumsberget	2.0×10^{-3}	0.0019
Kinnekulle	1.5×10^{-3}	0.0017
Mösseberg	2.0×10^{-3}	0.0021
Varvsberget	2.4×10^{-3}	0.0019
average Mts. E Västergötland	1.9×10^{-3}	0.0019
Hunneberg	6.2×10^{-3}	0.0036
Halleberg	5.7×10^{-3}	0.0038
average Mts. W Västergötland	6.0×10^{-3}	0.0037

remnants of one single sill were found. The average intensity and susceptibility values of all the samples of each mountain are listed in Table 5.

The values in Table 5 show that there is a significant difference between the intensities and the susceptibilities in the samples of the mountains in eastern and western Västergötland.

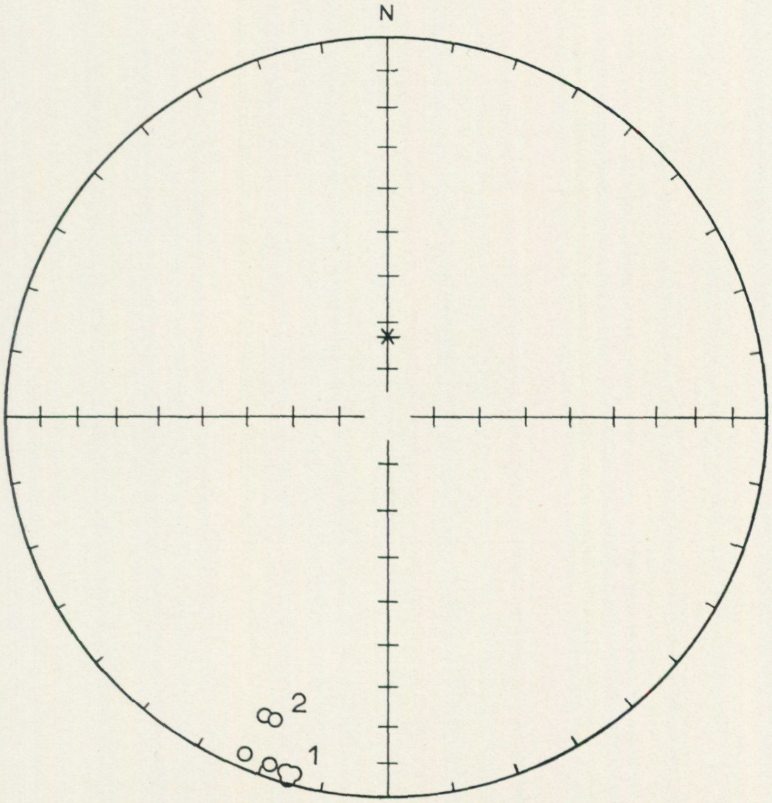


Fig. 13. Equal area projection of the average mountain directions of 1) the mountains in E Västergötland and 2) the mountains in W Västergötland. Directions pointing up in open circles.

At least one sample of each series was demagnetised completely in alternating fields. Some of the results are shown in Fig. 12, which prove that the NRM in the samples is composed of a soft and a more hard magnetization. The soft magnetization was eliminated by treatment in alternating fields of 200 or 300 Oe. This soft magnetization is probably due to viscous effects since the intrusion of the sills. Further stepwise demagnetization showed only a decrease in the intensity of the magnetization and no significant change in direction. The other samples were treated in alternating fields with three different intensities. The average directions in the mountains in eastern Västergötland were concordant, as were the average mountain directions in western Västergötland (Fig. 13 and Table 6).

The uniform directions together with the uniform susceptibilities and the uniform NRM intensities lead to the conclusion that most probably the dolerite caps in eastern Västergötland have once been parts of one single sill and that the dolerite caps in western Västergötland are remnants of another sill.

Table 6. Average directions, Fisher's best estimates (k) and cone of confidences (α_{95}) of the dolerites collected in Västergötland

mountain	series	N	decl.	incl.	k	α_{95}	average mountain direction				average of the mountain directions			
							decl.	incl.	k	α_{95}	decl.	incl	k	α_{95}
Billingen	ZMA MZR	24	199°	− 5°	177	2°	199°	− 3°	434	2°	197°	− 2°	467	4°
	ZMB	6	200°	− 5°	211	4°								
	ZMC	6	197°	− 2°	193	5°								
	ZMD	6	199°	− 2°	281	4°								
Gerumsberget	MZN	16					196°	− 3°	199°	3°				
Kinnekulle	MZO	5					203°	− 3°	292	5°				
Mösseberg	MZP	6					194°	− 2°	434	3°				
Varvsberget	MZQ	6					195°	− 1°	380	3°				
Halleberg	MZU	12					203°	−17°	123	4°	202°	−17°		
Hunneberg	MZV	15	198°	−16°	269	2°	200°	−17°						
	ZME	6	203°	−19°	639	3°								

The average magnetic direction of the mountains in eastern, respectively western Västergötland were declination 197°, inclination –2° and declination 202° and inclination –17°. The differences in the magnetic directions in both these sills may be explained by secular variation.

5.5. Paleozoic dolerites from Skåne

Samples from four dolerite dykes were collected in the centre of Skåne. The thicknesses of the dykes is some tens of centimeters. Three dykes (MZA, MZB and MZC) are exposed in quarries in the lower Cambrian quartzites. One dyke (MZD) is exposed in a quarry in the Pre-Gothian basement. The initial magnetic measurements of these samples showed intensities varying from 1.8×10^{-3} to 3.8×10^{-3} emu/cm³. At least one sample of each series was completely demagnetised in alternating fields, revealing that the NRM in these samples was composed of a weak viscous magnetization and a rather hard magnetization. The viscous magnetization was eliminated in all the samples by treatment in alternating fields of 200 Oe (Fig. 14). It represents about 10 % of the total NRM. Further stepwise demagnetization showed that the remaining part of the NRM represents one single magnetization.

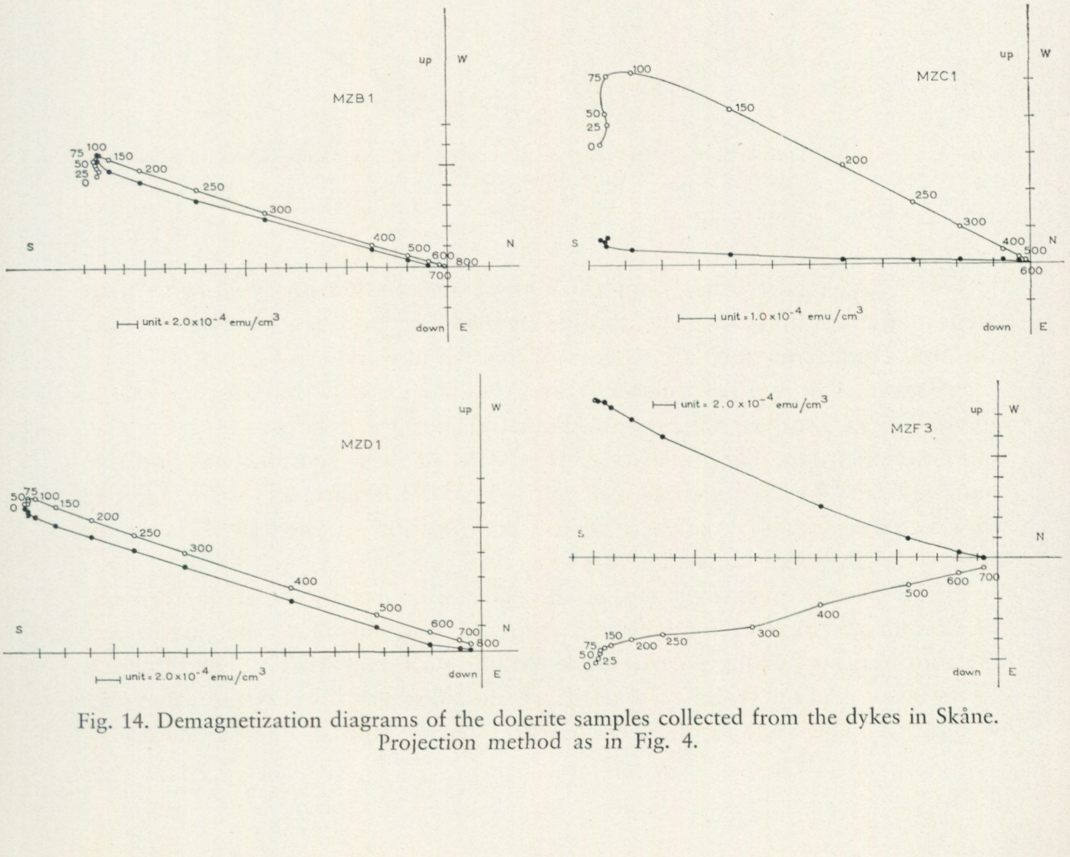


Fig. 14. Demagnetization diagrams of the dolerite samples collected from the dykes in Skåne. Projection method as in Fig. 4.

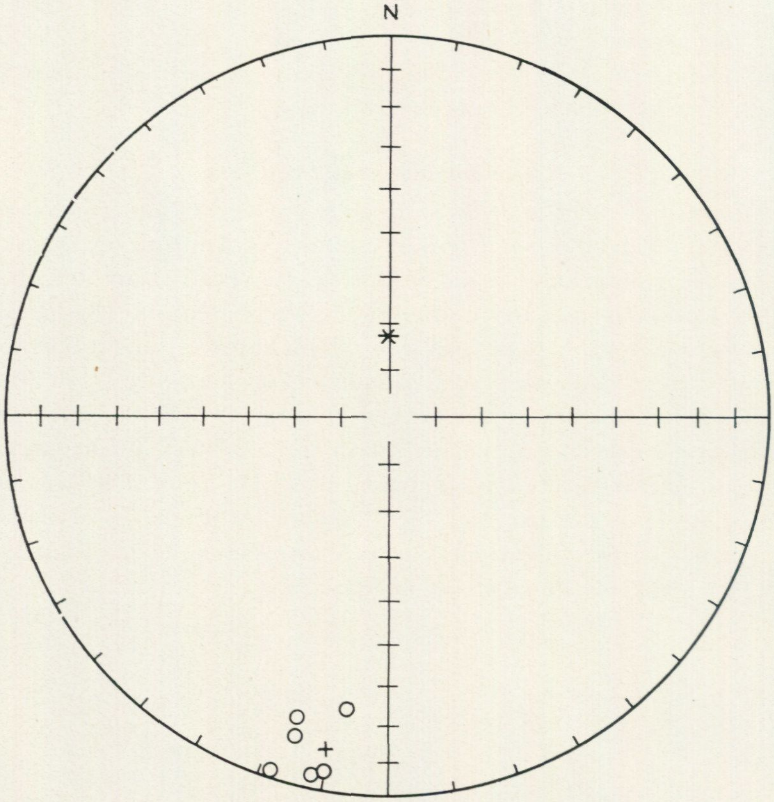


Fig. 15. Equal area projection of the average dyke directions in Skåne. Directions pointing up in open circles.

The NRM in the other samples of these series were analysed with three steps in alternating fields. The average cleaned direction of each dyke was calculated. These directions are listed in Table 7 and shown in Fig. 15.

Six samples of another dolerite dyke (MZH) were collected on the coast of the Baltic sea, south of Simrishamn. In this locality the dyke was found intruding Gothian rocks. The intensity of the NRM in these samples was approximately 2×10^{-3} emu/cm^3, the susceptibility 0.005. Treatment of the samples in alternating fields revealed a similar composition of the NRM as in the samples of the other dolerite dykes (Fig. 14).

In the western part of Skåne, in the dolerite quarry in the neighbourhood of Rönnarp, samples were collected from the northern wall, the middle and the southern wall of the dolerite dyke (MZE, MZF and MZG). The thickness of the dyke is about 40 m. The northern and southern borders are somewhat weathered. This was reproduced in the intensity and in the susceptibility.

Table 7. Average directions, Fisher's best estimates (k) and cone of confidences (α_{95}) of the rocks collected in Skåne

locality	series and number	decl.	incl.	k	α_{95}	average dyke direction				average direction of the dykes			
						decl.	incl.	k	α_{95}	decl.	incl.	k	α_{95}
Hedeberga	MZA 5					190°	– 7°	117	8°	190°	–11°	36	11°
Hedeberga	MZB 5					197°	–19°	2076	2°				
Dalby	MZC 6					188°	–24°	293	4°				
Dalby	MZD 5					196°	–14°	325	4°				
Rönnarp	MZE 6	198°	– 1°	258	4°	198°	– 1°						
	MZF 4	196°	+5°	203	5°								
	MZG 6	201°	– 8°	219	6°								
Simrishamn	MZH 6					192°	– 4°	285	4°				

These values were for the northern border and the southern border approximately 1×10^{-3} emu/cm^3 and 0.001. In the middle of the dyke the intensity of the NRM was 3×10^{-3} and the susceptibility 0.002.

Treatment of the samples in alternating fields revealed the same magnetic properties as in the samples of the other dolerite dykes in Skåne. The average magnetic directions of the samples from the northern, middle and southern part of the dyke are listed in Table 7. Remarkable differences are noticed in the average directions. Roughly there is another declination and a more upwards directed inclination in the middle of the dyke.

It is assumed that the differences are caused by the secular variation of the geomagnetic field during the cooling of the dolerite magma.

In Table 7 and in Fig. 15 the average directions of each dyke are given and from those the average direction of all the dykes was calculated. The average dyke direction was declination 190° and inclination –11°. The differences in the average inclinations for individual dykes were slight. In small dykes the cooling of the magma is of course rather rapid. So the magnetization of a small dyke represents the earth magnetic field during a relatively short time span. The differences of the magnetic directions in the dykes might conseqeuntly represent the secular variation due to slight differences in time of intrusion.

6. THERMAL EXPERIMENTS AND ANCIENT FIELD INTENSITY STUDIES

6.1. Apparatus

Thermal demagnetization as well as artificial thermal remagnetization experiments were made in order to test the NRM properties in the rock samples. For this purpose an electrically heated furnace placed in a field free space was constructed.

1) The field free space was created by three sets of square Helmholtz coils of 1.5 m. For the windings of the Helmholtz coils copper wire was used. Since the temperature coefficient of copper is 0.004, a fluctuation of only 2° C, caused by the heating of the furnace, would change the resistance of a set of coils with 0.8 %, which will result in a variation of the current through the coils if voltage stabilized power supplies are used. These disturbances should be about 350γ ($1\gamma = 10^{-5}$ Oe) if the earth magnetic field intensity is 0.44 Oe. In practice is was found that, to obtain reliable results, the magnetic field in the area used in the centre of the furnace should be less than 10γ during the whole heating and cooling cycle.

So, to avoid the fluctuations of the current, the Helmholtz coils were powered with current stabilized power supplies. The current required to cancel the earth magnetic field was found by placing an unidirectional probe of an Oerstedmeter (capable of measuring fields of 0.1γ) along each of the three mutually perpendicular axes of the Helmholtz coils. The diameter of the volume in which the fluctuations are less than 10γ was about 15 cm, so it was possible to treat 30 samples of about 11 cm^3 at the same time. After the heating cycle the field was measured again which still showed magnetic fields of less than 10γ.

2) The furnace was constructed of non-magnetic and non-metallic materials, with the exception of the heater windings. For the heater windings Nichrome wire was used, which is nonmagnetic in the applied temperature range. Around a frame of quartz bars sillimanite tubes were arranged. The sillimanite tubes contained the Nichrome windings. Each third part of the Nichrome windings was connected to one phase of a three phase current. With three variacs the current through each of the three sections could be regulated. The heating element was surrounded by loosely packed quartz wool and the whole was surrounded by isolating magnesium bricks.

The temperature in the furnace was controlled by three thermocouples. The output of one of them commanded a proportional temperature controller. The temperature controller regulated the current through the three sections of the heating element until the desired temperature of the furnace was reached and kept the furnace as long as necessary at that temperature. Of the other two thermocouples, one indicated the temperature in the furnace and the other one the temperature in a rock dummy in the furnace. The output of these thermocouples were registred on a recorder and if there were no more changes in the output it was assumed that the temperature was homogeneous in the rock samples. In order to avoid possible oxidation of the rock samples, the heating and cooling were made in argon gas.

6.2. Thermal demagnetization

In thermal demagnetization the rock samples were heated in steps to progressively higher temperatures and cooled to room temperature after each heating step in a zero field. After the cooling the intensity and the direction of the remaining magnetization was measured.

Thermal demagnetization is based on destroying the remanent magnetization of particles with blocking temperatures lower than the selected heating temperature. During the cooling, in a zero field, the domains in the particles acquire a random magnetization. The net effect of this random magnetization for the remanence is zero.

In contrast to the alternating field demagnetizing method the thermal effects have no preferential direction.

In the alternating field demagnetizing method, in which an alternating field of a certain strength is applied successively along three perpendicular axes, the maximum effect occurs in the domains with a magnetic moment directed parallel to the demagnetization axes. So, domains with a magnetic moment parallel to the applied field may already be demagnetised, whilst domains with the same coercive forces, but with another direction, may remain unaffected at the same strength of the alternating field. With our method of demagnetizing along three perpendicular axes one would expect that after each subsequent demagnetization step the remaining part of the magnetization will become more and more directed along the diagonal of the cube. In intrusive igneous rocks with a TRM, this effect was never observed to have any influence. This means that in these rocks the spreading of the directions of magnetic moments of domains contributing to the remanent magnetic direction is negligable. In rock samples with, for instance, a depositional remanent magnetization, however, the possibility of a larger spreading of the directions of the magnetic moments around the general direction of remanent magnetization exists. Dependent on the angle of the cone formed by individual magnetic moments of domains, treatment in alternating fields may then show a 'cleaned' magnetization which is not representative for the original remanent magnetization of the rock sample.

Since the thermal effects have no preferential direction, samples with a depositional remanent magnetization can better be tested thermally.

6.3. Thermal remagnetizations

The magnetic processes taking place during the formation of igneous rocks can be imitated by cooling rock samples from above their Curie temperatures to room temperature in fields comparable with the contemporary geomagnetic field intensity. These fields were created with the same set of Helmholtz coils as used in the thermal demagnetizing experiments.

For most rock types it has been shown that the TRM acquired upon cooling through the Curie points in fields up to one Oersted are proportional to the magnetic field in which it cools (Nagata, 1953). Thus if J is the intensity, H the field in which the rock sample has acquired its TRM and c is a constant depending on the rock type, then

$$J = c \cdot H$$

The magnetic intensity of dolerite samples acquired during cooling in fields of respectively 0.1, 0.2 and 0.3 Oe was measured. Fig. 16 shows the dependence of the average magnetic intensity acquired in these fields of ten dolerite samples from the sills in Västergötland.

Comparing the demagnetization diagrams of the original NRM of a sample with the demagnetization diagram of an artificial TRM of the same sample will give information about the TRM character of the original NRM.

In this study it is assumed that the acquisition of the remanent magnetization is independent of time.

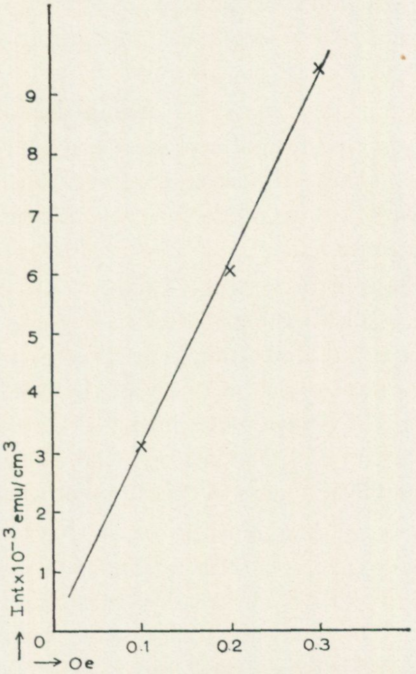


Fig. 16. Dependence of the magnetic intensity on the field intensities, in rock samples cooled from above their Curie temperatures (average of 10 dolerite samples).

6.4. Ancient field intensity studies

Comparing the artificially acquired magnetization with the original NRM intensity seems to be a simple method for the determination of the intensity of the geomagnetic field in the past.

If J_n is the NRM intensity acquired upon cooling in the original field H_o and J_a the artificial TRM intensity acquired upon cooling in a field H_a , then

$$H_o = H_a \cdot \frac{J_n}{J_a}$$

and if, H_{eq} is the equatorial magnetic field intensity and λ the paleolatitude, then

$$Heq = Ho\ (1+3\sin^2\lambda)^{-1/2}$$

However, objections can be made against this method. These are a) alteration of the NRM since the genesis of the rocks and b) alteration of the magnetic minerals in the rock samples during the laboratory heating and cooling experiments.

a) Alteration of the original NRM will be caused by the decay of the NRM and by the possible genesis of secondary magnetizations during the rock's history.

b) Alteration of the magnetic minerals during the laboratory experiments can be detected. The susceptibility of a rock sample will change if there is any transformation in the magnetic minerals. In general these changes are caused by oxidation or reduction. The oxidation can be avoided by heating and cooling the samples in argon gas.

Many studies have been made with the Thellier and Thellier (1959) method. With this method the natural partial TRM's are compared with the corresponding artificial partial TRM's. Another method is employed by Van Zijl et al., (1962), with this method the intensity of the NRM left after treatment in alternating fields of 220 Oe is compared with the intensity of an artificial TRM left after treatment in 220 Oe. The artificial TRM was acquired during cooling from above the Curie points in the ambient geomagnetic field.

In our study of the magnetic intensities of the NRM at different stages of its alternating field decay curves were compared with various artificial TRM's (acquired in various ambient field intensities) in the same rock samples at the corresponding stages of the alternating field decay curves. In comparing the intensities of NRM and artificial TRM one should remember that the intensity of the remanence remained after each demagnetization step depends both on the magnitude of the applied alternating field and the angle between this alternating field and the direction of the remanent magnetization. Corrections for these angles between the direction of the NRM and the nearest demagnetization direction were applied in the intensity studies in this Chapter.

As shown in the demagnetization diagrams in Chapter 5, the NRM in our rocks is normally composed of a primary magnetization and a secondary magnetization.

Only samples with a natural remanent magnetization which was composed of a very small viscous magnetization and a large stable magnetization were used in the thermal remagnetization experiments. For in samples containing a stronger secondary magnetization it is possible that during the acquirement of the secondary magnetization the original magnetization was affected. It follows that in this case the newly acquired virgin TRM may not be compared with the remnants of the TRM found in the samples. The artificial TRM's were acquired in our rock samples by cooling from above their Curie points in fields of 0.1, 0.2 and 0.3 Oe.

Samples in which the susceptibility was changed during the laboratory heating experiments were rejected.

Ancient field intensity studies were made on samples collected from:

1) the Precambrian hyperite-dolerite dykes in southern Sweden,

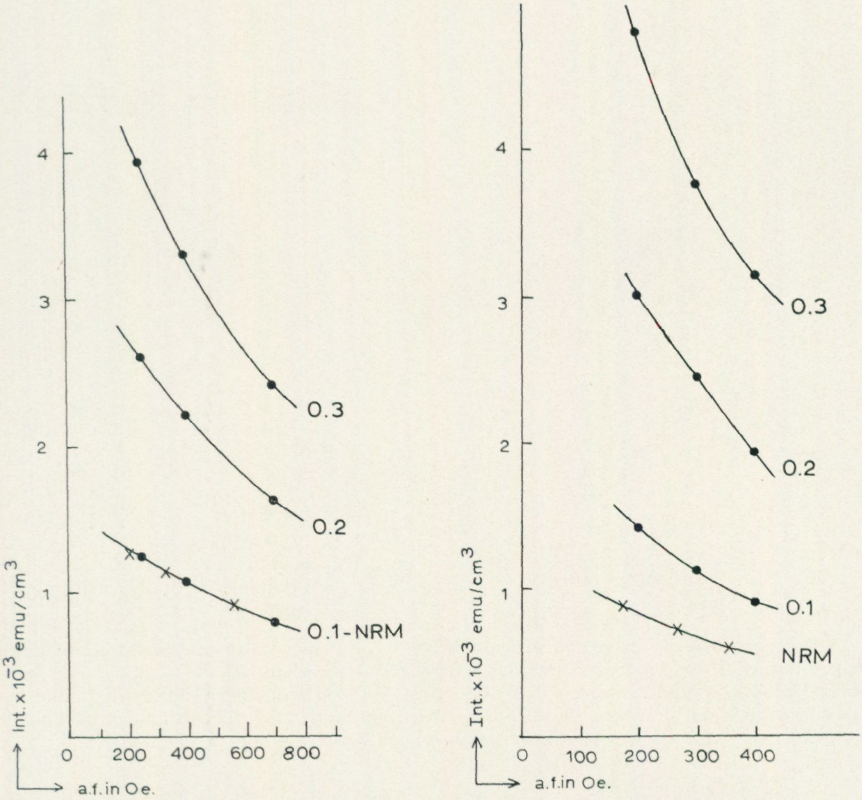


Fig. 17. Part of the decay curve of the original NRM (crosses), of the Precambrian hyperite-dolerite samples during alternating field demagnetization, compared with parts of the decay curves of the artificial TRM acquired in fields of 0.1, 0.2 and 0.3 Oe in the same samples (dots). Left, the mean decay curves of the four hyperite-dolerite samples with a negative polarity and right the mean decay curves of the two samples with a positive polarity.

2) the Paleozoic dolerite sills in Västergötland and the Paleozoic dolerite dykes in Skåne.

1) From the Precambrian hyperite-dolerite dykes of southern Sweden two samples with a positive polarity (MZK series) and four samples with a negative polarity (MZL and MZS series) were studied. The average demagnetization decay curves of the original NRM and of the artificial TRM's of the samples with a negative polarity and of the samples with a positive polarity are shown in Fig. 17.

Three points on the decay curves of the original NRM are compared with comparable points on the decay curves of the artificial TRM's. The local field intensities in the samples with a negative polarity range between 0.093 and 0.10

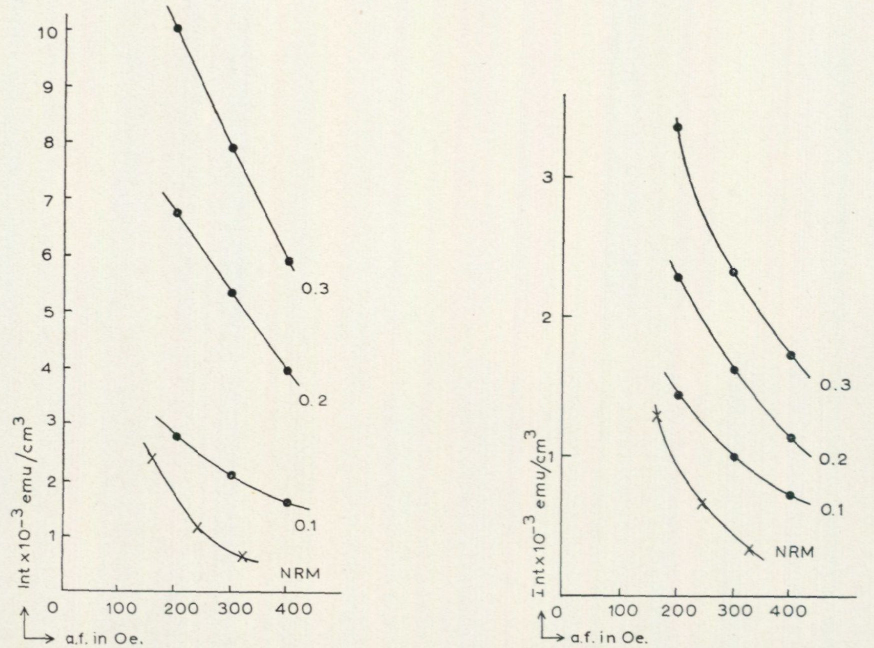


Fig. 18. Part of the decay curve of the original NRM, of Upper Carboniferous dolerite samples during alternating field demagnetization, compared with parts of the decay curves of the artificial TRM acquired in fields of 0.1, 0.2 and 0.3 Oe in the same samples. Left, the mean decay curves of seven dolerite samples of the dykes in Skåne and right the mean decay curves of ten samples of the sills in Västergötland.

Oe and the local field intensities in the samples with a positive polarity range between 0.054 and 0.063 Oe. The average values are 0.1 Oe and 0.06 Oe respectively. From these values and the paleolatitude, calculated from the inclination of the magnetization, the intensity of the equatorial field was calculated (Table 8).

From the local ancient field intensity the virtual magnetic dipole moment (M) can be calculated with the formula:

$$M = r^3(1+3\sin^2\lambda)^{-1/2} \cdot H$$

r = earth radius
H = local field intensity
λ = paleolatitude

These values are listed in Table 8. A significant fact is the difference in the equatorial field intensities during the two polarity periods.

2) For the geomagnetic intensity studies of the late Paleozoic ten samples of the dolerite sills in Västergötland and seven samples of the dolerite dykes in Skåne were used. Also in this case the artificial TRM was generated in fields of 0.1, 0.2 and 0.3 Oe.

Table 8. Ancient field intensities and virtual dipole moments

rock type	age in m.y.	number of samples	declination	inclination	polarity	paleo latitude	local field intensity in Oe.	equatorial field intensity	virtual magnetic dipole moment in 10^{25} gauss. cm^3
hyperite-dolerite dykes	1550 ± 100	4	126°	+45°	–	26°	0.10 ± 10 %	0.08 ± 10 %	1.8
hyperite-dolerite dykes	1550 ± 100	2	337°	– 53°	+	33°	0.06 ± 10 %	0.04 ± 10 %	0.9
dolerite sills	282 ± 5	10	199°	– 9°	–	5°	0.05 ± 20 %	0.05 ± 20 %	1.2
dolerite dykes	Upper-Carboniferous	7	190°	– 11°	–	5°	0.05 ± 20 %	0.05 ± 20 %	1.2

The decay curves of the original NRM and of the artificial TRM's of both these rock types are shown in Fig. 18.

Three points on the decay curves of the original NRM were compared with comparable points on the decay curves of the artificial TRM's. The values for the ancient local field intensity varied between 0.044 and 0.072 Oe and for the samples of the dolerite dykes intensities varying between 0.046 and 0.081 Oe.

The equatorial field intensity calculated from the average local field intensities and the paleolatitude is for the dolerites of the sills 0.05 Oe and for the dolerites of the dykes also 0.05 Oe (Table 8).

7. DISCUSSION OF THE RESULTS

7.1. Ancient field intensity studies

The intensity of the earth magnetic field is dependent on the latitude on earth. Therefore, the results of field intensity studies are often translated in equatorial field intensities or in virtual dipole moments of the earth (Chapter 6).

Comparison of the virtual dipole moments for geological time as listed by Smith (1967 and 1968) show great variations. These values are shown in Fig. 19.

In this figure a distinction is made between the data of Krs (1967) and Schwarz and Symons (1968) and the data obtained by many other authors. Both Krs as well as Schwarz and Symons obtained considerably higher data. In Fig. 19 these higher values are given in open circles. Krs has obtained a

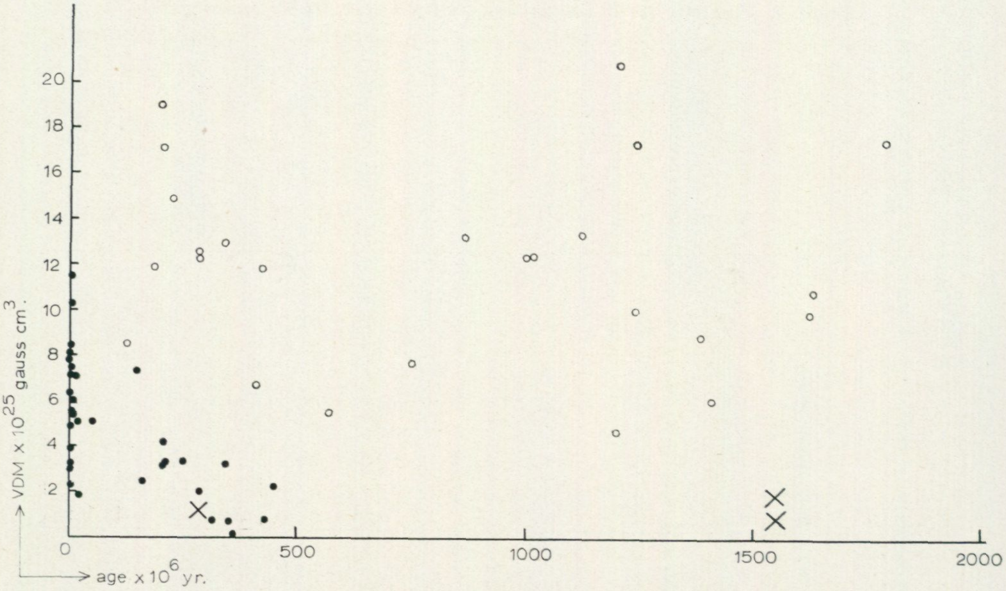


Fig. 19. Virtual dipole moments for geological time from the literature (the open circles represent the virtual dipole moments of Krs (1967a and 1967b) and of Schwarz and Symons (1968), the dots those of other previous authors). The crosses represent the values of this study.

Carboniferous-Permian virtual dipole moment of 13×10^{25} gauss. cm^3 and a Permian dipole moment of 12.8×10^{25} gauss. cm^3. Krs mentions that the Carboniferous-Permian cassiterite samples and the Permian ignimbrite sample possess significantly high paleomagnetic stability.

In the case of Schwarz and Symons each result given is obtained from one single sample. The natural remanent magnetic intensities in their samples were extremely high (10^{-2}–10^{-1} emu/cm^3). Schwarz and Symons analysed these samples with the Thellier and Thellier (1959) method in the temperature range between 300° and 500° C. As shown in their thermal decay curves the ration between the decay of the NRM and the increase of the partial TRM acquired in the samples after heating in the present geomagnetic field is constant in this temperature range. From this ratio, wich is supposed to be representative for the local ancient field intensity, the virtual dipole moments have been calculated. In the temperature range above 500° C, however, a distinctly different ratio can be observed in some of their decay curves, which would result in considerably lower virtual dipole moments. Consequently we surmise that in their case the original NRM intensities are probably mixed up with secondary remanent magnetizations.

The virtual geomagnetic dipole moments calculated from the Precambrian hyperite-dolerites (1550 ±100 m.y.) in our study (chapter 6) were 1.8×10^{25}

and 0.9×10^{25} gauss. cm^3, respectively. The difference of these two values may represent the fluctuation of the magnitude of the geomagnetic dipole moments between the two intrusion periods.

The samples of the dolerite sills in Västergötland gave the same values (1.2×10^{25} gauss. cm^3) for the earth magnetic dipole moment as detected in the samples from the dolerite dykes in Skåne.

This is in good agreement with the conclusion (Chapter 7.2.4.) that both types of dolerites intruded within a relatively short period in the Upper Carboniferous.

Dynamo theories of the origin of the earth magnetic field place the source of the main field within the earth core. At this moment there is some discussion as to whether the core has been growing to its present size throughout geological time (Urey, 1952; Runcorn, 1963) or was formed during the early history of the earth (Elsasser, 1963).

If the recently published data of Krs (1967) and of Schwarz and Symons (1968) are left out of consideration (in Fig. 19 open circles), then the virtual dipole moment of the earth has shown the tendency to increase during the last half billion years of geological time.

We need, however, more data about the strength of the earth magnetic field in particular in the Precambrian before we can establish a possible reliable relationship between the intensity of the earth magnetic field and the size of the earth core.

7.2. Paleomagnetic field directions and pole positions

The average directions of the most stable magnetizations determined in the rock samples as described in Chapter 5 and the paleomagnetic poles belonging to these average directions are listed in Table 9 and the poles are shown in Fig. 20.

7.2.1. PRECAMBRIAN ROCKS FROM DALARNA

The measurements and the analysis show that the NRM was rather stable in the rock samples collected in four localities of the Late-Jotnian or younger dolerites. The within site dispersion of the NRM direction of the series is, however, still rather high ($\alpha_{95} = 6°$ to $17°$).

Between the series there are large differences in the magnetic directions.

The paleomagnetic pole belonging to the average magnetic direction of these series is at 178° E and 23° N (nr. 1 in Fig. 20).

Age determinations were not made on these rocks, but since the dolerites have only invaded the Dala series and the Jotnian rocks and not the Lower Paleozoic sediments in the Siljan district, it is supposed that the dolerites are of Precambrian age.

In the samples of the Lower and Upper Dala series, the Dala granites and

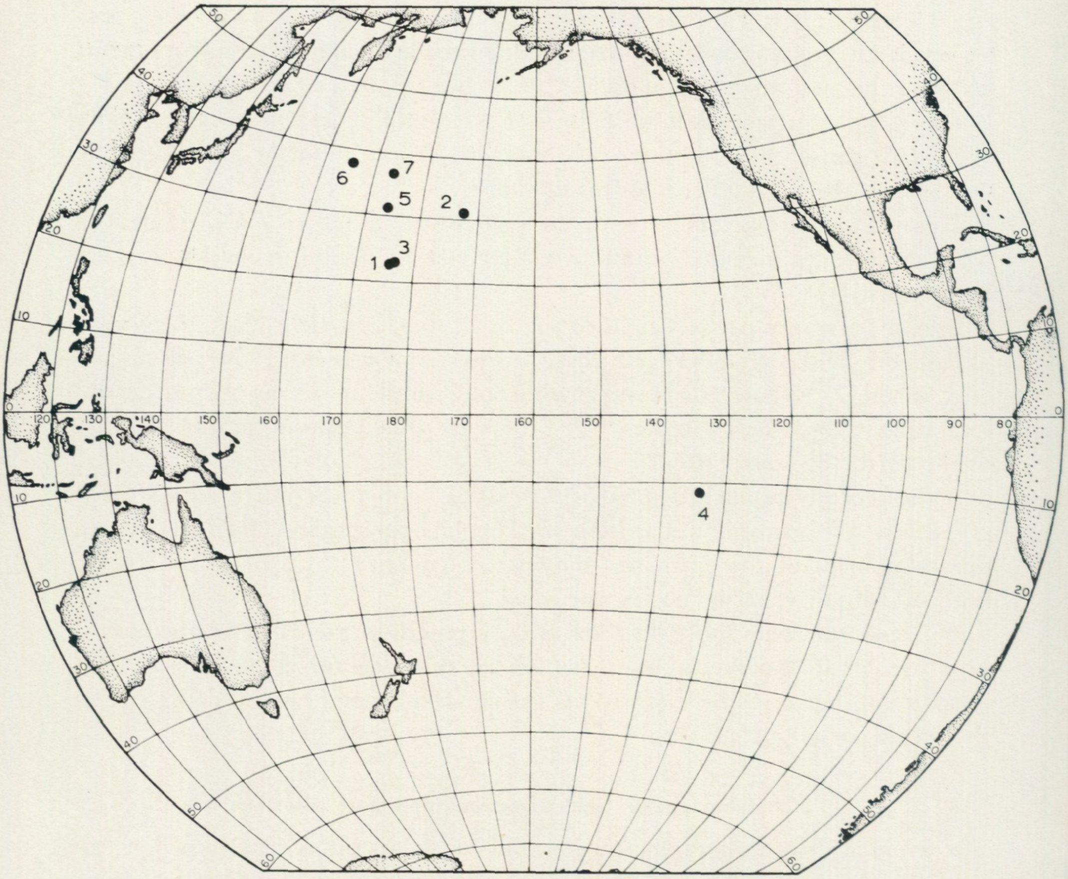


Fig. 20. Situation of the paleomagnetic poles found in the samples from 1) the Late Jotnian or younger dolerites, 2) the Jotnian basalts, 3) the Upper Dala porphyries, 4) the Gothian hyperite-dolerites, all of Precambrian age, 5) the Upper Carboniferous dolerite sill in E Västergötland, 6) the Upper Carboniferous dolerite sill in W Västergötland and 7) the Upper Carboniferous dolerite dykes in Skåne.

the Jotnian basalts, only those from two series of the porphyries rich in phenocrysts of the Upper Dala series and from two series of the Jotnian basalts showed more or less stable magnetizations. The pole positions belonging to the magnetizations in the samples of the two series of the porphyries are situated (in Fig. 20 numbers 2 and 3) a) very near to the Upper-Carboniferous poles of our study and b) near the lower Paleozoic poles of Norway (Storetvedt, 1967). This means either that the position of the paleomagnetic poles in the Paleozoic and in the Precambrian (Jotnian and Upper Dala period) were the same, or that the Precambrian rocks have acquired their stable magnetization during the Paleozoic. Taking into consideration the results of the age determinations the latter possibility is the most probable.

Table 9. Magnetic directions and pole positions of the rocks collected in the central and southern part of Sweden

Nr. fig. 20	Rock type	dated age × 10^6 y.	location		Nr. of sites	decl.	incl.	pole position	
1	Late Jotnian dolerite dykes		61° N	14° E	4	14°	− 9°	23° N	178° E
2	Jotnian basalts	745 − 931	61° N	13½° E	2	7°	+ 6°	32° N	174° W
3	Upper Dala volcanics	1570 ± 40	61½° N	14° E	2	17°	− 9°	23° N	176° W
	hyperite-dolerite dykes	835 ± 25	56½° N	14½° E	1	327½°	− 74½°	30° S	149° W
		781 ± 25	56½° N	14½° E	1	337°	− 53°	2° S	147° W
		1573 ± 50	57° N	14½° E	1	321½°	− 71½°	27° S	144° W
		1516 ± 50	59½° N	14° E	1	128°	+ 38½°	2° S	119° W
		886 ± 45	57° N	14½° E	1	124°	+ 51°	10° S	121° W
4	hyperite-dolerite average	1550 ± 100			5	317°	− 58°	12° S	134° W
5	dolerite sill eastern Västergötland	287 ± 15	58½° N	14° E	5 (mts.)	197°	− 2°	31° N	174° E
6	dolerite sill western Västergötland	279 ± 8	58½° N	12½° E	2 (mts.)	202°	− 17°	38° N	166° E
7	dolerite dykes Skåne	Upper-Carboniferous	55½° N	13½° E	6 (dykes)	190°	− 11°	37° N	174° E

From the situation of the magnetic poles, the spread of the K–Ar ages (from 931–605 m.y.), the fact that these ages are much younger than the Rb–Sr isochron age of the Dala porphyries and granites, and the proximity of the large Caledonian overthrust planes (present distance about 50 km), it may be concluded, that the Dala porphyries and granites, the Jotnian basalts and the late Jotnian or younger dolerites have acquired their present magnetization during the Caledonian orogeny.

The age measurements of the Jotnian basalt samples were like wise made according to the K–Ar method. They gave ages varying beetween 745 and 931 m.y. The age of the Jotnian, therefore is, at least 931 m.y. However, since the measured K–Ar ages of the underlying Dala porphyries and granites are certainly too young, it seems plausible that the measured ages of the Jotnian basalts are too young as well.

The soft and viscous NRM observed in most of the other samples can also be explained by the influences of the Caledonian orogeny. It is supposed that during the Caledonian orogeny the rocks lost any possible original remanent magnetization, under influence of a regional upwarming of the area to moderate temperatures. Instead of their original stable primary TRM, during the consecutive cooling, the rocks acquired a fairly soft moderate temperature TRM with rather low blocking temperatures, having low resistances against the later viscous decay. Only in the rocks from a few localities, representative magnetizations for the Caledonian orogeny remained.

7.2.2. PRECAMBRIAN HYPERITE-DOLERITES

The samples collected from the five hyperite-dolerite dykes intruded in the schistosity zone in southern Sweden all revealed a rather stable magnetization. The 'cleaned' magnetization in the samples of each series showed rather good within site concentrations ($\alpha_{95} = 1^\circ$ to 7°). Between the series there were variations however. Moreover the 'cleaned' magnetic direction of two dykes was nearly opposite to that in the other three dykes.

Age measurements performed with the K–Ar method revealed two different ages. Samples from three dykes gave ages of about 800–900 m.y. and samples of two other dykes an average age of 1550 ±100 m.y. The two K–Ar ages were found on dykes both with normal as well as reversed magnetizations.

As discussed in Chapter 2 it is assumed that the younger ages reflect the imprint of the Sveconorwegian event. Therefore, it is concluded that the remanent magnetization represents the direction of the earth magnetic field during the intrusion of the dolerite dykes in the Precambrian (1550 ±100 m.y.) and that during the younger Sveconorwegian orogeny the rocks of three dykes have lost their radiogenic argon whilst the remanent magnetization in these three dykes has not been affected during this event. Arguments in favour of this conclusion are a) the consistency over the five dykes, b) the difference in direction and according in pole position when compared with data from Paleozoic and younger rocks and c) the reversal, as expressed by the opposite direction in two of the five dykes. The differences in the magnetic directions may represent the secular variation of the earth magnetic field in the period between the first and the last hyperite-dolerite intrusion. The position of the paleomagnetic pole belonging to the average magnetic direction of the dykes is 134° W and 12° S (number 4 in Fig. 20).

Only few other Precambrian data of stable Europe are available, which, moreover have quite different ages. These data are:

a) Tärendö (Cornwell, 1968) with an age of 2000 m.y. gave a paleomagnetic pole at 132° W and 45° N. The gabbro samples were treated in fields of 150 Oe and in some cases the dispersion of the average site direction was lower before than after 'cleaning' in 150 Oe.

b) The Hame dolerites (Finland, Neuvonen, 1967) with an age of ± 1700 m.y. gave a paleomagnetic pole at 72° E and 67° N, which is in the present polar region. The magnetization in the Hame dolerites is thought by Neuvonen to be due to viscous magnetism.

c) Neuvonen (1965, 1966) reported in his studies on the dolerite samples of dykes in southern Finland pole positions at approximately 160° E and 5° N.

He assumed that the dykes have a Jotnian age and that the magnetization represents also the Jotnian. It does not seem unlikely (Neuvonen, 1966) that the dykes in southern Finland have a younger age. This would be in agreement with the situation of the paleomagnetic pole, lying in the neighbourhood of Paleozoic paleomagnetic poles of Europe.

d) Irving and Runcorn (1957), Irving (1957a) and Creer (1957a) have studied the late Precambrian Torridonian sandstones and the Longmyndian sediments of Great Britain. The remanent magnetizations revealed paleomagnetic pole positions at 137° W and 6° S for the Upper Torridonian, 118° W and 35° N for the Lower Torridonian and 120° W and 2° N for the Longmyndian. The differences in the locations of these paleomagnetic poles may be the consequence of insufficient cleaning of these samples studied during the early stages of paleomagnetic research.

e) Storetvedt (1965) reported in his study on the dolerite samples of dykes in southern Norway a magnetic direction which points to a pole position in the equatorial area of the Pacific.

As concluded by Storetvedt (1968) the deduced paleomagnetic field direction represents the geomagnetic field in a period in the Precambrian and so favours a Precambrian age for the intrusion of the dykes. This is in rather good agreement with the paleomagnetic results of the Precambrian hyperite-dolerite dykes in our study.

7.2.3. ORDOVICIAN LIMESTONES FROM VÄSTERGÖTLAND AND ÖLAND

The Ordovician limestones collected in Västergötland showed magnetic directions equal to the magnetic directions in the samples from the overlying dolerite caps. The paleomagnetic pole belonging to this direction is situated at 173° E and 31° N. As it is assumed that there has been apparent polar wandering in the Devonian and in the Carboniferous, it is concluded that the Ordovician sediments have acquired their present magnetization during the intrusion of the overlying dolerite sills in Upper Carboniferous times.

The Ordovician limestone samples from Öland contained a rather weak magnetization. Demagnetization either thermally or in alternating fields did not give reliable results.

7.2.4. PALEOZOIC DOLERITES FROM VÄSTERGÖTLAND AND SKÅNE (NRS. 5, 6 AND 7 IN FIG. 20)

The magnetic measurements of the samples from the dolerite sills in Västergötland (east and west) and from the dolerite dykes in Skåne gave closely comparable pole positions.

The age of the sills in E Västergötland and W Västergötland is 287 ±15 m.y. and 279 ±8 m.y., respectively. This age places the time of intrusion at the Carboniferous-Permian boundary.

The position of the paleomagnetic poles as calculated from the samples of the sills and from the samples of the dykes are not significantly different from each other. From this it is concluded that the dolerites in Västergötland and in Skåne have acquired their remanent magnetization during the same period.

The average magnetic pole position of Europe in the Upper Carboniferous calculated from the pole positions as given by Irving (1960, 1961, 1962) and Mc Elhinny (1968) in their lists 1–9 of Paleomagnetic directions and pole positions is 172° E and 37° N (average of the poles: list 1/pole 96, 2/36, 4/19+20, 4/23+25, 5/48+49+9/92, 6/54, 8/110, 8/111, 9/93, 9/94+95).

The situation of this paleomagnetic pole is not significantly different from the situation of the Upper Carboniferous poles determined in our study.

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