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PALEOMAGNETIC RECONNAISSANCE STUDY OF THE FLAMANVILLE GRANITE, WITH SPECIAL REFERENCE TO THE ANISOTROPY OF ITS SUSCEPTIBILITY

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SUMMARY

For a preliminary paleomagnetic investigation of the Flamanville granite (Normandy, France), ten samples were studied. The granite samples had a weak remanent magnetization and a high magnetic susceptibility. The direction of the characteristic remanent magnetization was consistent with other Carboniferous paleomagnetic results from Stable Europe.

The high magnetic susceptibility was distinctly anisotropic. The shape and orientation of the susceptibility ellipsoids were determined with the Utrecht astatic magnetometers, according to the method of A s (1967). This method has been extended and its practical use is discussed.

The orientation of the susceptibility ellipsoids could be interpreted in terms of the mode of emplacement of the granite.

INTRODUCTION

The granite massif of Flamanville in Normandy (France) has been the object of various geologic and petrographic studies since 1835, especially because of the occurrence of iron-ore beds in the adjacent Devonian rocks. The age of the granite has been estimated from geological evidence as Carboniferous (M a r t i n, 1952). This age has been confirmed by dating methods using pleochroitic halos as between 300 and 340 my (P a r e y n, 1959).

Most of the geologic and petrographic studies dealt with discussion of its mode of emplacement, until the structural study of M a r t i n (1952) provided evidence of what is generally referred to as magmatic emplacement, in contrast to former ideas of emplacement by assimilation.

Martin concluded that a simple upward movement was unlikely: "It is better to consider that the granite arose as a diapir in a zone of incompetent rocks". Martin's investigation clearly showed that a planar foliation exists within the granite, generally parallel to the walls of the body. This foliation, according to Martin, is made up by the co-planar orientation of the mafic minerals, and to a lesser extent by the felspars. Martin's conclusion was based not only on this foliation but also on an observed joint pattern, with preferred directions parallel to the planar structure (A joints) and perpendicular to it (B and C joints).

The aim of the present study was to determine whether any relationship could be recognized between rock-magnetic properties and the planar orientations. For a preliminary investigation ten samples were collected from unweathered coastal exposures and quarries in the granite (fig. 1a, b).

MAFIC MINERALS

A few specimens of the Flamanville granite have been studied in reflected and transmitted lights by Mr. J. Cramer, Vening Meinesz Laboratory, State University Utrecht. The dominant opaque mineral

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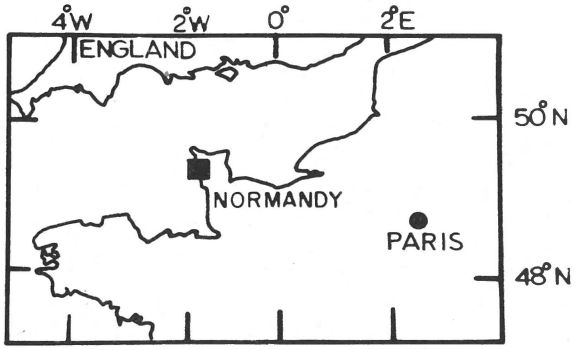


Fig. 1a
Regional map showing the location of the Flamanville area.

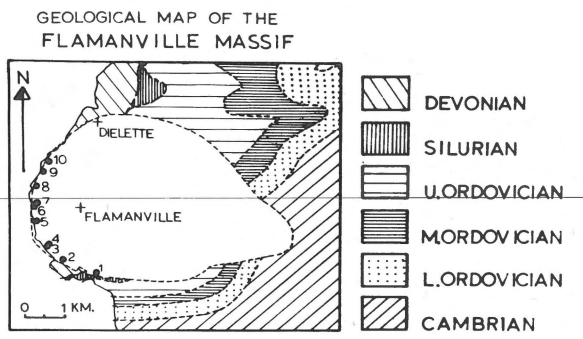


Fig. 1b
Schematic geological map of the Flamanville massif, after M a r t i n (1952). The sampling sites are indicated.

(up to 2 percent of the total volume) is a magnetite with martitization structures and some oxidation to hematite along the edges. In a quantitative analysis of the major elements, G o n i (1966) reported the FeO and Fe_2O_3 percentages, generally varying with some minor exceptions between 1-3%.

Elongated magnetite crystals are mostly intergrown with biotite and hornblende, aligned according to the principal cleavage pattern. Moreover clustered magnetite crystals with elongated outlines are found at the contact of the mafic minerals with the quartz or felspar. The dimensions of the magnetite crystals generally vary between 75μ to 125μ in length and 50μ to 75μ in width. To a lesser extent smaller idiomorph magnetite crystals are present, mostly in the felspars.

Thin parallel flakes of hematite are visible in the cleavage planes of biotite, with diameters of up to 100μ and a thickness of about 1μ.

From the shape and the prevalence of magnetite, as well as its high intrinsic susceptibility we assume that the anisotropy of the magnetic susceptibility (to be discussed below), is due to shape anisotropy of the magnetite.

THE NRM

Eight samples were used to determine the directions and intensities of the remanent magnetization components, using the astatic magnetometers and the A.F. demagnetization apparatus at Utrecht State University. Intensities of the total NRM ranged between 15.10^{-6} and 140.10^{-6} emu/cm^3, accompanied by Q-values between 0.1 and 0.7.

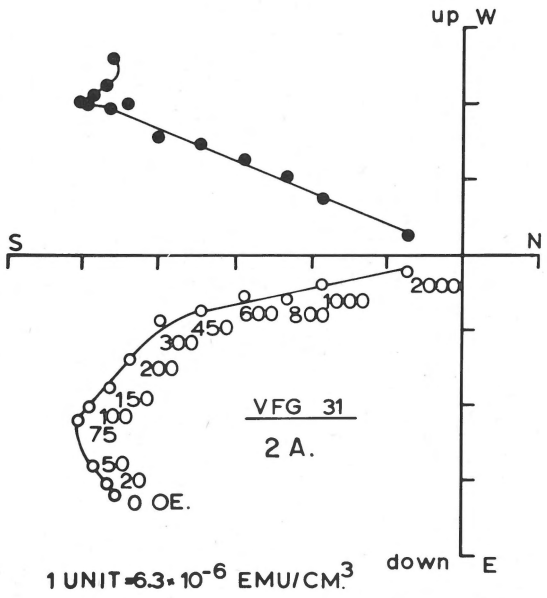
Two typical demagnetization diagrams are shown in fig. 2a, b. Demagnetization revealed two or three magnetic components in all samples. The softest magnetization, generally eliminated in fields of up to 50 Oe, is obviously viscous magnetization, since their directions were found to be induced in the laboratory with a few days. In some cases the A.F. demagnetization trajectory between 100 and 600 Oe revealed another secondary component with a direction conforming to the present-day geomagnetic field in France, thus being of recent origin as well.

Between 600 and 3000 Oe, only the hardest magnetization was destroyed. The latter magnetization had similar directions for all samples (fig. 3b), thus being characteristic for the Flamanville granite. In only a few samples (fig. 2a) could the direction of the characteristic magnetization be accurately determined; in the majority of the samples, however, the characteristic magnetization was as small as 15 percent of the total NRM, as can be seen for instance in fig. 2b. Because of the difficulties thus encountered a much larger number of samples is needed for a more reliable determination of the paleomagnetic direction. Preliminary mean direction; $D = 203°$, $I = +13.5°$, $a_{95} = 14.5°$ ($N = 8$).

DETERMINATION OF THE SUSCEPTIBILITY ELLIPSOID, USING AN ASTATIC MAGNETOMETER

Introduction

G r a h a m (1954) suggested the use of the magnetic anisotropic of rocks, as an aid to petrofabric



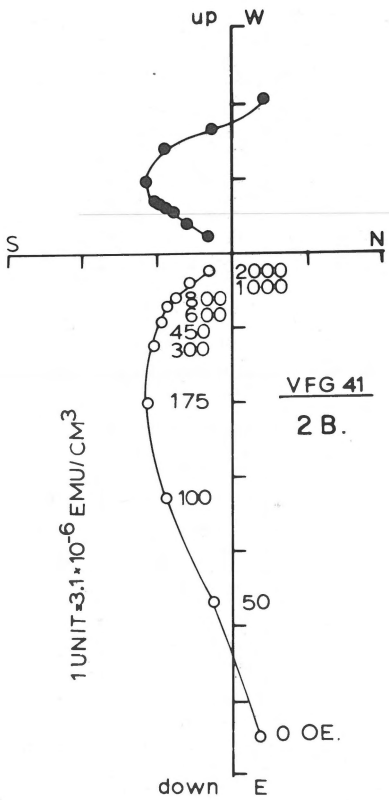


Fig. 2a,b
A.F. demagnetization diagrams. Plotted points represent successive positions in orthogonal protection, of the end point of the magnetic vector. ● Full symbols, denote projections on the horizontal plane. ○ Open symbols, denote projections on the north-south vertical plane. Numbers are peak values of the demagnetizing field in oersteds (Oe).

analysis. During the last decade a number of techniques have been developed for magnetic fabric analysis (MFA) in igneous, metamorphic and sedimentary rocks. Most of the results obtained confirm the relation between the textures of rocks either on macroscopic or microscopic scale and the orientation of the susceptibility ellipsoid. Even optically imperceptible textures could be determined by means of the greater resolving power of MFA techniques.

Routine techniques sufficiently sensitive for measuring susceptibility differences of 10^{-8} emu/cm^3 have been described, such as the low- and high-field torque meter methods ((B a n e r j e e et al. 1967; S t a c e y, 1960; S t o n e, 1967), the transformer bridge method (G i r d l e r, 1961; F u l l e r, 1967; G r a h a m, 1967; C h r i s t i e et al., 1969), and the translation inductometer (D a l y, 1967). The use of spinner magnetometers has been described as well, but sensitivities of only 10^{-6} emu/cm^3 are given (N o l t i m i e r, 1967).

A s (1967) suggested the use of the astatic magnetometer for the determination of the susceptibility ellipsoid. Following As, several computer programs were developed by one of us (C.T.K.), determining the remanent magnetization vector and the principal directions of the susceptibility ellipsoid

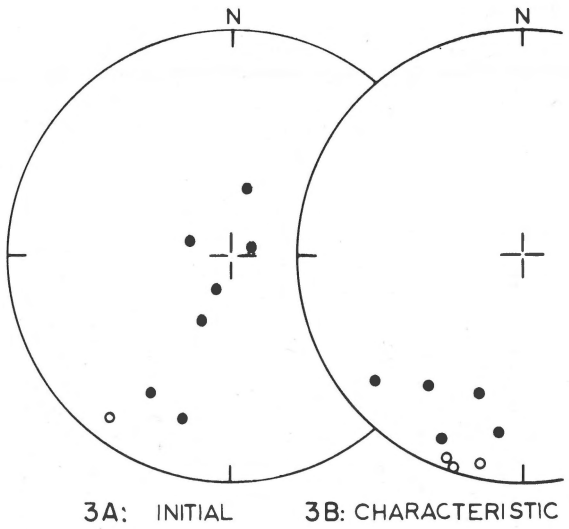


Fig. 3a,b
Equal area projection of initial and characteristic directions of remanent magnetization from 8 samples. ○ Open symbols, directions pointing upwards. ● Full symbols, directions pointing downwards.

from a set of readings of the astatic magnetometer. The practical limit in using the astatic magnetometer in susceptibility measurements is about 10^{-6} emu/cm^3.

When this sensitivity is compared with those of the above mentioned techniques, it is clear that specially designed apparatus has its advantage. However, in the case of highly anisotropic rocks with average bulk susceptibility the orientation of the susceptibility ellipsoid can be determined with a reasonable degree of accuracy.

General description of the method

The astatic magnetometers at the paleomagnetic laboratory, State University Utrecht, are placed in the earth's field without shielding Helmholtz coils. The torsion in the suspension wire of the magnetometers is negligible (A s, 1967). The restoring torque is supplied by the combined action of a small auxiliary magnet and the earth's field upon the astatic system. (This is in contrast with other techniques which use a torsion suspension and shield with Helmholtz coils). Deflections of the magnetometer are thus caused by remanent as well as induced magnetization of the sample.

The core specimens are mounted in small perspex cubes. Our notation of the orthogonal base system (Coordinates A, B and C) fixed relative to the perspex cube is the same as that used by A s (1967). As a standard measurement procedure readings are made by placing the sample in 24 different positions at the magnetometer, viz. eight positions with the A direction vertical, eight positions with B vertical and eight positions with C vertical. In between twelve readings are made of the rest position of the astatic system in order to correct for the drift of the apparatus.

A s (1967) showed the theoretical possibility of determining the six independent elements of the symmetric second rank susceptibility sensor from these 24 readings. He originally suggested the use of this determination procedure for hand samples, cast in paraffin wax or plaster of Paris. He realised, however, that the irregular shape of the hand samples would cause irregularities in the determination. The present use of field or laboratory-drilled cores of suitable length/diameter ratio reduces the influences of specimen shape upon the deflection of the magnetometer.

The susceptibility ellipsoid

Currently cores of 2.5 cm diameter ratio has been proposed by P o r a t h et al. (1966) as the optimum ratio reducing shape effects. The Flamanville specimens have a rather high anisotropy (up to 28%) and, moreover, a mean susceptibility in the order of 10^{-4} emu/cm^3; hence, according to K i n g (1965), no corrections for shape effects are involved in the computations.

The representation of the anisotropy of susceptibility by an ellipsoid is the geometrical equivalent of its mathematical description as a second order symmetric tensor[3], if we assume that the induced moment is a linear function of the (low) field strength; we may write in subscript notation $J_i = k_{ij}H_j$, where k_{ij} represents the tensor (see table 1), J_i the component of induced magnetization in the direction i and H_j the component of the ambient field in the direction j. The computations of the tensor elements as given in table 1 and the magnitude and directions of the orthogonal principal axes of the ellipsoid was programmed in ALGOL-60.

Diagonalization of the susceptibility tensor was performed by an iterative eigenvalue determination according to the Jacobi-method, as a standard numerical procedure in use at the Utrecht Electronic Computer Centre. The number of iterative steps depends upon the desired accuracy of fit of the ellipsoid with respect to the data. The non-diagonal terms of the transformed tensor are reduced so that

$$\sum_{i=1}^{i=3} \sum_{j=1}^{j=3} k_{ij}^2 \; (i \neq j)$$

is less than 10^{-20}.

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[3]) Several definitions of the susceptibility ellipsoid are currently in use. For reason of visibility we prefer to use a susceptibility ellipsoid, defined as the surface containing all end-points of the induced magnetization vectors when a unit field describes all directions in space, i.e. $\vec{k} = \vec{r}$. (Ellipsoide de grandeur, D a l y 1970).

This susceptibility ellipsoid must not be confused with the one that can be derived directly from the susceptibility tensor. This ellipsoid is very suitable for mathematical manipulation; however, the susceptibility in the direction of the radius vector equals the inverse square of the length of this radius vector, i.e. $\vec{k} = \vec{r}/r^2$. This inverse square relationship diminishes the visibility of this susceptibility ellipsoid.

This diagonalization yields three eigenvalues (k_{max}, k_{int}, k_{min}) and three orthogonal eigenvectors (principal susceptibility axes), forming a right-hand system. The three axes (eigenvectors) have no polarity.

In most cases the diagonalisation with the required degree of accuracy can be performed in about 5 steps. A further procedure involves transformation of the principal axes from the coordinate system of the sample cube to their orientation relative to present north and horizontal. Another procedure corrects for tectonic effects.

More sophisticated versions of the programming with greater resolving power for the determination of the non-diagonal terms (kij, $i \neq j$) are in development. These programs perform a least square approximation procedure and also consider the interaction of the horizontal components of magnetization upon the deflection of the magnetometer, causing the equations to become non-linear.

Discussion of the method

The accuracy of the method depends upon the degree of anisotropy and the intensity of the induced magnetization. The minimum measurable directional magnetization with the astatic magnetometer is 10^{-6} – 10^{-7} (emu/cm^3. The remanent magnetization, however, is measured together with the induced magnetization and influences the signal/noise ratio for the susceptibility ellipsoid determination in a negative way. The remanence has to be considered as noise together with the influences of sample inhomogenities, deviation from the dipole assumption for the sample, non-linear drift of the magnetometer and rapid changes of the local ambient field. Although the signal/noise ratio can be improved using more sophisticated programming of least square fitting of the deflection values, this ratio sets lower limits to the accuracy.

The components of the total magnetic field at the place of the sample have to be measured additionally by means of, for instance, a fluxgate-gradiometer. The maximum errors in the total field measurements are supposed to be in the order of 1%, thus having a negligible influence.

Tests of the accuracy involved i.e. the measurement of one sample with four different magnetometers (fig. 5) and 14 repeated measurements of one sample at three different distances from the magneto-

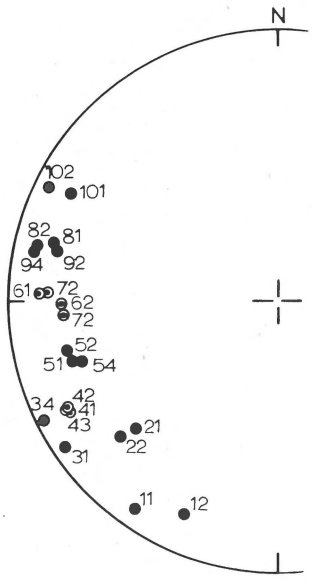

Fig. 4
West pointing directions of k_{min} axes from separate specimens. First digit(s) indicate(s) sample number, last digit indicates number of specimen drilled from out of this sample. ○ Double circles, directions pointing upwards. ● Full circles, directions pointing downwards. Stereographic projection.

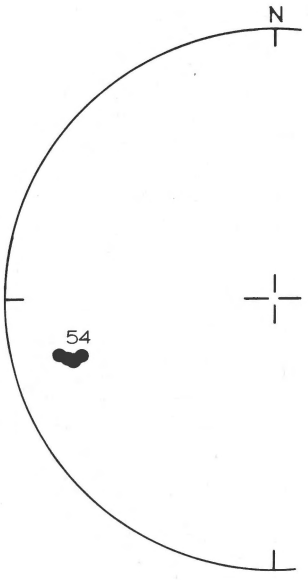

Fig. 5
West pointing k_{min} axes from specimen VFG 54, as measured with four different astatic magnetometers. Stereographic projection.

meter (fig. 6a). The obtained principal axes and in particular the important k_{min} axes were highly consistent.

Demagnetization with A.F. methods appeared to have negligible influence, though the mean susceptibility increased slightly with increasing peak values of the alternating field (fig. 6b).

For the samples from the Flamanville granite the k_{max} and k_{min} values were only slightly different, whereas k_{min} was considerably lower, so, as can be seen in fig. 6a, b, the k_{min} axes coincide very well; however, since the k_{max} and k_{int} values are close in value, they show more or less random directions in the plane normal to k_{min}. This random orientation is clearly visible in fig. 6b.

RESULTS

The orientation of the susceptibility ellipsoids of 10 samples (22 specimens) from the Flamanville granite were determined.. In fig. 7a,b,c,d some relevant quantities are shown: mean value of susceptibility $\bar{k}$, anisotropy percentage An%, percentage of magnetic foliation F and magnetic lineation L. The mean susceptibility $\bar{k}$ is calculated as $(k_{max}.k_{int}.k_{min})^{1/3}$; the $An\% = (k_{max} - k_{min}).100\%/k_{min}$; $F = (k_{int} - k_{min}).100\%/k$ and $L = (k_{max} - k_{int}).100\%/k$.

The mean susceptibility varies between 95.10^{-6} and 810.10^{-6} emu/cm^3, following the variable volume percentage of magnetic minerals (fig. 7a). The anisotropy percentage increases rather regularly from 7% in the SW (sample 1) up to 28% in the NW (sample 10). This between sample variation can be attributed to slight differences in the degree of magnetic foliation.

The computed values for the mean susceptibility $\bar{k}$ and the An% for the Flamanville granite are sufficiently high to ignore shielding effects of paramagnetic and diamagnetic crystals and matrix (having a $\bar{k}$ of appr. 10^{-6} emu/cm^3). For the Flamanville granite samples the k_{max} and k_{int} values were only slightly different, whereas k_{min} was considerably lower. Consequently the susceptibility ellipsoids are oblate spheroids, the factor of oblateness Ob = F/L varying between 1.5 and 11.5 (fig. 7c,d).

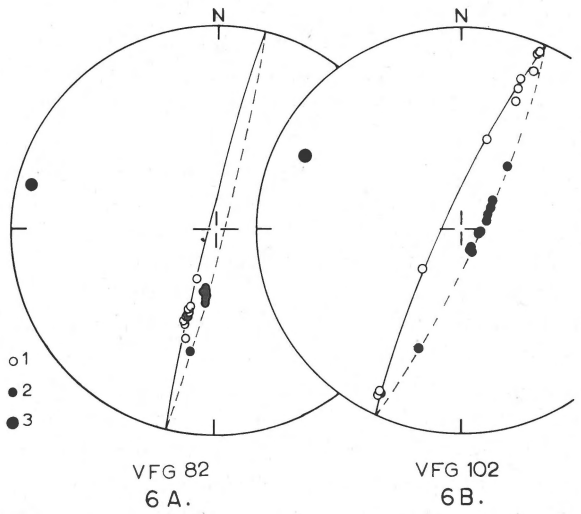

Fig. 6a
Orientation of the principal susceptibility axes from specimen VFG 82, obtained from 14 separated measurements at three different distances from the magnetometer.
Legend:
1: k_{max} axes, directions pointing upwards. 2: k_{int} axes, directions pointing downwards. 3: k_{min} axes, directions pointing westwards. Stereographic projection.
Fig. 6b
Orientation of the principal susceptibility axes from specimen VFG 102, measured after successive steps in a progressive A.F. demagnetization. Legend as above. Stereographic projection.

Some conclusions about the mode of emplacement of the Flamanville granite can be drawn from the susceptibility data. The samples were taken at more or less equally spaced intervals along the well-exposed seaside of the granite (fig. 1). The orientation of the k_{min} axes in the different samples is shown in fig. 4. The magnetic fabric analysis confirms the observations by Martin (1952) that there is a distinct foliation parallel to the walls of the granite, since the k_{min} axes coincide with the poles of the foliation planes which generally dip 80° landinwards. This is shown by the dip of about 10° of the majority of the k_{min} axes.

The intrusion is dated as post-Sudetic (Middle Carboniferous) and, according to Martin, no later tectonic phases have affected the intrusion. This is confirmed by the structural study of Guillon and Pizigo (1964), as quoted by Goni (1966). A sample from a quarry in the SW, where the foliation

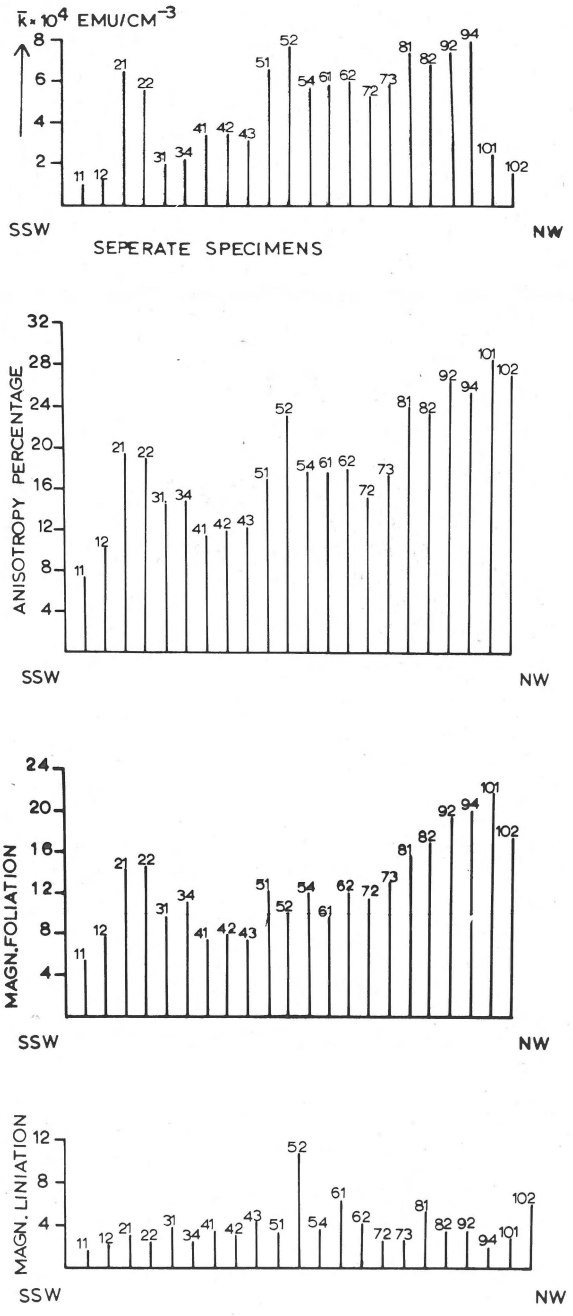

Fig. 7a,b,c,d
Representation of mean susceptibility k, anisotropy percentage An%, percentage of magnetic foliation F and percentage of magnetic lineation L, for individual specimens. First digit(s) indicate(s) sample number, last digit. Indicates number of specimen drilled from out of this sample.

is very clear, did not show any tectonic orientation of quartz-axes, though Guillon and Pizigo measured about 350 quartz-axes for every side of a block bordered by cleavage planes. So the structural peculiarities of the Flamanville granite originated entirely with the intrusion.

Though the small number of samples does not allow us to draw stringent conclusions, our results from the magnetic fabric analysis confirm Martin's conclusions concerning the mode of the emplacement. The foliation could have been caused by laminar flow and radially directed forces at the contract due to a diapir-like intrusion forcing away the country rocks by lateral expansion. Assimilation in situ as proposed by earlier investigators, can be ruled out.

The results obtained for the Flamanville granite are very similar to those obtained by S t o n e (1963) for the circular phonolite intrusion of Caf Tecut (Libya, post-Cretaceous). The average An% is the same as for the Flamanville granite and there is a strong correlation between the k_{min} directions and the normal to the flow planes i.e. the radial vectors. Stone concludes that the flow pattern for this intrusive phonolite more or less follows the contact of the intrusion.

CONCLUSION

Several workers, using torque meter methods or transformer bridges, reported a relationship between the foliation of rocks and the orientation of the k_{min} axes of its susceptibility ellipsoids. Our study of the Flamanville granite confirms the orientation of the minimum axes of susceptibility in a direction normal to be observed planar orientation of the mafic minerals. Moreover, the consistent results show that the astatic magnetometer is a quite feasible tool in the determination of the principal axes of the susceptibility ellipsoids of rocks.

The analysis of the natural remanent magnetization of the Flamanville granite proved the existence of a generally weak characteristic magnetization. We consider this magnetization to be original or primary, since the pole position determined from the mean direction of characteristic magnetization lies in between reliable Carboniferous pole position determined for Stable Europe (W i l s o n and E v e r i t t,

1963; Birkemayer, Krs and Nairn, 1969; Mulder, 1970; Storetvedt and Gidskehaug, 1969).

In view of the high value of the susceptibility anisotropy percentage, however, it looks interesting to investigate the possible relationship between the anisotropy in the magnetic susceptibility and a contingent deviation in the remanent magnetization vector, in order to correct the determined direction of the paleomagnetic field. A study on this subject is planned for the near future.

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TABLE 1

The six tensor elements have been computed from the 24 deflection values (A s, 1967) according to the following formulas:

$k_{11} = (A_1+A_2+A_3+A_4+A_5+A_6+A_7+A_8-2(n_1+n_2+n_3+n_4)).C/(Z.V.8)$

$k_{22} = (B_1+B_2+B_3+B_4+B_5+B_6+B_7+B_8-2(n_5+n_6+n_7+n_8)).C/(Z.V.8)$

$k_{33} = (C_1+C_2+C_3+C_4+C_5+C_6+C_7+C_8-2(n_9+n_{10}+n_{11}+n_{12})).C/(Z.V.8)$

$k_{21} = k_{12} = (-B_1+B_2-B_3+B_4-A_5+A_6-A_7+A_8+0.2(n_5-n_6+n_3-n_4)).C/(H.V.8)$

$k_{32} = k_{23} = (-C_1+C_2-C_3+C_4-B_5+B_6-B_7+B_8+0.2(n_9-n_{10}+n_7-n_8)).C/H.V.8)$

$k_{31} = k_{13} = (-A_1+A_2-A_3+A_4-C_5+C_6-C_7+C_8+0.2(n_1-n_2+n_{11}-n_{12})).C/(H.V.8)$

k_{ij}	: elements of the susceptibility tensor
A_i, B_i, C_i	: readings of the magnetometer, due to remanent and induced magnetization together, added to the rest position of the magnetometer
n_i	: rest position of the astatic system, read after four successive deflections
C	: calibration factor
Z	: vertical component of the ambient field at the magnetometer
H	: horizontal component of the ambient field
V	: volume of the sample

For the 7 astatic magnetometers at Utrecht State University, placed opposite to each other in east-west direction and having different astatic systems, a sign correction has to be made for the tensor elements.

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