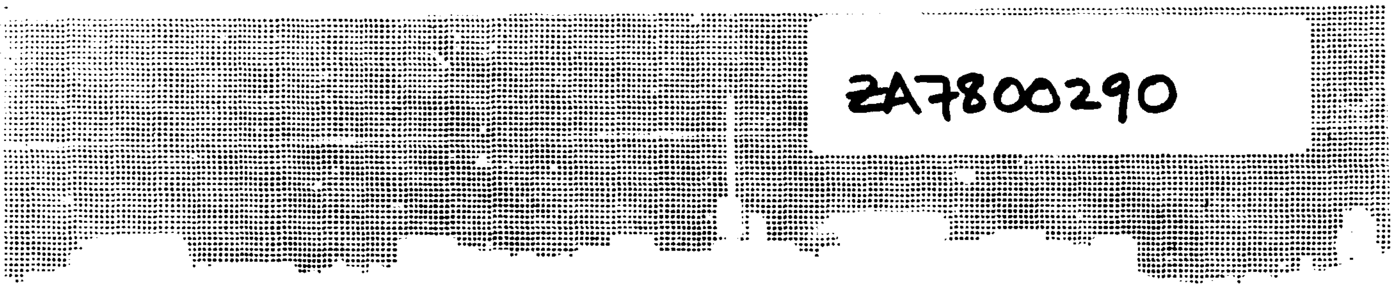

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# RESULTS OF A PALAEOMAGNETIC SURVEY UNDERTAKEN IN THE DAMARA MOBILE BELT, SOUTH WEST AFRICA, WITH SPECIAL REFERENCE TO THE MAGNETISATION OF THE URANIFEROUS PEGMATITIC GRANITES

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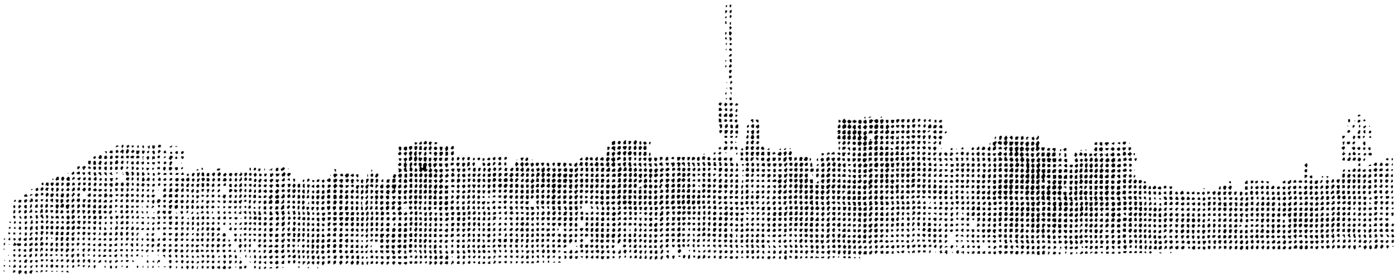

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# RESULTS OF A PALAEOMAGNETIC SURVEY UNDERTAKEN IN THE DAMARA MOBILE BELT, SOUTH WEST AFRICA, WITH SPECIAL REFERENCE TO THE MAGNETISATION OF THE URANIFEROUS PEGMATITIC GRANITES

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## CONTENTS

## SAMEVATTING

'n Projekstudie oor die korrelasie tussen lugmagnetiese en radiometriese gegewens wat 'n deel van die Mobiele Gordel Damara in Suidwes-Afrika dek en deur die Afdeling Geologie van die RAK uitgevoer is, het aan die lig gebring dat al die bekende voorkomste van uraan in die laat- tot na-tektoniese leukograniet (alaskiet) van die Damara-orogeen met negatiewe geomagnetiese anomalieë verband hou. Hoewel die uraanvoorkomste self nie opvallende geomagnetiese anomalieë toon nie, word hulle onmiddellike geologiese omgewing deur die negatiewe anomalieë gekenmerk wat gedeeltelik van streeksomvang is. Om die oorsprong van hierdie anomalieë te ondersoek, het die Raad op Atoomkrag en die Geologiese Opname van Suid-Afrika 'n paleomagnetiese studie van die gebied aangepak.

Daar is aanvaar dat die alaskitiese graniete die laaste fase van tektonisme verteenwoordig en dat die gesteente nie verder beweeg of geplooi het nie. Georiënteerde kerns is van 31 terreine in die mobiele gordel geneem waarvan 18 uit die negatiewe magnetiese sones gekies is wat meesal in noue verband met bekende uraanhoudende alaskitiese graniete staan. Die oorblywende terreine is vir doeleindes van vergelyking in gebiede met óf 'n normale of 'n magnetiese veld met hoë intensiteit verdeel. Natuurlike resmagnetisering, demagnetisering in 'n alternatiewe veld en termiese demagnetisering van die kernmonsters is gemeet deur 'n Digico 'Complete Results'-wentelmagnetometer in die paleomagnetiese laboratorium van die Geologiese Opname te gebruik.

'n Effektiewe geomagnetiese suidpoolposisie, met breedtegraad = 27,1 °N en lengtegraad = 350,8 °O, is uit die alaskitiese graniete en verwante metamorfiete van die Nosibgroep afgelei wat ongeveer 450 – 550-miljoen jaar oud is. (Jacob 1974, Kröner en Hawksworth 1977). Dit stem goed ooreen met die poolposisies (McElhinny *et al* 1974) wat van ander formasies met soortgelyke ouderdom verkry is. Hierbenewens is 'n voorlopige effektiewe geomagnetiese poolposisie, met breedtegraad = 43,2 °S en lengtegraad = 154,5 °O, vir die oergesteente in die gebied afgelei. In vergelyking met die pooldwaalpad van McElhinny en McWilliams (1977) dui dit op 'n ouderdom van naasteby 2 150-miljoen jaar. Hierdie syfer val binne die perke van akkuraatheid van 'n U-Pb-ouderdom van 1 925-miljoen jaar (+ 330, – 280-miljoen jaar) wat deur Jacob *et al* (1978) vir hierdie gesteente verkry is.

Paleomagnetiese getuienis dui daarop dat die negatiewe geomagnetiese anomalieë met 'n resmagnetisering verband hou wat uit die orogenetiese voorval Damara afkomstig is, die rigting wat van die aarde se huidige veld verskil en wat invloed op gesteente van die Nosibgroep uitgeoefen het. Afwesigheid van hierdie stabiele oorblywende rigting in gesteente wat die Nosibgroep stratigrafies oordek, gee rekenskap van die duidelike geomagnetiese tekens, in die vorm van negatiewe anomalieë, van die Nosibgroep.

Dit is hierdie tekens wat in lugopnames gebruik kan word om dagsome van die Nosibgroep, of vlak bedekte dagsome, of antiklinale of koepelvormige strukture uit te ken. Aangesien die uraanhoudende alaskiete hoofsaaklik stratigrafies tot die Nosibgroep beperk is, maak die negatiewe geomagnetiese anomalieë 'n belangrike prospekteermaatstaf uit aangesien hulle gebruik kan word vir die afbakening van teikengebiede vir verdere opsporing in gebiede wat deur sand, glooiingspuin en hardebankafsettings bedek is.

## ABSTRACT

A project study, undertaken by the Geology Division of the AEB, on the correlation between airborne magnetic and radiometric data covering a portion of the Damara Mobile Belt in South West Africa, has revealed that all the known occurrences of uranium in late- to post-tectonic leucogranite (alaskite) of the Damara orogeny are *associated with negative geomagnetic anomalies.* Although the uranium occurrences themselves do not display marked geomagnetic anomalies, their immediate geological environment is characterised by the negative anomalies, which are semi regional in extent. To investigate the origin of these anomalies, the Atomic Energy Board and the Geological Survey of South Africa undertook a palaeomagnetic study of the area.

It was assumed that the alaskitic granites represent the last phase of tectonism and that no further movement or folding of the rocks has occurred. Oriented cores were taken from 31 sites in the mobile belt, 18 of which were selected within the negative magnetic zones, mostly in close association with known uraniferous alaskitic granites. The remainder of the sites were selected, for purposes of comparison, in areas displaying either a normal or high magnetic field intensity. Measurement of natural remanent magnetisation, demagnetisation in an alternating field and thermal demagnetisation of the core specimens was carried out using a Digico 'Complete Results' spinner magnetometer at the palaeomagnetic laboratory of the Geological Survey.

A virtual geomagnetic south pole position, with latitude 27,1 °N and longitude 350,8 °E, was derived from the alaskitic granites and associated Nosib Group metamorphites which have ages in the range 450–550 Ma (Jacob 1974, Kroner and Hawksworth 1977). This is in good agreement with the pole positions (McElhinny *et al* 1974) obtained from other formations of similar age. In addition a tentative virtual geomagnetic pole position, with latitude 43,2 °S and longitude 154,5 °E, was derived for the basement rocks in the area. Comparison with the polar-wander path of McElhinny and McWilliams (1977) suggests an age of approximately 2 150 Ma, which is consistent to within the limits of accuracy of a U-Pb age of 1 925 Ma (+ 330, − 280 Ma) obtained by Jacob *et al* (1978) for these rocks.

Palaeomagnetic evidence suggests that the negative geomagnetic anomalies are associated with a remanent magnetisation, resulting from the Damara orogenic event, whose direction is removed from the earth's present field and which has affected rocks of the Nosib Group. Absence of this stable remanent direction in rocks stratigraphically overlying the Nosib Group accounts for the distinctive geomagnetic signature, in the form of negative anomalies, of the Nosib Group.

It is this signature which can be used in airborne surveys to identify rocks of the Nosib Group outcropping, or of shallow suboutcrop, in anticlines or dome-like structures. Since the uraniferous alaskites are mostly confined stratigraphically to the Nosib Group, the negative geomagnetic anomalies form an important prospecting criterion as they may be used to delineate target areas for further exploration in areas covered by sand, scree and duricrust deposits.

## ACKNOWLEDGEMENTS

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Palaeomagnetic measurements were carried out at the Geological Survey of South Africa and we wish to thank the Director for his authorisation to publish data thus obtained.

## 1. INTRODUCTION

Although gamma radiometry remains the most useful method in the search for new uranium deposits, certain unavoidable limitations do exist. The most serious of these are the problems of secular disequilibrium of the uranium decay series and absorption of gamma radiation by matter. The former is significant in the later stages of exploration when quantitative gamma spectrometry is applied, but is outside the scope of this paper. The latter, however, is a limiting factor in regional exploration programs since it takes only approximately 300 mm of rock or 600 mm of sand or scree to mask entirely the gamma radiation arising from buried uranium occurrences.

Other indirect techniques, therefore, have to be adopted in order to supplement the radiometric data and so enhance the probability of ultimate success. These include radon detection techniques and a variety of geochemical and geophysical prospection methods. In particular, the magnetic method, whereby the variations in intensity of the Earth's magnetic field are measured, remains relatively unaffected by surface cover. Although the uranium minerals themselves are, from an exploration point of view, non-magnetic, it is through their association with other magnetic minerals that a measure of correlation can often be achieved.

Part of the Damara Mobile Belt in South West Africa, indicated by the area of the geological map in Fig. 1, was flown in four stages by radiometric and magnetic airborne surveys, under contract to the Geological Survey of South Africa, during the period 1968 to 1975. Although the radiometric data successfully revealed numerous uranium occurrences, large areas of bedrock remained unexplored due to the often extensive cover of surficial sand and duricrust deposits. The Geology Division of the Atomic Energy Board thus commenced a study of the correlation between the radiometric and magnetic data in order to determine whether any additional information relating to the granitic uranium occurrences could be derived from the latter. The results obtained to date are presented in this report.

## 2. GEOLOGY OF THE AREA

Before discussing the correlation between uranium target areas and magnetic responses in the Damara Mobile Belt, it is necessary to review the geology of the area. Since a full discussion is beyond the scope of this paper, the review is intentionally brief. Greater detail may be found in the quoted references.

The stratigraphic classification and dominant lithologies of the constituent Groups within the area are summarised in Table I below. The stratigraphic nomenclature represents the latest (1977 unpublished) proposals made by the South African Committee for Stratigraphy. Fig. 1 shows the generalised geology of the area and was derived from personal field observations and mapping (in some instances unpublished) by Gevers, Haughton, Frommurze, Rossouw, Schwellnus, Smith, Linning, Jacob, Schoeman and officers of the Anglo American Corporation, during the period 1927 – 1976.

The rocks of the Damara Supergroup, which were emplaced onto a granite-gneiss basement containing remnants of the Precambrian Abbabis Group, are divided into two major sequences, viz. the Nosib Group in which the rocks are psammatic in character and the Swakop Group consisting of pelitic and calcareous rock types. The former is further subdivided into the basal, chiefly quartzitic, Etusis Formation and the overlying Khan Formation comprising a variety of amphibole-pyroxene gneisses and biotite schist.

The Khan Formation is overlain paraconformably by the Dome Gorge (previously Rössing) Formation of the Ugab (previously Hakos) Subgroup which consists mostly of pelitic schist and gneiss and in which the first major development of marble in the Damara Supergroup is seen. This is overlain by the Khomas Subgroup of the Swakop Group, comprising a sequence of chiefly pelitic and semi-pelitic biotite schist and gneiss, dolomitic and calcitic marble, calc-silicate and calc-granofels. Although the sequence is largely conformable, lateral sedimentological facies changes are evident. The lowermost member, viz. the Chuos Formation, which rests paraconformably on the Dome Gorge Formation, also contains minor quartzite and a tillite (mixtite) horizon.

The rocks of the Damara Supergroup have been subjected to high-grade regional metamorphism during the 500 Ma pan-African orogenic event, with the metamorphic grade (amphibolite facies) increasing towards the axial core of the mobile belt. From a consideration of mineral assemblages the temperature of metamorphism has been estimated to have reached 750 °C, at prevailing pressures of 0,4 – 0,5 GPa, in the vicinity of the confluence of the Khan and Swakop rivers (Nash 1971, Jacob 1974). Extensive granitisation has taken place and numerous phases of syntectonic, late-tectonic and post-tectonic granite and gneiss have been recognised. The red granite-gneiss suite, comprising gneiss, granite-gneiss and migmatite, is exposed in anticlinal structures and is partly the syntectonic, ultrametamorphic equivalent of the Nosib Group metamorphites. It is believed (Jacob 1974) that much of this suite may originally have been pre-Nosib in age and reactivated during the Damara orogeny.

Fractionation during crystallisation of the rocks yielded K-rich melts, enriched in volatiles and ore constituents, which finally crystallised as alaskitic pegmatitic granite and pegmatite.

The Salem granite suite appears stratigraphically above the level of the Chuos Formation and has formed through anatexis of the rocks of the Khomas Subgroup (Miller 1973, Jacob 1974). The suite comprises syntectonic, non-porphyritic and porphyritic biotite-granite and gneiss. Other late- to post-tectonic intrusive granites, which occur as irregular stocks or anastomosing veins, include the Bloedkoppie, Achas, Gawib and Donkerhoek granites.

The regional structure of the area follows a well-defined pattern comprising elongate synclines and anticlines, trending northeastwards. At least three other phases of deformation have been recognised (Jacob 1974), with the most prominent resulting in NNE- to NW-trending folds which, locally, have emphasised dome structures. Some controversy exists as to the origin of these mantled domes of red granite-gneiss, with some workers favouring dome formation through interference folding, while others favour formation through diapiric movement in an environment where a high degree of plasticity and anatexis prevailed.

Stormberg basalts and Dwyka sediments of the Karoo Supergroup are developed in the northwest and northeast of the area and are penetrated by intra- and post-Karoo granite intrusives, viz. the Brandberg, Messum, Cape Cross, Spitzkoppe and Erongoberg complexes.

Large portions of the area are covered by Tertiary to Recent surficial sand, scree and duricrust (calcrete, gypcrete) deposits.

## 3. URANIUM MINERALISATION

The radioactive mineralisation in the area has been discussed by numerous workers including Martin (1949), Smith (1965), von Backström (1970) and Jacob (1974). Briefly, the uranium mineralisation is confined largely within two regimes, viz. in granitic rocks and surficial calcretes (and gypcretes).

In the Salem granite-gneiss and especially the red granite-gneiss suites, anomalous, but essentially non-economic, quantities of uranium occur, mostly in association with thorium. Economically interesting uranium mineralisation occurs, however, in the late-phase alaskitic granite differentiates of the red granite-gneiss suite.

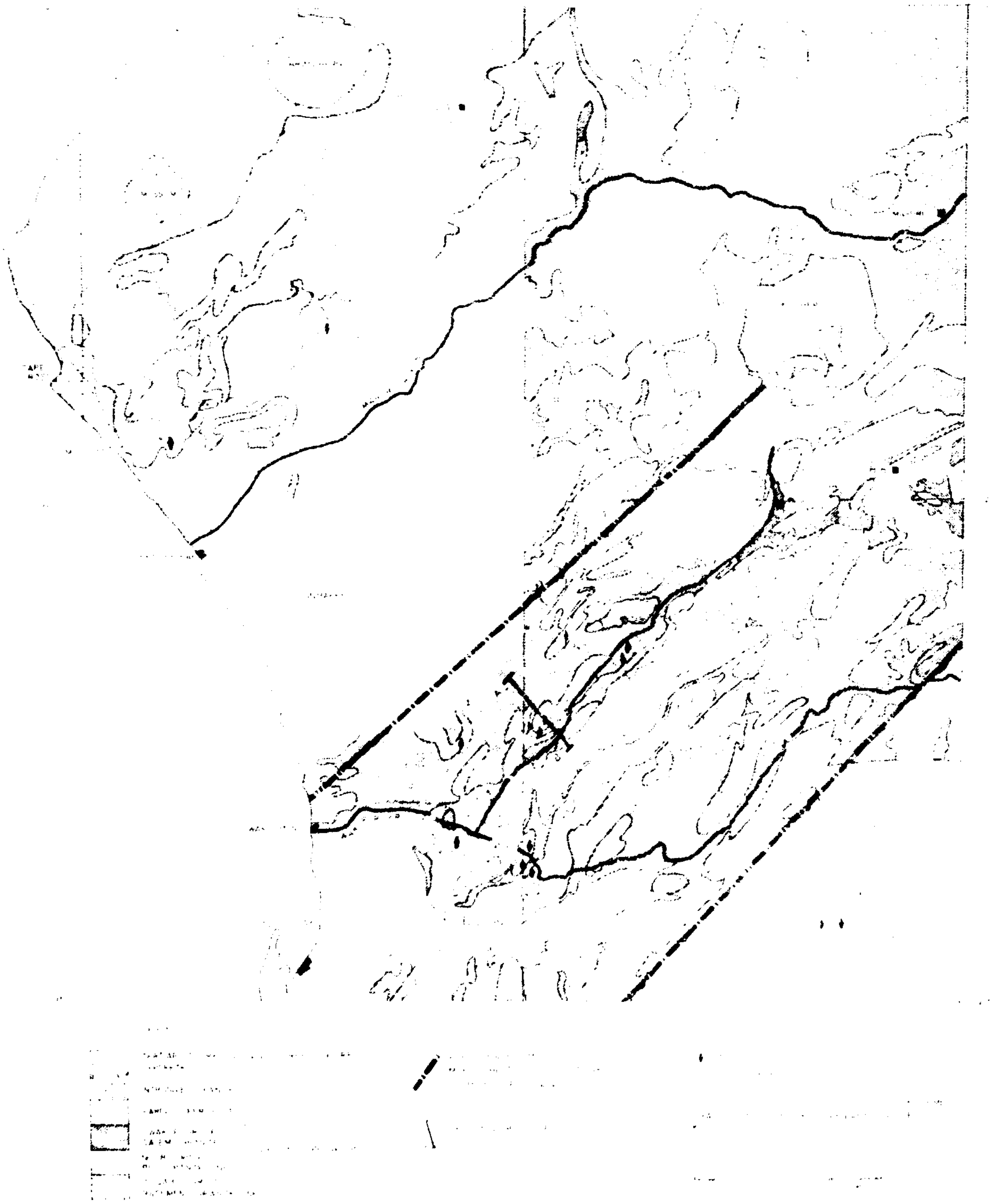


FIGURE 1 GENERALISED GEOLOGY OF PORTION OF THE DAMARA MOBILE BELT

## TABLE I

### LITHOSTRATIGRAPHIC SUBDIVISION OF THE DAMARA SUPERGROUP
(Proposals to the South African Committee for Stratigraphy – 1977 unpublished)

| Supergroup | Group | Subgroup | Formation | LITHOLOGY | GRANITIC EQUIVALENT (RADIOMETRIC AGE) |
|---|---|---|---|---|---|
| DAMARA | SWAKOP | KHOMAS | KUISEB | Biotite-rich quartzofelspathic schist, biotite-garnet-cordierite schist, minor amphibole schist, calc-silicate rock, marble, quartzite | Salem granitoid suite (590 Ma) |
| | | | KARIBIB | Marble, biotite schist, quartz schist, calc-silicate rock | Donkerhoek granite (550 Ma). Post-tectonic bodies of limited extent, i.e. Horebis, Gawib, Achas and Bloedkoppie granites |
| | | | CHUOS | Mixtite, pebble- and boulder-bearing schist, minor quartzite | |
| | | Discordance | | | |
| | | UGAB | DOME GORGE | Marble, quartzite, conglomerate, biotite schist, biotite-cordierite schist and gneiss, aluminous gneiss, biotite-hornblende schist, calc-silicate rock | Pegmatite |
| | Unconformity or conformable transition | | | | |
| | NOSIB | | KHAN | Pyroxene-bearing felspathic quartzite, amphibole-pyroxene gneiss, amphibole and biotite schist | Late to post-tectonic alaskitic granite and pegmatite (430 – 565 Ma). Red granite-gneiss suite (also partially derived from basement rocks) |
| | | | ETUSIS | Quartzite, arkose, conglomerate, quartzofelspathic gneiss, minor biotite schist, marble, amphibolite metarhyolite and calc-silicate rock | |

Numerous uraniferous occurrences have been found in this environment. In particular, the deposit at the Rössing mine is of this type (von Backström 1970, Berning *et al* 1976). The primary uraniferous minerals include uraninite and betafite whilst the secondary mineralisation comprises beta-uranophane, metatorbenite, meta-haiweeite, uranophane, carnotite, thorogummite and gummite (Hiemstra 1969).

Numerous sporadic occurrences of secondary uranium mineralisation (chiefly carnotite) occur in surficial calcrete and gypcrete.

## 4. CORRELATION BETWEEN MAGNETIC AND RADIOMETRIC RESPONSES

The airborne radiometric and magnetic maps of the area were compared, with the aim of establishing any possible magnetic characteristics associated with uranium mineralisation. Two significant features were evident, viz.:

(i) A regional magnetic/radiometric correlation exists, in that areas characterised by high geomagnetic anomalies often show sympathetically high total-count gamma-ray responses. This correlation, which was first noted by Toens (1974 unpublished), occurs chiefly over the red granite-gneiss. Investigations on the ground showed that the anomalous radiometric responses result from the relative increase in thorium concentration within these rocks and could also often be coupled with sympathetic, but non-economic, increases in the concentration of uranium. Although the overall concentrations of uranium and thorium are higher than in the surrounding rocks, the increases are not necessarily uniform and some outcrops yield a radiation level raised only slightly above background. The higher magnetic responses over the red granite-gneiss are thought to be due to relatively high concentrations of iron-rich minerals, especially magnetite.

At this stage it is felt that the magnetic highs related to the red granite-gneiss cannot be used directly as pathfinders to economic quantities of uranium, but can be beneficially applied to mapping the subsurface geology in areas covered by surficial deposits.

(ii) Certain negative (low) magnetic anomalies are unusual in that they occur over structures which, considering the present direction of the Earth's magnetic field, theoretically should not give rise to them at these latitudes. These anomalies often pervade areas of varying geological structure, indicating that a large degree of magnetic homogenisation has taken place. It was evident that every known occurrence of uranium in the late-phase alaskitic granites fell within such a magnetically anomalous zone.

Comparison of the magnetic data with the geology, in mapped areas, showed these anomalies to be confined stratigraphically to the rocks (and granitic equivalents) of the Etusis and (chiefly) the Khan Formation of the Nosib Group and, to a lesser extent, to the Dome Gorge Formation of the Swakop Group. It was also apparent that they do not represent these formations everywhere but are mostly associated with anticlinal and, in particular, dome type structural deformation.

An example of the negative magnetic anomalies in relation to the geology is shown in Section A--B (Fig. 2), drawn through the prominent dome (clearly visible on LANDSAT photographs), on the southern flank of which the Rössing mine is situated.

Although it cannot be said that the granitic uranium occurrences themselves can be directly located using magnetic techniques, their immediate geological environment is undoubtedly hallmarked by the negative magnetic anomalies. The anomalies, which are semi-regional in extent, thus delineate target areas in which granitic uranium occurrences might occur and thus form an important prospecting criterion.

The Geology Division of the Atomic Energy Board thus decided to investigate the cause of the negative magnetic anomalies, in view of their economic implications. It was believed (Corner 1975) that the anomalies arose from remagnetisation of the rocks, during the last phases of metamorphism and anatexis, in a magnetic field having a direction considerably different from that of the Earth's present-day field. Palaeomagnetic studies were therefore undertaken in conjunction with the Geological Survey of South Africa, in order to verify this hypothesis. The success of the investigations was dependent on the assumption that the alaskitic granite represents the last phase of tectonism and that no further movement or folding of the rocks had occurred (Jacob 1974).

## 5. PALAEOMAGNETIC WORK

### 5.1 Field Procedure

Oriented core samples were taken, by means of a portable drill, from 31 sites in the area between the Brandberg-Cape Cross lineament in the North and the Kuiseb River in the South. The site locations are indicated on the generalised geological map of the area (Fig. 1). At each site, 4 or 5 cores, each up to 100 mm in length, were drilled and oriented by means of sun and magnetic compasses. The cores, which were 25 mm in diameter, were subsequently cut up into specimens 25 mm in length, giving an average of 10 core specimens per site. Twenty of the sites were selected within negative magnetic zones, mostly in close association with the uraniferous alaskitic granites. Nine

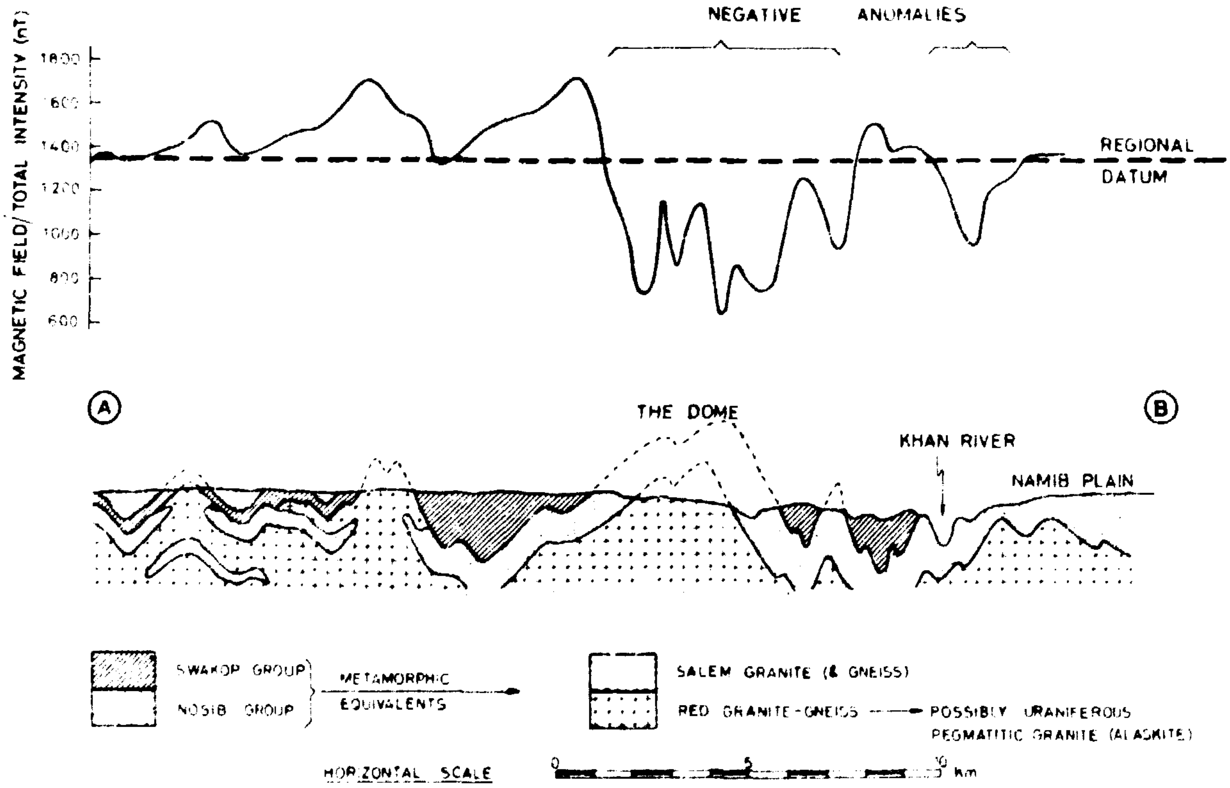


FIGURE 2 GEOLOGICAL SECTION ACROSS THE RÖSSING DOME SHOWING AEROMAGNETIC RESPONSES

were drilled in areas of either high or normal magnetic field intensity, for purposes of comparison, and the remaining two were chosen on outcrops of basement granite-gneiss. Table A1 in the Appendix gives the exact localities of the sites, the rock types sampled and the local intensity of the geomagnetic field.

## 5.2 Laboratory Instrumentation

Measurements of remanent magnetisation were carried out using a Digico 'Complete Results' spinner magnetometer. This instrument spins the core specimen at 7 Hz to produce an output signal, the amplitude of which is proportional to the intensity of magnetisation. The phase, relative to a reference signal produced by a 'chopper' on the main shaft, indicates the angle of the vector of magnetisation in a plane perpendicular to the axis of rotation. By suitable successive positioning of the sample, the three orthogonal components of the remanent magnetisation vector are determined.

A slightly modified form of the apparatus enabled continuous thermal demagnetisation to be carried out. Using this it was possible to measure remanence at the elevated temperature, thus obviating the need for cooling in a field-free space.

Alternating-field demagnetisation was carried out on an apparatus evolved from that described by McElhinny (1964). The sample was tumbled in the centre of a coil through which a decaying 50 Hz current flowed. This demagnetises all magnetic domains having coercivities below the maximum field produced by the peak (initial) current. To prevent the acquisition by the sample of an anhysteritic remanent magnetisation, the whole apparatus was contained in Helmholtz coils which annul the Earth's magnetic field.

The susceptibility was measured by introducing the sample into a coil system, thereby varying its impedance and hence the output from a secondary winding.

## 5.3 Laboratory Procedure and Results

The magnetic susceptibility of each core specimen was measured and the mean-site susceptibility calculated. The results are presented in Table II.

TABLE II

MAGNETIC SUSCEPTIBILITIES OF THE PALAEOMAGNETIC CORE SPECIMENS

| Site Number | Lithological Unit | Susceptibility (x4π.10$^{-6}$) | |
|---|---|---|---|
| | | Mean | Standard deviation* |
| 16 | Salem granite | 4,0 | 0,5 |
| 30 | Donkerhoek granite | 5,9 | 0,6 |
| 31 | | 4,0 | 1,6 |
| 1 | Alaskitic granite | 0,6 | 0,5 |
| 6 | | 1,2 | 0,8 |
| 22 | | 0,8 | 0,4 |
| 24 | | 2,3 | 0,9 |
| 29 | | 4,0 | 4,6 |
| 26 | | 269,0 | 100,0 |
| 27 | | 8,1 | 13,0 |
| 17 | | 0,2 | 0,4 |
| 11 | | 2,3 | 0,8 |
| 14 | | 222,0 | 174,0 |
| 4 | Red granite-gneiss | 378,0 | 676,0 |
| 5 | | 3,7 | 2,0 |
| 12 | | 650,0 | 378,0 |
| 15 | | 2 421,0 | 544,0 |
| 28 | | 0,9 | 0,1 |
| 2 | Khan Formation | 15,9 | 1,1 |
| 3 | | 65,6 | 7,3 |
| 10 | | 1 441,0 | 859,0 |
| 13 | | 60,6 | 18,0 |
| 18 | | 72,9 | 23,2 |
| 19 | | 1 709,0 | 796,0 |
| 25 | | 15,0 | 2,9 |
| 23 | | 737,0 | 521,0 |
| 7 | Etusis Formation | 8,0 | 4,6 |
| 8 | | 3,9 | 2,3 |
| 9 | | 7,8 | 3,4 |
| 20 | Basement granite-gneiss | 215,0 | 203,0 |
| 21 | | 248,0 | 349,0 |

*The often high standard deviations reflect the inhomogeneity of the magnetic minerals within the core specimens

The natural remanent magnetisation (NRM) of each core specimen was subsequently measured and at least one core per site demagnetised in an alternating field, in steps of 5, 10 or 20 mT up to 100 mT. If the direction of magnetisation remained stable, the remainder of the core specimens were demagnetised in a single step, usually in an alternating field of 80 mT. For those sites which displayed instability, the remainder of the cores were also subjected to step-by-step demagnetisation. The NRM and demagnetised directions were plotted stereographically for each site without any structural corrections having been made. These are given in the Appendix, and the site-mean directions are presented, together with the relevant Fisher statistics (Fisher 1953) in Table III. Some typical alternating-field demagnetisation responses are shown in Fig. 3.

At least one core per site was retained for thermal demagnetisation studies. Nine cores were demagnetised thermally in steps of 100 °C initially and as the Curie point was approached, this was reduced to intervals of 50 °C and 25 °C. Since the direction of magnetisation remained stable in all cases, no further thermal demagnetisation work was

TABLE III
APPROXIMATE SITE LOCALITIES
AND SITE-MEAN DIRECTIONS

| Site Number | Approximate Locality | Lithological Unit | Site-Mean | | $*\alpha_{95}^{o}$ | *N | *K |
|---|---|---|---|---|---|---|---|
| | | | Declination° | Inclination° | | | |
| 1 | Rössing mine | Alaskitic granite | 334,2 | 61,1 | 9,9 | 9 | 27,8 |
| 2 | Rössing mine | Khan Formation | 344,6 | 59,4 | 3,5 | 11 | 163,9 |
| 3 | Rössing Mountain | Khan Formation | 322,7 | 44,4 | 19,4 | 8 | 9,0 |
| 4 | Rössing dome | Red granite-gneiss | 329,7 | 54,5 | 11,8 | 8 | 22,9 |
| 5 | Rössing dome | Red granite-gneiss | 336,5 | -32,3 | 15,9 | 5 | 24,0 |
| 6 | Valencia | Alaskitic granite | 350,5 | -58,4 | 21,0 | 7 | 9,1 |
| 7 | Valencia | Etusis Formation | 325,5 | 44,7 | 3,2 | 12 | 180,3 |
| 8 | Valencia | Etusis Formation | 299,0 | 54,0 | 35,4 | 4 | 7,6 |
| 9 | Valencia | Etusis Formation | 316,9 | 29,4 | 11,2 | 13 | 14,5 |
| 10 | Palmenhorst | Khan Formation | 331,7 | 68,7 | 4,1 | 8 | 180,5 |
| 11 | Palmenhorst | Alaskitic granite | 336,8 | 44,1 | 17,4 | 8 | 11,0 |
| 12 | Palmenhorst | Red granite-gneiss | 18,2 | 52,4 | 12,4 | 6 | 29,7 |
| 13A | Trekkopje | Khan Formation | 322,1 | 68,1 | 13,0 | 3 | 90,4 |
| 13B | Trekkopje | Khan Formation | 23,5 | -53,4 | 9,1 | 7 | 44,1 |
| 15 | Trekkopje | Red granite-gneiss | 339,6 | 66,9 | 5,7 | 10 | 71,6 |
| 17 | Tsaun Beacon | Alaskitic granite | 319,7 | 58,9 | 31,5 | 7 | 4,6 |
| 18 | Tsaun Beacon | Khan Formation | 344,5 | 50,2 | 6,4 | 11 | 51,7 |
| 19 | Tsaun Beacon | Khan Formation | 145,2 | -19,3 | 3,8 | 7 | 244,8 |
| 20 | Kuiseb river | Basement granite-gneiss | 156,1 | -30,4 | 4,4 | 9 | 135,5 |
| 21 | Kuiseb river | Basement granite-gneiss | 151,4 | -34,2 | 3,5 | 11 | 166,0 |
| 22 | Hollands dome | Alaskitic granite | 348,3 | 48,3 | 4,8 | 10 | 100,5 |
| 23A | Hollands dome | Khan Formation | 316,7 | 32,9 | 6,8 | 3 | 321,8 |
| 23B | Hollands dome | Khan Formation | 2,6 | -43,2 | 10,8 | 8 | 26,8 |
| 24 | Hollands dome | Alaskitic granite | 323,4 | 58,9 | 17,1 | 8 | 11,4 |
| 25 | Ida mine | Khan Formation | 338,2 | 62,2 | 6,9 | 11 | 44,0 |
| 26 | Ida mine | Alaskitic granite | 340,5 | 50,2 | 18,1 | 10 | 8,0 |
| 27 | Ida mine | Alaskitic granite | 345,2 | 57,5 | 10,1 | 11 | 21,2 |
| 28 | Hollands dome | Red granite-gneiss | 351,0 | 62,3 | 10,3 | 5 | 55,9 |
| 29A | Ida dome | Alaskitic granite (Inside Halo) | 352,6 | 49,2 | 17,4 | 9 | 9,7 |
| 29B | Ida dome | Alaskitic granite (Outside Halo) | 344,3 | 50,6 | 18,4 | 4 | 25,8 |

*Fisher statistics: $\alpha_{95}^{o}$ is the radius of the cone of 95 % confidence of the mean direction;
N is the number of core specimens;
K is Fisher's dispersion parameter

conducted. The thermal demagnetisation responses are given in Fig. 4.

Subsequently, the core specimens were crushed for whole-rock analyses and at least one or two specimens per site were retained for petrological studies. The results of this work will be reported at a later date.

## 6. DISCUSSION OF THE RESULTS

### 6.1 Alternating-Field Demagnetisation

The magnetisation of the core specimens from the sites drilled into alaskites and rocks of the Etusis and Khan Formations, remained largely stable to demagnetisation in an alternating field. As can be seen from Fig. 3, the intensities were typically reduced in a field of up to 10 mT, and thereafter remained constant or increased slightly.

The directions of magnetisation also remained constant and, with the exception of sites 6, 10, 17, 18, 23 and 27, yielded significant results when grouped at the 95 % level of confidence (within site). In a number of cases the grouping showed a statistically significant improvement over its NRM counterpart.

The total-field NRM of the red granite-gneiss sites, with the exception of site 15, was scattered, indicating these rocks to have been subjected to secondary magnetisation. After demagnetisation, the magnetisation of all the red granite-gneiss sites exhibited significant within-site grouping, indicating that the secondary magnetisation had affected only domains of low coercivity.

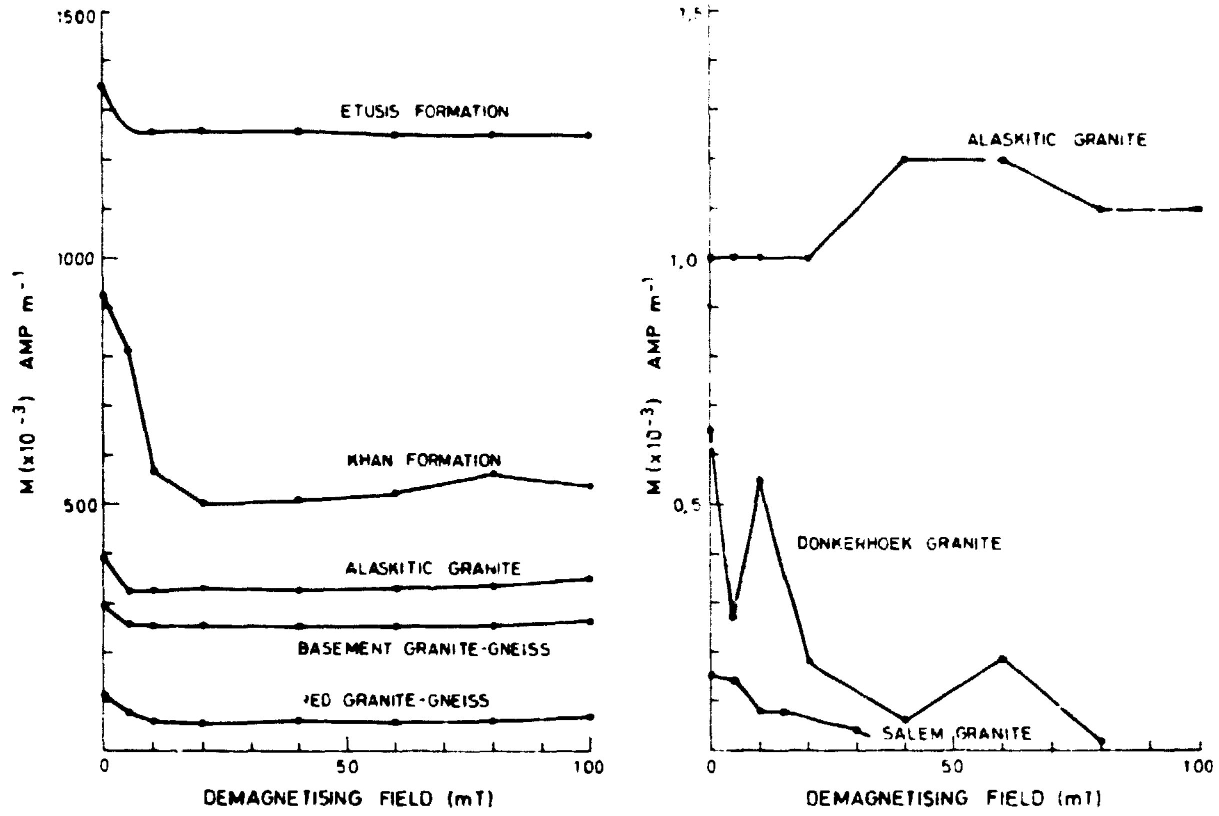


FIGURE 3 TYPICAL ALTERNATING-FIELD DEMAGNETISATION RESPONSES

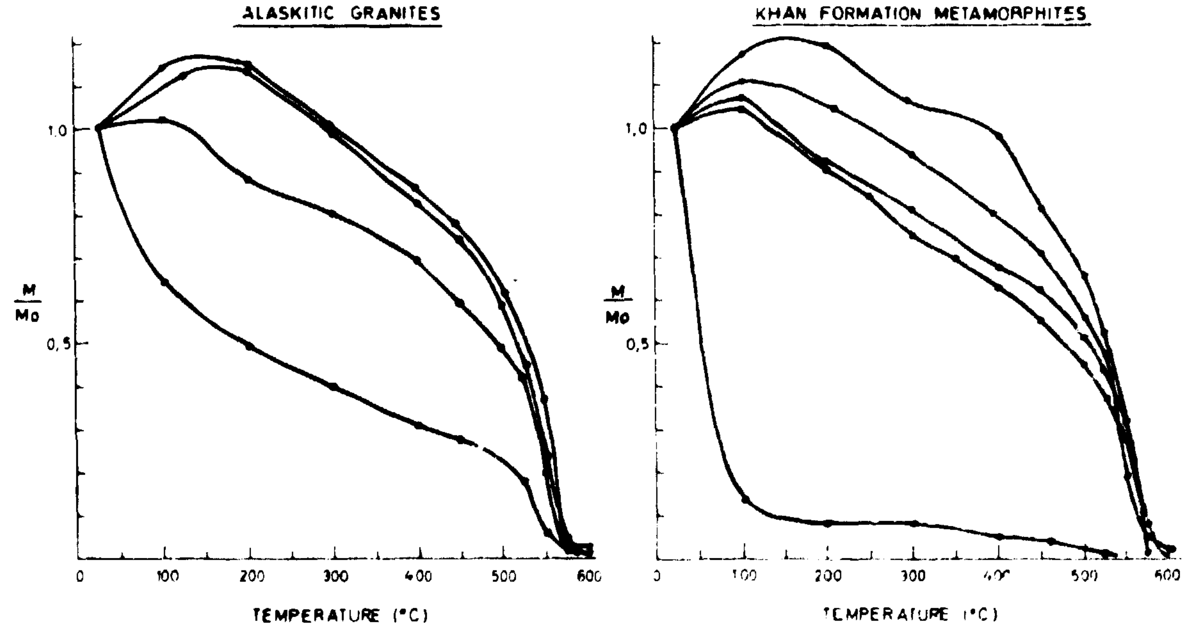


FIGURE 4 THERMAL DEMAGNETISATION RESPONSES

The intensities of magnetisation of the Salem and Donkerhoek granites displayed a rapid decrease with progressively higher alternating fields, to levels comparable to the noise level of the instrument. The scattered NRM directions failed to yield any significant grouping after demagnetisation. The alaskitic granites from Trekkopje (Site 14) also suffered a large reduction in intensity of magnetisation with demagnetisation and failed to give a significant grouping. This was possibly due to widespread oxidation of the magnetite grains observed in hand specimen.

## 6.2 Thermal Demagnetisation

The nine core specimens subjected to thermal demagnetisation initially showed only a slight change of direction of magnetisation (up to 200 °C), and thereafter remained stable. These directions were in good agreement with those derived after alternating field demagnetisation, and no further thermal work was carried out since it was thought unlikely to yield additional significant information.

The thermal demagnetisation responses in Fig. 4 show that magnetite is most probably the chief remanence carrier, since Curie points of roughly 570 °C are indicated (Curie point for magnetite = 580 °C). The fall-off in intensities seen from roughly 250 °C possibly results from a small titanium component in the magnetites.

## 6.3 Mean Directions of Magnetisation for the Nosib Group and Basement Rocks

Those sites which yielded statistically significant means at the 95 % level of confidence are plotted stereographically in Fig. 5. Three distinct groupings of remanent direction are evident (Table IV).

Group A consists of 22 sites (or parts thereof) in Nosib Group metarhyolites, red granite gneiss and alaskite, and has yielded a between-site direction of Declination = 333.4 ° and Inclination = 55,0 °.

Group B comprises 5 sites (or parts thereof) which have a between-site direction of Declination = 354,1 ° and Inclination = 48,7 °. These sites were derived from alaskites in the Ida dome and at Valencia, from red granite-gneiss in the Rossing dome, and from the Khan Formation in the Hollands dome and at Trekkopje. There is, however, no geologic reason why these rocks should yield directions different from those of Group A, and the similarity between Group B and the Earth's present field direction suggests that these sites have been remagnetised, possibly due to recent weathering or oxidation (see par. 6.5). Support for this hypothesis comes from certain localities (e.g. Khan Formation at Trekkopje) where some of the cores yield a Group A direction and others a Group B.

The Group C direction (D = 150,7 °; I = -28,0 °) is significantly different, at the 95 % level of confidence, from a reversal of the Group A direction. The sites which yield the Group C direction are the two from basement granite-gneiss and one (site 19) situated at the Tsaun beacon south of Brandberg. This latter site is anomalous since its remanent magnetisation vector does not fall in Group A although it was drilled in the same Formation and in close proximity (500 m) to site 18 which did. As these rocks are situated towards the edge of the mobile belt, it is possible that they were only remagnetised locally and that the pre-metamorphic direction of magnetisation has not been completely destroyed.

Some controversy exists as to whether the rocks at Tsaun beacon should be assigned to the Khan Formation as concluded by Jacob and Kroner (1977) or whether they belong to the Precambrian Tsaun Formation (Botha *et al* 1975). The palaeomagnetic results do not clarify the situation as the direction of magnetisation at site 19, which grouped with the basement granite-gneiss sampled in the Kuiseb River, could also be consistent with that for unmetamorphosed Nosib rocks sampled elsewhere (McElhinny and McWilliams 1976, Henthorn 1978).

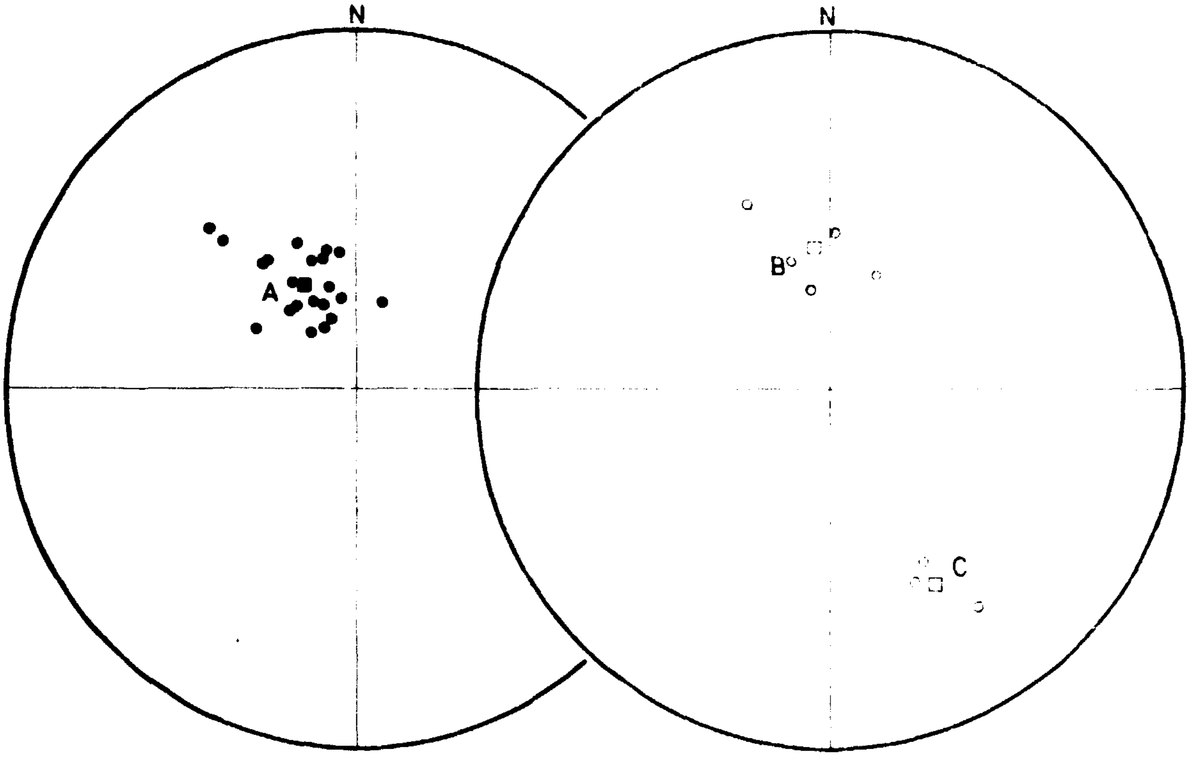
## 6.4 Palaeomagnetic Pole Positions

The virtual geomagnetic pole (VGP) positions of the South Pole were calculated for Groups A and C, using the conventional premise that the Earth's field is that of a geocentric dipole. These pole positions, listed in Table IV, are plotted in Figs. 6 and 7 which show the polar-wander

TABLE IV
MEAN DIRECTIONS OF MAGNETISATION
AND PALAEOMAGNETIC POLE POSITIONS

| Group | Mean Direction | | $^*\alpha_{95}$° | *N | *K | Virtual Geomagnetic Pole | |
|---|---|---|---|---|---|---|---|
| | Declination° | Inclination° | | | | Latitude° | Longitude° |
| A | 333,4 | 55,0 | 5,4 | 22 | 33,1 | 27,1 | 350,8 |
| B | 354,1 | 48,7 | 15,2 | 5 | 26,2 | 80,6 | 227,0 |
| C | 150,7 | 28,0 | 14,0 | 3 | 78,4 | 43,2 | 154,6 |

*as defined in Table III



■ A Overall mean of sites (22) drilled into rocks of the Nosib Group and granitic equivalents

□ B Overall mean of sites (5) approximating the direction of the Earth's present - day field (Nosib Group)

□ C Overall mean of sites (3) drilled into basement granite - gneiss and relatively unmetamorphosed Nosib Group rocks

FIGURE 5 SITE-MEAN DIRECTIONS OF NOSIB GROUP AND BASEMENT ROCKS

paths during the late Precambrian to Palaeozoic and early Precambrian periods, respectively (McElhinny *et al* 1974, McElhinny and McWilliams 1977). It must be stressed that the polar-wander curves shown are generalised paths obtained from numerous, often scattered, previously derived pole positions, with the swarth encompassing the majority of results.

The pole position derived for the Damara metamorphites and granites in this study is in good agreement with the five pole positions (McElhinny *et al* 1974) shown in Fig. 6. In addition, the radiometric ages for these rocks (Kröner and Hawksworth 1977) lie in the range 450 – 550 Ma and agree well with the Upper Cambrian-Silurian ages reported for the other VGP's mentioned.

It can be seen from Fig. 7 that the pole position derived for the basement rocks (and site 19) does not fall on the indicated polar-wander path (McElhinny and McWilliams 1977) but lies further to the east. However, the data, from which the polar-wander path was derived, are sparse for this period of time and it is not unreasonable to redraw the curve to pass through the basement VGP position as suggested in Fig. 7. Reservation must be expressed, however, since this pole position was derived from relatively few sites (3). Further basement sites are to be sampled in order to verify this result.

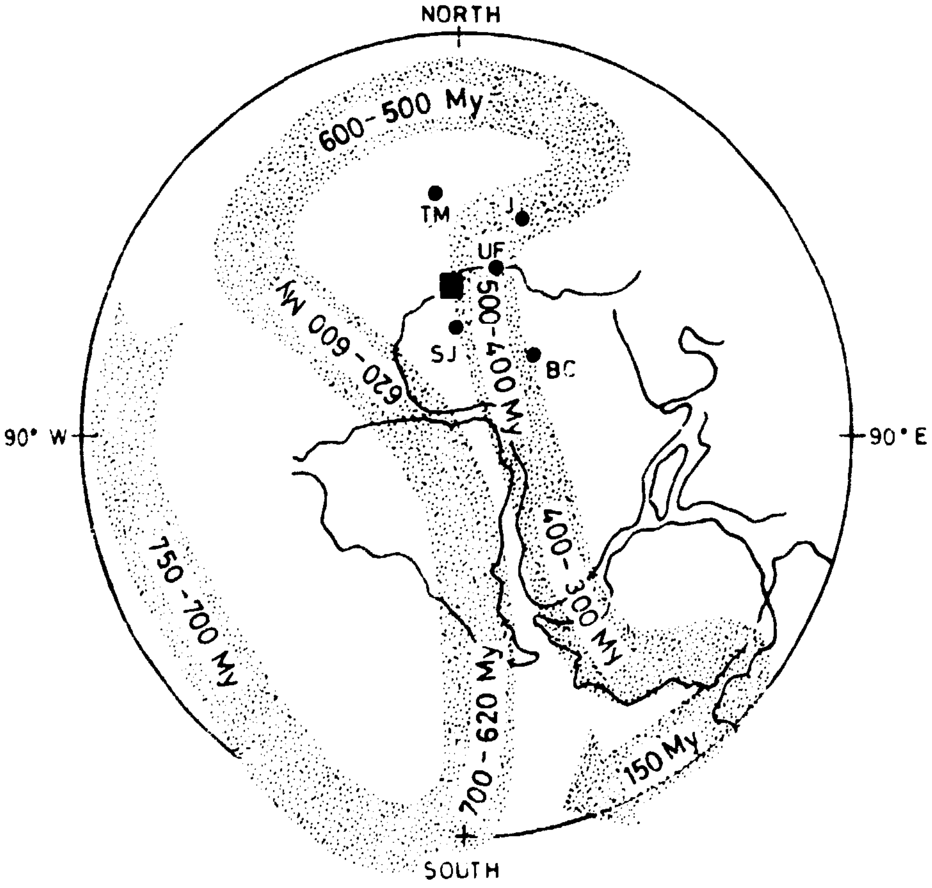
Comparison of this VGP with the above polar-wander path nevertheless suggests an age of approximately 2 150 Ma which is within the limits of accuracy of the radiometric U-Pb age of 1 925 Ma (+ 330, −280 Ma) obtained by Jacob *et al* (1978) for these rocks. The suggestion (see par. 6.3) that the Group C pole position (antipole) relates to the time of emplacement of the Nosib suite of rocks is obviously tenable only for site 19 and not the basement granite-gneiss.

## 6.5 Oxidation Haloes

It has been noted by numerous geologists that the uraniferous alaskitic granites often display ring-like variations in colour, giving the appearance of haloes. These appear as reddish-brown irregular rings, the majority having diameters ranging from 200 - 1 000 mm, which surround a fresh-looking greyish granite. Outside the rings the granite has a light cream to brown colour and, to the naked eye, a fresh appearance. The cause of this phenomenon is not entirely understood and for this reason the term 'oxidation halo', used in this text, is perhaps a misnomer in that it implies a knowledge of the origin of the rings.

Site 29 was selected on a fresh granite face showing abundant haloes, in order to see whether palaeomagnetism could assist in establishing their origin. Eight core specimens were drilled inside the haloes, four outside and one on a halo itself. Referring to the stereo-plot for Site 29 in the Appendix, the eight specimens from inside the haloes yield a mean direction of magnetisation (A) similar to the direction for the other Damara metamorphites, whereas the four from outside the haloes yield a mean direction (B) close to that of the present-day Earth's field. The single specimen, from a halo itself, (westernmost data point) appears to be intermediate.

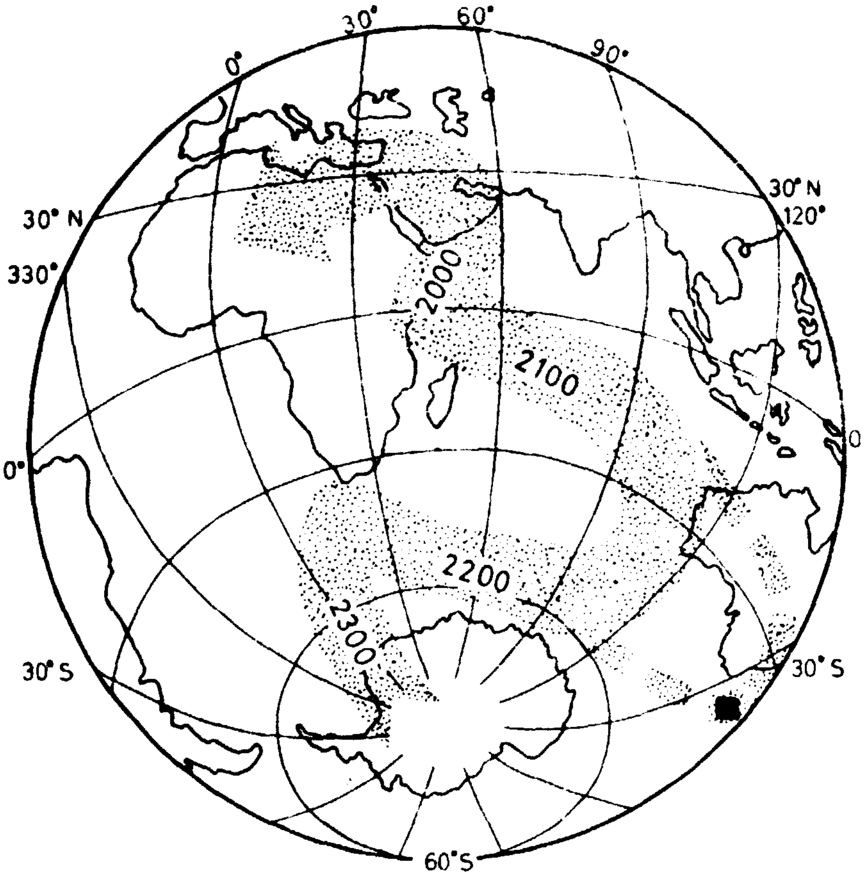
FIG. 6 : LATE PRECAMBRIAN TO PALAEOZOIC POLAR-WANDER PATH FOR GONDWANALAND (Mc Elhinny *et al* 1974)



■ Pole position derived from rocks of the Damara Mobile Belt

● Pole positions of upper cambrian-silurian ages, from Table Mountain Series (TM), Salta and Jujuy Formations (SJ), Urucum Formation (UF), Jinduckia Formation (J) and Upper Lake Frome Group (BC)

## FIG. 7 : APPARENT PRECAMBRIAN POLAR-WANDER PATH FOR AFRICAN CRATONS (McElhinny *et al* 1977)



■ Tentative pole position derived for basement rocks

## 7. CONCLUSIONS

(i) The initial assumption that the alaskitic granites represent the last phase of tectonism and that little or no movement has subsequently occurred, appears correct in view of the good grouping of magnetic directions obtained from the sites selected in the Nosib metamorphites and alaskitic granites. These rocks have proved suitable material for palaeomagnetic studies, although the same is not true for the Salem and Donkerhoek granites which failed to yield signigicant directions of magnetisation.

(ii) The hypothesis that the negative magnetic anomalies, associated with the uraniferous alaskitic granites, arose from the remagnetisation of the rocks in a magnetic field considerably different from the Earth's present field, is fully supported by the palaeomagnetic results. The position of the VGP derived for the 500 Ma Damara orogeny, which plots on the Moroccan coast, is in good agreement with other pole positions for that period. The tentative VGP for the basement rocks suggests that a slight change may need to be made to the polar-wander path of McElhinny and McWilliams (1977) to accommodate this. On this assumption the polar-wander path implies an age for the basement rocks of approximately 2 150 Ma. This is within the limits of accuracy of a radiometric U-Pb age of 1 925 Ma (+ 330, − 280 Ma) determined by Jacob *et al* (1978) for these rocks.

The question arises as to why, if the direction of magnetisation was reset at the time of the Damara orogeny, the entire mobile belt is not characterised by a regional negative magnetic anomaly, rather than just the environs of the uraniferous granite occurrences.

Of the sites collected from the granitic equivalents of the Swakop Group (i.e. Salem and Donkerhoek granites), none had directions of magnetisation which were significant at the between-site level, thus no abnormal negative geomagnetic anomaly can be associated with these rocks.

Considering the Nosib rocks, however, although most had a natural remanent magnetisation which largely reflects the field at the time of the 500 Ma event, five sites had stable directions of magnetisation approximating to that of the earth's present geomagnetic field, a direction which has been more or less unchanged since the Jurassic. At two of these sites both groups of directions were evident. This, together with the existence of 'oxidation haloes' (e.g. at the Hollands Dome site) makes it apparent that the secondary direction is more than the effect of normal weathering and must be due to hydrothermal/metasomatic alteration, possibly associated with the period of post-Karoo granitic instrusion. This secondary magnetisation, which manifests itself locally as a normal or high geomagnetic field, is not confined to a particular rock type or area within the suite of rocks sampled. Nevertheless, where rocks of the Nosib Group are well developed an overall negative geomagnetic anomaly prevails. Since the Damara remanent direction is not developed in rocks above the Nosib Group the negative anomaly can be used in the area as a Group stratigraphic marker. Since the uraniferous alaskites are mostly confined stratigraphically to the Nosib Group, these anomalies form an important prospecting criterion as they may be used to delineate target areas for further exploration in areas covered by sand, scree and duricrust deposits.

(iv) Regarding the phenomenon of the so-called oxidation haloes, it is concluded from the palaeomagnetic results that the alaskitic granite, enclosed by the haloes, is the original fresh rock and that the haloes themselves represent an encroaching alteration front (possibly through oxidation) which has already destroyed the initial thermo-remanent magnetisation of the surrounding rock.

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# 9. APPENDIX

| | |
|---|---|
| TABLE A1 : | Localities and Lithologies of the Palaeomagnetic Sample Sites |
| Sites 1 – 31: | Stereographic plots of the NRM and demagnetised directions |

### TABLE A1
### LOCALITIES, LITHOLOGIES AND LOCAL MAGNETIC FIELD INTENSITY OF THE PALAEOMAGNETIC SAMPLES SITES

| Site Number | Approximate Locality | Latitude | Longitude | Magnetic intensity – Total field (nT) | Formational unit, Lithology |
|---|---|---|---|---|---|
| 1 | Rössing mine | 22°28,48' | 15°2,79' | 30 230 (low) | Alaskitic granite |
| 2 | Rossing mine | 22°28,48' | 15°2,79' | 30 950 (high) | Khan Formation |
| 3 | Rössing mountain | 22°30 44' | 14°51,58' | 29 790 (low) | Khan Formation |
| 4 | Rossing dome | 22°27,49' | 15°3,66' | 29 820 (low) | Red granite-gneiss |
| 5 | Rössing dome | 22°26,66' | 15°3,48' | 31 220 (high) | Red granite-gneiss |
| 6 | Farm Valencia | 22°20,91' | 15°13,54' | 30 850 (normal) | Alaskitic granite |
| 7 | Farm Valencia | 22°19,15' | 15°14,63' | 30 325 (low) | Etusis Formation |
| 8 | Farm Valencia | 22°19,15' | 15°14,60' | 30 540 (low) | Etusis Formation |
| 9 | Farm Valencia | 22°19,01' | 15°14,85' | 30 020 (low) | Etusis Formation |
| 10 | Farm Palmenhorst | 22°40,82' | 14°51,21' | 30 300 (low) | Khan Formation |
| 11 | Farm Palmenhorst | 22°40,95' | 14°51,03' | 30 580 (low) | Alaskitic granite |
| 12 | Farm Palmenhorst | 22°40,90' | 14°51,21' | 30 080 (low) | Red granite-gneiss |
| 13 | Farm Trekkopje | 22°17,07' | 15°6,37' | 31 090 (high) | Khan Formation (? ) |
| 14 | Farm Trekkopje | 22°17,04' | 15°6,26' | 30 990 (high) | Alaskitic granite |
| 15 | Farm Trekkopje | 22°17,04' | 15°6,26' | 31 350 (high) | Red granite-gneiss |
| 16 | Mile 72 | 21°50,77' | 14°11,14' | 30 770 (normal) | Salem granite |
| 17 | Tsaun beacon | 21°40,1' | 14°33,9' | 30 550 (low) | Alaskitic granite |
| 18 | Tsaun beacon | 21°39,9' | 14°33,5' | 30 600 (low) | Khan Formation |
| 19 | Tsaun beacon | 21°39,9' | 14°33,5' | 30 600 (low) | Khan Formation |
| 20 | Kuiseb river | 23°20,73' | 14°50,66' | 30 550 (low) | Basement granite-gneiss |
| 21 | Kuiseb river | 23°14,86' | 14°55,37' | 30 575 (low) | Basement granite-gneiss |
| 22 | Hollands dome | 22°46,04' | 15°1,06' | 30 140 (low) | Alaskitic granite |
| 23 | Hollands dome | 22°45,86' | 15°1,12' | 30 420 (low) | Khan Formation |
| 24 | Hollands dome | 22°45,86' | 15°1,12' | 30 420 (low) | Alaskitic granite |
| 25 | Ida mine | 22°41,68' | 15°1,64' | 29 800 (low) | Khan Formation |
| 26 | Ida mine | 22°41,68' | 15°1,64' | 29 850 (low) | Alaskitic granite |
| 27 | Ida mine | 22°41,68' | 15°1,82' | 30 560 (low) | Alaskitic granite |
| 28 | Hollands dome | 22°45,86' | 15°0,94' | 31 400 (high) | Red granite-gneiss |
| 29 | Ida dome | 22°45,24' | 15°0,29' | 30 705 (normal) | Alaskitic granite |
| 30 | Farm Onanis | 22°51,81' | 15°43,68' | 30 590 (low) | Donkerhoek granite |
| 31 | Farm Oranis | 22°49,16' | 15°44,63' | 30 600 (low) | Donkerhoek granite |

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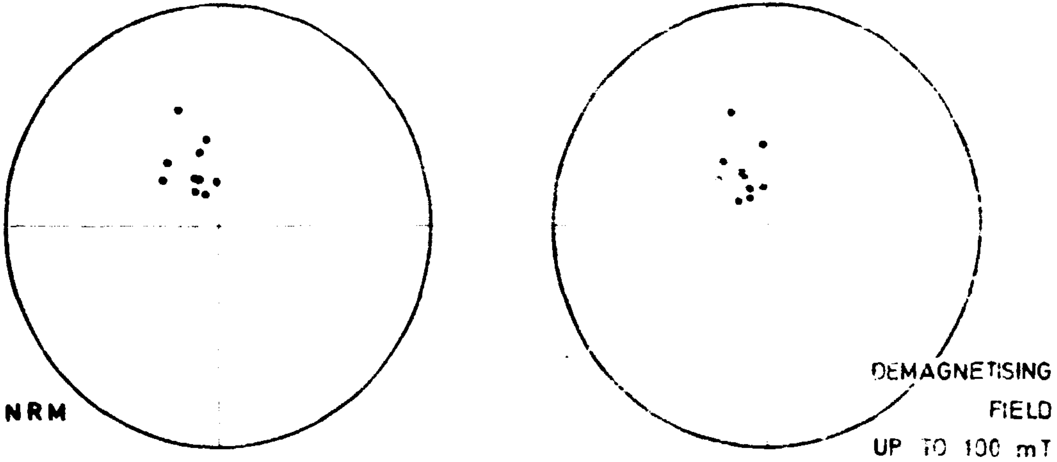
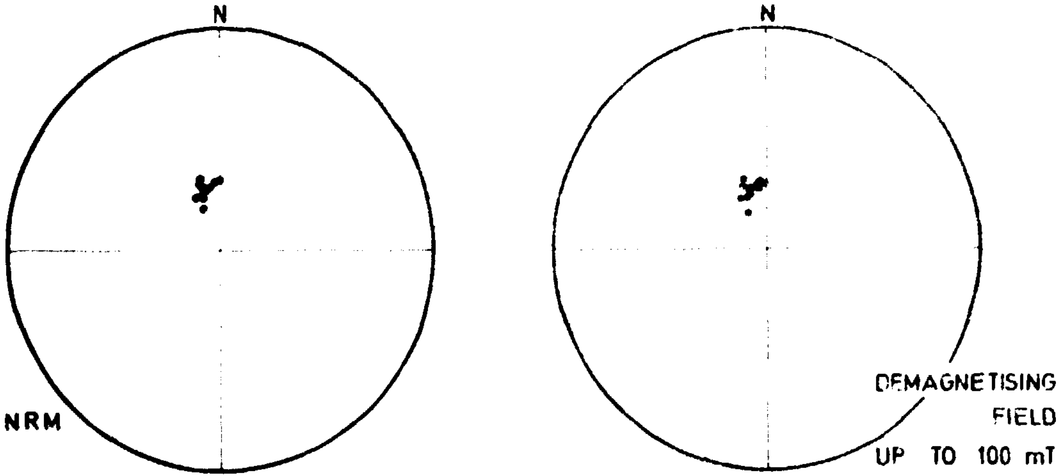
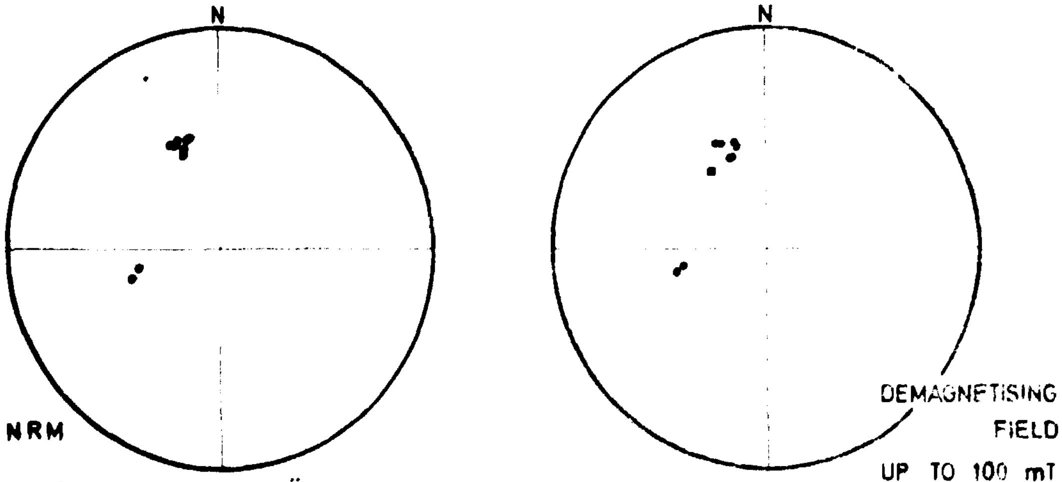


**SITE 1** **RÖSSING MINE : ALASKITIC GRANITE**

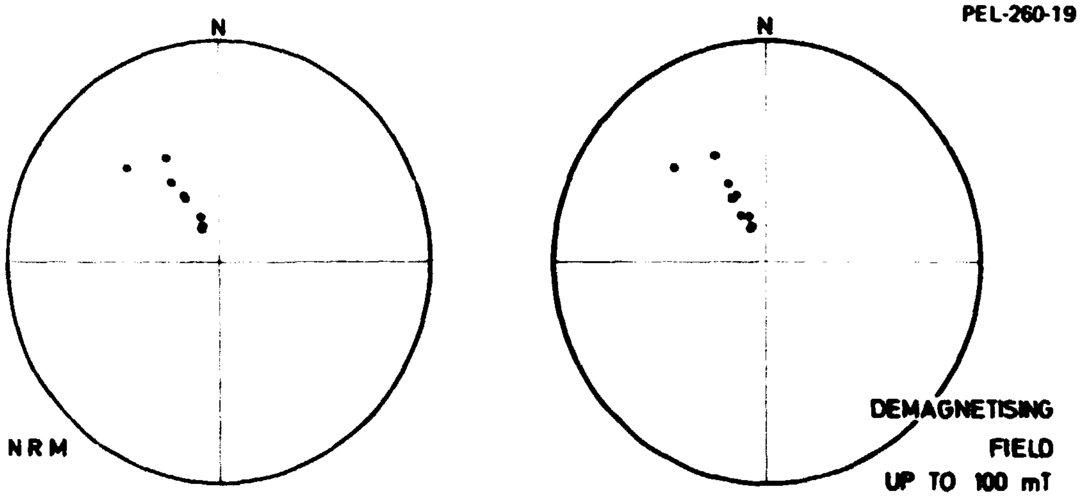


**SITE 2** **RÖSSING MINE : KHAN FORMATION**

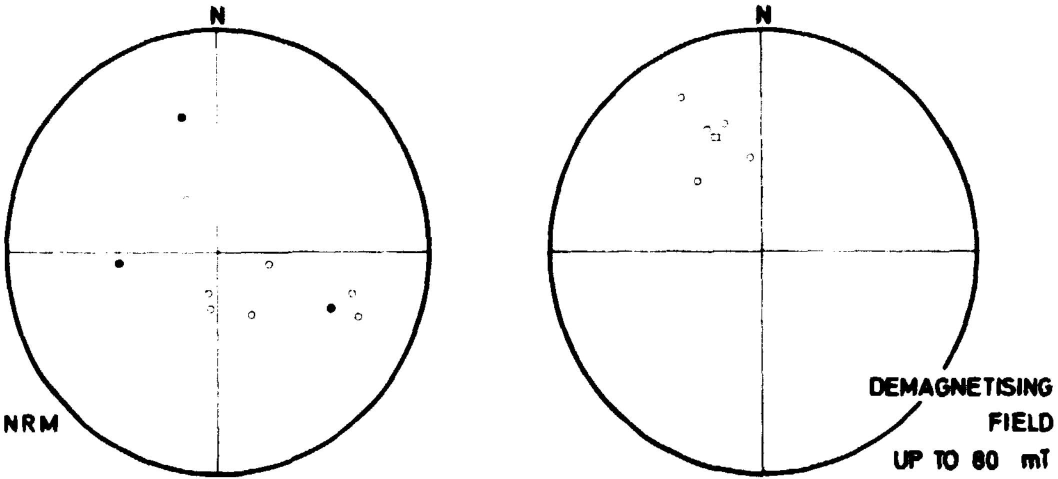


**SITE 3** **RÖSSING MOUNTAIN : KHAN FORMATION**

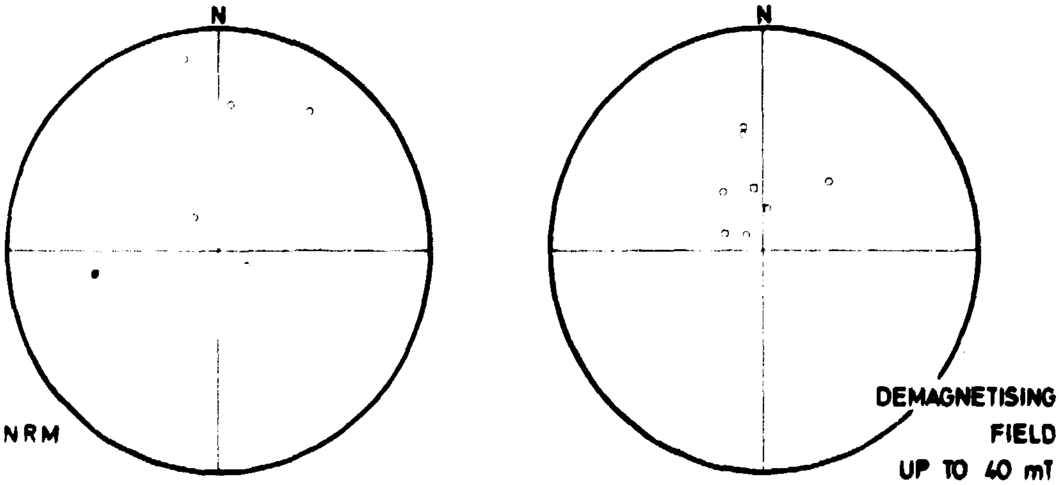
● POSITIVE INCLINATION NEGATIVE INCLINATION ■ SITE MEANS



SITE 4 RÖSSING DOME : RED GRANITE-GNEISS



SITE 5 RÖSSING DOME : RED GRANITE - GNEISS



SITE 6 VALENCIA : ALASKITIC GRANITE

● POSITIVE INCLINATION ○ NEGATIVE INCLINATION ■,□ SITE MEANS

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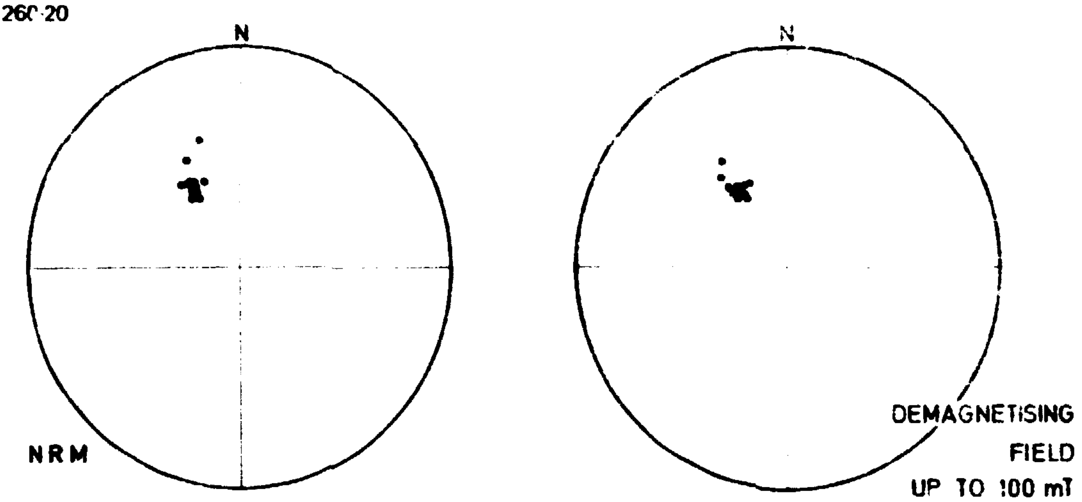
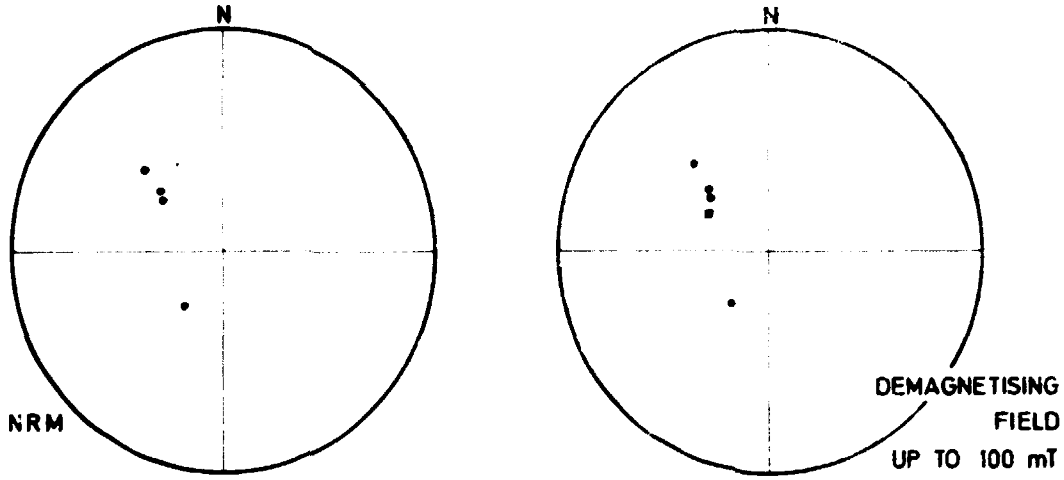
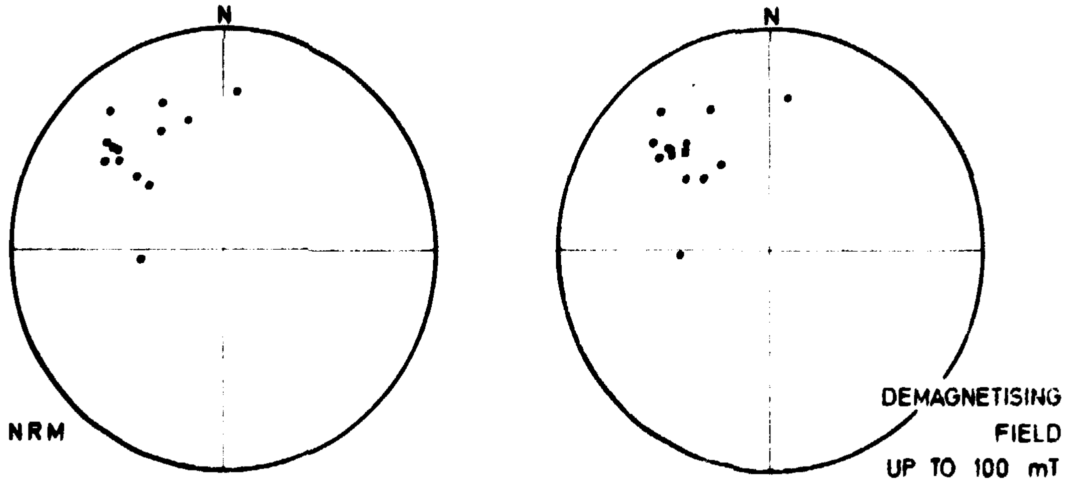


SITE 7 VALENCIA : ETUSIS FORMATION

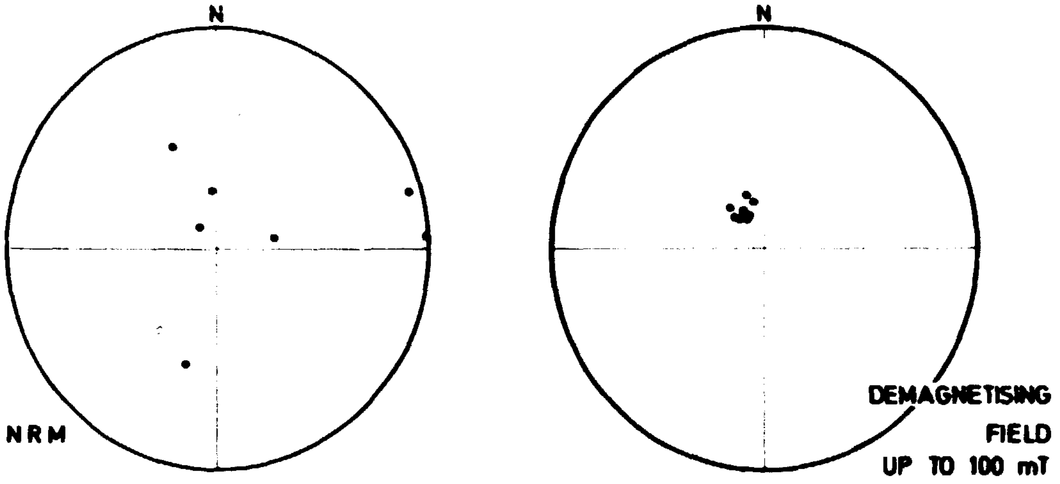


SITE 8 VALENCIA : ETUSIS FORMATION

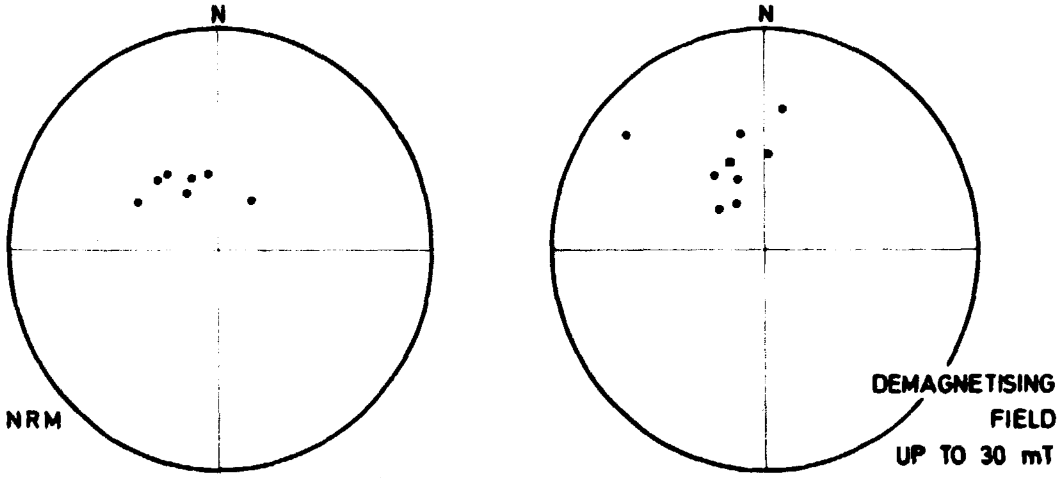


SITE 9 VALENCIA : ETUSIS FORMATION

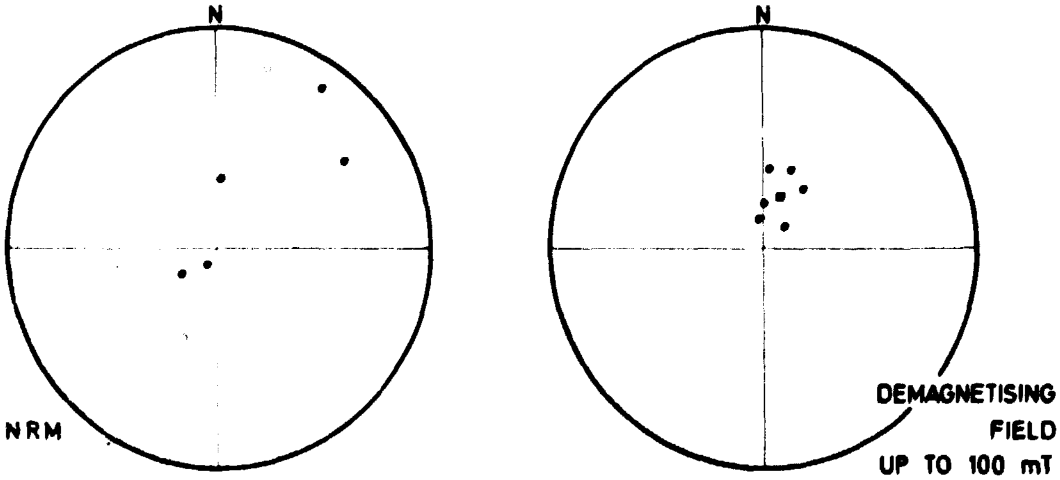
● POSITIVE INCLINATION ○ NEGATIVE INCLINATION ■ □ SITE MEANS



SITE 10 PALMENHORST : KHAN FORMATION

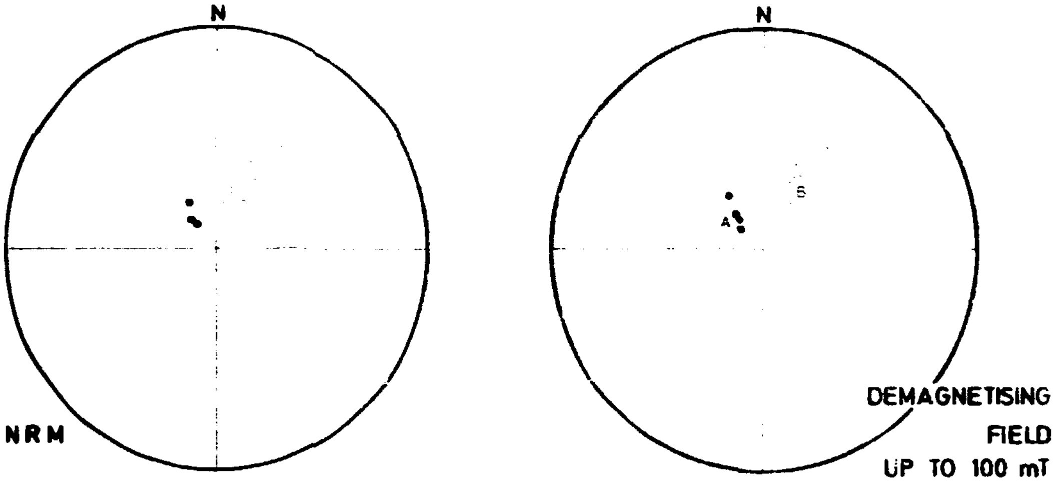


SITE 11 PALMENHORST : ALASKITIC GRANITE

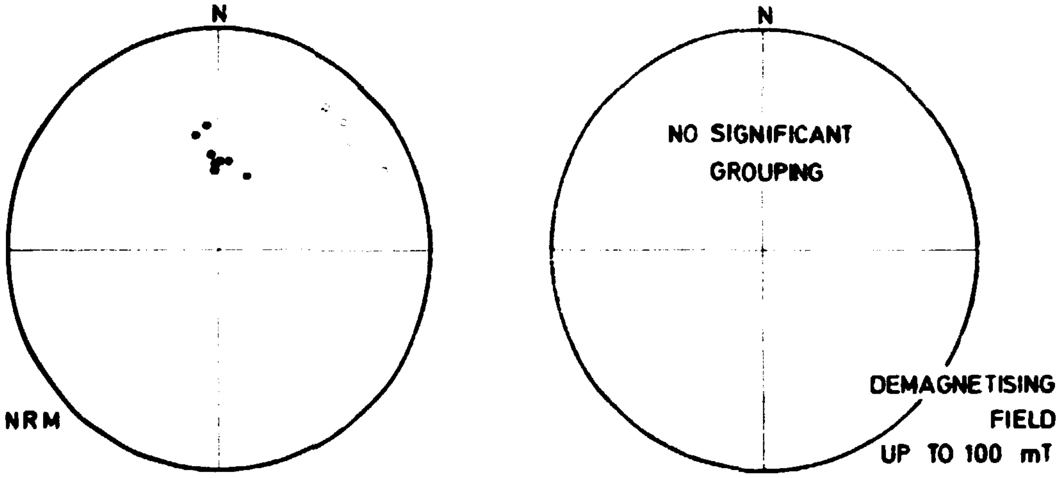


SITE 12 PALMENHORST : RED GRANITE - GNEISS

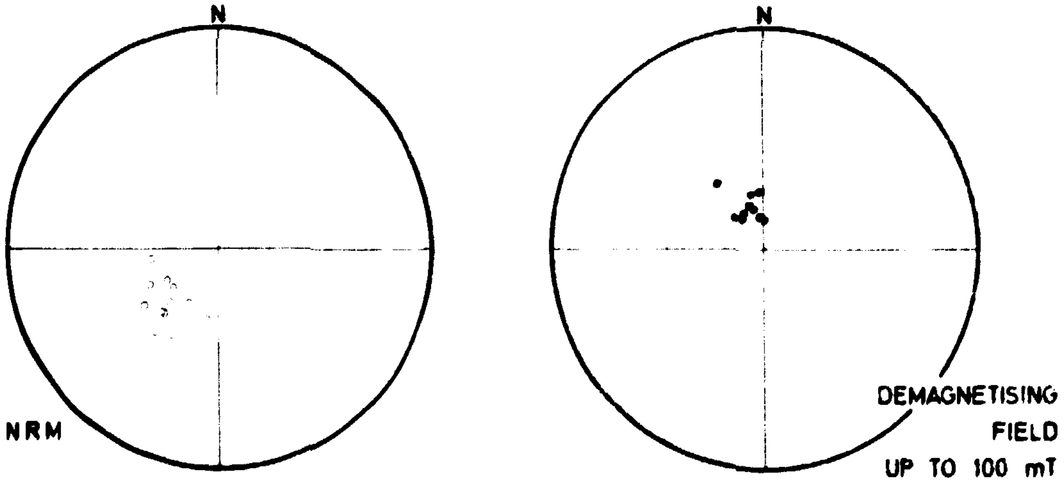
● POSITIVE INCLINATION ○ NEGATIVE INCLINATION ■ , □ SITE MEANS



SITE 13 TREKKOPJE : KHAN FORMATION

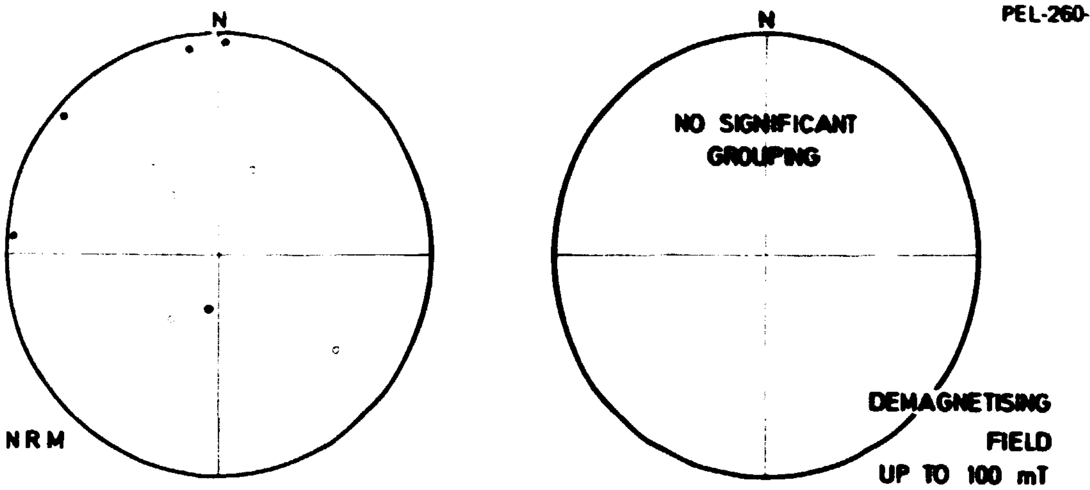


SITE 14 TREKKOPJE : ALASKITIC GRANITE

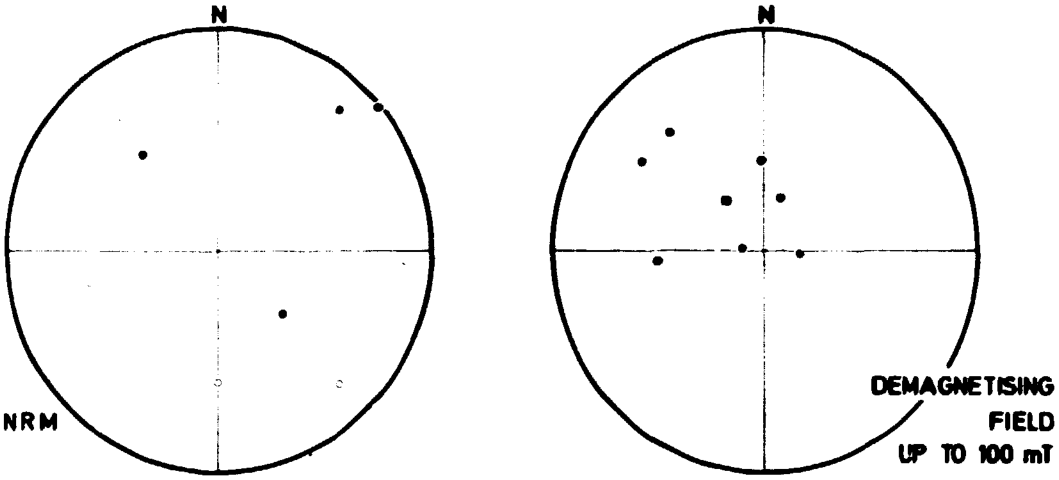


SITE 15 TREKKOPJE : RED GRANITE - GNEISS

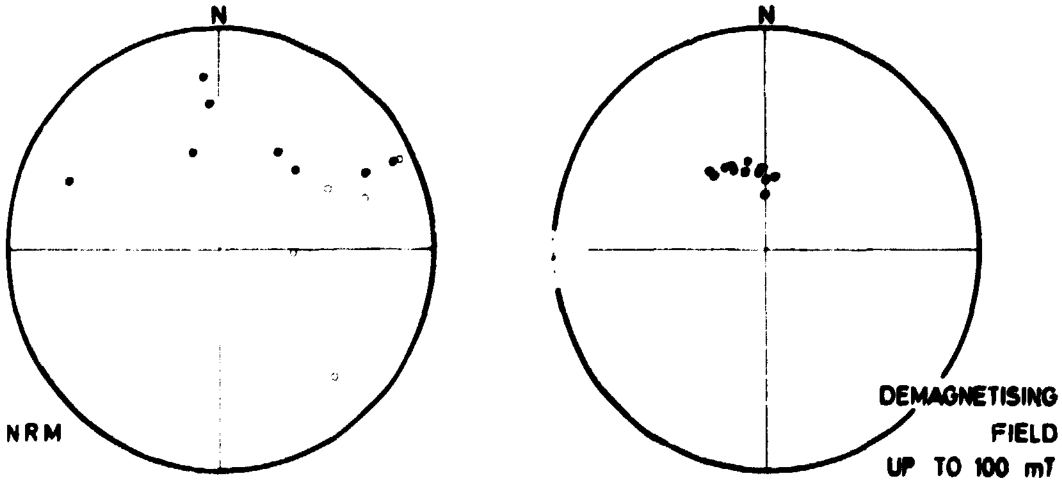
● POSITIVE INCLINATION ○ NEGATIVE INCLINATION ■,□ SITE MEANS



SITE 16 MILE 72 : SALEM GRANITE



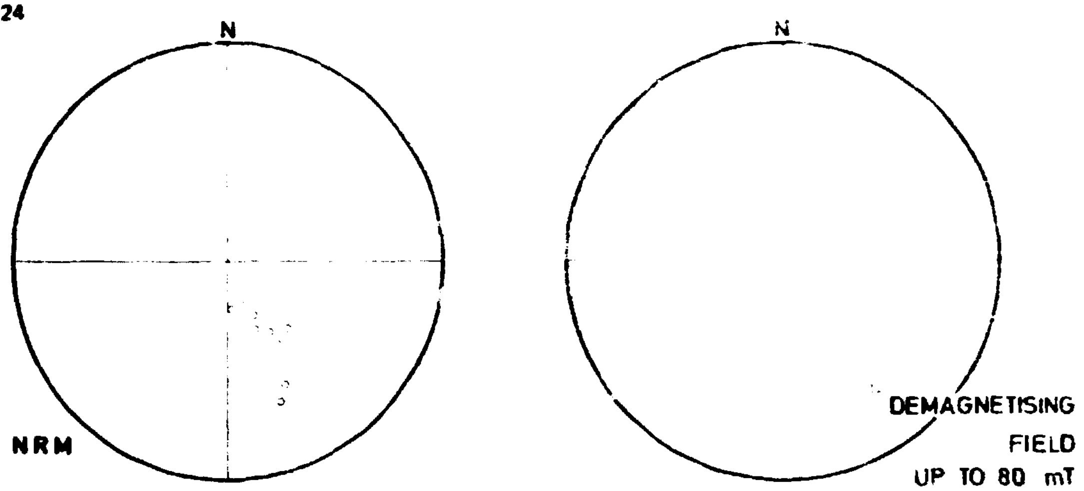
SITE 17 TSAUN BEACON : ALASKITIC GRANITE



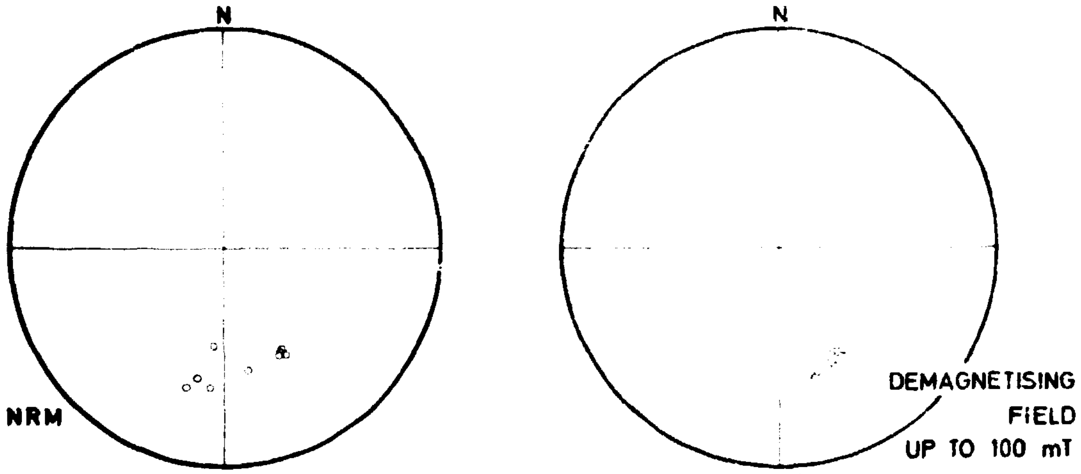
SITE 18 TSAUN BEACON : KHAN FORMATION

• POSITIVE INCLINATION ○ NEGATIVE INCLINATION ■ □ SITE MEANS

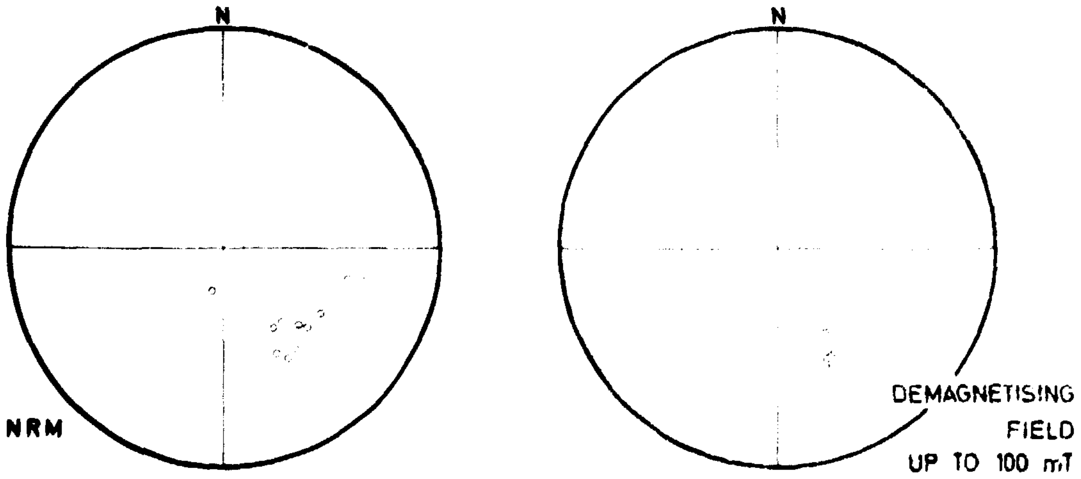
PEL-260-24



SITE 19 TSAUN BEACON : KHAN FORMATION

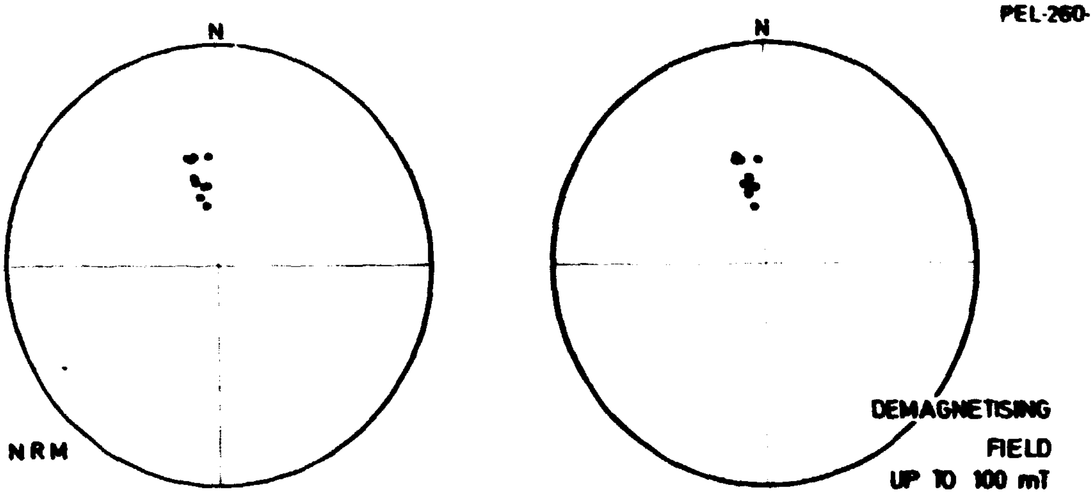


SITE 20 KUISEB RIVER : BASEMENT GRANITE-GNEISS

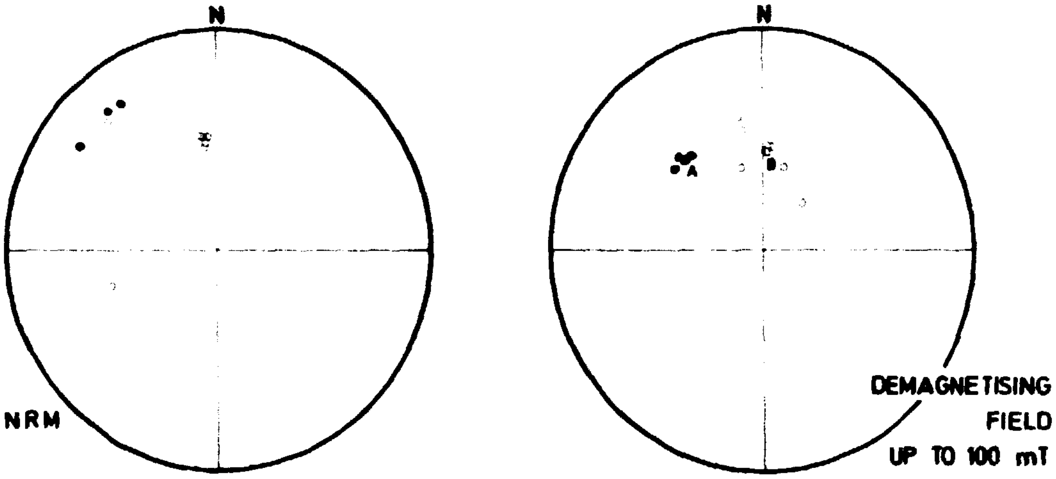


SITE 21 KUISEB RIVER : BASEMENT GRANITE - GNEISS

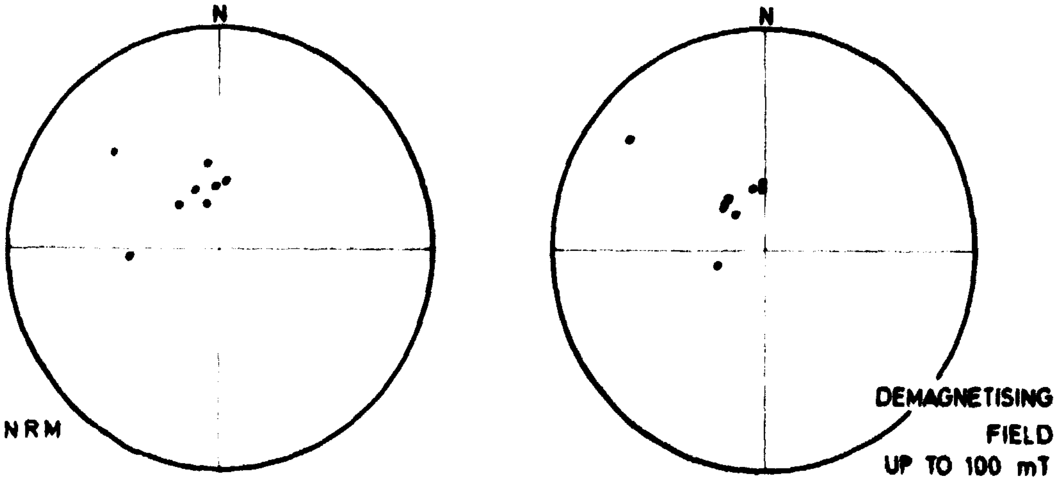
● POSITIVE INCLINATION ○ NEGATIVE INCLINATION ■ □ SITE MEANS



SITE 22 HOLLANDS DOME : ALASKITIC GRANITE



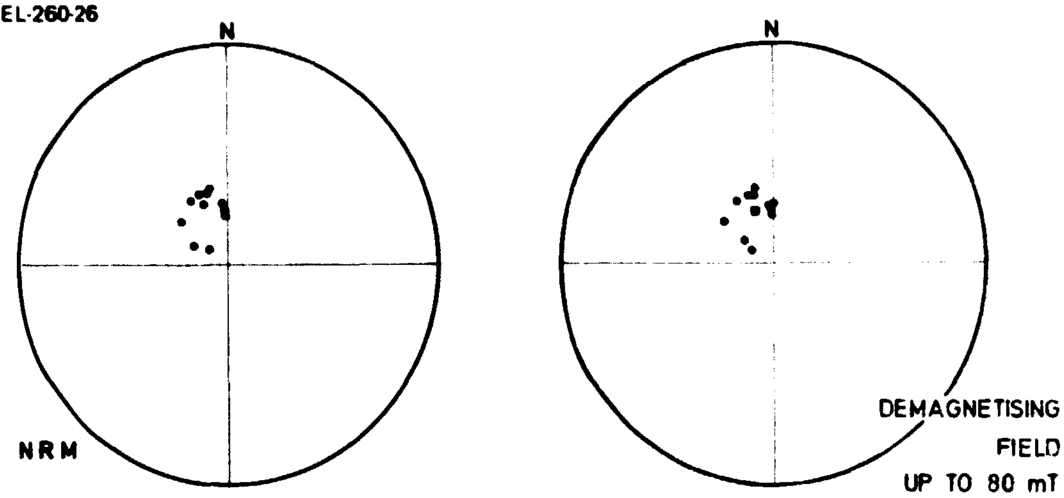
SITE 23 HOLLANDS DOME : KHAN FORMATION



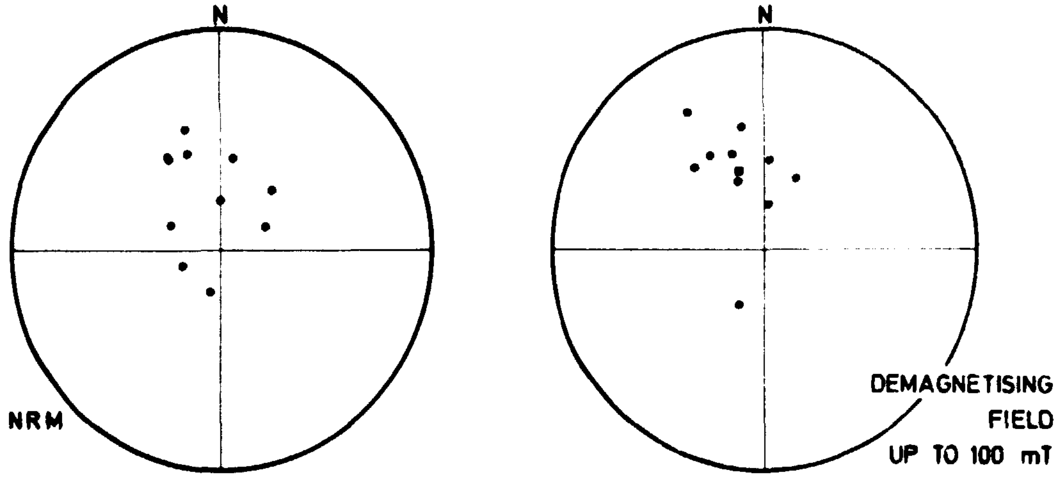
SITE 24 HOLLANDS DOME : ALASKITIC GRANITE

● POSITIVE INCLINATION ○ NEGATIVE INCLINATION ■ □ SITE MEANS

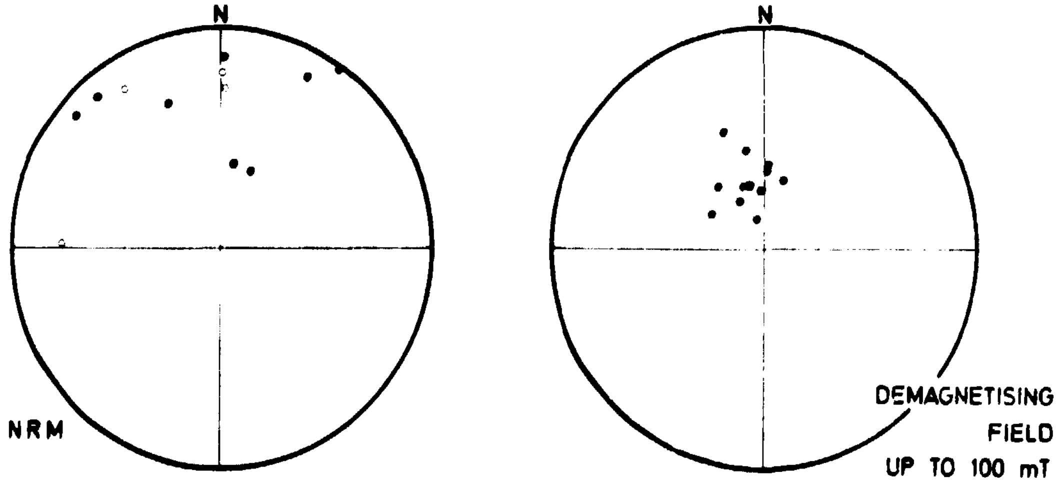
PEL-260-26



**SITE 25 IDA MINE : KHAN FORMATION**



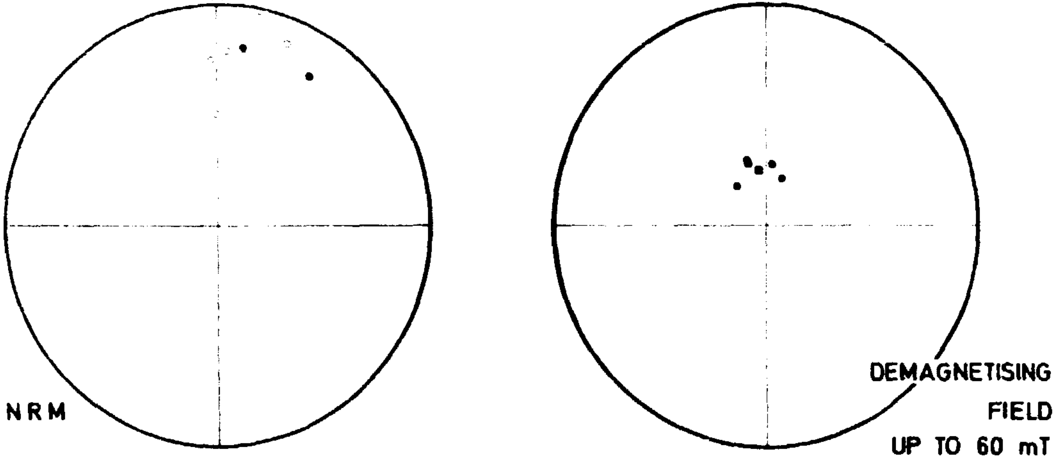
**SITE 26 IDA MINE : ALASKITIC GRANITE**



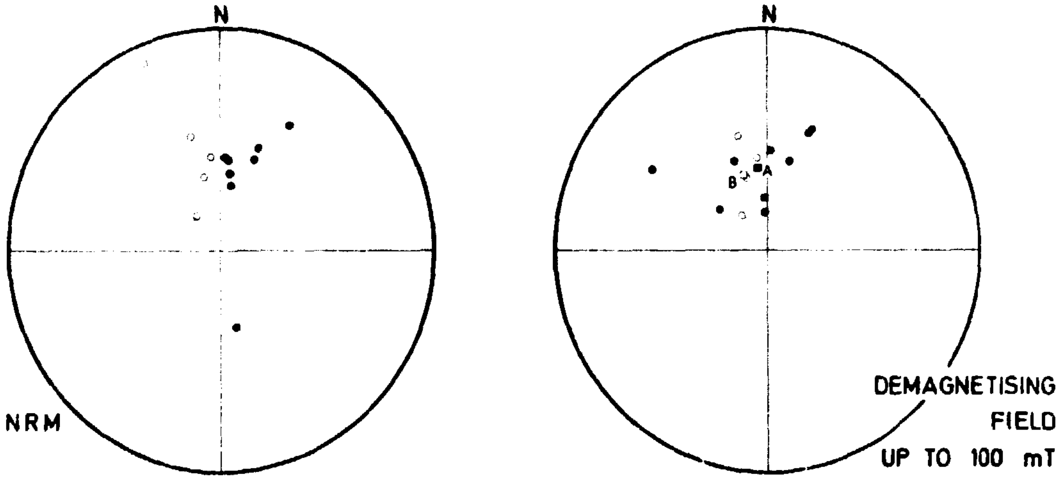
**SITE 27 IDA MINE : ALASKITIC GRANITE**

● POSITIVE INCLINATION ○ NEGATIVE INCLINATION ■ , □ SITE MEANS

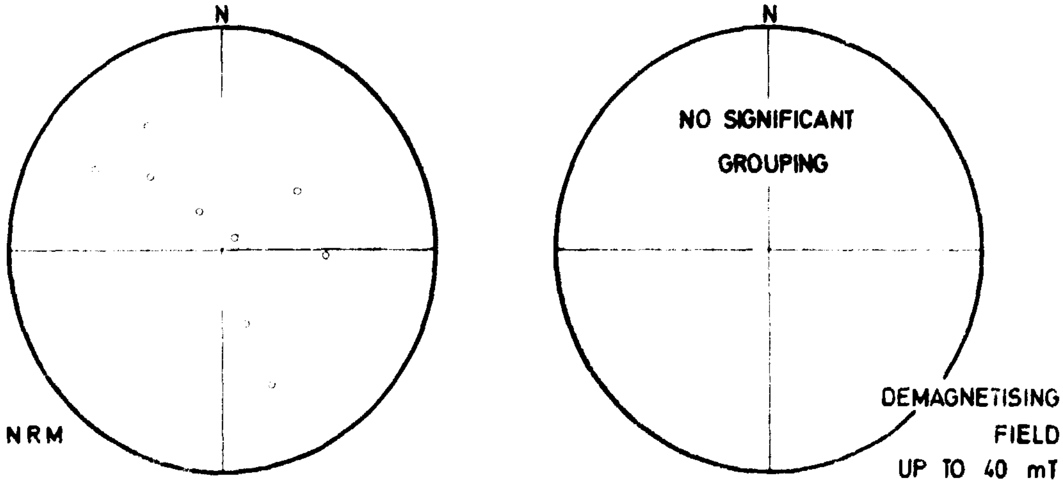
PEL-260-27



SITE 28 HOLLANDS DOME : RED GRANITE-GNEISS



SITE 29 IDA DOME : ALASKITIC GRANITE SHOWING OXIDATION HALOES



SITE 30 ONANIS : DONKERHOEK GRANITE

● POSITIVE INCLINATION ○ NEGATIVE INCLINATION ■,□ SITE MEANS

SITE 31 ONANIS : DONKERHOEK GRANITE

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