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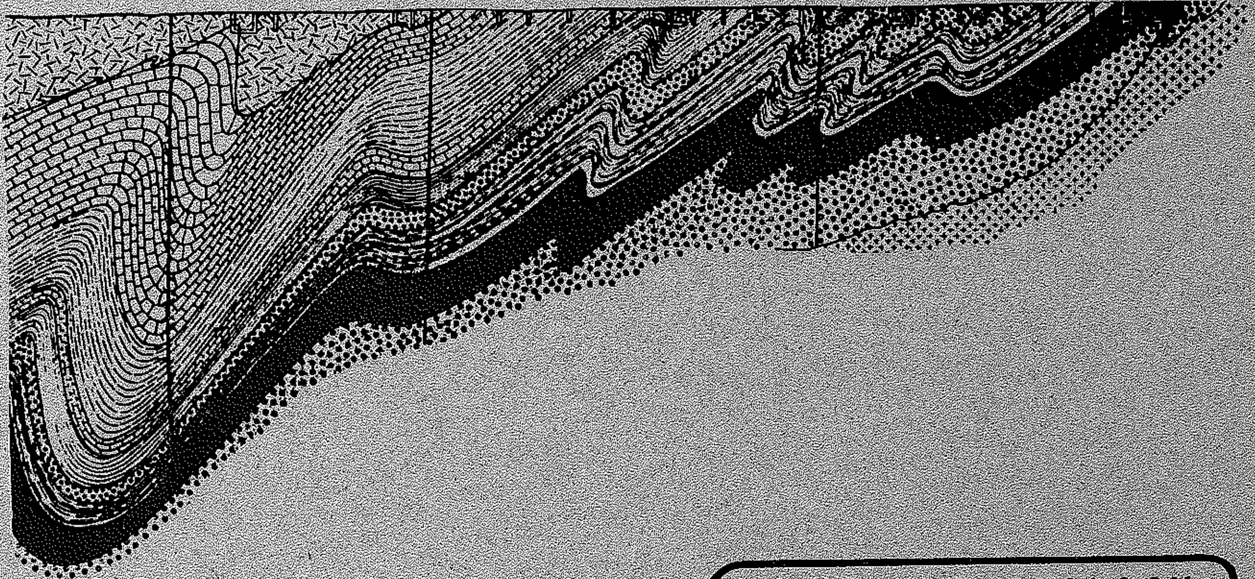

ECONOMIC GEOLOGY

RESEARCH UNIT

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THE MODE OF EMPLACEMENT OF CERTAIN Li- AND Be-BEARING PEGMATITES IN THE KARIBIB DISTRICT, SOUTH WEST ARICA.

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C O N T E N T S

ABSTRACT

A study has been made of the structural environment of pegmatites in three selected areas. In two of these (Karlsbrunn and Albrechtshöhe-Koliombo) the pegmatite emplacement is closely related to tensional openings co-genetic with wrench-faulting. The wrench-faulting is a late, post folding manifestation of the Damara-Otavi orogeny. In the third area (Brockmann's pegmatite on Tsaobismund 58) the ore-body is considered to occupy a regular a-c tension joint which is related to the main phase of folding of the orogeny. The tension joint possibly became opened during later phases of the same orogeny when a culmination of two anticlinal trends formed.

Folding within the Albrechtshöhe-Koliombo area possibly took place during three separate phases which predate the development of wrench-faulting. To date the various phases the following principle was employed: With similar folding the superimposed lineations and folds lie essentially in a single plane, the a-b plane (or axial plane of the new folds). This plane is oriented at right angles to the idealized compressive force producing the folds.

A magmatic origin for the complex Li- and Be-bearing pegmatites is suggested by:

(a) the occurrence of pegmatites of essentially similar chemical composition in various rock types

(b) the occurrence of such complex pegmatites in dolomitic marbles which phenomenon would exclude a secretion-diffusion origin.

THE MODE OF EMPLACEMENT OF CERTAIN Li- AND Be-BEARING PEGMATITES IN THE KARIBIB DISTRICT, SOUTH WEST AFRICA.

INTRODUCTION.

An investigation of lithium and beryllium bearing pegmatites of the Karibib District in Central Southwest Africa is at present being carried out by the Economic Geology Research Unit of the Witwatersrand University. The main object of the investigation is to gather as much information as possible on these pegmatites with the aim of suggesting certain geological conditions which might aid in the future search for areas of localization.

Eleven pegmatites have been mapped in detail since the project was started in June, 1959. All of these occur in the Karibib District. The locality of nine of the pegmatites is shown in PLATE I. They all lie within a 20 mile radius of Karibib, which itself is approximately 90 miles west-northwest of Windhoek. The remaining two pegmatites occurring outside of the area shown in PLATE I, are the van der Made pegmatite in the Erongo Schlucht just north of Usakos (approximately 20 miles west of Karibib), and Brockmann's pegmatite on Tsaobismund 58 near the Potberg (i.e. approximately 45 miles southwest of Karibib).

A regional geological study of the area around the Khan and Swakop rivers, and including the mineralized pegmatite area of the Karibib District, is also being carried out by the Research Unit and will aid in the understanding of the mode of formation of these ores. This study was started in January, 1960, and the results are to be published later (SMITH, manuscript in preparation).

This report is confined to one particular aspect of the study of pegmatites, viz. the mode of emplacement of the complex Li- and Be-pegmatite type. It was considered that an investigation of this problem would lay a solid foundation for subsequent detailed studies of the genesis of these pegmatites. Furthermore, if it were established that certain structural conditions favoured their emplacement, knowledge of the genesis of such conditions could possibly assist in the locating of further occurrences of presently undiscovered ores.

In order to establish the mode of emplacement, the following two points are considered to be of major importance:

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(a). Have the pegmatites formed from a local secretion-diffusion mechanism, or have they crystallized from a pegmatite magma?

(b). What were the structural conditions that influenced pegmatite emplacement?

All possible relationships of the pegmatite to the wall rock, and the character of the wall rock itself were used to answer the first question.

The structural environment of the pegmatites was determined from the relationships of the pegmatites to the regional structure and to smaller structures (e.g. lineations, foliations, axial plane cleavages).

In the Albrechtshöhe-Koliombo area the smaller structures as indicated above were treated statistically and then used in the interpretation of the tectonic history.

The following three areas were selected for the study of the structural environment of the pegmatites:-

(a). The Karlsbrunn pegmatite (PLATE I).

(b). Pegmatites of the Albrechtshöhe-Koliombo area (PLATE I the rectangular area in the northeast).

(c). Brockmann's pegmatite on Tsaobismund 58.

The mapped area of PLATE II represents approximately ten square miles. Within this area 1,123 small structural details were recorded (lineations, foliations, axial plane cleavages).

REGIONAL GEOLOGY.

STRATIGRAPHY.

The Li- and Be-pegmatites occur in rocks of the Damara System. The stratigraphy of this System, which is described briefly below, is cited from the original investigations by FROMMURZE, GEVERS and ROSSOUW (1942) recently revised by SMITH (op. cit.).

		STRATIGRAPHICAL UNIT	APPROXIMATE THICKNESS
DAMARA SYSTEM		Khomas Schist Series	10,000'+
		Upper Marble Series	0-1,800'
		Chuos Tillite	0-200'
		Lower Marble Series	0-600'
	Quartzite Series	Khan Facies	0-3,500'
		Chuos Facies	0-10,000'

---HIATUS---
ABBABIS SYSTEM

LITHOLOGY.

(a). QUARTZITE SERIES.

The Chuos Facies consists of red, often feldspathic quartzites. Argillaceous and conglomeratic bands are locally developed. With metamorphism micaceous and/or sillimanitic quartzites are formed. A basal conglomerate is occasionally present.

Grey-green well-bedded calc-granulites with locally intercalated biotite schists and feldspathic quartzite characterize the Khan Facies.

(b). LOWER MARBLE SERIES:(not developed in the Karibib district).

The predominating rocks are white crystalline marbles with intercalations of biotite schist and granular quartzite. Pebble horizons have a limited local distribution. At the base an amphibole-biotite schist is occasionally found.

(c). CHUOS TILLITE.

Essentially a glacial conglomerate with a granulitic schistose matrix.

(d). UPPER MARBLE SERIES.

The series is composed mainly of massive blue-and-white dolomitic marbles. Chert bands are abundant. Calc-silicates are developed locally. As in the case of the Lower Marble Series, an amphibole-biotite schist may sometimes be found at the base.

(e). KHOMAS SCHIST SERIES.

This series comprises a group of well-bedded biotite schists alternating with biotite-quartz schists. Cordierite, garnet, andalusite, actinolite, hornblende and sillimanite may be developed in the schists.

(f). METAMORPHIC AND IGNEOUS ROCK TYPES.

Apart from the normal meta-sediments described under Lithology above, there occur various migmatites, gneisses and granites each characteristic of its stratigraphical environment. These rocks range from red quartzo-feldspathic gneisses through quartz dioritic rocks to biotite gneisses and granites. In addition, later intrusive granites either rich in biotite or deficient in this mineral, are developed. These granites are of limited size and have a restricted distribution. According to SMITH (op.cit.), the Li- and Be-bearing pegmatites are associated with, but post-date, the formation of these granite bodies. Age determinations done on minerals from these pegmatites give values of 510 million years (NICOLAYSEN, personal communication).

STRUCTURE.

The Damara rocks are folded along axes trending dominantly northeast. The structure consists essentially of a pattern of elongate domes and basins. A weaker trend of folds almost at right angles to the above northeasterly axial direction is apparent. Isoclinal folding as well as axial plane folding is common.

THEORETICAL CONSIDERATIONS.

BRIEF REVIEW OF THEORIES ON GENESIS OF PEGMATITES.

No attempt will be made to give a complete review of the present theories on pegmatite genesis. The reader is referred to a comprehen sive account by JAHNS (1955) on the present state of knowledge on pegmatite genesis, which is accompanied by an extensive list of references on the subject.

Two theories on the origin of pegmatites are currently most acceptable. The first is the magmatic theory which envisages a pegmatitic phase to represent segregations from parent igneous masses. The pegmatites may be found within the mother pluton or may be injected into the surrounding rock. This residual pegmatite phase is considered to consist of a silicate and aluminium silicate system rich in volatile constituents. The gross composition differs little from that of ordinary igneous rocks. (JAHNS op. cit.)

Crystallization is imagined to have taken place in situ from the pegmatite magma. There are differing opinions as to whether the pegmatite crystallized under open or closed system conditions. (JAHNS, op. cit.). CAMERON, JAHNS, McNAIR and PAGE (1949) have proposed that the pegmatite may have crystallized in a "restricted system" which implies that nothing is added to the system from its source after its emplacement, but that material is allowed to escape from it during crystallization.

The second theory on pegmatite genesis, called the metamorphic-metasomatic theory, is one in which diffusion is essential (RAMBERG, 1956). A main feature of this hypothesis is the supposition of an energy gradient, generally a pressure gradient, along which ions, atoms or molecules may diffuse. These particles migrate and become fixed in tensional (often dilating) openings in the form of pegmatites.

In the dilation, or diffusion-secretion type of pegmatite, the composition of the pegmatite does not have to be the same as the nearest host-rock. The differences in the mobilities of various constituents are supposed to give rise to a most effective differentiation during the formation of the pegmatite (RAMBERG, 1956). The same author admits, however, that pegmatites may also gain substance from more distant sources, such as the mobile constituents of granitization which will become fixed in the pegmatites.

Non-dilation replacement pegmatites can also be added to the metamorphic-metasomatic group. Here the alteration of the wall-rock to a pegmatitic rock is considered to have started along a joint (RAMBERG, 1952). Replacement of the wall-rock by some media supposedly takes place, assimilating the quartzo-feldspathic material of the wall-rock and driving away the calco-ferromagnesian constituents which then border the pegmatite in the form of a "basic front" of hornblende and/or biotite.

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Subtle differences between a pegmatite formed from a magma which has reacted with and metasomatized part of the wall-rock, and a pegmatite formed solely by the replacement of the wall-rock from a joint are indeed difficult to distinguish.

Ramberg has developed his theory mainly from a study of pegmatites in West Greenland which, judging from his descriptions, do not represent economically mineralized bodies. They are found in deeply eroded roots of two Precambrian orogens in which gneisses and other metamorphic rocks are present. The rather simple type of quartzo-feldspathic pegmatites with minor accessories found in these regions are possibly characteristic of this metamorphic environment, in which secretion types of pegmatites do seem to have formed.

The complex pegmatites (e.g. Li- and Be-bearing types) are possibly of a different nature, and their genesis is not necessarily the same as that of the pegmatites of West Greenland.

To summarize, the emplacement of pegmatites may occur as a result of the following processes:-

(a). Injection of a pegmatite magma.

(b). Secretion from the surrounding rocks.

(c). Concretionary growth where pegmatites grow by pushing apart the country rock in a manner similar to the growth of porphyroblasts. According to RAMBERG (1952), such pegmatites developed as crystalline bodies in crystalline surroundings.

(d). Replacement.

DEFINITIONS AND METHODS USED IN DETERMINING THE TECTONIC ENVIRONMENT OF THE PEGMATITES.

Ideally, structural data on the country rock, obtained from measurements on as many scales as possible should be used as a means of determining the conditions that influenced the localization of the relevant pegmatite. If, however, the relationship of the macroscopic structure is sufficiently conclusive it would seem unnecessary to seek confirmatory evidence in a study of related mesoscopic and microscopic structures. (For definitions of macro-, meso- and microscopic scales see WEISS, 1958). Thus, in the present study one of the pegmatite areas (Karlsbrunn) was studied on a macroscopic scale only. Conditions in the Albrechtshöhe-Koliombo area are similar to those at Karlsbrunn, but it was decided to attempt to unravel the tectonic history by employing statistical analysis of mesoscopic structural features in addition to the assessment of the macroscopic structural data. The same applies to the Tsaobismund 58 area.

Statistical analysis of structural geometry involves the measurement and recording of small structural features such as lineations, foliations and axial plane cleavages (for definitions see below). These are then plotted on a Schmidt-type stereographic projection and treated statistically.

The interpretation of such projections has become a rather specialized branch of geology and the reader is referred to an excellent introduction to the subject - "Structural Analysis of the Basement System at Turoka, Kenya", by WEISS (1958). For further information on this subject including the principles involved in the interpretation reference should be made to papers by WEISS(1959) and RAMSAY (1960).

The present paper makes use of several terms which are defined as follows:-

<u>Foliation</u> : "A visible set, or sets, of parallel surfaces of inhomogeneity defined either by lithological variation or preferred dimensional orientation of minerals or by both". (WEISS, 1958).

<u>Lineation</u> : There are three main types of lineation according to WEISS (op. cit.):-

1. "Lineations caused by folding on a microscopic scale of a fabric surface. This structure is homologous with folding on a larger scale."

2. "Lineations caused by elongation of fabric elements such as individual grains, groups of grains, small heterogeneous inclusions, etc."

3. "Lineations caused by mutually inclined sets of fabric surfaces. A parallel lineation occurs in each set of surfaces."

Similar Folding : The basis of similar folding is the presence of cleavage surfaces along which movement has taken place. These are generally inclined to, and penetrate, the main foliation surfaces (e.g. sedimentary bedding).

De Sitter includes the following types in similar folding:- (DE SITTER, 1956)

---slaty cleavage folding.

---fracture cleavage folding.

---accordion folding.

---chevron folding or oblique shear folding.

Concentric Folding : means that "the internal movement is parallel to the bedding plane". An essential feature is that the thickness of any folded bed remains unchanged (DE SITTER, 1956).

The interpretation of the statistical data in the present paper is based on the principles involved in the process of superposed folding. Ascertaining the effect of folding of earlier lineations and establishing what positions they adopt in space, was considered to be of less importance than determining the attitude of lineations superposed on pre-existing structures. The principles involved in the former process are presented by WEISS (1959) and RAMSAY (1960). The second, somewhat simpler case is discussed below as it has a direct bearing on the Albrechtshöhe-Koliombo area.

When lineations formed by similar folding (axial plane cleavage acting as slip surfaces) are superimposed on to an existing structure (such as an unsymmetrical arrangement of foliation planes), the only ideal parameter constant in the new set of lineations would be the axial plane of the new folds. Assuming a uniform orientation of the axial plane cleavage slip surfaces, the lineations formed by the intersection of these surfaces with the unsymmetrical arrangement of pre-existing foliation surfaces would either be axial plane cleavage foliation intersections or small folds formed by slip on the fairly uniformly oriented plane surfaces. In either case, the only constant parameter would be the axial plane containing all the lineations. On a stereographic plot the superposed lineations would then fall on a great circle.

In nature, conditions would not be ideal. There would be a distinct spread in the lineations on either side of the axial plane of the superposed folds because the axial plane cleavage slip surfaces are not statistically parallel but show a small, but significant divergence from the axial plane (DE SITTER, 1956). In the case of isoclinal folding, this spread would be minimized and the ideal conditions would be approached. Such conditions are, therefore, to be expected in the Albrechtshöhe-Koliombo area where isoclinal folding is prominent.

It is of interest to note that for ideal conditions the superposed lineations will always lie on a great circle, irrespective of what the pre-existing structure was. Thus, the orientation of the applied force necessary to give rise to these superposed lineations is represented by the pole to the great circle containing these lineations, or, in other words, the pole to the average uniform slip surface (which is generally an axial plane cleavage).

There are other types of similar folds (e.g. chevron folds) in which the cleavage direction is an oblique shear direction (DE SITTER, 1956). The same author states, however, that, in his general experience, slaty and fracture cleavage are both roughly parallel to the axial plane of the fold. True schistosity which would represent a more advanced stage of the two preceding types of cleavage, would thus also tend to have a similar orientation.

Another point of consequence is that the lineations referred to above would only apply to the intersection of axial plane cleavage and foliation, and micro- and small-folds developed by slip folding on essentially parallel surfaces. These lineations are thus also governed by the original geometrical attitude of the beds (folia) prior to the super-position of the later lineations.

Preferred orientation of minerals indicates lineations governed to a greater degree by the ideal tectonic axes, which could therefore have a different vector direction. Lineations controlled by the original attitude of the foliation may be anywhere in the a - b plane, while mineral orientations may be parallel to the a - or b - axis. (For a definition of tectonic axes see DE SITTER 1956, WEISS 1958). If there were minerals that grew with their elongation parallel to the directed compressive force, these lineations would then lie parallel to the c-axis. It is therefore essential to realise what type of lineation is being measured.

This premise that superimposed lineations (formed by similar folding along axial plane cleavage slip surfaces) are controlled by, and lie close to the axial plane of the superposed folds, forms the basis of the interpretation used in establishing the structural history of the Albrechtshöhe-Koliombo area, (page 14).

INTERPRETATION OF FIELD OBSERVATIONS.

GEOLOGICAL ENVIRONMENT OF THE LITHIUM- AND BERYLLIUM BEARING PEGMATITES.

The Li- and Be- pegmatites of the Karibib District, and Brockmann's pegmatite, are considered to be associated with the period of Damara metamorphism and Salem granite formation, (SMITH, manuscript in preparation).

These pegmatites occur in rocks of varying character. (PLATE I). They are known to lie in Damara Marbles (e.g. Helicon II on Okongava Ost) and in Damara quartzite, e.g. Brockmann's pegmatite on Tsaobismund 58, and Henckert's pegmatite on Dernburg, (see PLATE I). (Brockmann's pegmatite does not occur in this area). The main pegmatite in the Albrechtshöhe-Koliombo area transects the Damara Marble Series, a transition zone between the marbles and the Khomas Schists, and finally the Khomas Schists (PLATE II).

It would thus seem that the mineralized pegmatites bear no significant chemical relationship to their wall rocks. The pegmatite composition is characterized by silica, alumina, alkalis, Be, Ta, Cb, P, B, F and remains fairly constant in spite of the fact that the pegmatites are found in rocks of varying stratigraphical position and type (quartzite, marble, banded limestone-biotite schists).

Furthermore, some of these bodies occur in, and are completely surrounded by, carbonate rocks (Damara Marble Series), e.g. Helicon II on Okongava, Berger's pegmatite on Koliombo, Karlsbrunn. (See PLATES I and II).

It is considered unlikely that dolomitic marbles would constitute a substantial source of silica, alumina and some of the unusual elements indicated above, which are necessary to produce a pegmatite by a secretion-diffusion mechanism.

On the basis of these data, it seems justifiable to assume a magmatic source for this type of pegmatite. The discussion of the structural condition which might have controlled the emplacement of the pegmatites will be based on the assumption that these bodies were derived from a magma.

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SPECIFIC EXAMPLES OF PEGMATITE EMPLACEMENT.

(a). The Karlsbrunn Pegmatite. (PLATES I and III).

This is a lithium pegmatite with beryl, columbite occurring in the Damara Marble Series. The main pegmatite body has a "phacolithic shape" (i.e. in the sense of its shape only; it has not been folded and shows no signs of internal deformation), part of the pegmatite being almost vertical while the remainder is almost horizontal. A smaller body occurs just northeast of this and has the shape of a vertical lense. The vertical dyke-like portions of the pegmatite are those that have been considered in this study. The strike and dip of the main vertical portion of the pegmatite is suggested by the Jooste beryl quarry. The latter, which is a vertical narrow cut, defines the strike and dip of a very rich beryl zone which has been mined out. The cut is approximately 70' long, 8'± wide, and at present 20' - 30' deep. The floor is filled with rubble so it is possible that the workings continued even deeper. The strike and dip of this beryl zone is taken to represent the strike and dip of a wide dyke displaying typical zoning. The strike is north-south (magnetic).

Another vertical dyke-like portion of the pegmatite, underlying the flat part, is found some 450' to the northeast of the Jooste beryl quarry. Here the central part of the pegmatite consists of a continuous zone of mixed quartz, grey- and pink-lepidolite, petalite and albite. This central core zone has an average width of 10', is vertical over an exposed height of 30' - 40' and can be traced for a distance of 120'. The strike of the mineralized zone is north-south (magnetic) and the remainder of the pegmatite can be taken to have a similar attitude. The observable eastern contact of this pegmatite with the limestone is steep, the strike being essentially parallel to that of the mineralized zone.

These two vertical portions of an extremely complex structure of the pegmatite are considered significant. The remaining part of the pegmatite is essentially flat lying fairly conformable with the foliation. The wall-rock roof cover is eroded away so that the exact control of the flat lying portion of the pegmatite is impossible to ascertain.

The Karlsbrunn pegmatite is located close to a major fault (PLATE III), striking approximately *N.35.E. At two

* All directions given in this manuscript are magnetic bearings.

localities on this fault the displacement was determined. The fault cuts across a closed anticlinal structure. The displacement of the northern contact of the Damara Quartzite Series and the Marble Series indicates that the eastern side of the fault has suffered a relative movement to the north. The dip of the metasediments is to the north at this locality.

The displacement on the southern side of the anticline was found to be the same, viz. to the north, in spite of the fact that the beds dipped southwards. Two useful markers could be used in establishing this fact, the Chuos Tillite, which is developed locally, and an amphibolitic horizon occurring in the succession above the tillite.

Thus, it can be established that the absolute displacement on the fault must have been essentially horizontal. The fault, therefore, probably represents a wrench fault as defined by ANDERSON (1951). It is a left lateral type, i.e. the relative movement is counter-clockwise.

Ideally, the major horizontal compressive force required to produce such a wrench fault would be approximately 30° counter-clockwise from the fault. (MOODY and HILL, 1956). Tensional openings, should theoretically always lie in the same direction as the major compressive force. The angles formed by the strike of the vertical dyke-like portions of the Karlsbrunn pegmatite and the strike of the wrench fault are approximately 35° . The small angular difference between the ideal direction required to produce the wrench fault, and the actual direction of the vertical dyke-like portions of the Karlsbrunn pegmatite suggests that these portions of the pegmatite occupy true tensional openings.

On the immediate west of the Karlsbrunn wrench near the southern Quartzite-Marble Series contact, narrow 1' - 3' wide pegmatite dykes have the two pronounced magnetic orientations:-

Strike.	Dip.
360°	80° West.
260°	70° North.

The northerly strike belongs to the same system as the Karlsbrunn vertical dyke-like portions. The other direction is completely at right-angles to this, and is found also in the Albrechtshöhe-Koliombo area which has been subjected to the same stress conditions. The explanation is given in the next section (page 27).

A similar parallel fault occurs approximately two miles to the east of the Karlsbrunn wrench. The relative movement on this fault could not be determined with the same degree of certainty as at Karlsbrunn. However, the faults are considered to be similar as regards attitude, displacement and time of formation because:-

i. They are parallel to each other.

ii. Dolomitic limestone fragments cemented by chert-like material occur in both.

iii. The apparent displacement of a calc-silicate horizon at one locality on the eastern fault suggests a movement in the same direction as the Karlsbrunn wrench. (See PLATE II).

iv. Pegmatite emplacement is closely connected with this period of faulting. This has been described above in the case of the western wrench fault passing close to Karlsbrunn. The eastern fault zone has pegmatite mineralization in it,as well as pegmatite mineralization developed in a manner identical to that at Karlsbrunn (see page 26).

The Karlsbrunn pegmatite illustrates two important features:-

i. It occurs in dolomitic marbles, and therefore, a secretion-diffusion hypothesis involving enrichment of elements and compounds such as silica, alumina, alkalis, Be, B, P, F, Ta, Cb, Sn is therefore unlikely.

ii. The vertical dyke-like portions of the Karlsbrunn pegmatite can be related to tensional openings caused in conjunction with a period of wrench faulting occurring in the area.

(b). The Pegmatites of the Albrechtshöhe-Koliombo Area.

(i). GENERAL GEOLOGY.

A regional geological map has been compiled by SMITH and is included to show the location of the Albrechtshöhe-Koliombo area, as well as some of the pegmatites of the Karibib District (PLATE I and II). (SMITH, manuscript in preparation).

This area was selected for two reasons:-

---It is one of the few areas that contains pegmatites of the same group (late tectonic). This pegmatite group is known to carry economic minerals, e.g. beryl, lithium minerals, tantalite-columbite, and tourmaline. Earlier syn- or pre-tectonic, pegmatites occurring in this area are generally simple quartz feldspar mica types with minor accessories;

---The area is suitable for structural analysis, i.e. statistical assessment of lineations and foliations.

Most of the area is underlain by tightly folded (virtually isoclinal) Damara Marbles (PLATE II). The marbles occasionally contain calc-silicate horizones which facilitate easy macroscopic determinations of foliations and lineations (micro- and small folds). At two localities, lineations measured in the calc-silicate horizons revealed that there was no dominant statistical orientation over outcrops of a few square feet, thus suggesting that plastic flow had taken place.

(ii). PEGMATITES.

Several pegmatites occur within the area, the majority of which are barren. Mineralized bodies show no signs of deformation and distinctly crosscut the structure. They are, therefore, late tectonic (see page 27). The characteristics of this group of pegmatites are discussed below.

Attention is drawn to the Central "S" - shaped pegmatite body. (PLATE II). The greater part of the pegmatite is made up of pink microcline-perthite crystals of varying size (up to 2' - 3') lying in a groundmass of intergrown quartz-muscovite. Albite may be present in the groundmass and is scattered throughout in varying amounts. Beryl has been found on rare occasions in the quartz muscovite groundmass. Scattered in this uniform feldspar-quartz-muscovite material are small, local bodies rich in Li-mica, and bodies of massive, dominantly albite rock.

Small quartz blows are sometimes irregularly developed in the main "S" - shaped pegmatite body without any major symmetry, and these are generally 1' - 3' in width and may be followed over distances of 20' - 30'. On their margins, or intermingled with the quartz, minerals such as pink lepidolite, amblygonite, beryl, tourmaline and columbite may occur. Albite is characteristically developed in platy aggregates accompanying these ore minerals.

A large concentration of Li mineralization is found in the northeastern extremity of the "S" - shaped pegmatite. (BROCKMANN'S PROPERTY in PLATE II). This ore body is rich in Li minerals lepidolite and amblygonite, and also contains minor beryl and tantalo-columbite. Separation of the minerals into fairly well defined zones is a prominent feature of this area.

This "S" - shaped pegmatite is thus mineralized only at local, irregularly dispersed centres, the maximum concentration of economic minerals occurring at the northeastern extremity. In this paper the whole pegmatite dyke is regarded as a single unit.

Other mineralized pegmatites are those of Berger on Koliombo and Brockmann on Albrechtshöhe. The latter is not indicated on the map (PLATE II). These two bodies contain Li and Be minerals.

The other pegmatites indicated on the map (PLATE II) are essentially the microcline-albite-quartz-muscovite-type, which locally may develop a quartz core and minor lithium, beryllium, tourmaline mineralization.

The similarity of mineralogy and general character of the majority of pegmatites in this area suggest that they belong to one single phase of pegmatite intrusion. Genetically they may be considered as a group consisting of the common reddish pegmatite type with its typical microcline-albite-quartz-muscovite assemblage, and with local differentiates of Li, Be and associated mineralization.

This group of pegmatites is considered to be late tectonic, (see pages 26 to 28). There are, however, a few narrow, simple quartz-feldspar pegmatites and quartz veins in the area (Fig.1, PLATE IV), which are folded together with the foliation. This relationship strongly suggests that they are pre- or syntectonic. Such pegmatites do not give rise to Li and Be ores.

Of the different types of pegmatites of varying ages, only the complex group are considered in this text.

(iii). STRUCTURAL GEOLOGY.

Statistical analysis was employed as the means of interpretation of the structural geometry in the Albrechtshöhe-Koliombo area. This involved measurement of lineations, foliations and axial plane cleavages in the field. Observations were made at 600 points. At each point the geometrical attitude of the above features were recorded if developed. Many readings of the same feature (e.g. lineations) were taken if these were abundant and well developed at the observation point. On PLATE V, the orientations measured at each point have been recorded. If two obviously different directions were observed at one point, both directions have been plotted.

The nature of the structure varies appreciably over relatively short distances within the area and to facilitate description, the district has been divided into sub-areas. (PLATE II). The data from each sub-area have been recorded on an equal-area Schmidt-type projection and contours drawn for one percent areas. The projections have been plotted on the upper hemisphere.

Three distinct phases of folding have been recognized in the Albrechtshöhe-Koliombo area and these give rise to three definite sets of lineations L_1, L_2

and L_3 in order of decreasing age. The evidence for postulating three periods of folding is given in the discussion of the data collected for all the sub areas.

Sub Area I:

This sub-area shows a certain degree of simplicity and thus a higher degree of homogeneity than other more complex sub-areas. As can be seen from the maps (PLATE II and V) the structure of the area represents a fairly uniform synclinal structure plunging gently to the east-southeast. Lineations in the area are not as symmetrical as would be expected from the simple macro-structure. (PLATE VI fig. 2). From the lineation plot, however, the concentration of points defining the fold axis shows a spread, but would appear to have a maximum at 300° dipping at 16° eastsouth-east.

In the field the main set of lineations (L_1) is folded by later sets which plunge in approximately south-easterly (L_2) and south-westerly (L_3) directions. (See fig. 2, PLATE IV).

The change in direction and angle of plunge of the L_1 lineations about a uniformly plunging fold (L_2 or L_3 lineations) would tend to indicate the former are folded by the latter, (e.g. fig. 2 PLATE IV). A curious feature of the lineation plot for this sub-area (PLATE VI , fig. 2) is the marked spread on a great circle. The significance of this great circle can be better understood from a plot of the foliation data (PLATE VI , fig. 1). The foliation data show a well defined double maximum lying on a great circle, the pole to which is the lineation L_1 which defines the plunge of the synclinal structure. These maxima indicate that the structure is almost isoclinal. (The poles to the foliation and axial plane surfaces tend to be concentrated in a relatively small area.) The two-point maximum is due to the fact that the southern limb of the fold is steeper than the northern limb. (PLATE VI , fig. 3).

If a point in the centre of these two maxima is taken to represent the pole of the axial plane, then it can be seen that the subsequently plotted trace of this plane forms a great circle which contains all the lineations. (PLATE VI) In other words, the axial plane of the fold (and since the fold is approximately isoclinal the axial plane would apply to the average orientation of all foliations and axial plane cleavages of the sub-area) very rigidly controls the positions of the lineations L_2 and L_3. The original attitude of the bedsafter L_1 folding gave rise to a series of almost parallel-orientated foliation surfaces in which the new superposed lineations lie. The control of superposed lineations by the previous geometrical attitude of the foliation is particularly clear in the case of L_2 which developes into two distinct maxima, the northernmost one, L_2' controlled, to a high degree by the shallower dip of the northern limb of the syncline (PLATEVI , figs.2 and3).

Lineations L_2, L_2' and L_3 are thus rigidly controlled by the original geometrical attitude of the syncline, and on this reasoning alone, it can be concluded that the L_2 and L_3 lineations have been superimposed on an older L_1 structure.

The spread on the lineations, i.e. the spread other than that producing the maxima, is determined by the foliations differing slightly in attitude from the axial plane of the L_1 fold.

The concentration of L_2 lineations (PLATEVI fig.2) defines a pole to a second great circle of poles to foliation planes which is clearly present in fig.3 PLATE VI.

In this sub-area then it can be established that a primary period of folding (L_1) was followed by two distinctly later sets which have not been dated with respect to one another.

Sub-Area II:

This area also has a simpler structure than some of the other sub-areas, and for this reason was chosen to characterise a certain trend and orientation of folds, and thus possibly, a certain age of folds within the whole area.

The trend of the lineations, and the trend of tightly folded synclinal structures are almost at right angles to those in sub-area I. (PLATES II andV ; compare fig.2 PLATEVI and fig.2 PLATEVII).

The foliation plot displays the isoclinal nature of the folds (PLATE VII fig.1). It can be established that all foliations have essentially the same orientation. A statistical plot of all the foliations defines a distinct maximum which is the pole to the axial plane of the isoclinal folds. The limbs of the folds are very long in relation to their turnovers or crests. This is also shown by the fact that essentially all the foliations have a similar orientation. Due to the isoclinal nature of the folds the orientation of the axial plane cleavages and the foliations are virtually the same, (see PLATE VIII fig.1). For this reason, these two parameters have been plotted together in all the foliation diagrams of the Albrechtshöhe-Koliombo area, as all the folding is essentially isoclinal.

The trace of the axial plane is again seen to be the great circle containing the spread on all the lineations of Sub-Area II. (PLATE VII fig.2).

A weak set of lineations lying at right angles to L_2 has been observed on a few occasions only. These are mainly boudin structures, but in other cases appear to be later folds. The boudins have been observed in the banded limestone-biotite schist sequence (fig.1 ,PLATE IX). The fact that these boudins are perpendicular to the statistical fold axis would tend to suggest that they are manifestations of one and the same period of folding. The tension required to develop the boudins was possibly a result of a regular a - c plane of weakness in the competent biotite schist bands.

Such joints, perpendicular to lineations are also shown in fig.2 , PLATE VIII . The cracks are filled with recrystallized carbonate material.

Where the boudins are not developed foliation bands may be exposed with small finger-wide folds extending straight across the main lineation L_2. The L_2 lineations change in attitude about the crests of the small folds which have a uniform direction, and which might suggest that the latter are superposed. These small folds might also represent folded indentations near to closely existing boudins that have weathered away.

In this sub-area it can therefore be established that there is tight isoclinal folding (S_2 maxima) in which the folds plunge at an angle of 40° to the south (L_2 maxima). (PLATE VII). Since all the foliation surfaces are virtually parallel with the plane defined by the S_2 maximum, the lineations are controlled by the attitude of this plane, which in comparison to Sub-Area I could indicate superposition of folding. In some cases, however, the boudins which are formed at 90° from the fold axis may be genetically related to the same act of folding.

There are not enough data to date with certainty other lineations that lie on the axial plane trace; they may be contemporaneous with L_2 (e.g. boudins) or possibly later. At one locality lineations of possibly later age than L_2 occur. These fold the L_2 lineations as can be seen in fig. 2 PLATE IX. The orientation of these lineations are as follows:-

	Bearing:	Plunge:
L_2	186°	44°S
L_2	185°	34° S
L_3 (?)	202°	44° SW

Sub-Area III:

The pattern of folding in this sub-area is essentially uniform. PLATE X fig. 1, shows that the folds are essentially isoclinal. Lineations show a weak spread which lie on the axial plane of the folds, (PLATE X fig. 2).

It was observed at one locality that two distinctly different sets of lineations do in fact occur, e.g.

	Bearing:	Plunge:
L_2 folded (?)	161°	30° S.E.
do.	94°	44° E.
L_3 (?)	24°	5° N.N.E.
do.	20°	9° N.N.E.

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Positive age relations between the two could not be determined.

Sub-Area IV:

This area is similar to Sub-Area III. The lineations show a spread on the axial plane of the fold. The axial plane is defined by foliation data. (PLATE XI, fig. 1). Trends of S_1 foliation also seem to be indicated in fig. 1 of PLATE XI.

The last two sub-areas (III and IV) show clearly that the foliation is essentially of the same orientation in each sub-area. In both areas lineations show a decisive spread on a great circle which is the axial plane of the folds.

In Sub-Area IV the spread of the lineations on the axial plane of the folds may possibly be fortuitous. L_1 lineations might be present and their position as determined from Sub-Area I would be fairly close to the axial plane of the folds as found in Sub-Area IV. (Compare fig. 2 of PLATE VI with fig. 2 of PLATE XI). The foliation data of Sub-Area IV (PLATE XI fig. 1) would support this view in that S_1 foliations are possibly present.

Considering the axial plane control of lineations in Sub-Areas III and IV this phenomenon could be explained on the grounds suggested on pages 8 to 9, i.e. when lineations are superimposed the only constant parameter common to these lineations is the great circle in which they lie. (This great circle is the axial plane of the new superposed folds).

Sub-Area V:

It has been established that three major sets of lineations are present in the four sub-areas described above. The foliation plot shows that the two previously determined sets can be accommodated in the diagram, indicating that S_1 and S_2 are present in this sub-area (PLATE XII, figs. 1 and 3.

Two maxima are present. Comparing these with the simple type areas, (Sub-Areas I and II), they are seen to represent axial planes of folds trending west-north-west and north-east respectively. If these maxima are critically examined, the correlation of the respective sets of folds to those of Sub-Areas I and II do not coincide perfectly. It might be argued that a single great circle with L_2 as the pole could be drawn through both the maxima. This is certainly possible but two distinct fold directions are chosen because on the macro-scale both sets of folds do occur (see PLATE II). It therefore seems more likely that two separate fold systems are present. Later folding might account for the slight displacement of the two foliation maxima of Sub-Area V from their ideal positions as determined in Sub-Areas I and II. Finally it can be seen in Sub-Area I that the great circle containing S_2 foliations passes straight through the S_1 foliation maxima (PLATE VI fig. 1).

The spread of the lineations is controlled essentially by the axial planes of these two dominant fold directions (PLATE XII, fig. 2). Again the folds show isoclinal tendencies.

The L_3 lineations show a spread on a third great circle (PLATE XII, fig. 2). The maximum of this group of lineations corresponds closely with the maximum for the same lineation when it is superposed on a L_1 structure (PLATE VI fig. 2). From the discussion on pages 8 and 9, this spread of L_3 on a great circle might be due to its superposition on previously existing structures which, in this case, would be an L_1 or L_2 structure.

In Sub-Areas II and III there is evidence of folding definitely later than L_2. Simple reasoning from data of Sub-Area I where L_2 and L_3 are later than L_1 suggests that folds which are later than L_2 (e.g. Sub-Areas II and III) are most likely to be L_3, unless yet other ages of folds are present.

Furthermore, field relations observed at one locality suggested that L_3 is later than L_2 (PLATE XIII). These photo's (PLATE XIII) show that the intensities of the fold sets at this locality are almost equal. The reason for assuming L_3 later than L_2 is the fact that the L_3 folds maintained a fairly constant direction while the L_2 folds plunged to the north and to the south.

The phenomenon of the controlled spread of the lineations on the axial planes of the two major fold sets observed in this sub-area, can be explained partly in the light of the discussion on pages 8 to 9 . In the approximate isoclinal fold where the original structure L_1 is not destroyed the axial plane of this fold rigidly controls the spread of later superposed lineations, - Sub-Area I. In other cases where the L_2 structure is dominant, the axial plane of these folds will contain the spread of contemporaneous lineations and will also contain the superposed lineations which are not sufficiently pronounced to destroy its overall L_2 structure.

Sub-Area VI:

This area is extremely complex and, although further, more detailed work is advisable, the observations made clearly demonstrate certain relationships.

The lineations themselves show a very marked spread. In the field it was established that L_2 folded L_1, PLATE XIV. A similar picture evolves from the lineation plot (PLATE XV, figs. 1 and 2).

From the interpretation of Sub-Area I the trend of superposed L_2 lineations was established. (PLATE VI fig. 3). This trend represents the great circle formed by the axial plane trace of the L_2 folds. Falling on the same great circle are the maxima for L_2 lineations of Sub-Areas II, III and V (fig. 2 PLATE XV). The reason for this type of spread has been outlined on pages 8 and 9.

The spread on the lineations observed on the most north-westerly exposure of banded limestone-biotite schist in Sub-Area VI have been plotted separately on Fig. 2, PLATE XV. The great circle containing these lineations has a slightly different attitude than the ideal L_2 axial plane as determined in Sub-Area II, and the associated spread of L_2 on the first-formed structure as determined in Sub-Area I. This deviation is possibly due to the effect of L_3 folding which might have disturbed the ideal pattern. However, this does show that the lineations in Fig. 1, PLATE XV, can, in part, be accounted for by the superposition of L_2 on L_1. The reason for the more complete spread of L_2 lineations in Sub-Area VI, is that here the crests of the L_1 folds have been exposed, while in Sub-Area I, for example, only the limbs of the fold were exposed.

L_3 is also present in this sub-area. The other great circle containing L_2 lineations has been interpreted as the folded equivalent of L_2 lineations by L_3 folds. That one is dealing with L_2 lineations in this case is verified by the fact that the great circle passes through the unfolded maximum position of L_2 on a pre-existing L_1 structure. In the case of similar folds, a folded lineation will fall on a great circle, (WEISS 1959, RAMSAY 1960).

Having obtained from Sub-Area V the spread of L_3 lineations superimposed on an L_1 and L_2 structure, and assuming this spread to coincide with the trace of the axial plane of the L_3 folds, the tectonic axes of this final phase of folding can be determined by using the method of RAMSAY (1960), see fig. 1 PLATE XVI.

STRUCTURAL SYNTHESIS.

By integrating the interpretations made of the lineation studies described above, it is now possible to attempt a kinematic and possibly dynamic, analysis of the folding in the Albrechtshöhe-Koliombo area. The basic assumption has been made that the attitude of the beds was originally horizontal.

The first period of folding was about axes trending west-north-west, giving rise to the almost isoclinal fold found in Sub-Area I. Such folds possibly existed in the other sub-areas as well. (e.g. the same trend is found in Sub-Area V; the presence of S_1 foliations is suggested by the data of Sub-Area IV). Unfolding of the synclinal structure of Sub-Area I would bring the foliations down to a plane practically horizontal except for a slight tilt to the east-south-east, brought about by the regional fold axis plunging in this direction at an angle of 16°. This tilting of the fold axis might possibly be due to later phases of folding.

In order to account for the nature of these folds in which the foliations dip fairly steeply towards the south-west (70° for the south limb and 45° for the north limb), a slight rotation of the directive forces is invoked which probably resulted from the changes in the stress field due to the piling up of sediments. (See PLATE XVII).

The second phase of folding gave rise to northerly-trending structures which plunge at about 40° to the south in Sub-Area II where the folds are best developed. The attitude of these folds was governed by the original attitude of the beds, i.e. eastwest foliations of Sub-Area I. This conclusion is supported by the fact that the fold axis for the L_2 folds in Sub-Area II corresponds well with the northernmost superposed L_2 maximum on an L_1 structure in Sub-Area I (PLATE VI, fig.3, PLATE VII, fig. 3).

Knowing the fabric which existed prior to L_2 folding, it can be established that the ideal directive force required to produce the L_2 folds would be represented by the pole to the L_2 lineation spread, e.g. fig. 2 PLATE XV. The spread on the lineations is therefore in the a - b plane, or, in other words, the axial plane.

The interpretation of the final phase of folding L_3 is slightly more difficult. From previous evidence it has been suggested that there was a folding phase later than L_1 and L_2. The only phase of superposed folding in a complex area such as Sub-Area V, which shows a spread controlled by its uniform axial plane intersecting L_1 and L_2 folds and combinations of these, is L_3. The evidence would seem to suggest that L_3 is the latest phase of folding.

The interpretation of this last phase of folding is shown in Fig. 1 PLATE XVI. The orientation of the idealized compressive force required to produce the L_3 folds is represented by the pole to the L_3 lineation spread.

The interpretation of L_3 folds in time is based on rather weak evidence. The final synthesis in Fig. I PLATE XVI shows steeply dipping a - c joint planes with a strike of 304°. Drainage patterns have been analysed and one group has a direction of 299° (mean of 20 values) which might be a manifestation of the L_3 folding.

The ideal directed forces required to produce L_2 and L_3 folds are essentially similar, e.g. L_2 folds require a force acting in a west-north-west direction, acting downwards at 38°, while the force required to produce the L_3 folds acts in an east-south-east direction downwards at 10°. The essential difference is, therefore, merely a rotation of the ideal directed force in a vertical plane.

Without more detailed knowledge of the regional geology, it is impossible to determine whether these three phases of folding are part of one act or if they are related to definitely different ages of folding.

The structural synthesis has so far been confined to folding only. The wrench fault passing through the area also requires consideration.

The pegmatite emplacement is closely related in time to the wrench fault. Pegmatites are found in the fault zone itself. These are possibly the result of minor irregularities in the planar shear surface where crushing and tensional openings might have developed. Furthermore, in the bottom left hand section of PLATE II, several pegmatites occur which have a pronounced linear trend. The angle made between the strike of these pegmatites and the wrench fault is 26° (average). This angle approximates to the accepted 30° angle made between the surface of shearing and the maximum compressive force required to produce a wrench fault (MOODY and HILL 1956, BADGLEY 1959). Tension cracks would have developed parallel to the main compressive force. The emplacement of these pegmatites occurring in the south-west corner of the map area, therefore, appears to be related to a period of compression resulting in the wrench fault.

Having seen that only some of the pegmatites within the area are related to wrench faulting and its associated stress field, there remains to be explained the mode of emplacement of other pegmatites in the area, e.g. those bodies occurring in Sub-Area V. Here the pegmatites show two distinct trends. One is the northerly trend which forms part of the Large "S"-shaped pegmatite. This is the same direction that the pegmatites have in the south-western part of the map area. The second pegmatite trend is east-west.

The pegmatites occasionally appear to be conformable to the foliation in plan. In three dimensions, however, they cut across the foliation and generally have a steep dip, e.g. Brockmann's pegmatite dips at 70° to the north.

The pegmatites show, therefore, a characteristic orientation either north-south or east-west. This two-directional trend was also found to be present adjacent to the Karlsbrunn wrench. It can thus be seen that two directions virtually at right angles to each other have influenced the pegmatite emplacement over a large area. The north-south direction is that of tensional opening as explained above. The east-west trend is possibly explained by the existence of tension joints

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formed by the elastic release of the major compression (DE SITTER, 1956).

There must have been an elapse of time between the north-south tension joints and the east-west tension joints. However, both produce zones of potential weakness with a certain amount of tensional opening which influenced pegmatite emplacement.

That tensional openings controlled the pegmatite emplacement is also suggested by the immediate wall-rocks of the pegmatites. Foliations and structures in the wall-rock show no signs of bending or deformation to indicate a forceful injection of a magma. It would seem that a quiet, permissive emplacement of pegmatite magma took place where tensional openings had produced a favourable environment, (see PLATE XVIII).

There still remains the question of the age relations of the wrench faulting and the three distinct phases of folding which are present in the area. The pegmatites which are related to the period of wrench faulting give no evidence of having been folded, i.e. they show no signs of internal deformation or cataclasis. It would seem, therefore, that the folding took place prior to the emplacement.

The possibility that wrench fault mechanics might have accounted for the third period of folding (L_3) also has to be considered. This period gives rise to so few lineations, that it is not nearly as intense as the two preceding periods (L_1 and L_2) and, therefore, it might not notic ably affect, or fold the pegmatites. L_3 folding might also have been contemporaneous with the pegmatite emplacement.

The basis for considering a relationship between L_3 folding and the wrench fault is that a re-orientation of the stress field takes place after the initial development of fractures. After the formation of the wrench fault, a secondary stress field would have been established in each block, which in turn would have given rise to second order shears and folds (MOODY and HILL 1956, BADGLEY 1959). The L_3 period of folding could be fitted into such a pattern, but only if numerous assumptions were made.

The strongest objection to this interpretation would be the lack of folds perpendicular to the major compressive force producing the wrench fault. If such first order folds were not produced, then it is difficult to imagine how the second order folds could have formed.

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It is felt that the rocks in the area, having been folded so intensely during the different periods of deformation prior to the faulting, would have resisted the development of any further folds. Consequently, fracturing rather than folding would have been the result of a compressive force following three distinct phases of folding.

The Albrechtshöhe-Koliombo Area demonstrates clearly the influence of structure on the pegmatite emplacement. Here pegmatites occur in both dolomitic marbles and Khomas schists. A secretion-diffusion origin is unlikely for these pegmatites (see page 10). A pegmatite magma, possibly a mobilized product of palingenic origin, and which was emplaced in tensional joints, seems to suit the data most satisfactorily.

This interpretation of a very small area in the Damara-Otavi geosyncline has rather well documented phases of separate deformations. The critical questions are how large is the time interval between each phase, are these separate phases related to a single or different orogenies, and how does this pattern fit into the larger framework of the Damara-Otavi orogeny?

Dr. Martin, Chief Geologist of the Windhoek Regional Office of the Union Geological Survey, feels that these independent phases of folding could well be fitted into a broader picture; his attempted synthesis is given below.

> "The Damara-Otavi orogenic belt crosses the boundary between Angola and South West Africa in the northwest. Right through the Kaokoveld, for a distance of about 250 miles, it has a north-north-west trend. Locally, however, different directions occur, e.g. the east-west synclinal zone of the Etoroha mountains.
>
> In the southern Kaokoveld, the belt swings through an arc of nearly 90° into the east-north-east direction, which is characteristic for the central part of the country. This general east-north-east trend is made up of individual zones striking east-west and north-east to south-west. The southern boundary of the Damara belt forms an almost symmetrical arc composed of structural units striking east-west, north-east and north-south. The belt then assumes again a north-northwest direction, represented in the neighbourhood of the Orange River by the folds of the Kaigas, Numees and Nama beds.

Thus, all the directions found in the small area analysed in this paper occur also as major elements, in the orogenic belt as a whole. This raises the question whether the deformations in the different parts of the orogenic belt show a sequence in time similar to the one found in this analysis.

This is not the case. There is no evidence to suggest different ages for the north-northwest trending branches of the belt. The conclusion seems, therefore, unavoidable that the sequence of differently oriented deformations, established by the foregoing analysis, was not caused by changes in the directions of the regional stresses. It is, therefore, of interest to see in how far the local conditions can explain the changes of the stress pattern.

(1). The first folds and lineations are oriented more or less east-west, whilst the general trend is northeast. East-west striking folds occur too along the northern and southern margin of the geosyncline, and here it can be shown in a number of instances that this particular direction conforms to similar striking elements of the pre-Damara-Otavi basement. These formed basins and ridges which first guided the sedimentation and subsequently formed a fairly rigid frame to which the folds had to conform.

In the area under consideration, where the basal members of the Damara system form big anticlines, a similar dependence of the first phase of folding on older, east-west striking structures is to be expected. Under these circumstances, a northwest-southeast compression can well have produced the east-west striking L_1.

(2). As just mentioned, the regional main compressive stress seems to have had a southeast-northwest direction. This, too, is the direction of the compressive stress required for the production of L_2 (see PLATE XV). If the direction of L_1 was due to the influence of the pre-Damara frame, then the transition to L_2 can have been caused by the softening effect of the increasing metamorphism which enabled the regional stress to overcome the resistance of the older structures. This does, however, not explain the steep plunge of the L_2 lineations. There is no folded belt which does not show plunging folds. These are often termed "cross-folds," and are attributed to a second phase of folding with stresses at right angles to the first one. This interpretation is in most cases wrong. Folding experiments, approaching natural conditions show that axial plunges appear already in the initial stages of folding and become progressively more pronounced with increqsing compression. The mechanical reason has been elucidated by studies of the deformation of fossils.

With this method, H. BREDDIN (1954) was able to show that even folding of moderate intensity produces very considerable plastic deformations of the rocks. He found in slates, normal to the axial plane cleavage, compressions of up to 53% and parallel to the cleavage planes, both in the vertical and horizontal directions, extensions of up to 32%. The lateral (parallel "b") stretching of the material can only be accommodated by a co-genetic folding of the fold axes. Under conditions of moderate folding intensity it produces plunges of 20 to 30 degrees. Under conditions of higher metamorphism, this deformation assumes far greater proportions and can produce not only vertical, but even overturned fold axes. Such intense co-genetic cross structures have recently been described by E.P. SAGGERSON etc. (1960), from the basement system of Kenya. They are characteristic of most highly metamorphosed areas. Where the metamorphism becomes high enough to produce granitisation, this deformation may be intensified to such an extent that some of the larger anticlines become diapirs.

In our case, the rise of the Karlsbrunn anticline may very well have modified the regional stresses in such a way as to produce the plunges of L_2.

(3). The last and minor deformation L_3 can probably be explained by a slight disharmonic movement of the incompetent marbles and schists over the plunging nose of the more competent Karlsbrunn anticline. That the latter was more competent is proved by its nearly circular outline and its nearly symmetrical dips.

(4). The wrench fault with its associated tension fissures seems to indicate a main compressive stress acting in a north-northwest instead of the assumed northwest direction. However, this fault may be a rejuvenated pre-Damara fault and may thus form an angle with the ideal direction required by the regional stresses. This interpretation is suggested by the existence, to the southeast of Windhoek, of numerous north - south pre-Damara faults.

It seems thus possible to tie the sequence of deformations into a single major phase of folding progressing through different stages of metamorphism. In order to prove this interpretation, it would be necessary to analyse, in similar detail, the structures of a second area, in which the major folds plunge in the opposite direction.

The explanation of the east-west pegmatites by elastic release seems to me rather unsatisfactory. This explanation was advanced by DE SITTER for basic dykes intruded into a fairly high and cool level of the crust. Even for these, the interpretation is mechanically doubtful. Under conditions favouring the emplacement of pegmatites, the elastic deformation is probably relieved by plastic deformation and recrystallisation. I would, therefore, like to suggest a different explanation.

The lack of deformation of the pegmatites indicates a post-kinematic intrusion. In the development of an orogenic belt the cessation of the folding stresses is, as a rule, followed by the beginning of the isostatic uplift. This up-arching of the folded belt must produce a state approaching universal tension, whilst at the same time, highly charged pegmatitic magma is still present. Under such conditions this residual magma may become intrusive into all existing planes of weakness or inhomogeneity, regardless of what their origin may have been. This mode of emplacement would effectively explain the presence of undeformed pegmatites in bedding planes, cleavage planes, a - c and other joints and wrench faults.

Additional detailed work in another area would be necessary to prove or disprove this suggestion."

(c). Brockmann's Pegmatite on Tsaobismund 58: PLATE XIX.

This pegmatite occurs in Damara Quartzites. Although it is a considerable distance from the Karibib pegmatites, it is considered to be of the same age as the latter group. The pegmatite has an extremely rich beryl zone in which columbite is also present. Li is incorporated in phosphates which occur as huge rounded masses (up to 5 feet in diameter) on the margin of the quartz core.

The structural investigations were restricted to a study of an anticline containing the pegmatite and plunging to the north-east. Lineations and foliations could not be measured at regular intervals in the generally featureless Damara quartzites forming the core of the anticline. Observations of these parameters were made in the Marble Series in which dolomitic marbles are intercalated with schist bands.

The beryl-bearing pegmatite lies almost at right angles to the anticlinal trend leading to an original assumption that it was formed in tension joints during normal folding.

In other rock groups, i.e. in the Marble Series and Khomas Schist Series, large, white granite bodies which are irregularly pegmatoid, are syntectonic or slightly pre-tectonic. Some dyke-like bodies, cross cutting Khomas schists, and up to several feet in thickness, are distinctly folded. Other sill-like bodies which sometimes transgress the foliation, but generally conform to the structure of the surrounding meta-sediments, appear to be syn-tectonic.

The beryl-pegmatite is mineralogically very different from that of this earlier group of whitish granites and pegmatites. The occurrence of pinkish brown microcline is particularly characteristic of the beryl pegmatite as is its complex mineralogy (triplite, beryl, muscovite, columbite, uranium minerals). The pre- and syn-tectonic types are simple quartz-feldspar varieties with muscovite and biotite and relatively few accessories.

The Brockmann beryl pegmatite also cross cuts the structure, which fact supports its classification as late tectonic. Again there are no signs of internal deformation to indicate that the pegmatite has been folded.

A plot of the structural data displays the nature of the anticline, i.e. its northeast plunge. (PLATE XVI, fig. 2).

A complete understanding of the sequence of structural events can be gained only from an investigation on a more regional scale.

However, the anticline structure does seem to have had an influence on the pegmatite emplacement. Instead of massing themselves in a cluster to form a pole to the great circle containing the foliation poles, the lineations show a spread in a northeasterly direction. This could be due to either folding of the lineations or superposition of the lineations on a previous structure.

In either case it seems reasonable to relate the pegmatite site to the north-easterly fold axis trend, i.e. to an a - c joint plane. Although the lineations do not lie exactly perpendicular to the plane of the pegmatite, one observation measured immediately adjacent to the pegmatite did show this relationship (see PLATE XVI , fig. 2). The other lineations were all measured in the Marble Series and are thus undoubtedly affected by the factors indicated above to account for the north-easterly trend of the lineations.

This north-easterly trend is regional, the fold axes themselves either plunging to the north-east or the south-west. This spread is apparently due to a later phase of folding, the axes of which folds are almost at right angles to the north-easterly trending folds.

Such folding would tend to upen up on a - c joint plane as described above, particularly when the joint plane lies in a brittle, competent, rock such as the quartzites. Such a phenomenon would also develop at the intersection of two anticlinal trends.

D I S C U S S I O N.

Detailed structural analysis has been undertaken with the aim of solving the tectonic history of the Albrechtshöhe-Koliombo area. An analysis of this nature was considered an essential part of determining whether there was any relationship between structure and the mode of emplacement of certain complex pegmatites.

Although the emplacement of the pegmatites post-dates most of the tectonism, certain conclusions concerning folding and the mode of emplacement of the complex pegmatites from this area can be reported.

The structural studies outlined in this paper show that in the case of superposition of folding the axial plane of the superposed folds for the most part contains the spread of contemporaneously formed lineations when projected onto a stereographic net. The controlling condition in the case discussed is that folding is of a similar type, and takes place along slip surfaces essentially parallel to the axial planes of the folds, (i.e. axial-plane cleavage surfaces) and at right angles to the compressive stress.

The fairly uniform composition of the Li- and Be-bearing pegmatites, and their occurrence in rock types of varying composition (quartzite, dolomitic marbles, biotite schist) suggest a magmatic origin. This igneous activity is considered to have been associated with the Damara period of metamorphism and granite formation. Strong evidence against possible pegmatite formation by a local secretion-diffusion mechanism is considered to be the occurrence of pegmatite bodies in dolomitic marble.

On a regional scale, the genesis of pegmatites must be viewed against the background of their geologic setting. They need not be of the same origin everywhere. The simple Greenlandic pegmatites described (RAMBERG, 1956), are clearly related to the metamorphic grade of their environment and have formed by metamorphic-metasomatic processes. The complex pegmatites of the Karibib District are associated with an orogenic cycle involving metamorphism and granitization culminating in late instrusive magmatic granites. The ore-bodies are intimately connected with the latter and are therefore found in such plutons as well as within the surrounding meta-sediments. Occasionally, these plutons are "pegmatites" themselves, being made up of a very coarse grained granite.

Structure has played an important part in the emplacement of the pegmatites, tensional openings being favoured loci.

The distribution of mineralized pegmatites is not systematic in the Karibib District. The only generalization that can be made is that they must be sought for in areas of late tectonic intrusive granites. Environs of this nature are common in tectonic belts throughout the world. The primary composition of the granitic magmas will determine the nature of the minerals finally crystallizing in residual fractions. In terms of derived magmas, this will also depend on the initial composition of the rocks undergoing tectonism, metamorphism and mobilization. It remains to be seen which rocks might possibly constitute the most likely source of Li and Be in the Damara and Ababis Systems.

A possible source is suggested by KEITH and DEGENS (1959), who state that B and Li are geochemical "indicators" of shales

/36...

of a marine environment. The biotite schist horizons of the Damara System, within which large scale granitization effects are frequently prominent, may thus have contributed to the final pegmatitic end product.

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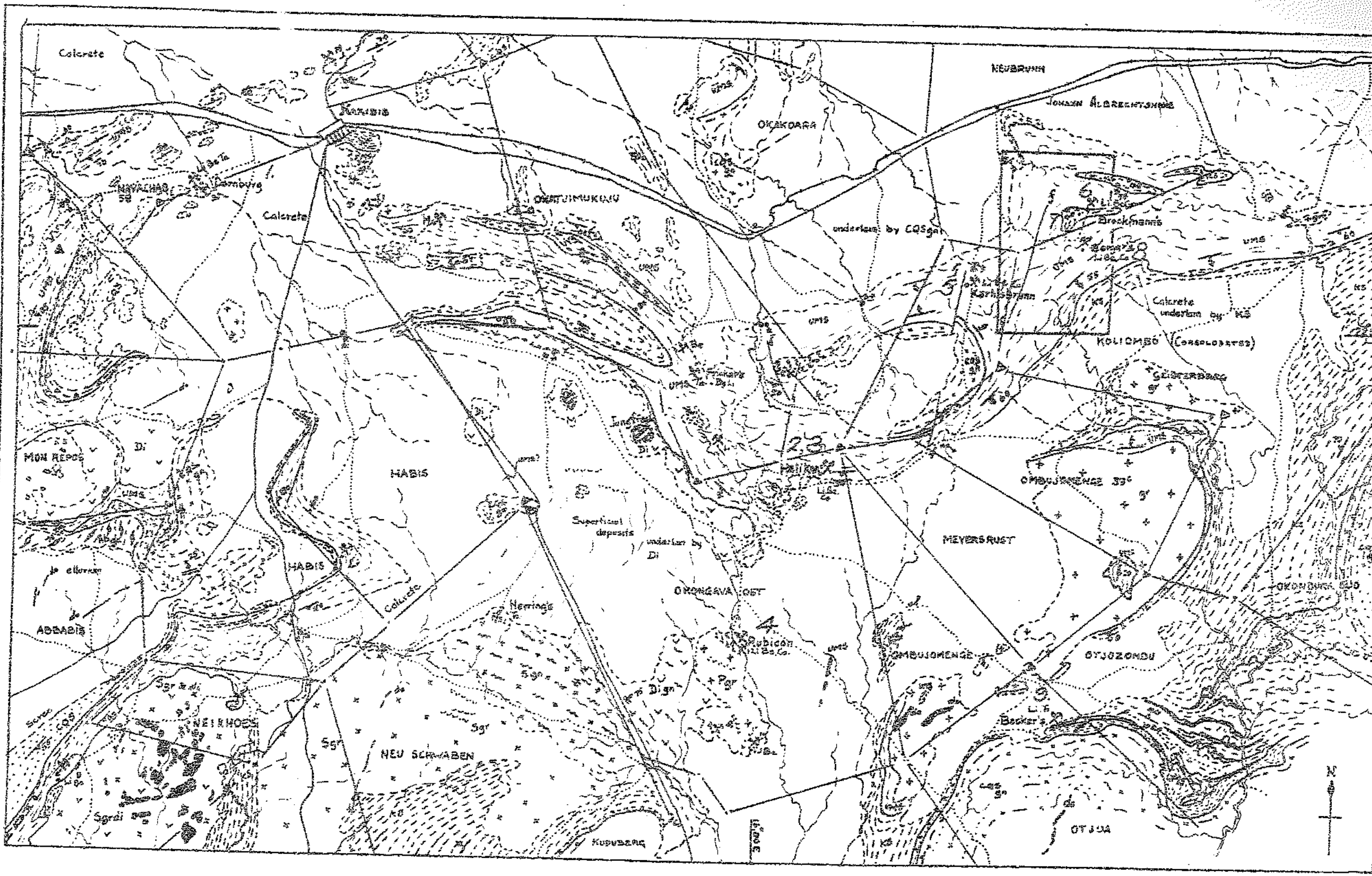


Geological Map of part of the Mineralized Pegmatite Area

Karibib District

South West Africa

PLATE I.

REFERENCE

RAILWAY

MAIN & SUBSID. ROADS

RIVER BEDS & WATER COURSES

FARM HOUSE & WINDMILL

STRIKE OF VERTICAL, DIPPING & FLAT BEDDING

STRIKE & DIP OF OVERTURNED DRAG FOLDED BEDDING & FOLIATION

STRIKE & DIP OF FOLIATION

PLUNGE OF LINEATION

FAULT & BRECCIA ZONES

MINES & PROSPECTS Li = LITHIUM Be = BERYL Ta = TANTALITE Co = COLUMBITE.
To = TOURMALINE M = MARBLE Cu = COPPER

SUPERFICIAL DEPOSITS
Alluvium, rock debris, aeolian sand, calcrete

KARROO

DOLERITE DYKES

SHALE & EXTRUSIVE LAVA

METASEDIMENTS (early syntectonic) →

GRANITIZED PRODUCTS IN SITU (mid – syntectonic) →

INTRUSIVE (Late tectonic)

DAMARA SYSTEM

KS — KHOMAS SCHIST SERIES Quartzo felspathic biotite schist with variable content of garnet, cordierite & amphibole

DIORITE (Di) & DIORITE GNEISS (Dign) with orthoamphibolite

SALEM GNEISS (Sgn)

SALEM GRANITE (Sgr) Porphyritic & non-porph. biot granite

} SALEM GRANITE GROUP

RED HOMOGENEOUS GRANITE & PEGMATITE

UMS — UPPER MARBLE SERIES Massive blue & white marbles occasionally cont. intercolated KS & amphibole schist & Calc silicate bands (CaSi)

Biotite (KS) schists → Sgn other intercolations unaffected

N.B. 1 Early to mid-syntectonic pegmatites are ubiquitous in all metasediments.

2. Metasediment remnants are abundant in their granitized equivalents.

CHUOS TILLITE

CQS — CHUOS QUARTZITE SERIES Red felspathic quartzites & quartz biot schist. Sillimanite sometimes developed hn = hornfels

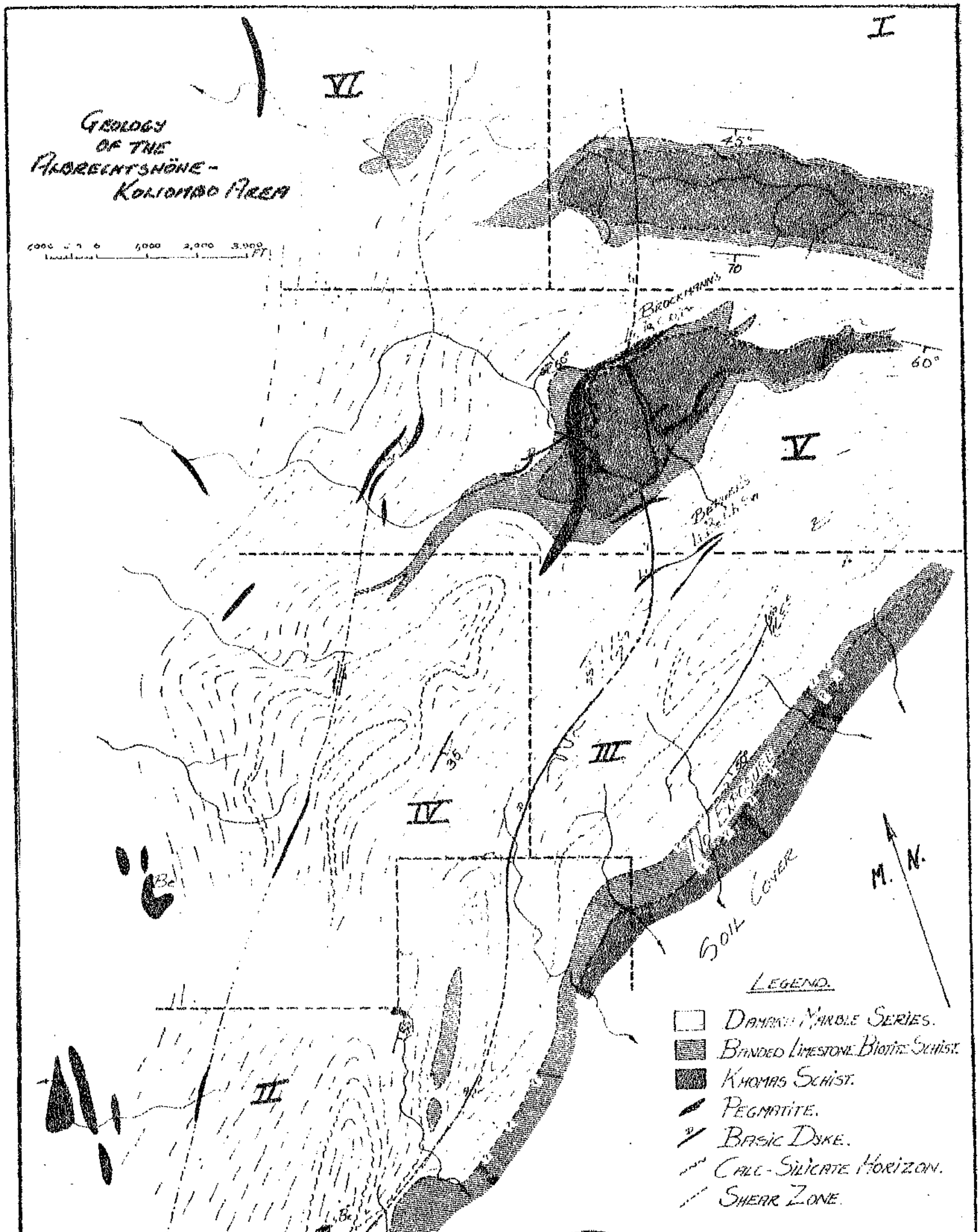
Red gneissose granite frequently porphyroblastic

ABBABIS SYSTEM

ABBABIS GNEISS Quartzo felspathic muscovite gneiss

ABBABIS rocks generally unrecognisable in granitised environment.

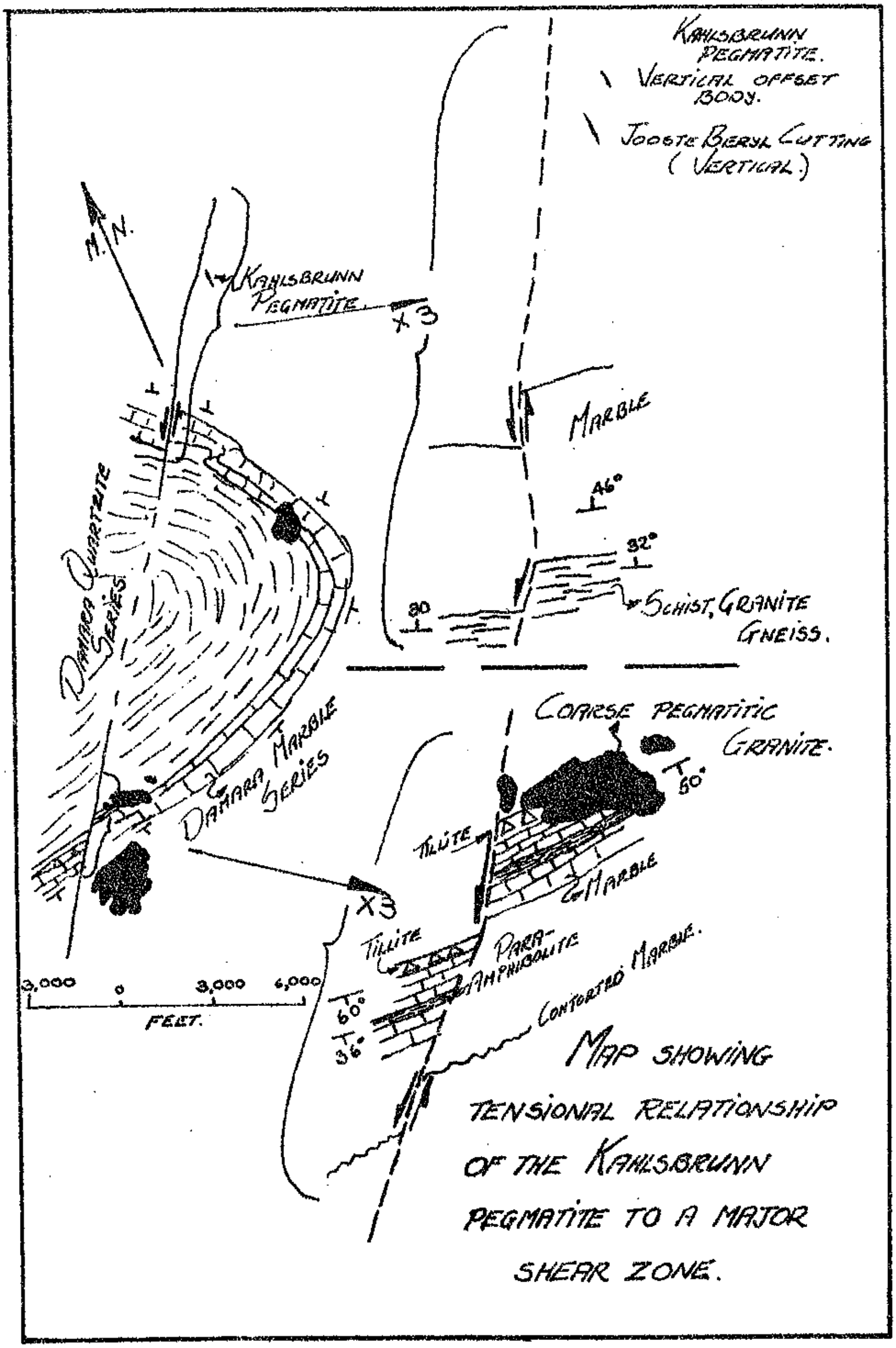
PLATE Ia



GEOLOGY OF THE ALBRECHTSHÖHE - KOLIOMBO AREA
I
II
III
IV
V
VI
45°
70
60°
36
BROCKMANNS
SOIL COVER
M. N.
LEGEND.
DAMARA MARBLE SERIES.
BANDED LIMESTONE BIOTITE SCHIST.
KHOMAS SCHIST.
PEGMATITE.
BASIC DYKE.
CALC-SILICATE HORIZON.
SHEAR ZONE.

PLATE II

PLATE III



KAHLSBRUNN PEGMATITE.
VERTICAL OFFSET BODY.
JOOSTE BERYL CUTTING (VERTICAL.)
M.N.
KAHLSBRUNN PEGMATITE.
X3
MARBLE
46°
32°
30
SCHIST, GRANITE GNEISS.
DAMARA QUARTZITE SERIES
DAMARA MARBLE SERIES
CORRSE PEGMATITIC GRANITE.
50°
TILLITE
MARBLE
X3
TILLITE
PARA-AMPHIBOLITE
CONTORTED MARBLE.
60°
36°
3,000 0 3,000 6,000
FEET.
MAP SHOWING TENSIONAL RELATIONSHIP OF THE KAHLSBRUNN PEGMATITE TO A MAJOR SHEAR ZONE.

PLATE IV.

Fig. 1.

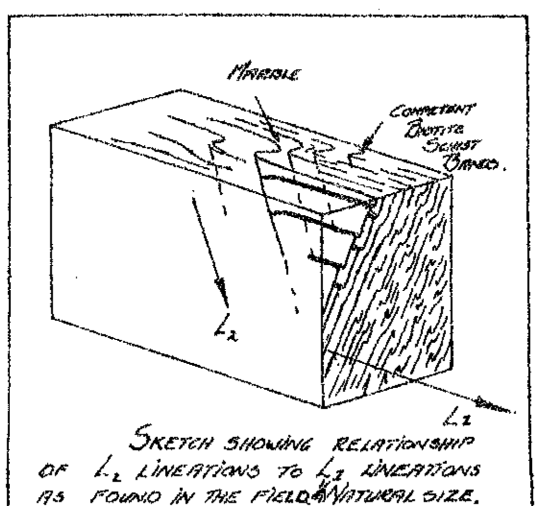


Fig. 2.

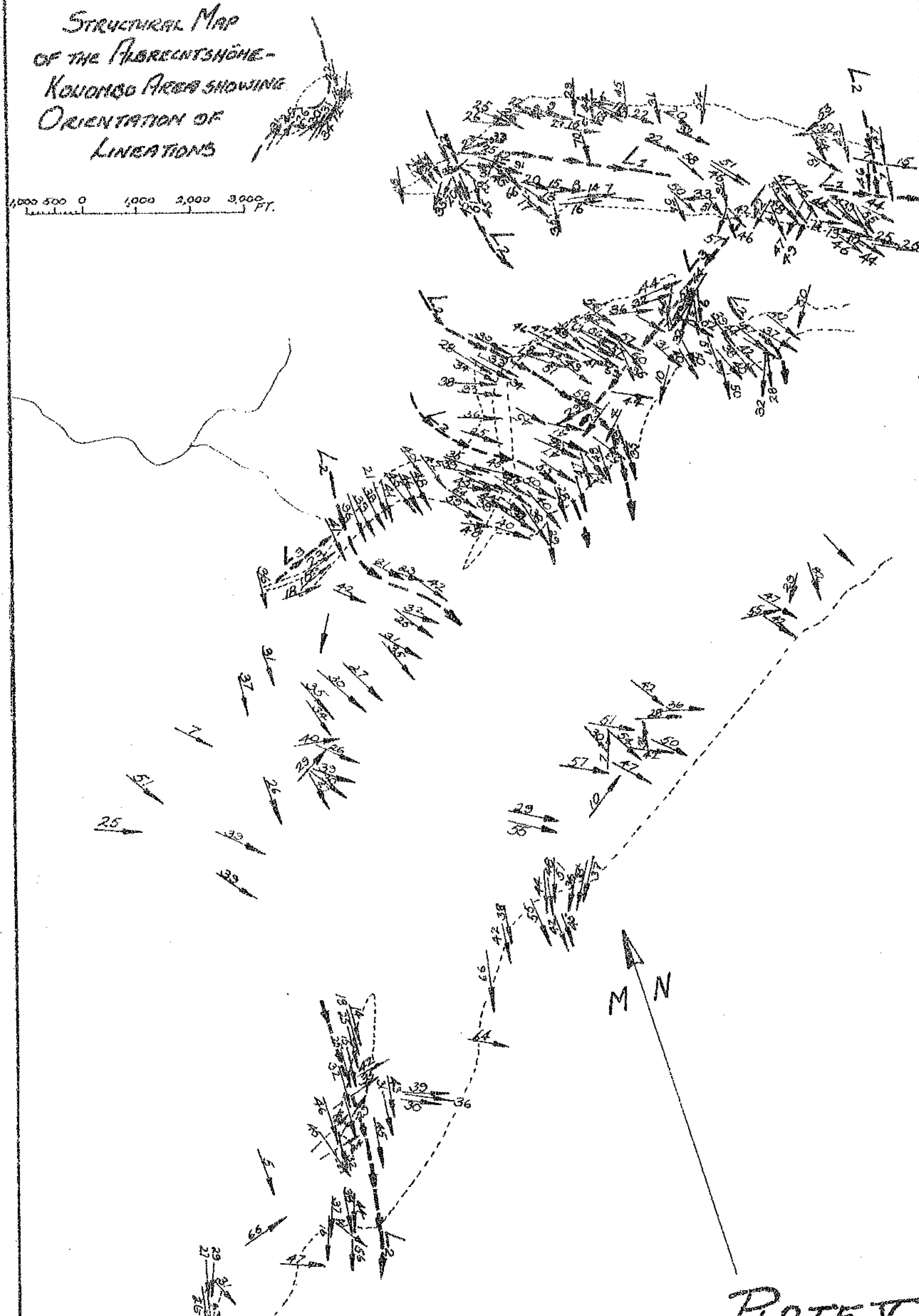

STRUCTURAL MAP
OF THE ALBRECHTSHÖHE-
KOLONGO AREA SHOWING
ORIENTATION OF
LINEATIONS
1,000 500 0 1,000 2,000 3,000 FT.
L1
L2
L3
M N

PLATE V

PLATE VI.

Sub Area 1.

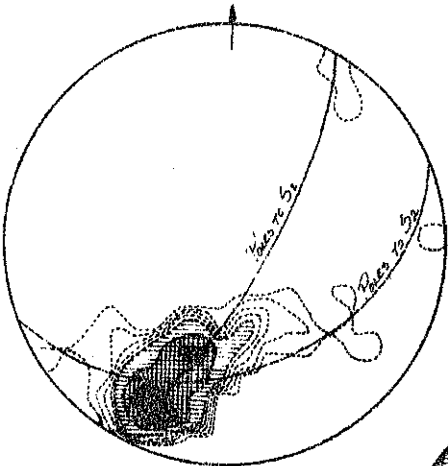


Figure 1.

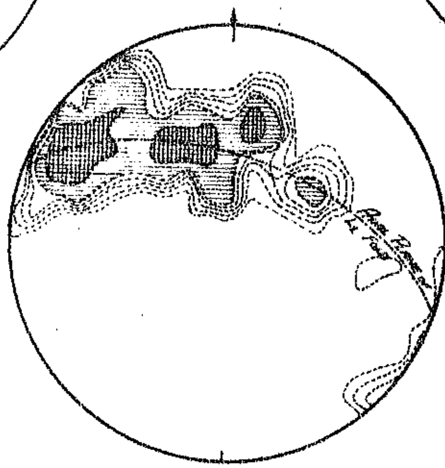


Figure 2.

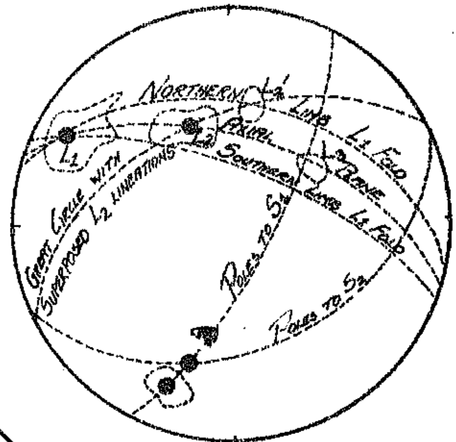


Figure 3.

Figure 1. : Poles to foliation and axial plane cleavage. (94 points). Contours at 1,2,3,4,5,10,15 points per 1% area.

Figure 2. : Lineation plot. (100 points). Contours at 1,2,3,4,5,10 points per 1% area.

Figure 3. : Composite interpretation of Figure 1 and Figure 2. Great circles and poles to great circles shown in relation to statistically determined maxima.

PLATE VII.

Sub Area II.

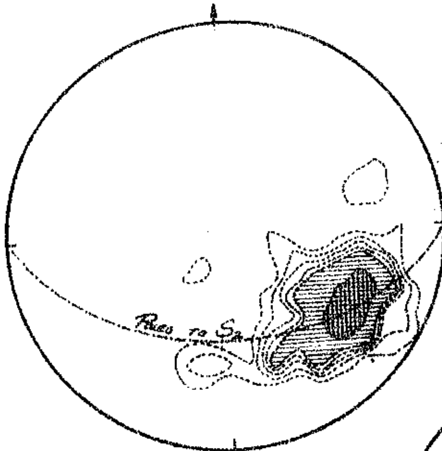


Figure 1.

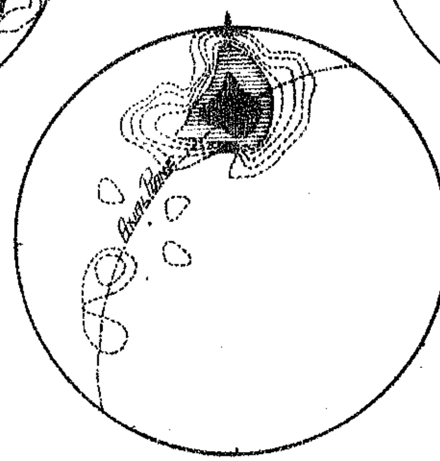


Figure 2.

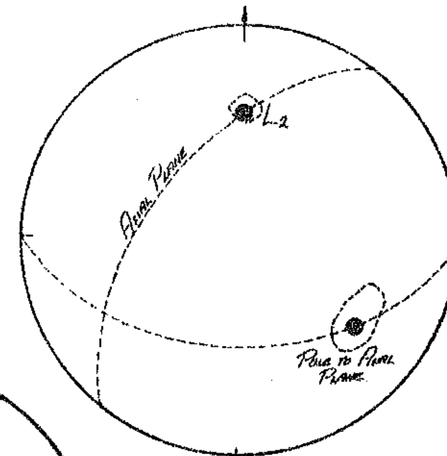


Figure 3.

Figure 1. : Poles to foliation and axial plane cleavage. (71 points). Contours at 1,2,3,4,5,10 points per 1% area.

Figure 2. : Lineation plot. (73 points). Contours at 1,2,3,4,5,10,15 points per 1% area.

Figure 3. : Composite interpretation of Figures 1 and 2. Great circles and poles to great circles shown in relation to statistically determined maxima.

PLATE VIII.

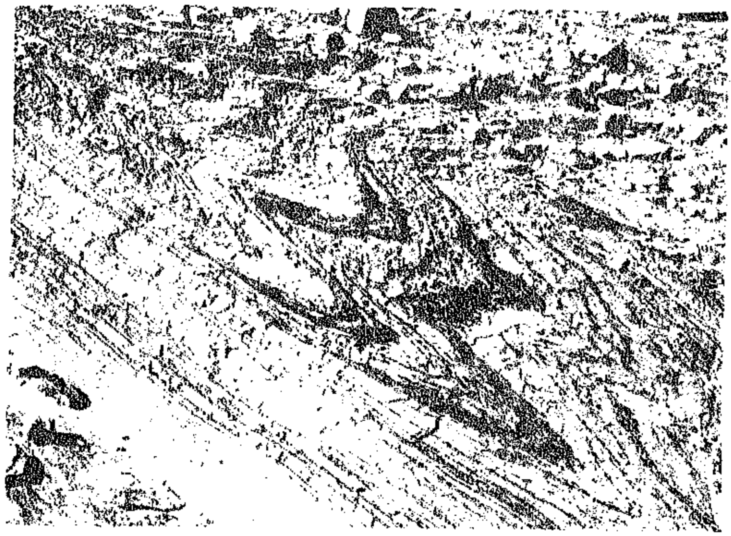
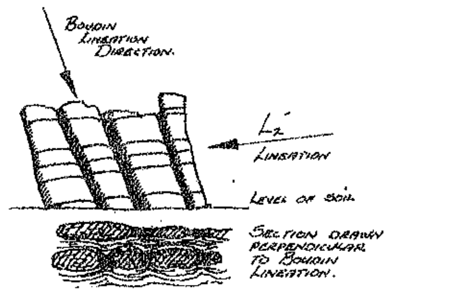


Figure 1: Foliation and axial plane cleavages having essentially the same orientation. Banded limestone-biotite schist.

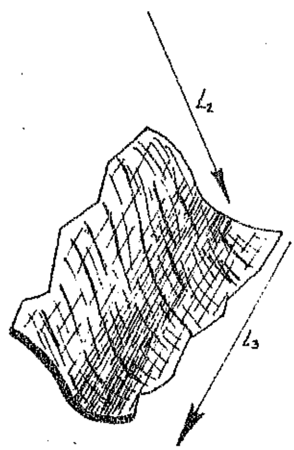
Figure 2: Small tension joints developed perpendicularly to the lineations in a competent biotite schist intercalation in limestone.

PLATE IX.



Biotite rich Schist.
Recrystallized Coarse Carbonate.
Banded Marble.

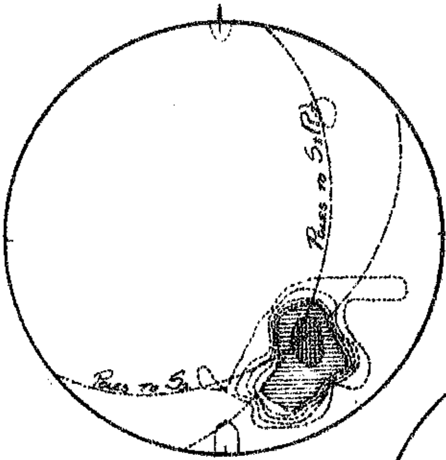
Formation of Boudins almost at right angles to the micro-fold lineations L_2. They form in the competent biotite rich schist bands, which are inter-bedded with marble. 1/4 Natural size.

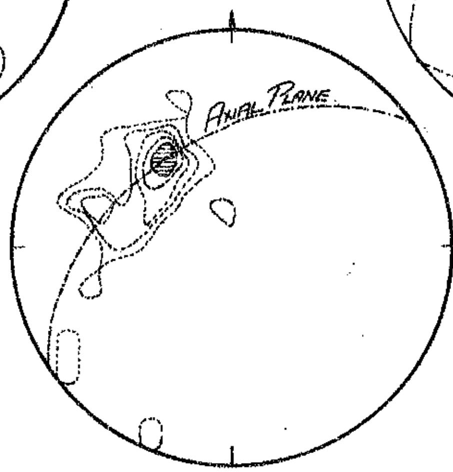


One set of lineations L_2 (micro-folds) folded by later L_3 small folds. 1/4 Nat. size.

PLATE X.

Sub Area III.





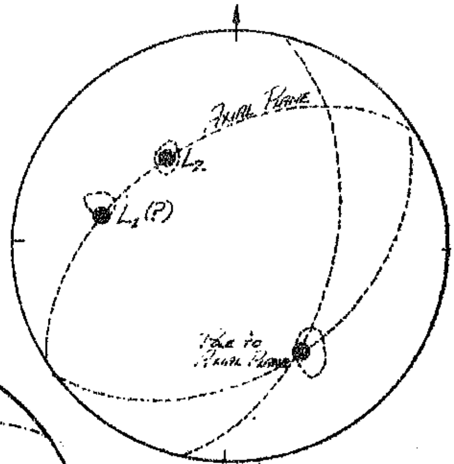


Figure 1. Figure 2. Figure 3.

Figure 1. : Poles to foliation and axial plane cleavages. (53 points). Contours at 1,2,3,4,5,10 points per 1% area.

Figure 2. : Lineation plot. (34 points). Contours at 1,2,3,4,5 points per 1% area.

Figure 3. : Composite interpretation of Figures 1 and 2. Great circles and poles to great circles shown in relation to statistically determined maxima.

PLATE XI.

Sub Area IV.

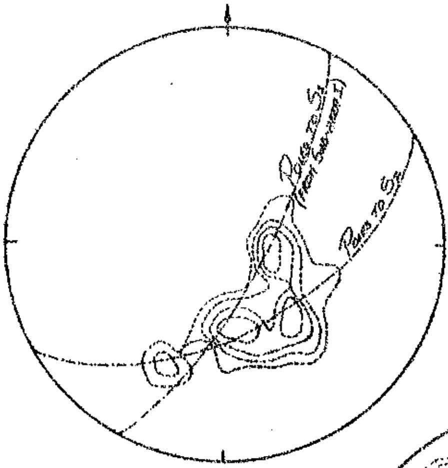


Figure 1.

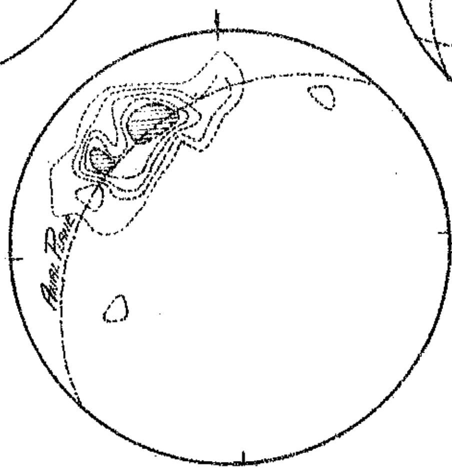


Figure 2.

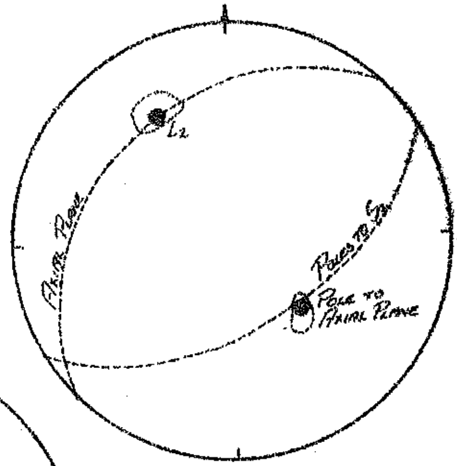


Figure 3.

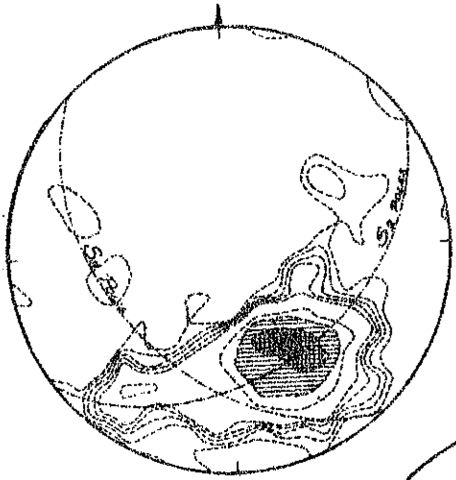
Figure 1. : Poles to foliation and axial plane cleavage. (27 points). Contours at 1,2,3,4, points per 1% area. Remnant S_1 folds possibly present as is indicated by the accommodation of the S_1 great circle from Sub Area I.

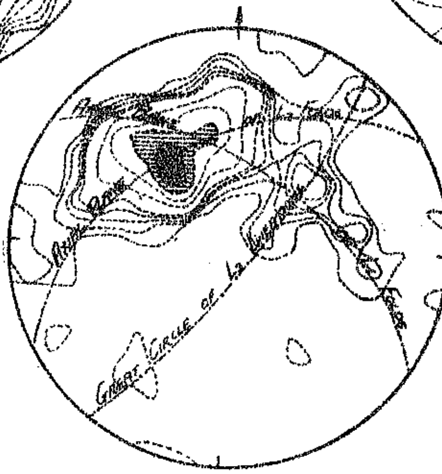
Figure 2. : Lineation plot. (39 points). Contours at 1,2,3,4,5 points per 1% area.

Figure 3. : Composite interpretation of Figure 1 and Figure 2. Great circles and poles to great circles shown in relation to statistically determined maxima.

PLATE XII.

Sub Area V.





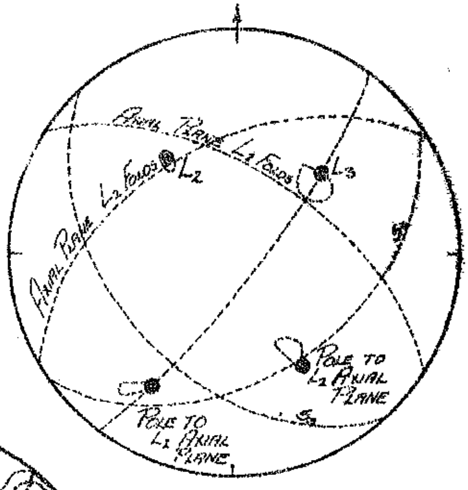


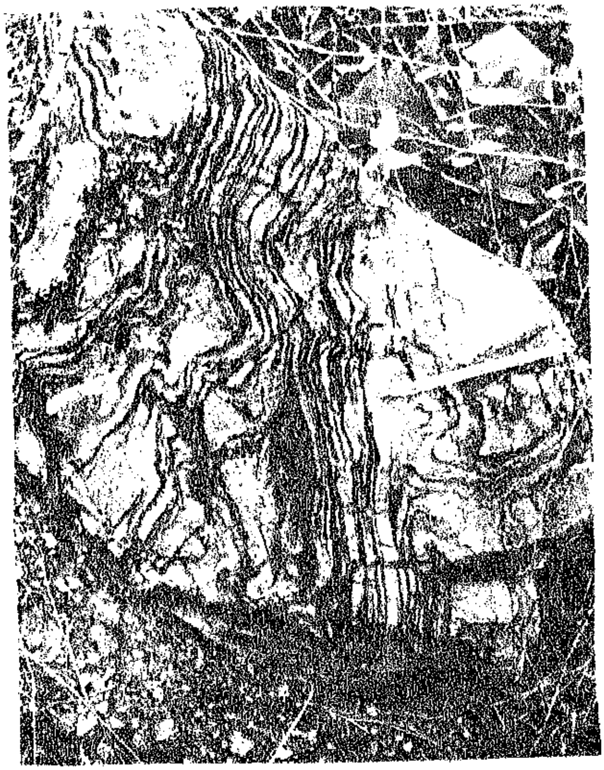
Figure 1. Figure 2. Figure 3.

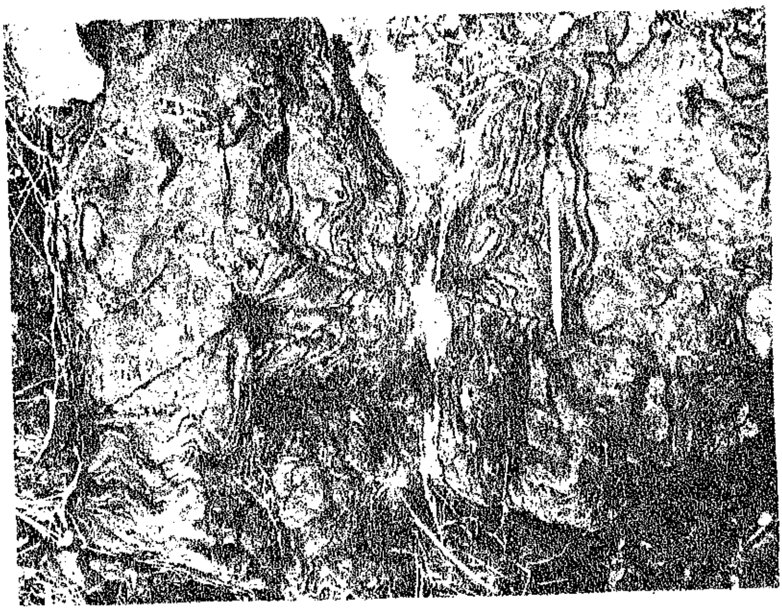
Figure 1. : Poles to foliation and axial plane cleavage. (231 points). Contours at 1,2,3,4,5,10,15,25,30 points per 1% area.

Figure 2. : Lineation plot. (286 points). Contours at 1,2,3,4,5,10,15, 20,25,30 points per 1% area.

Figure 3. : Composite interpretation of Figure 1 and Figure 2. Great circles and poles to great circles shown in relation to statistically determined maxima.

PLATE XIII.





L_3 lineations (vertical) folding other lineations almost at right angles to them. (L_2).

PLATE XIV

Sub Area VI : L_1 Lineations, (diagonal-trending small folds across photo) folded by later L_2 lineation (folds parallel to the length of the photo).

PLATE XV.

Sub Area VI.

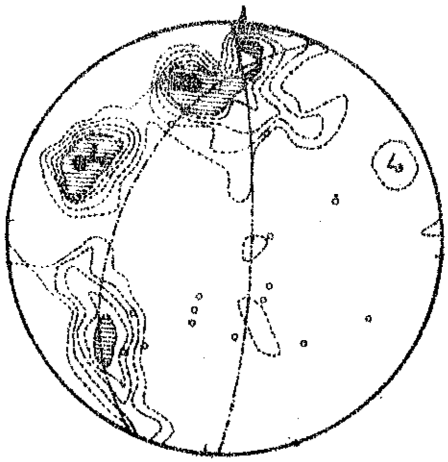


Figure 1.

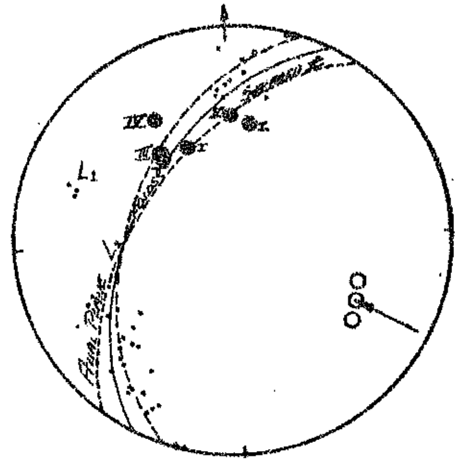


Figure 2.

Figure 1. : Pole to foliations (small open circles) and lineation plot (contoured). The latter are contoured at 1,2,3,4,5 and 10 points per 1% area. 100 lineations recorded.

Figure 2. : N.W. isolated outcrop of banded limestone biotite schist in this sub area. Small dots are lineations. Axial plane of L_2 folds of Sub Area II is shown with a pole to it. A great circle with its pole is drawn through the lineations. A mean idealized axial plane of L_2 folds has been constructed from the two observed axial planes. The pole to this shows the idealized compressive force required to produce these folds. Large dots L_2 maxima from various sub areas indicated by Roman numerals.

PLATE XVI.

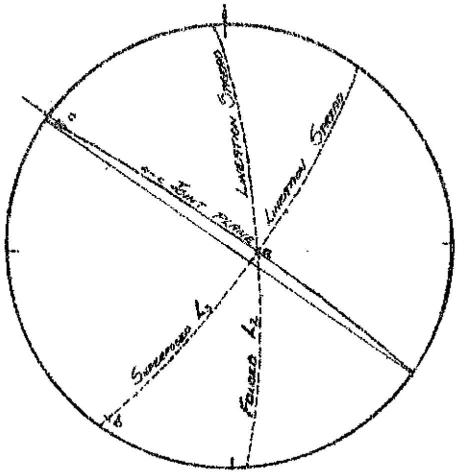


Figure 1.

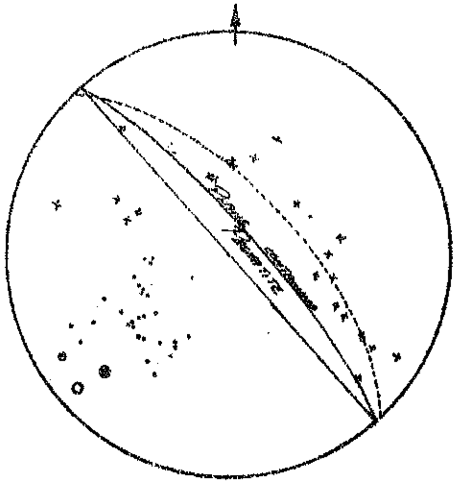
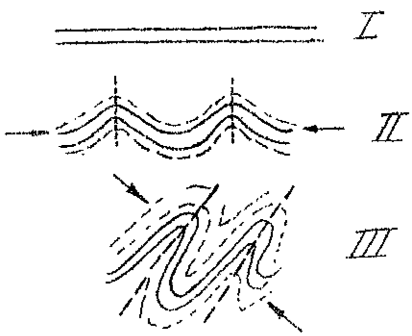


Figure 2.

Figure 1. : Albrechtshöhe-Koliombo Area. Analysis of the third phase of folding with tectonic axes. See text.

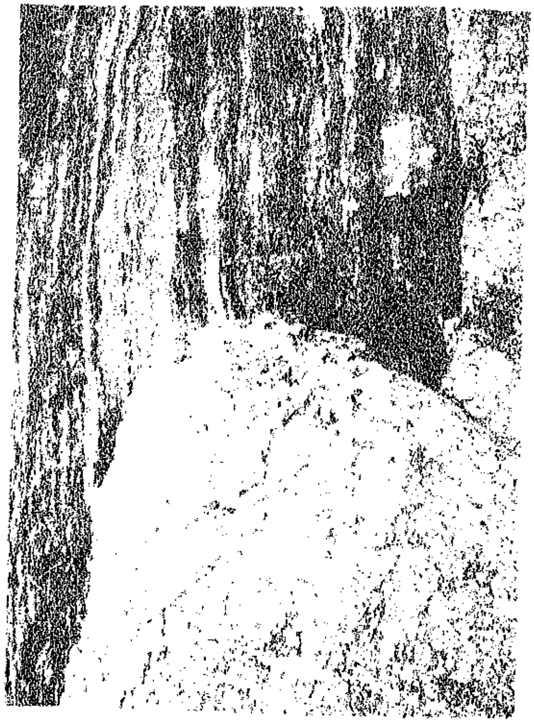
Figure 2. : Mr. Brockmann's pegmatite. Crosses are poles to foliations. Small black dots are lineations. Large black dot is the pole to the circle drawn through the foliation poles. Medium black dot is a lineation measured right next to the pegmatite. Open circle is the pole to the plane containing the pegmatite.

PLATE XVII



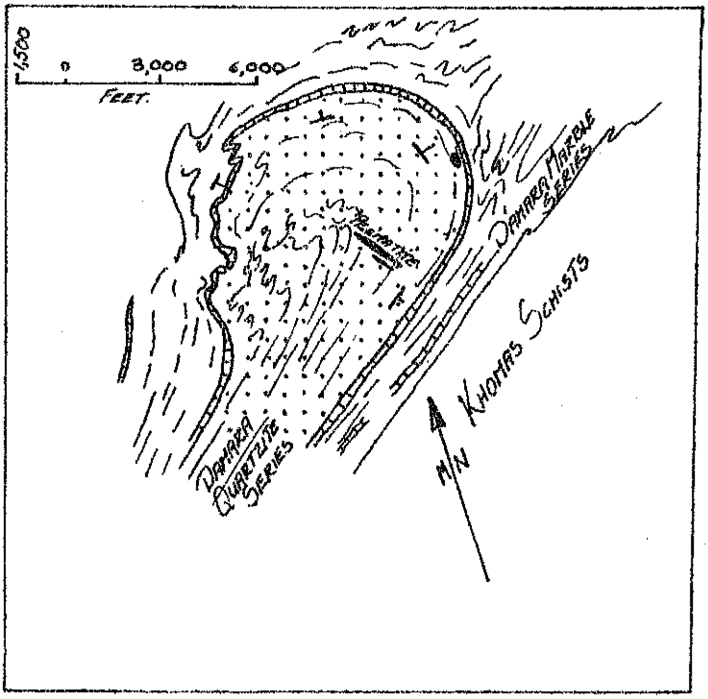
PICTORIAL DEMONSTRATION OF THE ROTATION OF THE STRESS FIELD WITH INTENSE FOLDING RESULTING IN ISO-CLINAL FOLDS. SEE TEXT.

PLATE XVIII



These photos illustrate the permissive introduction of pegmatite into the banded limestone-biotite schist. The foliations are quite unaffected by the pegmatite.

PLATE XIX



Location of Brockmanns pegmatite in an anticline of Damara Quartzites on the Farm Tsaobismund 58.