

GEOCHRONOLOGICAL AND PALAEOMAGNETIC RECONNAISSANCE SURVEY IN PARTS OF CENTRAL AND SOUTHERN SWEDEN

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Palaeomagnetic investigations and isotopic age determinations were made on various Precambrian and Palaeozoic rocks from southern and central Sweden. (1) In Dalarna (central Sweden), Rb-Sr determinations show that the Upper Dala volcanics and the Dala "Garberg granite" have a Gothian age of 1405 ± 30 million years. K-Ar measurements on these rocks and on Jotnian basalts evidence processes of (partial) argon loss in younger time. Palaeomagnetic measurements reveal that the rocks in this region have been remagnetized in Lower Palaeozoic (probably Caledonian) time. (2) K-Ar measurements suggest that the Precambrian hyperite-dolerite dykes in the "central schistosity zone"

(southern Sweden) were intruded about 1550 ± 100 million years ago. In the southern part of this zone the dykes show "over-printed" ages of 800–900 million years. The hyperite-dolerite dykes indicate a magnetic pole position at approximately 15° S and 135° W. This Precambrian pole position is thought to have an age of about 1550 ± 100 million years. (3) Palaeozoic dolerite sills in Västergötland (southern Sweden) and dykes in Skåne show an Upper Palaeozoic initial remanent magnetic direction with a pole position at approximately 35° N and 175° E, which is in excellent agreement with the K-Ar age of 282 ± 5 million years (Permian/Carboniferous) measured on two sills.

1. Introduction

In order to test the possibility of obtaining information about the magnetic pole positions in southern and central Sweden through the geological column, a reconnaissance survey has been carried out on various Precambrian and Palaeozoic igneous rocks and limestones. There is, however, much uncertainty with regard to the ages of most of the igneous rocks involved. Therefore, in connection with this survey, isotopic age determinations were performed on a number of basalts, dolerites, rhyolites and a granite, with the intention of determining if relevant age information could be obtained. In total sixteen rocks have been dated. The sampling sites are shown in fig. 1. Whole-rock samples of four rhyolites and the granite were analyzed according to the Rb-Sr and K-Ar methods. Four basalts and seven dolerites were studied by the whole-rock K-Ar method.

The studies have been made on samples from the following regions (fig. 1):

- 1) Precambrian volcanics and intrusives in Dalarna;

- 2) Precambrian hyperite-dolerite dykes in Skåne, Småland and Värmland;
- 3) Palaeozoic dolerite sills and limestones in Västergötland;
- 4) Palaeozoic dolerite dykes in Skåne.

2. Analytical procedures and techniques

2.1. Palaeomagnetic measurements

Oriented hand samples were obtained in Dalarna, while in Skåne and Västergötland oriented core samples were drilled with a portable rock-drill. The magnetic measurements were made with the astatic magnetometers described by As (1960). The Natural Remanent Magnetization (N.R.M.) was analyzed according to the method of demagnetization by a.c. magnetic fields described by AS and ZIJDERVELD (1958) and ZIJDERVELD (1957). In order to eliminate the weak secondary magnetization of the Dalarna rocks and the samples of the Palaeozoic dolerite dykes and sills, a.c. fields of 200 Oe peak value have been applied. For eliminating the secondary component of the Precambrian hyperite-dolerites a field of 400 Oe was required. All samples were further stepwise demagnetized by a.c. fields, if necessary up to 3000 Oe peak value. For each sampling

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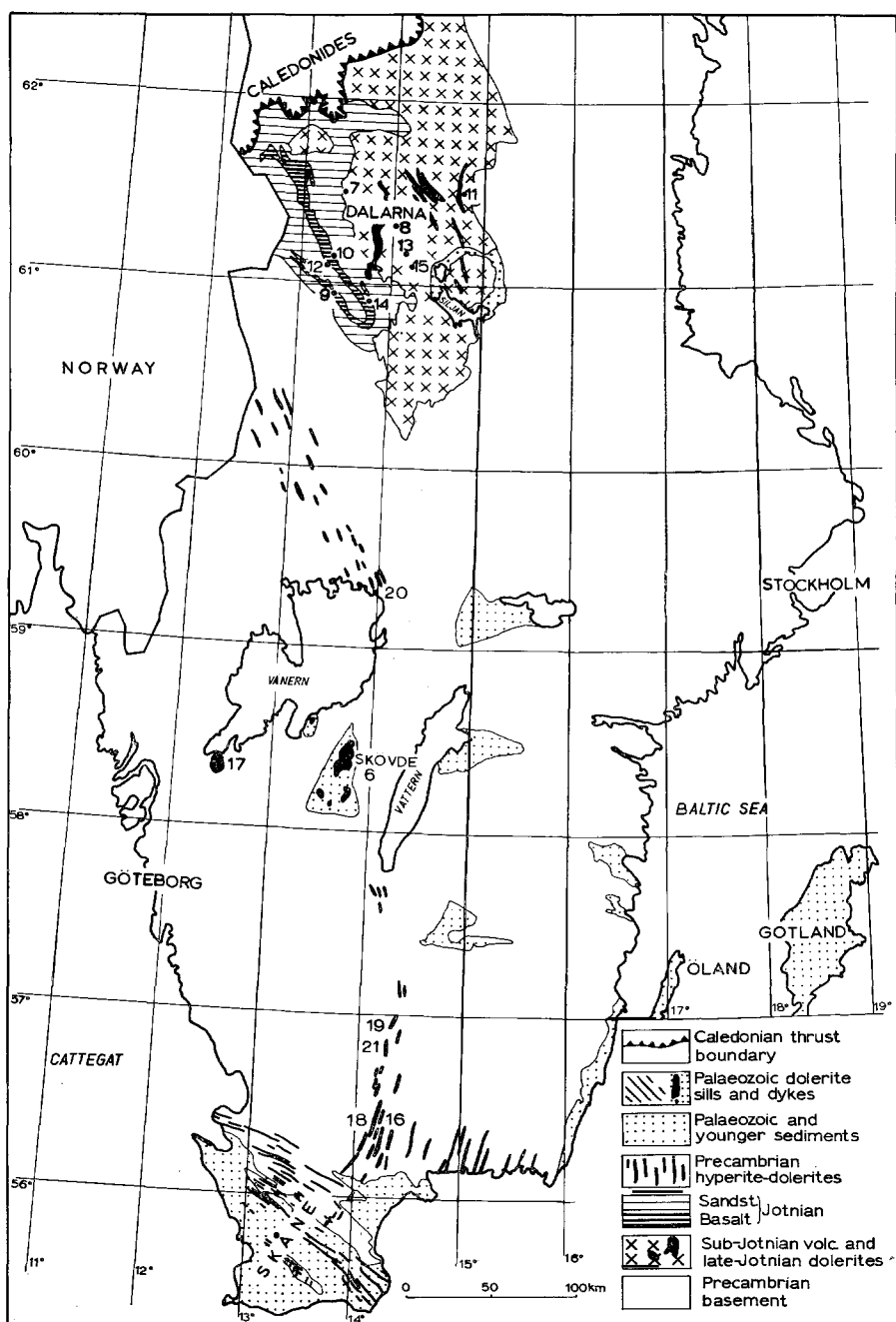


Fig. 1. Sketch map of southern and central Sweden showing the geological setting of the samples investigated. The figures 6–21 refer to the sampling sites of the dated samples 66 Dal 6–68 Dal 21 (cf. table 2, table 3 and table 4). 6: olivine dolerite; 7, 8, 11, 13: porphyric albite rhyolites; 9, 10, 12, 14: basalts ("Öje diabas"); 15: albite granite ("Garberg granite"); 16, 18, 19, 20, 21: "hyperite-dolerites" (16, 21: biotite-bearing hypersthene dolerites; 18: biotite dolerite; 19: biotite-bearing hornblende dolerite; 20: biotite-bearing olivine dolerite); 17: quartz dolerite.

TABLE 1

Average directions of remanent magnetization. The numbers refer to the sampling sites shown in fig. 1.

| | Nr. sampling site | Location | N* | D | I | k | α_{95} | Pole position | ∂p | ∂m |
|-----------------------------|----------------------|---------------|--------|-------|--------|------|---------------|---------------|--------------|--------------|
| Upper Dala volcanics | 7, 8, 11, 13 | 61½° N 14° E | 3 (27) | 18° | — 1° | 22 | 27° | 27° N 174° E | 13½° | 27° |
| Jotnian basalts | 9, 10, 12, 14 | 61° N 13½° E | 2 (16) | 7° | + 6° | 584 | 10° | 32° N 174° W | 5° | 10° |
| Late Jotnian dolerite dykes | | 61° N 14° E | 4 (27) | 14° | — 9° | 6 | 40° | 23° N 178° E | 20½° | 40° |
| Hyperite-dolerite dyke | 16 | 56½° N 14½° E | 1 (50) | 327½° | — 74½° | 338 | 1° | 30° S 149° W | 1½° | 2° |
| Hyperite-dolerite dyke | 18 | 56½° N 14½° E | 1 (5) | 337° | — 53° | 163 | 6° | 2° S 147° W | 6° | 8° |
| Hyperite-dolerite dyke | 19 | 57° N 14½° E | 1 (5) | 321½° | — 71½° | 1372 | 2° | 27° S 144° W | 3° | 3° |
| Hyperite-dolerite dyke | 20 | 59½° N 14° E | 1 (5) | 128° | + 38½° | 117 | 7° | 2° S 119° W | 5° | 8° |
| Hyperite-dolerite dyke | 21 | 57° N 14½° E | 1 (5) | 124° | + 51° | 1892 | 2° | 10° S 121° W | 2° | 3° |
| Hyperite-dolerite dykes | average | | 5 (70) | 317° | — 58° | 23 | 16° | 12° S 134° W | 17° | 23° |
| Dolerite sill Mt. Billingen | 6 | 58½° N 14° E | 9 (80) | 198° | — 3° | 529 | 2° | 31° N 174° E | 1° | 2° |
| Dolerite sill Mt. Hunneberg | 17 | 58½° N 12½° E | 3 (33) | 201° | — 17° | 660 | 5° | 38° N 177° E | 3° | 5° |
| Dolerite dykes from Skåne | | 55½° N 13½° E | 8 (48) | 195° | — 9° | 60 | 7° | 37° N 174° E | 4° | 7° |

* N = 3 (27) means 3 sites, 27 samples.

site the average direction of remanent magnetization was computed. The data are listed in table 1.

Where necessary, the directions have been corrected for tectonic tilt using the bedding of adjoining sediments.

2.2. Isotopic age determinations

Splits of crushed and pulverized whole-rock samples were analyzed for their Rb and Sr contents, both by stable isotope dilution (BOELRIJK, 1966) and by X-ray fluorescence. The isotope measurements were made on a 20 cm, 60° mass-spectrometer, utilizing thermal ionization and multiplier detection. A single (Ta) filament source was employed for Sr measurements, whereas Rb analyses were made with a double (Re) filament source. $^{87}\text{Sr}/^{86}\text{Sr}$ ratios were obtained by direct measurements on unspiked samples; the ratios were normalized for $^{88}\text{Sr}/^{86}\text{Sr} = 8.3751$ in order to reduce effects of mass discrimination. The signals of the ion beams were recorded either in the conventional way on a chart recorder, or by a digital voltmeter with a printer system¹.

¹ This digital method of recording and analyzing the mass-spectrum data was designed by E. H. Hebeda. The input of a digital voltmeter is connected to the D.C. amplifier output. Via a serialiser the digital voltmeter is connected with four printers with accumulating registers. When a mass peak is scanned magnetically, the digital voltmeter is switched by a level detector to "maximum mode". In this mode the voltmeter stores only the maximum voltage, i.e. the top of the mass peak. When the voltage drops below an adjusted value, the level detector produces a

trigger signal. This signal activates one printer, which records the stored mass height in volts. Simultaneously, the scanning unit starts scanning the next mass. Each mass is recorded on a separate printer. After ten scans each printer totalizes automatically the ten peak heights recorded. Since the scanning pattern is up and down and the time intervals between the successive masses are made equal, any increase or decrease in ion emission is thus corrected for. At least four groups of ten scans are recorded. From the totals of each group the isotope ratios are computed.

Potassium determinations were made by flame-photometry with a lithium internal standard. Argon was determined by standard isotope dilution techniques (using ^{38}Ar as tracer) on a Reynolds-type glass mass-spectrometer; the measurements were made by the static method.

TABLE 2

Rb-Sr data for the Dala porphyries and Garberg granite

| Sample | $^{87}\text{Sr}/^{86}\text{Sr}$ | Rb (ppm Wt.) | Sr (ppm Wt.) | $^{87}\text{Rb}/^{86}\text{Sr}$ |
|-----------|---------------------------------|-----------------|-----------------|---------------------------------|
| 66 Dal 7 | 1.162 | 228 | 31.3 | 21.8 |
| 66 Dal 8 | 0.7899 | 180 | 140 | 3.74 |
| 66 Dal 11 | 0.7718 | 144 | 139 | 3.01 |
| 66 Dal 13 | 0.7422 | 176.5 | 316 | 1.62 |
| 66 Dal 15 | 0.7526 | 191 | 272 | 2.04 |

trigger signal. This signal activates one printer, which records the stored mass height in volts. Simultaneously, the scanning unit starts scanning the next mass. Each mass is recorded on a separate printer. After ten scans each printer totalizes automatically the ten peak heights recorded. Since the scanning pattern is up and down and the time intervals between the successive masses are made equal, any increase or decrease in ion emission is thus corrected for. At least four groups of ten scans are recorded. From the totals of each group the isotope ratios are computed.

TABLE 3
K-Ar data and calculated ages for the Dala porphyries and Garberg granite

| Sample | K (Wt. %) | Rad. ^{40}Ar (ppm Wt.) | Age million years |
|-----------|--------------|------------------------------------|----------------------|
| 66 Dal 7 | 4.44 | 0.223 | 605 ± 30 |
| 66 Dal 8 | 5.43 | 0.330 | 701 ± 35 |
| 66 Dal 11 | 5.38 | 0.383 | 806 ± 40 |
| 66 Dal 13 | 4.64 | 0.389 | 921 ± 45 |
| 66 Dal 15 | 3.98 | 0.251 | 736 ± 36 |

The relevant analytical data and calculated ages are presented in table 2, table 3 and table 4. All data are average values of two to four analyses. Ages were computed using the following constants:

for ^{87}Rb : $\lambda = 1.47 \times 10^{-11} \text{ yr}^{-1}$;

for ^{40}K : $\lambda_e = 5.85 \times 10^{-11} \text{ yr}^{-1}$; $\lambda_\beta = 4.72 \times 10^{-10} \text{ yr}^{-1}$, and atom % ^{40}K in K = 0.0118.

TABLE 4
K-Ar data and calculated ages for dolerites and basalts from southern and central Sweden

| Sample | K (Wt. %) | Rad. ^{40}Ar (ppm Wt.) | Age million years |
|-----------|--------------|------------------------------------|----------------------|
| 66 Dal 6 | 0.389 | 8.50×10^{-3} | 287 ± 15 |
| 66 Dal 9 | 0.89 | 75.6×10^{-3} | 931 ± 28 |
| 66 Dal 10 | 0.497 | 38.8×10^{-3} | 873 ± 45 |
| 66 Dal 12 | 1.99 | 0.128 | 745 ± 25 |
| 66 Dal 14 | 1.37 | 0.108 | 873 ± 45 |
| 67 Dal 16 | 1.45 | 0.108 | 838 ± 25 |
| 67 Dal 17 | 0.639 | 13.55×10^{-3} | 279 ± 8 |
| 68 Dal 18 | 2.41 | 0.165 | 781 ± 25 |
| 68 Dal 19 | 0.791 | 0.137 | 1573 ± 50 |
| 68 Dal 20 | 0.634 | 0.105 | 1516 ± 50 |
| 68 Dal 21 | 1.03 | 82.1×10^{-3} | 886 ± 45 |

3. Results and discussion

3.1. Precambrian volcanics and intrusives from Dalarna

An elaborate study of the geology of this region was recently published by HJELMQVIST (1966). Among the Jotnian and sub-Jotnian supracrustal rocks he distinguishes the following main units:

Late Jotnian dolerite dykes ("Åsby diabas" and "Särna diabas")

Jotnian sandstones, divided by thick basalt flows ("Öje diabas") in an upper and a lower section

sub-Jotnian { Dala granites (including the "Garberg granite")
Upper Dala volcanics
Lower Dala volcanics.

Upper and Lower Dala volcanics are mainly composed of various types of porphyries (in part of ignimbritic character). The Dala volcanics have been intruded by the Dala granites. The "Öje diabas" is made of thick and persistent extrusive basalt flows, locally displaying pronounced pillow structures. The Late Jotnian dolerite dykes cut the Jotnian sediments.

A Rb-Sr isochron plot of porphyries belonging to the Upper Dala volcanics shows that the whole-rock data-points are linearly correlated (table 2 and fig. 2). The isochron gives an age of 1405 ± 30 million years with an initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratio of 0.7097 ± 0.0023 . This age places the extrusion of the Dala porphyries within the Gothian cycle (MAGNUSSON, 1965). The Garberg granite sample also fits nicely into the isochron, indicating that the time interval between eruption of the porphyries and intrusion of the Garberg granite into the porphyries must have been relatively short. This supports the hypothesis by RUTTEN (1966) that the Dala granites are no normal intrusive batholiths, but that they represent rheo-ignimbritic masses related to the eruption of the Dala porphyries.

These Rb-Sr age data differ from those obtained by WELIN *et al.* (1966), who concluded on the basis of Rb-Sr determinations on three Dala porphyry samples

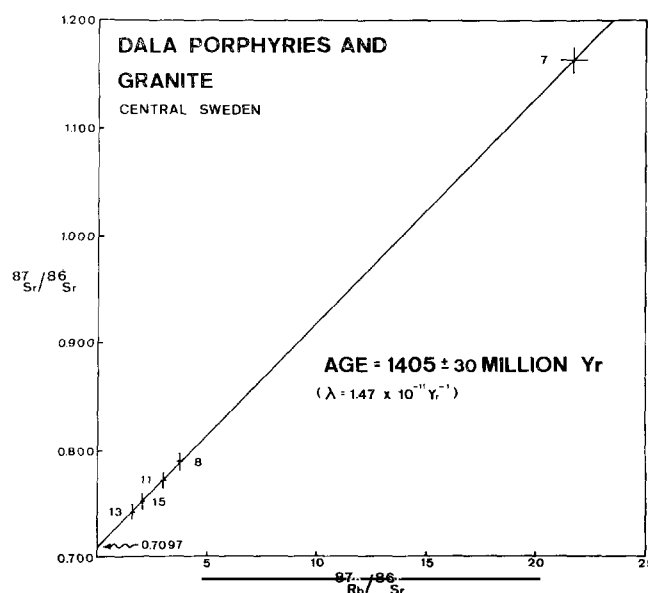


Fig. 2. $^{87}\text{Sr}/^{86}\text{Sr}$ versus $^{87}\text{Rb}/^{86}\text{Sr}$ isochron for whole-rock samples of four Upper Dala porphyries and the Garberg granite. Error bars estimated at $\pm 3\%$ for the $^{87}\text{Rb}/^{86}\text{Sr}$ ratios and $\pm 1\%$ for the $^{87}\text{Sr}/^{86}\text{Sr}$ ratios.

to an age of about 1595 million years (WELIN's figure of 1685 million years was recomputed with the ^{87}Rb decay constant used in this study). This difference is unexplained. Possibly, WELIN *et al.* (1966) were dealing with samples containing (xenolithic) older material.

K-Ar determinations on the Upper Dala porphyries and Garberg granite yield much younger apparent ages: scattering between 605 and 921 million years (table 3). These ages might be interpreted as functions of argon leakage due to mild regional metamorphic (thermal) events in younger time. In part, the argon leakage could have resulted from episodic loss during the Sveconorwegian orogenic period, about 1100–900 million years ago, the youngest Precambrian period of igneous activity wide-spread in southern Scandinavia (WELIN, 1966). Episodic loss of some argon due to Caledonian disturbances is also possible, however, in view of the apparent K-Ar ages much younger than about 900 million years. Moreover, the thrust boundaries of the large Caledonian nappes lie only 50–100 km NW of the sampling sites (fig. 1).

Similar considerations apply to the "Öje diabas". K-Ar determinations on samples of this extrusive mass yield apparent ages between 745 and 931 million years (table 4). Ages in this range seem to be too young for the basalt flows, which are intercalated between Jotnian Dala sandstones. (MAGNUSSON, 1965, mentions an age of 1200–1300 million years for the Dala sandstones). The apparent ages lower than about 900 million years might suggest that these rocks, after a possible episodic argon loss during the Sveconorwegian orogeny, have undergone also some partial "rejuvenation" process in Caledonian time.

Palaeomagnetic measurements were made on 180 samples from the sub-Jotnian and Jotnian sequence. However, most of the samples from the Jotnian sandstones, the Lower Dala volcanics and the Dala granites proved to be unsuitable for palaeomagnetic studies, as their N.R.M. is entirely due to viscous magnetism.

In only 70 of the samples investigated the demagnetization by a.c. magnetic fields revealed, besides a soft recent magnetization, another component of N.R.M. with a direction strongly divergent from that of the present magnetic field. All these samples are from the Upper Dala volcanics, the Jotnian basalts and the late-Jotnian dolerite dykes. The direction of this stable remanence is similar in all samples (fig. 3). The average

direction corresponds with a virtual magnetic pole position at approximately 20° N and 175° E, which is situated amidst the European Lower Palaeozoic poles as discussed by IRVING (1964) and STORETVEDT (1967). Therefore, it is concluded that the stable N.R.M. of the rocks under consideration is due to remagnetization in Lower Palaeozoic (probably Caledonian) time.

If the complete remagnetization of the rocks reflects Caledonian disturbances, it is noteworthy that this event is much less recorded in the K-Ar age pattern. The K-Ar data show that only very limited losses of radiogenic argon have occurred in Caledonian time. Apparently, the initial remanent magnetization in these basaltic and rhyolitic rocks was less resistant towards mild metamorphism than the whole-rock K-Ar age.

3.2. *Precambrian hyperite-dolerite dykes from Skåne, Småland and Värmland*

An elongated zone of hyperite-dolerite dykes invading gneisses and granites extends from south Sweden into Norway (the so-called "central schistosity zone" according to MAGNUSSON, 1965). From five hyperite-dolerite dykes 70 samples were collected for palaeomagnetic studies. Besides a small amount of soft recent magnetization, these samples reveal a component of N.R.M. distinctly different from the recent field (fig. 4). No correction for tectonic tilt was possible, but the good agreement in remanent directions between samples from all dykes indicates that the direction has not been tectonically disturbed. The remanence corresponds with a magnetic pole position at approximately 15° S and 135° W, quite different from the European Palaeozoic and younger poles listed by IRVING (1964). Therefore, it is concluded that this N.R.M. refers to a Precambrian pole position.

Samples from the five hyperite-dolerite dykes have been dated by the whole-rock K-Ar method, yielding apparent ages ranging from 781 to 1573 million years (table 4). Three dykes give ages around 800–900 million years, while the other two dykes have ages of about 1500–1600 million years. The younger ages, measured on dykes in the southern part of the "central schistosity zone", may represent "overprinted ages" due to the Sveconorwegian event (ages in this range are widespread in south-western Sweden, cf. MAGNUSSON, 1965). The two dykes with ages of 1500–1600 million years are

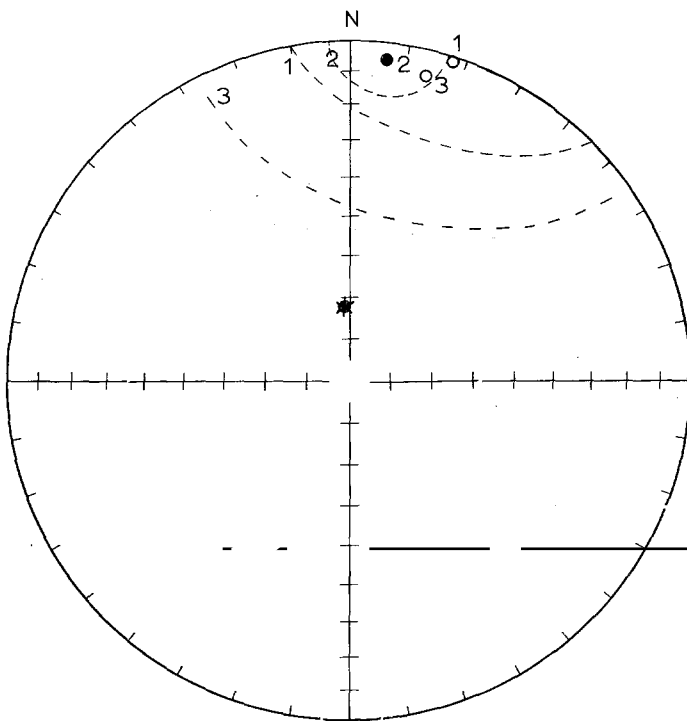


Fig. 3

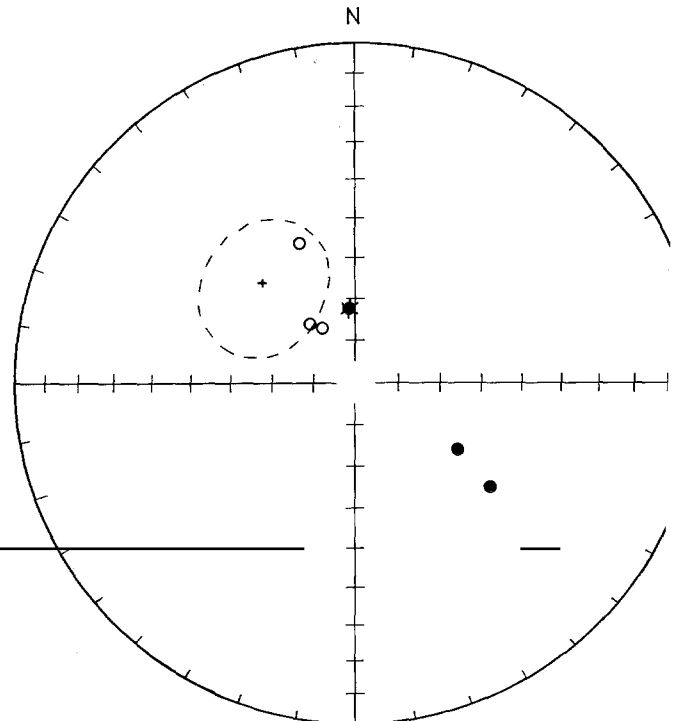


Fig. 4

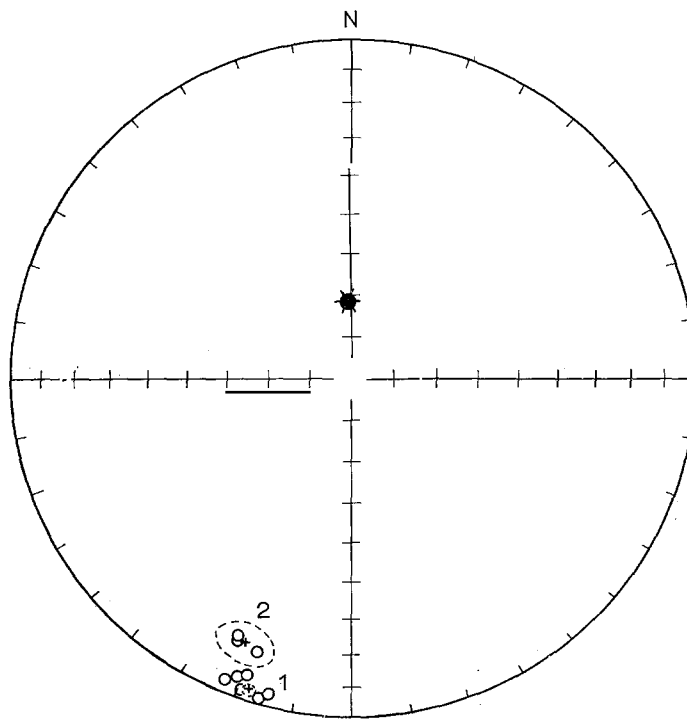


Fig. 5

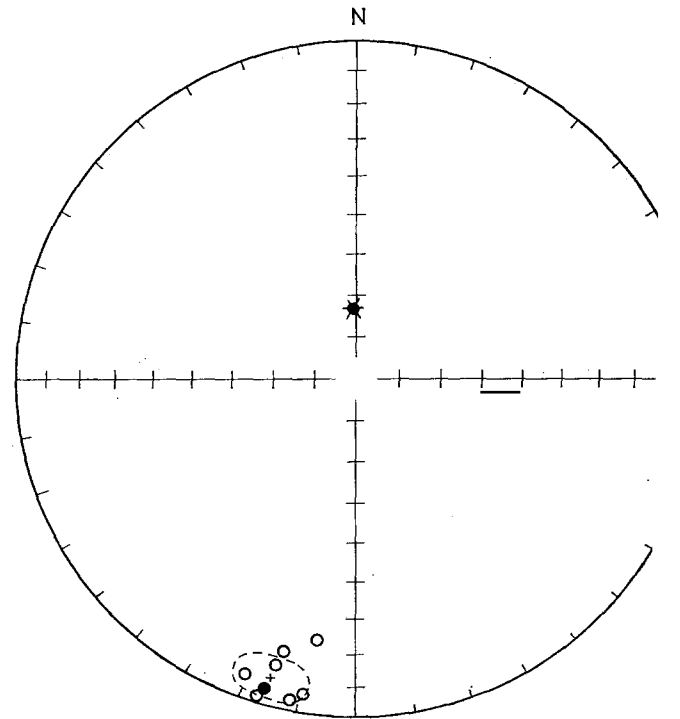


Fig. 6

Fig. 3-6. Mean site directions of remanent magnetization (or mean directions of groups of sites in fig. 3) after tectonic correction and magnetic "cleaning". Equal area projection. Directions pointing up in open circles, pointing down in full dots.

* Present geomagnetic field direction. + Average direction of remanent magnetization in all sampling sites. ----- Circles of confidence (95% level).

Fig. 3: 1 = Upper Dala volcanics, 2 = Jotnian basalts, 3 = Late Jotnian dolerites. Fig. 4: Precambrian hyperite-dolerite dykes from the "central schistosity zone". Fig. 5: Upper Palaeozoic dolerite sills from Västergötland: 1 = Mt. Billingen, 2 = Mt. Hunneberg. Fig. 6: Upper Palaeozoic dolerite dykes from Skåne.

situated more to the north (some 15 and 270 km, respectively). MAGNUSSON (1965) mentions a K-Ar age of 1270 million years for the so-called Vaggeryd syenite, which sends dykes into the hyperite-dolerites. Therefore, an age of approximately 1550 ± 100 million years does not seem improbable for the intrusion of the hyperite-dolerite dykes.

A remarkable fact is that the remanent magnetic direction in two of the dykes is reversed with regard to the direction in the other three dykes. There is no relation between magnetic polarity and K-Ar age. This strongly suggests that the N.R.M. direction represents the initial remanent magnetization of the dykes and is not due to a remagnetization in younger time.

Tentatively, it may thus be concluded that the Precambrian pole position revealed by the hyperite-dolerite dykes has an age of approximately 1550 ± 100 million years.

3.3 Palaeozoic dolerite sills and limestones from Västergötland

Between the lakes Vänern and Vättern in Västergötland 113 samples from various dolerite sills and 23 samples from the Ordovician limestone underlying the dolerite sills were collected. The dolerites have intruded into Lower Palaeozoic sediments (MAGNUSSON *et al.*, 1960; THORSLUND and JAANUSSON, 1960).

All the dolerite samples contain a stable N.R.M. distinctly different from the present magnetic field direction (fig. 5). The average stable remanent direction gives a virtual pole position at approximately 35° N and 175° E, which falls among the European Upper Palaeozoic pole positions as listed by IRVING (1964).

The results of the palaeomagnetic measurements are in excellent agreement with K-Ar whole-rock age determinations on samples from the dolerite caps at Mt. Billingen and Mt. Hunneberg (66 Dal 6 and 66 Dal 17, respectively). These determinations point to an age of 282 ± 5 million years (table 4): approximately at the Permian/Carboniferous boundary according to the GEOLOGICAL SOCIETY PHANEROZOIC TIME-SCALE (1964).

Ordovician limestones, collected below two sills, show a direction of stable N.R.M. identical to that of the dolerites. Obviously, the limestones have been remagnetized during the intrusion of the sills in Permian/Carboniferous time.

3.4 Palaeozoic dolerite dykes from Skåne

From eight dolerite dykes in Skåne 48 samples were investigated. The dykes have a roughly NW-SE strike and invade pre-Gothian gneisses and Lower Palaeozoic sediments (HJELMQVIST, 1939).

The average stable remanent direction of the dolerite samples is identical to the magnetic direction of the dolerite sills in Västergötland (fig. 6). Therefore, it is concluded that they have the same Permian/Carboniferous age.

4. Conclusions

1. Whole-rock Rb-Sr studies point to a Gothian age of 1405 ± 30 million years for the sub-Jotnian Upper Dala porphyries and Garberg granite in Dalarna.

2. All samples from Dalarna investigated by K-Ar dating (Upper Dala volcanics, Garberg granite and Jotnian basalts) appear to have suffered from processes of (partial) argon loss.

3. The stable component of N.R.M. measured on samples from Dalarna is due to remagnetization in Lower Palaeozoic (probably Caledonian) time. The K-Ar age pattern has been much less influenced than the initial N.R.M. by Caledonian (?) disturbances. Obviously, the initial remanent magnetization of these basaltic and rhyolitic rocks was more sensitive to a mild metamorphic event than the whole-rock K-Ar age.

4. K-Ar age measurements suggest an age of approximately 1550 ± 100 million years for the intrusion of the hyperite-dolerite dykes in the "central schistosity zone" of southern Sweden. In the southern part of this zone, the dykes have "overprinted" K-Ar ages of about 800-900 million years.

5. The stable N.R.M. in the hyperite-dolerite dykes points to a Precambrian pole position at approximately 15° S and 135° W. The reversed magnetic polarity in part of the dykes strongly suggests that this N.R.M. represents the initial remanent magnetization. It is suggested that the probable age of 1550 ± 100 million years for the intrusion of the hyperite-dolerites also is the age of the pole position revealed by the dykes.

6. As contrasted with the effects observed in the basaltic and rhyolitic rocks from Dalarna, the initial remanent magnetization of the hyperite-dolerites in

southern Sweden seems to be more resistant towards metamorphism than the whole-rock K-Ar age. This contrasting behaviour might be due to different types of metamorphism or to differences in physical properties of the rocks.

7. Dolerite sills in Västergötland and dolerite dykes in Skåne have a N.R.M. representing an Upper Palaeozoic pole position at approximately 35° N and 175° E. This is in excellent agreement with the K-Ar age of 282 ± 5 million years (Permian/Carboniferous) measured on two of the sills in Västergötland.

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