GEOLOGY ALONG THE NORTHWESTERN MARGIN OF THE KHOMAS HIGHLANDS BETWEEN OTJIMBINGWE-KARIBIB AND OKAHANDJA, SOUTH WEST AFRICA

by

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[Plates I—XX]

ABSTRACT

The general stratigraphy and lithology of the DAMARA SYSTEM is described and variations in facies outlined. The new correlation of these sediments (eugeosynclinal) with those of the OTAVI SYSTEM (miogeosynclinal) in the north is briefly referred to, as well as suggestions that the sediments of the NAMA SYSTEM in the south may represent a shallow-water foreland facies. The old subdivision of the DAMARA SYSTEM is brought into line with the new stratigraphic nomenclature.

In the detailed description of rock types and stratigraphic succession of the area it is conclusively shown that no break in sedimentation (unconformity) is present between the basal rudaceous and psammitic deposits and overlying predominantly calcareous and pelitic sediments, as has been claimed for the marginal areas of the DAMARA geosyncline. It is emphasised that local conditions cannot be generalised over so vast a sedimentational basin.

It is shown that the main geosyncline was initially divided into two portions by a median geanticlinal ridge, termed the ABBABIS swell.

Two strongly contrasted tectonic styles are developed. The supra-structure of the Khomas Highlands is marked by regular isoclinal folding and meso-grade metamorphism (garnetiferous biotite schists and metagreywackes). Gneisses, granites, and related rocks are absent. The infra-structure is characterised by highly complex folding in which domes and basins, brachyanticlinal and -synclines dominate; the sediments are mostly much more highly metamorphic (up to granulite facies) and intimately mingled with gneisses and granites. A considerable portion of these was formed in situ by processes of ultrametamorphism: reddish, sillimanite-bearing leucogneisses and granites from felspathic arenaceous deposits below the resistant Marble Horizon, and porphyritic biotite granites (Salem type) from the pelitic and semipelitic sediments above the latter.

Outwards from the region of ultrametamorphism sillimanite is succeeded in schistose rocks by andalusite and this in turn by staurolite. Concentric mineral banding in spindle-shaped boudins of amphibole-pyroxene-garnet granulite indicates metamorphism to have proceeded pari passu with deformation by the dominant NW—SE directed stress.

A large sheet of allochthonous granite (Donkerhoek) was intruded in late-tectonic times between infra- and supra-structure, thereby enabling differential movements between the two styles of folding to be accommodated. Where this granite locally projects into the basal portion of the supra-structure, a zone of pronounced lateral shear has been developed, marked by strongly developed minor folding and fracture-cleavage. Very striking is the stress-orientation of myriads of andalusite porphyroblasts in this zone: predominantly along fracture-cleavage, but subordinately also along bedding-slip planes. A detailed analysis of this local late tectonic phase is given and illustrated with numerous diagrams and photos.

Two types of pegmatites are present: isolated deep-level bodies originating from below the Marble Horizon and often containing columbite-tantalite, beryl, and lithium minerals; and a profusion of pegmatites, mostly barren except for muscovite, schorl, and almandite, associated with the Donkerhoek granite intruded at a higher level.

I. INTRODUCTION

The dissolution of the Geological Survey of South West Africa during the depression of 1932 terminated the pioneer days of geologic mapping within the great Damara orogen [Reuning, Deutsche Kolonialgesellschaft (27), Gevers, Frommurze, Haughton, and De Kock (5-18)]. The work of Martin and Korn and the final re-establishment of a geological survey after the Second World War, the renewed interest taken by Mining and Exploration Companies in the Territory, as well as

* Numbers in brackets refer to Literature Index.
by University Research Institutes, have resulted in a large amount of new information, much of which regrettably is as yet unpublished.

In his brief 1961 summary “The Damara System in South West Africa”, Martin, until recently Chief Geologist to the South West African Administration, has incorporated some of the newer information, to a very large extent accumulated by himself (24).

Gradually a clearer overall picture of the great Damara geosyncline, its sedimentational history, tectonic deformation, metamorphism and magmatism, is emerging. Now that aerial photographs are available, the task of systematic detailed mapping has been rendered incomparably easier than in the pioneer plane-table days, of the difficulties and hardships of which, particularly in the Namib Desert, the author still has vivid memories. Great gaps, however, remain. It is the purpose of this paper to fill one of these: The region to the northwest of the Khomas Highlands between Otjimbingwe-Karibib and Okahandja. In many ways, only an outline can be given; much precise petrological work on metamorphism still remains to be done; a detailed analysis of all relevant minor structures, according to modern techniques, would be most rewarding.

Smith (31 and 32) and Roering (28), of the Economic Geology Research Unit of the University of the Witwatersrand, extended their mapping of the region farther west into the extreme northwestern corner of the geological map accompanying this paper. The author is indebted to them for permission to make use of their work in this area. He also wishes to express his indebtedness to the South West African Administration for the free issue of aerial photographs.

In particular the author wishes to record his deep gratitude to the late Dr. E. Lübbert for providing hospitality on his farm Gross Barmen and all required transport facilities, as well as generous general assistance. Thanks are also due to Mr. and Mrs. F. Schmidt of Gross Barmen, as well as to Mr. K. Schneidenberger of Rüdenau.

II. TOPOGRAPHY

The region depicted on the geological map (Plate I) is almost in its entirety part of the drainage system of the Swakop River, which traverses it diagonally from the northeast to the southwest. Only to the north of the Windhoek-Walvisbay railway line do run-off channels lead into the Upper Khan River.

The topography south of the Swakop is as strikingly different from that to the north as is, for the most part, also the geology. As far west as the Lievenberg the normally dry river course is close to the highly dissected northwestern edge of the extremely rugged Khomas Highlands, an elevated residual peneplain, rising to heights of close on 6000 feet. The uniformly trending quartz-biotite schists and flaggy biotitic quartz schists building up this rugged tract are much more weather-resistant than the granites underlying extensive areas to the north of the river. With the exception of some red aplitic granites southwest of Okasise and of the Geisterberg (Geol. Map, Plate I), the ordinary granites form low ground, often sand-covered, which rises gently from the Swakop River towards the watershed along which the railway line has been built. Also the rather fissile biotite-andalusite and biotite-sillimanite schists of the lower Khomas Series, within which the Swakop has entrenched itself between Osona and Tugab, weather rather easily. The numerous pegmatites emplaced within them, however, stand out sharply as walls of varying width [Air Photo (19)]. The particularly massive pegmatites
immediately to the east of Okahandja have given rise to a prominent ridge, which in the Merker T.P. reaches 5,200 feet above sea-level.

A striking feature north of the river are the "inselberg" ridges and elliptical mountains built up by the weather-resistant lower members of the Damara System where these have been upfolded into brachyanticlines and domes. The elongate, westwards widening Kaliombo ridge is built up of tightly folded crystalline limestones (marbles); the dome structures consist of metaquartzites and derived leucogneisses and aplitic, as well as pegmatitic, granites, fringed along their lower flanks by marbles and extremely tough para-amphibolites and amphibole-pyroxene-garnet granulites.

The highest point on the Okandura mountain rises to 5,362 feet above sea-level, i.e. some 1,650 feet above the adjacent valley floor. The Kuduberg in the northeastern section of the Otjua brachyanticline reaches 5,090 feet. The Trigonometrical Beacon on the Waldau ridge stands at 5,035 feet, which is only about 700 feet above its southern base. The Lievenberg rises to 4,969 feet, approximately 1,800 feet above the floor of the Swakop River skirting its southern flank.

From Osona (4,030 feet) the Swakop River drops 1,380 feet down to Otjimbingwe (2,650 feet). The highest point of the railway line on the northern watershed, near Waldau Station, is 4,674 feet above sea-level.

The morphological features and origin of the Khomas Highlands and of the "inselberg" topography of the general region have been described in detail by Gevers (17) and Martin (22).

III. GENERAL STRATIGRAPHY AND LITHOLOGY OF THE DAMARA SYSTEM

For a better understanding of various points raised in the description of the stratigraphic succession and lithology of the area under discussion, a brief review of these features over the entire Damara orogen, as far as available, is given first. Gevers and Frommurze, the originators of the term, for the sake of terminological simplicity used the dominant rock types in Western Damaraland as a basis of subdivision (6 and 14-16). A basal group of rudaceous and psammitic sediments was named the Quartzite Series, and an overlying group, composed predominantly of crystalline dolomitic limestones, the Marble Series. A great thickness of then following biotitic schistose rocks was termed the Khomas Schist Series, building up, as they do, the entire length and breadth of the Khomas Highlands.

Somewhat later Gevers found that towards the region of the Khan and Swakop Canyons the Quartzite Series, particularly in its upper portion, underwent a striking change in facies, the ordinary reddish quartzites being largely replaced by dark greenish, epidotic "quartzites" termed Khan quartzites (14). To this succession he also added the Chuos Tillite, first discovered in considerable thickness along the southern flanks of the Chuos mountains below the Marble Series (8). Recently Smith found the tillite, in intermittent outcrops in the Khan Canyon area, also to be underlain by dolomitic marbles not present in the type area. On the assumption that glacial horizons in regions separated by only 40-50 miles would be a more reliable indicator of contemporaneity than limestone deposition, he accordingly separated the group composed predominantly of carbonate rocks into an Upper and a Lower Marble Series separated by the Chuos Tillite. The upper is the persistent member, the lower being intermittent in development and completely absent farther east (31, p.44). It is of interest in this connection that also in the Windhoek and Rehoboth districts, some 130-150 miles to the southeast of the type area, the
glacial deposits occur not only within, but also above the main Marble zone (9 and 13). In this area there thus appear to have occurred several glacial phases; a similar possibility cannot, therefore, be excluded for western Damaraland.

The various groups of the Damara System display the following lithological features:

The basal Quartzite Series (Chuos Quartzites) is composed, from the base upwards, of intermittent conglomerates followed by coarse, sometimes conglomeratic, arkoses, felspathic grits, and well-bedded medium-grained quartzites. The coarse basal members are normally very massive and unbedded, and frequently rendered markedly gneissose by regional metamorphism.

The constituent quartz grains are, on the whole, rather angular. This is in keeping with the frequent rapid change in thickness, particularly of the very coarse basal members. Obviously these rudaceous and psammitic sediments were laid down very irregularly on an uneven floor. Their total thickness, however, often runs into many thousand feet, and south of Windhoek and north of the middle reaches of the Swakop River they build up high mountain ranges.

The Khan Quartzite facies of the westernmost region is composed predominantly of dark, greyish-green, quartzose calc-granulites, with locally interbedded felspathic quartzites and biotite schists (14-16 and 31-32).

Chuos Tillite.—In western Damaraland coarse morainic material is well developed, overlain in certain areas by thinly-laminated varved schists which may extend into the lowermost portion of the Khomas Series, particularly where the Marble Series is attenuated (8). In the Windhoek and Rehoboth districts the glacial horizon is indicated in the main by pebbly schists and phyllites, pebbly marls, and even pebbly marbles of the Marble Series, as well as pebbly biotite schists in the lowermost part of the Khomas Series. The “pebbles” are of very varying size and distribution and often faceted in typical glacial fashion. The phyllites and biotite schists, enclosing them, are often thinly laminated (varves) (9 and 13).

Though often in a highly metamorphosed state, the glacial origin of these rocks has been well documented (11). Both grounded ice sheets and floating ice are indicated as the agents of transport and deposition.

Marble Series.—While bands of crystalline, mostly dolomitic, limestone are to be found also in other horizons, the majority, comprising in the Karibib area units more than a thousand feet thick, occupy a definite stratigraphic horizon above the Quartzite Series.

The macroscopic appearance of these carbonate rocks differs greatly with the intensity of metamorphic alteration, principally the extent to which they have undergone recrystallisation. While coarsely recrystallised in some areas, in others they are fine-grained and then normally of greyish-blue colour. Fine-grained yellow, reddish, brown, and dark, almost black, varieties also occur. Small flakes of graphite are not uncommon. In the southern Windhoek district the limestones are not only intercalated with graphitic schists and phyllites, but the greater portion of carbonate rocks may grade into a graphitic facies. The more highly recrystallised purer types are mostly white in colour. Tremolite, in places also actinolite, is widely developed; along intrusive contacts sometimes also skarn (calc-silicate rock). Banded para-amphibolites, derived from the alteration of interbedded layers of impure ferruginous and argillaceous limestone, as well as of marls, are often conspicuous.
Chert bands are not uncommon and frequently highly contorted by plastic flow of the enclosing limestones.

Khomas Series.—This uppermost, and thickest, division of the Damara System is composed predominantly of metamorphosed pelitic and semipelitic sediments, mostly biotite schists, generally garnetiferous, and flaggy biotite quartz schists (metagreywackes). Muscovite-bearing varieties are subordinate. Hornblende schists are comparatively rare except in the lower portion of the Khomas schists, which frequently also includes bands of crystalline dolomitic limestone, par amphibolite, and, more locally, amphibole-pyroxene granulite. Sillimanite-, andalusite- and staurolite-bearing schists are wide-spread in zones of higher metamorphism, where cordierite is also sometimes developed. Kyanite schists occur sporadically.

While dark biotitic quartz schists are common, purer quartzites are found only in the lower part of the Khomas Series. South of Windhoek a number of such lenses swell to great thickness to build up the Auas mountains. In contrast with the basal (Chuos) quartzites these rocks are fine-grained, non-conglomeratic and of white, yellowish, and grey colour. Deep red tints are not met with. Generally sericitic, their unaltered felspar content is mostly low and often absent. They are well bedded and frequently flaggy.

Ortho-amphibolites derived from basic intrusives, possibly also effusives, are common only in the southern Khomas and Windhoek Highlands. A small body of chlorite-serpentine rock was found within Khomas schists near Windhoek (13, p.238).

While grouped together as “schists”, these rocks are not everywhere fully schistose, but include also phyllites, and northwards towards the Ugab river, even micaceous slates.

Iron and Manganese ores.—Iron-rich sediments, frequently metamorphosed to itabirite and in places forming workable ore, are developed in several horizons of the Damara System: within both the upper and lower Marble Series and, in the Kaokoveld, also in association with the Chuos Tillite (13, pp.233-234, and 24, p.93), as well as within the lowermost Khomas Series (13, p.236).

The highly metamorphosed manganese ores at Otjosondu, northeast of Oka-handja, with their associated itabirites, are intercalated in marbles, schists and quartzites, which most likely also belong to the main Marble horizon, though their position in the lowermost Khomas Series cannot be excluded (30, pp.25-32).

Thickness of Damara System.—Owing to the very variable thickness of its lower members (Quartzite, Tillite, and Marble Series), as well as the difficulty of unravelling the detailed structure of the Khomas and Windhoek Highlands due to the monotonous uniformity of rock types, the total thickness of the Damara System is as yet not accurately known. It must, however, run into many thousands of metres, i.e. ten thousands of feet (24, p.93).

IV. CORRELATION AND NEW STRATIGRAPHIC NOMENCLATURE

Already in the pioneer mapping by Gevers, Frommurze, and Haughton it was noted that towards the Ugab river in the north a decrease in general metamorphism of the carbonate, pelitic and semipelitic sediments of the Damara System is evident. Jeppe drew further attention to this feature in 1952 (20). Finally Martin showed in 1950 (23 and 24) that still farther north the metasediments of the Damara System
pass by degrees of lessening metamorphism into the sediments of the *Otavi System*. This was later substantiated also by other workers (1 and 33).

While the highly tectonised *Damara* sediments were deposited in a eugeosynclinal environment (basic effusives, however, are not very abundant and serpentinites of "Alpine" type very scarce), the comparatively gently folded *Otavi* sediments correspond rather well with miogeosynclinal deposition (24, p.92).

The *Damara-Otavi System* is hence now divided into a northern (*Otavi*) and a southern (*Damara*) facies, as recently outlined by Martin (24). It had been suggested that, on the basis of an alleged widespread unconformity, the basal rudaceous and psammmitic sediments should be entirely separated from the overlying groups. Martin, however, disputed the validity of this separation (24, p.92). In the area described in the present paper, there is no sign whatsoever of any break in sedimentation. Apart from local wedging out of the basal members, due to deposition on an uneven, gradually infilled and slowly subsiding land surface, there is no evidence for a real unconformity also in the type area of western Damaraland.

Since well-developed tillites in the *Otavi* region separate an upper carbonate group (*Tsunegeb Stage*) from a lower (*Abenab Stage*) (33), Smith's subdivision of the *Marble Series* into an upper and lower group has been accepted as general. It will be shown, however, that sedimentation in the initial stages of development of the Damara geosyncline was so variable that, where the *Chuos Tillite* is absent and limestone as well as quartzite bands in the lowermost *Khomos Series* locally swell to considerable thickness, this subdivision of the *Marble Series* may become inapplicable for mapping purposes.

It is only to be expected that in a geosyncline of such wide areal extent as the Damara, there should not only be considerable sedimentological variation due to unequal rates of subsidence and changing nature of the source-areas, but also local breaks in sedimentation and possibly even angular unconformities, particularly in the marginal regions. There is always a considerable measure of risk in generalising local conditions.

The "official" stratigraphic nomenclature of the Geological Survey for the *Damara System* is now as follows:

<table>
<thead>
<tr>
<th>Damara System</th>
<th>Khomas Series</th>
<th>Upper Stage:</th>
<th>Upper Marble</th>
</tr>
</thead>
<tbody>
<tr>
<td>Swakop Facies</td>
<td>Hakos Series</td>
<td>Lower Stage:</td>
<td>Lower Marble</td>
</tr>
<tr>
<td></td>
<td>Nosib Formation</td>
<td></td>
<td><em>Etusis, Khan</em> and <em>Kamtsas Quartzite Members.</em></td>
</tr>
</tbody>
</table>

Söhinge (33, p.235) has gone back to the old correlation of the northern *Otavi System* with the sediments of the *Nama System* widespread in southern South West Africa (Namaland). Also Martin (24) and Smith (31) favour the idea that the latter represent a largely undeformed southern "foreland" facies of the eugeosynclinal *Damara* sediments farther north. Since erosion has removed a direct connection, no gradational passage can be observed.

Many aspects of detailed stratigraphic grouping and correlation are still in a state of flux. No continuous section across the entire width (230 miles) of the *Damara* orogen has as yet been mapped.
V. AGE OF DAMARA SEDIMENTS.

Eight recent determinations by Burger, Nicolaysen and Rethemeyer, quoted by Smith (31, p.110), on uraninite, davidite, yttrotantalite and -columbite, as well as biotite, from the Khan Canyon region all gave ages of $510 \pm 40$ million years; one on monazite yielded $520 \pm 20$ million years. Earlier age determinations by Nicolaysen, Jamieson and Schreiner on lepidolite from pegmatites in the Karibib area also yielded a mean of $510$ million years (25, p.588).

This would relegate the formation of the above-named minerals to the Cambrian. Roering (28) has shown, however, that the lithium-bearing pegmatites in the Karibib District were emplaced very late in the orogenic cycle, largely along tension-fractures and faults developed when the deeply depressed rocks had again attained a sufficiently brittle state (28, pp.24-28). Taking into account, as already suggested by Martin (24, p.94), that the first orogenic phases must have begun considerably earlier and were preceded by a lengthy period of sedimentation in a slowly deepening geosyncline, makes it probable that the Damara sediments are of late Precambrian age.

VI. ROCK TYPES AND STRATIGRAPHIC SUCCESSION IN THE REGION BETWEEN OKAHANDJA AND OTJIMBINGWE-KARIBIB

With the exception of surficial sand, calcrete, alluvial gravels and numbers of Kaoko (Karroo) dolerite dykes, the entire area described in this paper is underlain by metasediments of the Damara System together with gneisses, granites, aplites and pegmatites associated with the subsequent metamorphism and magmatism of the Damara orogeny.

Only in the eastern area, between Osona and Rüdenau, are complete sections undisrupted by intrusive granite available (Geol. Map, Plate I). Exposures on Gross Barmen and Rüdenau are mostly excellent and the rock succession can be studied in great detail.

Quartzite Series (Nosib Formation: Etusis Quartzite Member). Owing to the tight compression of the Waldau ridge dome, overfolded to the south, the lowermost rocks, such as basal conglomerates, are not exposed. The major outcropping rock types are massive, highly felspathic arkoses, grits and quartzites frequently indistinguishable from reddish and yellowish leucogneisses and aplitic granites of medium to fine grain. Discrete pegmatitic veins and schlieren of coarser grain are common. Partial and complete granitisation of these sediments is indicated. Towards the top of the succession definite sedimentary origin is proved by gradual transition into less massively-bedded felspathic quartzites, with scattered orbicules and discs of sillimanite, which is found in lesser abundance also in the more granitic-looking and gneissose rocks. The distinctly bedded felspathic quartzites are followed upwards by extremely well-bedded, highly siliceous quartzites, succeeded in turn by softer quartzites studded with light-coloured orbicules and discs, sometimes more than an inch in diameter, composed mainly of sillimanite with subordinate quartz. In some layers these are closely massed; in others somewhat more scattered, though still abundant. Even in this horizon some felspathic layers closely resemble aplitic granite.

In the felspathic quartzites, grits and arkoses, detrital felspar must have been the source-material of sillimanite (cf. aplit dykes, Chapter VII, F). In most of the uppermost layers, however, devoid of macroscopically visible felspar, a primary clay content must have been increasingly responsible; not only does biotite appear
in the main body of the rock as well as in the sillimanite orbicules, but narrow interbedded layers of coarse biotite schists, containing aggregations of sillimanite with a higher biotite content, become progressively more common and of greater width. A final thick layer of coarse sillimanite-biotite schist, of low resistance to weathering, is responsible for a marked furrow on the southeastern slopes of the Waldau ridge. Above this rock follows absolutely conformably a very massive black amphibolite, up to 60 feet thick, representing the lowest member of the *Marble (Hakos)* Series.

**Chuos Tillite.**—The only occurrence of coarse metamorphosed morainic tillite in the area was discovered by Roering (28) in the western portion of the Kaliombo limestone ridge, on the southern flanks of a small dome. The tillite material overlies the upfolded quartzites and is immediately followed by crystalline dolomitic limestone (Geol. Map, Plate I).

Extremely thinly laminated "sandy" biotite schists are, however, widely developed within and above the *Main Marble* horizon and extend well up into the *Khomas* schists as far south as the Swakop river. (Photos 12-17, Plates VIII-XI) The light quartz-rich bands are generally wider than the dark biotitic layers, which are often only a few millimetres thick. Moreover, the slides examined show distinct gradation not only of the biotite content, but also of the size of the mostly angular quartz grains. These are largest in the most light-coloured, central portions of the quartz-rich bands and progressively smaller towards the dark, biotite-rich laminae. Particle-size gradation is typical of glacial varves. In the southern Windhoek District, some 60-80 miles to the southeast, similar thinly banded schists and phyllites within and above the *Marble* horizon contain, as already stated, abundant typically faceted, randomly distributed erratics of all shapes and sizes, which clearly prove their glacial origin at least in the latter region (13).

**Marble (Hakos) Series.**—The development of this group is strikingly different from that in the Karibib type area to the west, where massive marble bands, more than 1,000 feet thick, build prominent hills and mountains. Along the southern fringe of the Waldau ridge dome, however, crystalline limestone bands are nowhere more than 30-40 feet thick and quite subordinate to prominent black para-amphibolites and various amphibole-pyroxene granulites interspersed in coarse sillimanite-biotite-(muscovite) and thinly laminated "sandy" biotite schists. The whole succession, ± 1200 feet thick, represents alternating highly metamorphosed clayey sands, sandy clays, and clays, often calcareous and ferruginous (marls), with interspersed purer limestones.

An up to 60 feet thick, massive band of black amphibolite is usually conspicuous near the base of the whole succession. It has already been mentioned that in the Windhoek District ortho-amphibolites are met with in marble- and para-amphibolite-bearing horizons of the lower *Khomas Series* (13, p.237). Similar rocks of possible effusive origin occur higher up in the sequence.

In the area under discussion, however, these rocks are all para-amphibolites. Even the very massive black amphibolites often show narrow, discontinuous bands of lighter colour made up of quartz, pyroxene, calcite, and sphene in varying proportions. Many of these rocks show very pronounced banding. A very striking type is built up of light bands, up to more than one inch wide and composed almost purely of quartz, alternating with dark layers, either thicker or thinner, consisting mainly of amphibole, subordinate pyroxene, and smaller quartz grains. Magnetite
is sometimes present. Quite probably these rocks represent highly metamorphosed, banded sideritic-ankeritic cherts or banded ironstones, viz. in part at least chemical precipitates. They are often highly contorted. Associated highly siliceous banded quartzites, with very narrow, or barely developed, separating dark layers and often also highly contorted, no doubt represent recrystallised iron-poor jaspilites and cherts (Plate III, Photo 1). That banded amphibolites developed and not the widespread itabirite schists (13 and 24, p.93,) is probably related to the high CaO content of these sediments and their recrystallisation under the metamorphic conditions of the amphibolite-granulite facies, with only subordinate shearing stress.

A different variety occurs in the foot-hills of the Waldau ridge on Rüdenau. A greyish-green, predominantly pyroxene-bearing granulite speckled with garnet alternates with ordinary “sandy” biotite schist in bands of varying thickness. The granulite layers are up to 8-10 inches wide and, where exposed, these rocks are not nearly as contorted as the former, more thinly banded types. (Photo 2, Plate III). Originally they must have been in the nature of alternating ferruginous marls and sandy clays. Only the purer dolomitic limestones recrystallised to white marbles, sometimes showing small flakes of graphite. Whether black para-amphibolites, with quite subordinate pyroxene and garnet, or lighter-coloured granulites, in which pyroxenes are present in abundance or dominate over amphibole, developed from the impure intercalated sediments must have depended largely on the relative proportion of iron. The abundance or otherwise of plagioclase was no doubt mainly determined by the amount of admixed clay; that of quartz by the latter and the abundance of primary quartz grains. Calcite in varying amounts was found in many slides. Sphene is practically ubiquitous. Reddish garnet is present in varying amounts, often sufficient to be included in the rock name.

A noteworthy feature is the presence of untwinned felspar and microcline. (35, pp.554-557).

The development of the Main Marble horizon in this region shows great variations both in rock types and in thickness. Not only did primary sedimentational conditions fluctuate widely, but varying degrees of metamorphism, tectonic deformation, and disruption by intrusive granites during the subsequent orogeny also resulted in important secondary effects. On the scale of the map (Plate I) much generalisation had perforce to be employed. This applies particularly to the Waldau upfold, largely obscured by calcrite and sand, and the area between this structure and the northern foot of the Waldau ridge dome. Here not only extensive sand cover, but also intense disruption of the sediments by granite make it difficult to unravel details. The representation on the map is therefore rather schematic.

While along the southeastern flanks of the Waldau ridge para-amphibolites and amphibole-pyroxene granulites completely predominate over crystalline limestone bands, the latter are already much more massively developed along the southwestern fringe of the dome (Löwenberg) in the upper part of the horizon, though great thicknesses of extremely tough granulites still characterise its lower portion. Along the northwestern flanks of the dome only a narrow width of intensely disturbed and disrupted black para-amphibolite remains. Only 4-5 miles to the northeast, around Waldau, however, great thicknesses of marble are again in evidence.

Around the Lievenberg dome, in the south, para-amphibolites and amphibole-pyroxene (garnet) granulites preponderate considerably over narrow bands of
marble. Not only have these rocks been intensely crumpled, but so disrupted by intrusive sheets and tongues of granite that, along the northern foot of the dome, the combined outcrop width of these rocks is roughly two miles (Geol. Map, Plate I).

Along the southeastern, southern and southwestern flanks of the Otjua brachy­anticline, in the western portion of the map, para-amphibolites and amphibole-pyro­roxene granulites are still present in considerable development, mostly in the upper and lower portion of the group. Northwards there is a marked decrease in their relative abundance. At the northwestern foot of the Okandura dome, where also marbles have shrunk to a total thickness of less than 200 feet, they are altogether absent. Also in the Kaliombo ridge their development is not striking. Instead, there is in places a very considerable development of tremolite within the marbles towards the western end of the ridge, e.g. around the Karlsbrunn and Helicon II pegmatites (shown as Li on Map, Plate I).

In this western region a great primary depositional increase in purer dolomitic limestones, relative to marls, is evident. There are also far fewer intercalations of clay (biotite schists). In these respects this area conforms with general conditions in the adjacent Karibib District and the area farther west. The enormous outcrop widths of marble met with over large sections, however, are in part, often major, due to folding and flowage. This is immediately apparent in the narrow tract between the Okandura and Otjua domes, particularly where these two structures are linked, as well as along the southwestern fringe of the complex Otjua brachyanticline. The striking attenuation of the entire carbonate zone at the northwestern foot of the Okandura dome may also to a considerable extent be due to deformation and flow. The enormously crinkled chert bands found in some localities indicate a high degree of plasticity of the enclosing marbles at the time of deformation and recrystallisation (16 p.32 and 31 p.54).

Khomas Series

**Khomas Series.**—Owing to regional and local variation in depositional features it is often a moot point where to draw the boundary between the *Marble (Hakos)* and *Khomas Series*. In the area to the west, Smith appears to have drawn it at the uppermost marble band, even when separated from the main mass of crystalline limestones by thick zones of biotite schists (31, p.56). In the Windhoek district Gevers (13, p.236 et seq) placed the entire, up to several thousand feet thick, zone of Auas quartzites and separating schists, para-amphibolites and limestones into the lower *Khomas Series*.

It is evident from the already given details of the Waldau ridge section that there is no sign whatsoever of a sedimentational break between the *Quartzite (Nosib Formation)* and *Marble (Hakos) Series*, but, quite to the contrary, a gradual change, with recurring fluctuations, from sandy sediments of progressively decreasing grain size into clayey sands, sandy clays, and clays alternating with marls and dolomitic limestones. The transition from the main para-amphibolite, amphibole-pyro­roxene granulite and marble horizon into overlying predominantly pelitic and semi-pelitic sediments is equally gradational. Deposition of fine-grained sand, marl and limestone recurred over several thousand feet of the lower *Khomas* schists. The majority of thicker intercalations of these non-pelitic sediments, however, are found near the base of the latter within a vertical thickness of more than one thou­sand feet.
Over several miles south of the Waldau ridge very coarse, knotted and spotted, sillimanite-biotite schists, often with muscovite, are the main rock type, until the numerous interspersed more "sandy" biotite schists begin to dominate, finally to the exclusion of the former. The sillimanite-bearing rocks are in certain bands coarse enough to be designated gneisses.

Narrow bands of black amphibolite, with subordinate lenses of amphibole-pyroxene granulite and occasional limestone, persist for many hundreds of feet into the schistose rocks, until they are once more aggregated into a second, subsidiary "marble" zone, shown as *Upper Marble Horizon* on the legend to the map. This is well exposed on the northern portion of Gross Barmen, from where it stretches in a northeasterly direction towards the lime-kilns on the Okahandja-Karibib road, a few miles to the northwest of the former village. In the west it appears to peter out on Rüdenau.

This zone shows the same variations in the relative proportions of marble, para-amphibolite, amphibole-pyroxene granulite and intercalated sillimanite and "sandy" biotite schists as the *Main Marble horizon*. The entire zone has a maximum thickness of several hundred feet. This is more than that of the *Main Marble Horizon* where the latter is greatly attenuated over certain sections farther west. Furthermore, individual limestone bands within this upper zone swell to greater thickness than in the main horizon of this locality. At the lime-kilns near Okahandja there are some half dozen individual bands, the thickest of which is 30-40 feet wide.

Along the banks of the Gross Woldau River up to 60 feet thick white marble bands are exposed at three individual localities spread over about one mile. Reversals of dip, however, indicate folding; repetition of the same horizon cannot therefore be excluded.

These features make evident the difficulty, in the absence of complete sections particularly when the *Chuos Tillite* is not developed, of deciding whether isolated outcrops of marble and para-amphibolite actually represent the *Main Marble horizon* or not. Smith's (31) subdivision of the latter into an *Upper* and *Lower Marble Series* practically necessitates the presence of the tillite, which over large areas is only very intermittently developed. Attention has already been drawn to the possibility of more than one glacial phase. According to Smith, the *Main Marble Horizon* of the entire area under discussion would be his *Upper Marble Series*, because the one single small occurrence of tillite in the western portion of the Kaliombo ridge is wedged between the basal quartzites and overlying dolomitic marbles, as is the case for some 60 miles westwards. It is true that Smith lists not only para-amphibolites and biotite schists, but also subordinate, discontinuous quartz schists, highly siliceous quartzites, and sporadic "pebble-washes" at different stratigraphic levels as members of his *Lower Marble Series* (31 pp.44-48). With the exception of pebble layers, which in any case are stressed to be very sporadic in distribution, all of these rock types also occur in the *Main Marble Horizon* of the area under description.

Absolute uniformity cannot be expected in a geosyncline of such great extent as the Damara. It is quite possible that what in this paper is described as the *Main Marble horizon* includes both of Smith's *Upper* and *Lower Marble Series*. It is a moot point, in the absence of the tillite and outcrops of underlying psammitic and rudaceous sediments, to what extent even thick developments of marble, e.g.
in the vast area between the Khan River and the northern rim of the geosyncline near Fransfontein, are all strictly contemporaneous horizons.

Continuing the Gross Barmen Rüdenau section south of the Waldau ridge, fine-grained, mostly flaggy, brownish-yellow quartzites reappear in considerable numbers within "sandy" biotite schists a short distance above the Main Marble horizon. In two horizons, over one hundred feet thick, they exceed in number and thickness the intervening schists. Many contain sillimanite, often in the form of orbicules, discs and knots; some are sericitic. Also purer bands of very fine-grained white, highly siliceous quartzite are common, varying in width from a few inches to several feet, on the farm Waldau farther north even up to 60-80 feet. These can often be seen to grade into the intercalated biotite schists. Where comparatively thin and rapidly alternating with the latter, these rocks are often contorted in astonishing fashion (Photos 3-5 Plates IV and V).

Similar white quartzite bands recur at intervals for several miles southwards. They sometimes contain a profusion of sillimanite-quartz orbicules, frequently of the size of golf balls. On account of their very fine, sugary grain any felspar present is not readily identifiable macroscopically. Some of these rocks were hence at first taken to be unusually fine-grained, concordant aplites. Microscopic examination, however, showed potash felspar either to be scarce or, in the highly sillimanitic types, too low for aplites.

After the cessation of sillimanite in readily recognisable form within coarse schists, fine-grained biotite schists with numerous intercalations of usually laminated "sandy" types continue southwards to beyond the Swakop River. (Photos 8, 9, 12 and 13, Plates VI to IX). Andalusite porphyroblasts now replace sillimanite. Beginning with knots, sometimes more than half an inch in diameter, composed of biotite, quartz and andalusite, smallish plates appear already north of the "Chinese Wall" swarm of pegmatites on Gross Barmen (Air Photo 19). These rapidly increase in size southwards, assuming the form of elongate prisms and rods very frequently several inches, occasionally 6-8 inches long. Small flakes of biotite and grains of quartz and magnetite are often poikilitically enclosed within the porphyroblasts, which also exhibit extensive replacement by muscovite, particularly near pegmatites.

In the well-exposed area around the Hot Springs of Gross Barmen and along the northern banks of the Swakop River, the enclosing host rocks are biotite schists differentiated into bands of varying biotite content, ranging in width from less than a foot to several feet. Originally these rocks must have been alternating layers of clay, sandy clay, and clayey sand. Narrow lenticles, from a few inches down to less than \( \frac{1}{2} \) inch thick, of white quartzite, usually speckled with biotite only along their margins, still occur in certain of the more sandy layers.

Many bands, usually the more sandy ones, are thinly laminated on a scale frequently akin to "varves"; the darker more biotite layers ranging down to mere lines less than a millimetre thick (Photos 8, 11, 12, 14, 17, 19, Plates VI, VII, VIII, IX, XI and XII). Several microscopic slides show grading of the quartz grains, those in the dark biotite-rich laminations being smaller than in the lighter, more quartzose. This feature indicates the thin banding to be, in part at least, a primary sedimentational feature. The possibility of the presence of true, i.e. glacial, varves has already been mentioned.

But almost certainly part of the fine banding is due to ionic migration in solution during recrystallisation under the influence of differential shear parallel to the
bedding (cleavage- and segregation-banding), in the same way as the very pronounced fracture-cleavage is often marked by narrow films of parallel biotite flakes. Most andalusite porphyroblasts have grown on fracture-cleavage planes (Photos 16-24, Plates X-XIV).

Narrow lenticular bands, mostly less than 1 foot and often only a few inches thick, of amphibole-pyroxene-garnet granulite continue in certain horizons all the way down the Swakop River (Photos 10, 11, 14-19; Plates VII-XII). They are particularly numerous along the northern banks of the latter and in the rocky sides and floor of the lower Gross Waldau River, where, together with even narrower bands of white quartzite, they are very useful in bringing out minor structures. Frequently they exhibit a striking mineral banding: dark hornblende is concentrated on the outside and followed inwards by a zone of white minerals (quartz with variable amounts of calcite and twinned plagioclase) speckled to varying degree with green diopsidic pyroxene and pink garnet (almandite), the latter increasing inwards to form a garnet-rich core (Photo 10, Plate VII). While the calcite content is variable, sphene was found to be present in nearly all slides.

Immediately south of Gross Barmen andalusite porphyroblasts continue into the south bank of the Swakop River, but then cease. Exposures within the valley bottom are poor, but within a few hundred yards southwards small light-brown crystals of staurolite were found in the soil on Ravensberg. Up-river there is a striking development of staurolite near the junction of the Swakop with the Otjiwa River on the farm Okuandua (Geol. Map, Plate I). Around a zone of pegmatites north of the Swakop the crystals are large (up to 1½ inches long) and universally grey in colour. This, as is the case also with andalusite under similar conditions, is due to extensive replacement of staurolite and included quartz by fine-grained muscovite. Southwards the crystals become progressively smaller and change, away from the pegmatites, into ordinary unreplaced pale-brown staurolite. Over a width of many hundred yards the surface is strewn with these crystals, interpenetration twins in the form of short stumpy crosses being quite common.

Still farther south staurolite ceases and ordinary monotonous garnetiferous biotite schists, together with abundant flaggy and platy biotitic quartz schists, (metagreywacke) build up the main mass of the Khomas Highlands.

VI. METAMORPHISM

A remarkably clear metamorphic sequence, indicating a general progressive increase of grade towards the gneisses and granites in the north, is thus in evidence in this region. Ordinary garnetiferous biotite schists of medium metamorphic grade pass through a broad staurolite zone and a 1½—2 miles wide andalusite belt into a high-grade sillimanite- amphibolite-granulite zone, within and beyond which granitisation of suitable rock types is wide spread. The influence of pegmatitic offshoots of granite bodies makes itself felt mainly in a coarser degree of recrystallisation of the biotite and sillimanite schists, and in secondary hydrous alteration (muscovitisation) of the anhydrous aluminium silicates sillimanite and andalusite, as well as of staurolite.

The artificiality, in many ways, of the depth-zone concept is manifested by the intimate association of “medium grade” types (“sandy” biotite schists) with “high-grade” sillimanite schists and granulites. The strong, often overriding, influence of chemical and mineralogical composition, as well as of the availability and pressure of hydrous fluids (water), is obvious (35, p.554-556).
Metamorphic zoning along the roughly 220 mile long stretch between Okahandja and the Atlantic coast near Swakopmund, in large part mapped by the author and revised by Smith, is, however, by no means everywhere as distinct as in the Gross Barmen-Rüdenau section just described. While its main features are regional, this particular section is the best developed example known to the author. Although sillimanite is widely developed in the felspar-bearing arenaceous sediments and the overlying, originally clayey sands and sandy clays, nowhere else has the author come across such a striking development of sillimanite-quartz orbicules, often attaining the size of golf balls, as in the Waldau ridge dome and the quartzite bands of the adjoining area on Rüdenau and Gross Barmen. Also nowhere else have discs and knots crowded with sheaf-like sillimanite been noticed in such profusion as in the coarse sillimanite-biotite-(muscovite) schists, often coarse enough to be termed gneisses, within the Marble (Hakos) and lower Khomas Series of this locality.

While sporadically developed as much smaller porphyroblasts elsewhere, the outcrops along the Swakop River on Gross Barmen and Rüdenau represent the most spectacular development of andalusite, with regard to both profusion and size, seen by the author anywhere in the world (Photos 16-24, Plates X-XVI). Professor J. B. Thomson, Jnr., of Harvard University, however, has informed the author that certain schists in the Appalachian orogenic belt of Vermont and the adjacent New England States contain andalusite in equal profusion and, in places, of even larger size.

Eastwards, towards Okahandja, this zone of large andalusite porphyroblasts is mostly obscured by sand; westwards its spectacular development appears to recede rapidly. Already on Klein Barmen and Tugab macroscopically readily identifiable andalusite was not observed on any significant scale. The same applies to the area still farther to the southwest. Andalusite has, however, been identified in knots within schists as far west as Donkerhoek on the edge of the Namib desert.

In the western region cordierite appears to be far more widely developed than andalusite (Smith 31, pp.59 and 62).

Staurolite is macroscopically visible at intervals along the whole of the granite contact-zone of the Khomas Highland schists from Okahandja to Donkerhoek. The most prolific development of this mineral was seen in the vicinity of the old Gorob copper mine in the Namib desert. Here wind action has in places led to the accumulation of an ankle-deep deflation-residue composed almost entirely of staurolite crystals with prism-lengths of up to several inches.

The main metamorphic features of the crystalline dolomitic limestones, paragonites and amphibole-pyroxene-garnet granulites of the Main and Upper Marble horizons have already been discussed. It should be noted that all of these rocks in this area are situated within the sillimanite zone.

No kyanite-bearing rocks, such as sporadically occur along the southern margin of the Damara orogen in the Windhoek district, have been observed anywhere. Also Smith makes no mention of this mineral in his description of the area farther west (31).

VII. GNEISSES, GRANITES, APLITES, AND PEGMATITES

A. Rocks within Brachyanticlines and Domes

The reddish and yellowish sillimanite-bearing leucogneisses and aplitic granites into which the arkoses, felspathic grits and quartzites grade within the Waldau ridge dome, have already been described. The abundant development within rocks
still recognisable as sediments of discrete, i.e. isolated, not interconnected, reddish pegmatitic schlieren and veins was also mentioned. Similar bodies of aplitic texture also occur. These features are met with even in some of the comparatively narrow quartzite layers intercalated in schists, within the sillimanite zone, of the lowermost Khomas Series. Not infrequently can they be seen to invade the adjacent schists for short distances, thus proving sufficient mobility for injection.

Between the Waldau ridge dome and railway occur many, often thick, elongate bodies of aplitic granite that are definitely intrusive. The reddish types may have been injected from inside the dome into the Khomas schists, though none were seen to cut across the immediately overlying rocks of the Main Marble horizon. The majority are no doubt connected with the large intrusive sheet of Donkerhoek granite to be described presently. It should be noted that the latter, while predominantly light grey in colour, is in places also reddish, as for instance over a wide tract around Okasise.

That the mobilised reddish aplitic and pegmatitic material was actually extruded from inside the dome structures through the rocks of the Main Marble horizon into overlying schistose rocks is proved by scattered red aplites and pegmatites in their immediate surroundings. These are mostly narrow and seldom extend for more than a mile or two away from the base of the domes and brachy anticlines. Though never very abundant, they are nevertheless sufficiently common to serve as indicators, if one were to keep one's eyes to the ground, of the proximity of a structural upfold (antiform).

In the northwestern portion of the Otjua brachyanticline aplitic and pegmatitic granites, into which sillimanite-rich felspathic quartzites and grits as well as massive arkoses can be seen to grade, were in places mobilised sufficiently to be injected not only into the adjacent highly metamorphosed psammitic rocks (Chuos-Etusis), but, more rarely, also into the overlying amphibolites and amphibole-garnet granulites of the Marble (Hakos) Series. The morphologically very striking Geisterberg, adjacent to the northeastern rim of the Ombujomene dome (Geol. Map, Plate I) and rising to a height of 5260 feet above sea-level, represents a larger mass of red granite extruded from within the neighbouring dome.

In the majority of upfolds (antiforms) in the area under discussion the sillimanite-bearing arenaceous and arkosic metasediments of the Chuos (Etusis) Series grade into reddish and yellowish leucogneisses, with concordant banding and foliation, and massive red aplitic granites. White pegmatitic schlieren and veins are widespread and also dykes and sills not uncommon, larger masses of pegmatitic granite are in general subordinate. In the Ombujomene dome, however, leucogneisses are very inconspicuous and the red granite, which almost entirely fills it, is rather coarse and to a very considerable extent pegmatitic. Transformation of the felspathic arenaceous sediments is thus not only practically complete, but also must have proceeded under conditions of high volatile concentration. It is not surprising, therefore, that it is in this neighbourhood that pegmatites begin to assume economic importance, carrying lepidolite, petalite, amblygonite, beryl, columbite-tantalite, etc.

Except in the gneisses generated from schistose zones in the uppermost part of the Quartzite Series (Etusis) in which bitotite may be conspicuous, muscovite is the dominant mica that in varying proportions accompanies quartz and felspar in these rocks. The ultrametamorphism is thus largely isochemical. That sodic plagioclase is often conspicuous, as noted by Smith (31, pp.68-75, and pp.91-95),
is not surprising in view of the fact that the underlying older Abbabis gneisses are largely granodioritic in composition. In the massive, homogeneous, red granites, particularly those extruded from the domes and brachyanticlines into overlying Khomas schists, a variable biotite content is often noted, as in the rock of the Geisterberg. Usually, however, it is low and exceeded by muscovite. Practically universally these rocks are very leucocratic and, as stated, predominantly aplitic in texture. In the more highly pegmatitic varieties conditions of recrystallisation seem not to have been purely isochemical; addition of potassium, as well as of sodium in some instances and, to a lesser extent, of silica, appears to have taken place. Possibly, however, this may merely have involved redistribution, i.e. more local concentration, of primary components.

For details reference should be made to the work of Smith (31, 32) and Roering and Gevers (29).

While Gevers and Frommurze originally regarded the massive aplitic and pegmatitic granites within and outside the dome and anticlinal structures as of truly magmatic injection origin, the author, after mapping the area under description, independently came to the same conclusion as Smith for the region farther west, viz. that their bulk is autochthonous and was formed more or less in situ by ultra-
metamorphic granitisation of the arkosic and arenaceous sediments of the Chuos Series (Etusis). This fact is particularly well demonstrated in this region. It must be recorded that Martin communicated this view to the author for the Lievenberg already in 1957.

B. Salem Granite

This biotite-rich porphyritic granite so widely distributed in the region to the west and northwest is not represented in the area under description, though somewhat similar types of granite are found locally. Gevers and Frommurze (6) stressed that this type is met with mostly in synclinal structures within Khomas schists above the rocks of the Marble (Hakos) Series. They also noted frequent gradational transition from ordinary biotite schists through progressively felspathised rock (dents de cheval) into biotite-rich porphyritic granite still showing parallelism of abundant felspar phenocrysts with the strike and foliation of the enclosing schists (15, pp.409-411). They further mentioned that inwards the felspar phenocrysts often become progressively more disoriented and the biotite content of the rock less, finally at some localities to form a core of massive, less foliated and less markedly porphyritic, biotite granite. Under the influence of Sederholm's classic concept of marginal interaction and contamination, they nevertheless regarded the core portion of these bodies as being of injected magmatic origin.

Smith, however, has now produced an array of convincing evidence indicating that the Salem granite is for the most part an autochthonous product of largely isochemical granitisation. For details reference should be made to his work (31 and 32).

It will presently be shown, however, that in the region under description local development of porphyritic Salem-type granites is the result of initial felspathisation (dents de cheval) and final assimilation of Khomas schists by an undoubtedly intrusive granite (Donkerhoek).

C. Diorites and Quartz Diorite

These rocks, occurring in the horizon of the Khomas schists to the west of the Ombujomenge dome and Otjua brachyanticline, have already been described by
Gevers (15 pp.403-406) and more recently by Smith (31, pp.81-86); they need no further elaboration here.

D. Donkerhoek Granite

1. Field relationships.

Gevers, Frommurze and Haughton (5, 6, 15, 16, 18), followed by Smith (31, 32), have shown that, contrary to Reuning's early reconnaissance picture of vast granite masses (the so-called Hereroland granite), the various types of granite occur predominantly in the form of smaller concordant massifs separated by a sedimentary framework of rocks belonging mainly to the Marble (Hakos) Series. The resistance of crystalline dolomitic limestones to magmatism and tectonic disruption has been commented on both by the early workers (5, 6, 15, 16, 18) and more recently by Smith (31, p.93). This resistance, while to be expected from chemical composition under deep-seated conditions, inhibiting dissociation of CaCO$_3$ and CaMg(CO$_3$)$_2$, as well as from the capacity for plastic flow, is nevertheless often astonishing. Both underlying (Chuos-Etusis quartzites) and overlying rocks (Khomas schists) may have been altered beyond recognition by ultrametamorphic granitisation, but marble bands, even if only a few dozen feet thick, are still found in their proper stratigraphic horizon and structural position as sole remnants of the normal rock succession. Even definitely intrusive granites appear to have found the marbles and associated amphibole-pyroxene rocks difficult to deal with in a purely mechanical way. A glance at the area between the Waldau and Waldau ridge domes, as well as the surroundings of the Lievenberg dome, as depicted on the geological map (Plate I), is sufficient to indicate that these rocks provided considerable obstacles in the emplacement of the vast intrusive sheet of Donkerhoek granite.

The latter, from where it appears from under the Kalahari sand northeast of Okahandja to where it once more gets buried by the sand and rubble of the Namib desert west and southwest of Donkerhoek, represents the most extensive individual granite body in the whole of central South West Africa.

The mode of emplacement of this great sheet of granite along the entire northwestern margin of the Khomas Highlands provides several features of special interest. Even this vast mass of intrusive granite, exposed over a length of some 150 miles and up to 30 miles wide, exhibits clearly a large measure of control by pre-existing tectonic structures and the mechanical characteristics of the invaded rocks. A glance at the geological map (Plate I) suffices to show that this enormous igneous sheet, widening westwards in the Donkerhoek region to 30 miles, is largely concordant.

At first it follows the general NNE to NE strike of the Khomas schists. On encountering the dome structures around Waldau, it leaves these intact to insert itself into the overlying fissile Khomas schists, which it disrupts in tongue-like fashion. It then swings round the western flanks of the Waldau ridge dome, sending a narrow tongue deep into the Khomas schists along its southwestern flanks. The small, highly aplitic body of Klein Barmen no doubt merely represents a roof protuberance through upwarped schists, separated from the large mass of granite around Onjossa by a narrow belt of schists intensely seamed with concordant pegmatites, while at the same time the granite is crowded with conformable schist xenoliths. The abrupt change in strike of the invaded schists in this area is noteworthy; it soon reverts, however, to the regional NE to ENE strike (Geol. Map, Plate I).
In the south, the Lievenberg dome is once more left intact, the granite inserting itself in narrow sheets between the overlying rocks. A long tongue of highly aplitic granite extends deep into the Khomas schists, accompanied by swarms of pegmatites. The Kaliombo marble ridge, in the north, is also left intact, as are also the domes and brachyanticlines farther to the south. Between the Otjua brachyanticline and Lievenberg dome, the granite is crowded with large and small xenoliths of Khomas schists, only a few of which are shown on the map. Around the latter dome itself much of what is designated as granite is actually closely interleaved “mixed rock”, as is frequently the case also on Sneyrivier, where again only a few of the schist xenoliths are shown on the map.

Westwards, beyond the confines of the geological map (Plate I), the gradually widening sheet of granite continues in the same fashion. Along its northwestern margin it skirts a string of upfolds (brachyanticlines and domes), usually leaving a narrow strip of schists between itself and the rocks of the Marble (Hakos) Series. Nowhere, however, does it break through into the gaps between individual upfolds, thus conforming only to the wider tectonic structure and transgressing its detail (14–16, 31).

After surmounting the obstacles of the Waldau, Waldau ridge, and Lievenberg domes, the southeastern margin of the granite sheet, below the escarpment of the Khomas Highlands, closely follows the regular NE to ENE strike of the steeply northward dipping schists. Viewed superficially the contact appears to be remarkably rectilinear. In detail, however, there are indentations where tongues of granite invade the schists, accompanied by vast swarms of pegmatite. The representation on the geological map immediately south of Otjimbingwe is very schematic; actually there is a broad contact-zone, up to several miles wide, in which the marginal granite is crowded with strips of schists and the main body of the latter laced with innumerable pegmatites.

At Donkerhoek, below the northwestern corner of the Khomas Highlands some 35 miles to the southwest of Otjimbingwe, the contact, highly indented by tongues of granite, after an initial westward turn swings into a south-southwesterly and then southerly direction, in conformity with the sediments of the Damara orogen in this region. Isolated outcrops within the sand- and rubble-covered Tinkas Flats of the interior Namib desert indicate the width of the sheet to be still very considerable in this region. In the Donkerhoek mountains the schists can be seen to finger out in the granite; southwards the contact is in part transgressive, but over large stretches also concordant (Maps accompanying 15 and 16).

Returning to the area under detailed description, it is striking to note how this intrusive sheet of granite, after the initial rectilinear, concordant contact to the north and northeast of Okahandja, swings around the upfolded dome structures, inserting itself between the resistant rocks of the Marble (Hakos) Series and overlying fissile schists. Each inward bend and tongue of granite is projected into the schists by vast swarms of concordant pegmatites, often extending for many miles in the same line of strike (Geol. Map, Plate I, and Air Photo (19). The whole structural configuration is that of fissile schists being “opened up” by the upward push of intruding granite. The small “enclosed” body at Klein Barmen probably represents, as already stated, a protuberance (cupola) in the roof of the granite. The intense metamorphism of the rocks immediately to the east, on Rüdenau and Gross Barmen, with their spectacular development of sillimanite orbicules and large porphyroblasts of andalusite and staurolite, cannot be explained solely by the
profusion of pegmatites. These are even more profuse around Tugab and along extensive stretches of the contact towards Otimbingwe and beyond, where no such striking intense porphyroblastic development of these minerals is to be seen. The general and detailed picture suggests an eastward continuation of the Klein Barmen cupola at relatively shallow depth. Whilst the granite margin farther to the southwest is a steeply dipping “wall-contact”, the particularly intensely metamorphosed rocks on Rüdenau and Gross Barmen probably represent the roof of an eastward plunging concealed offshoot of the main granite mass (Section, Plate II).

The fact that the domes and brachy-anticlines play such a dominant rôle in the configuration of the injected granite [definitely admitted to be intrusive (allochthonous) also by Smith (31), suggests its emplacement to have taken place subsequent to the formation of these structures. The Donkerhoek granite is thus most likely very late-tectonic. It will be shown in a subsequent chapter that the shearing movements responsible for the striking development of intense fracture-cleavage in the surroundings of the Hot Springs on Gross Barmen proceeded pari passu with the formation of andalusite porphyroblasts and that the emplacement of the granite itself most likely was responsible for these structural features.

2. Petrography.

By far the most dominant rock of this great intrusive sheet is a medium-grained, light grey leucocratic granite that often, particularly marginally and in offshoots, is markedly aplitic. To the north of Donkerhoek in the far west, where this granite builds imposing domical mountains, the granite, though of medium grain, is extremely poor in femic minerals and almost white in colour; hence the name Witwater Berge.

Reddish granites, apparently forming part of the Donkerhoek sheet, outcrop over an extensive tract around Okasise Station. Similar granite is also found along the road between Okahandja and Waldau Station. The bright red aplitic granite building the conspicuous Rote Klippen and the very prominent Kegelberg to the south-southwest of Okasise probably also belongs to this massif. Though very reminiscent of the red aplitic granite generated from Chuos (Etusis) arkoses and felspathic quartzites within the dome structures, as already described, their outcrops are rather too remote from both Okandura and Waldau ridge domes for this derivation to be assumed. Pale red aplitic granites are widespread around the Okandu Thermal Spring, where they undoubtedly are a phase of the Donkerhoek granite mass.

Microcline, with subordinate microperthite, is the characteristic felspar. In aplitic varieties granophyric intergrowth of microcline and quartz is not uncommon. Sodic plagioclase is normally quite subordinate. Red almandite garnet is often scattered throughout the rock. In typical specimens biotite is only sparingly present. In many instances muscovite exceeds the latter. However, where intermingled with abundant xenoliths of biotite schist or where interleaved with the latter rock, biotite is often quite conspicuous and may even be abundant. Such contaminated biotitic varieties are frequently of coarser grain and may develop a semiporphyritic and even porphyritic texture, e.g. southwest of Onjossa in the neighbourhood of the extensive N-S striking xenolith of biotite schist shown on the map (Plate I). Such porphyritic types, here obviously due to incorporation of biotite schists with microcline porphyroblasts, are strongly reminiscent of the Salem granite for which Smith, in the majority of cases rightly, claims largely isochemical transformation origin (31, pp.76-81, and 101-107).
Interesting features of a similar kind are well exposed along the Swakop River immediately to the southwest of the Lievenberg dome. Here there occur quite extensive outcrops of a coarsely porphyritic, grey granite containing absolutely idiomorphic crystals of potash felspar, up to 4 inches long, embedded, more sparingly than normally is the case in typical Salem granite, in a medium- to fine-grained felspar-quartz matrix with fairly abundant biotite. The felspar phenocrysts are unusually perfect in shape and not rarely twinned (Carlsbad); some exhibit macroscopic zoning with small biotite flakes along zone boundaries. This beautiful rock is cut by isolated dykes of pink to pale red aplitic and pegmatitic granite.

Its outcrop area is surrounded by a zone of "mixed rock" composed of knotted schists interleaved with reddish and light grey aplitic and pegmatitic granite. Dent de cheval porphyroblasts of potash felspar increase in abundance and size with intensity of injection, finally to merge into a porphyritic biotite granite identical with that just described except for a somewhat smaller size of the felspar porphyroblasts. There is thus no doubt that this Salem-type granite along the contact of the normally leucocratic, non-porphyritic, Donkerhoek granite was developed in situ not purely isochemically, but by the addition of granitic material to engulfed biotite schists.

E. Pegmatites

The myriads of pegmatites associated with the Donkerhoek granite, depicted only schematically on the geological map (Plate I), vary in size from bodies more than a mile long and several hundred feet wide down to narrow stringers. With few exceptions, e.g. one massive and several neighbouring smaller bodies oriented at right angles to the strike of the Khomas schists on Rüdenau, the pegmatites occurring within the latter are all concordant.

Only one pegmatite, not far from the homestead on Tugab, was temporarily worked for beryl. The rest, as far as now known, are all barren of economic minerals. They are composed of microcline and microcline-perthite, varying quantities of albite, quartz, and variable, locally conspicuous, amounts of muscovite, black schorl tourmaline, and red almandite garnet. In the main swarm of pegmatites north of the Swakop River, on Rüdenau and Gross Garmen, schorl is often very abundant.

The economic pegmatites, carrying lithium minerals, beryl, columbite-tantalite, etc., in the northwestern area of the map and beyond, all occur in proximity to reddish, often pegmatic, granites surrounding the Ombujomenge dome, filled largely with pegmatitic granite as already described. Becker's pegmatite on Otjua is immediately adjacent to this dome within its fringing crystalline limestone girdle. Also Berger's and Brockmann's pegmatites on Kalimo and Albrechtshöhe, as well as the Karlsbrunn and Helicon I and II pegmatites, are located in marbles, close to or not far from outcrops of this late-stage type of granite. The great Rubicon pegmatite forms the base of a small body of reddish pegmatitic granite injected into dioritic rocks not far above the Marble horizon. The mineralised, zoned portion grades upwards into very coarse pegmatitic rock composed largely of euhedral crystals of microcline-perthite embedded in an albite-rich matrix (29). The columbite-tantalite-microline-rich Dernburg pegmatite, west of Karibib, is located at a lower level, within Chaos (Etusis) quartzites. Also Brockmann's beryl-rich pegmatite 40 miles to the southsouthwest, on Tsaboismund, is situated in rocks of the same group within a dome structure.
It is significant that all of these well-zoned, mineralised pegmatites are located in rocks belonging to stratigraphic levels below the Donkerhoek granite sheet. It would seem, therefore, that they, together with their smallish parent pegmatitic granites, although also late-stage, belong to a deeper level than the Donkerhoek granite and associated swarms of unzoned, non-mineralised pegmatites. It is not suggested that all of the materials of the mineralised pegmatites around Karibib were derived from the metasediments of the Ckl-tos (Nosib) Series. It is quite clear, as emphasised by Roering and Gevers (29), that these pegmatites bear no readily ascertainable chemical and mineralogical relationship to their wall-rocks. Detailed geochemical investigations (minor and trace-element distribution) were unfortunately not possible. It is merely pointed out at this stage that the two groups of pegmatites appear to have crystallised at different depth levels.

Smith (31, p.107) has suggested that the quartzo-felspathic material of the pegmatites emplaced in the roof zone of dome structures need not necessarily have been derived from great distances. He also pointed out that the very resistant marble cover may have exerted a ‘damming up’ action on volatiles, thus promoting not only coarse crystallisation but also the concentration of normally more widely disseminated elements.

It is possibly also significant that the majority of these lithium- and beryl-bearing pegmatites are located not far from, frequently close to, the northwestern margin of the vast Donkerhoek granite sheet. Both were intruded late in the tectonic history of the Damara geosyncline. Possibly the emplacement of such a vast mass of granite helped to raise the thermal gradient in its stratigraphic floor sufficiently for ultrametamorphic and magmatic processes to be once more stimulated. Unfortunately no direct evidence concerning the precise age-relationship of the two types of granite could be ascertained in the field.

F. Sillimanite-bearing Aplites

It was already mentioned that in the central portion of Gross Barmen and adjacent Rüdenau there occur within Khomas schists numerous very white, fine-grained, concordant sheets, from one to several feet in width, often crowded with orbicules of sillimanite and quartz of the size of golf balls. At first taken to be sheared aplites, microscopic investigation showed that in many instances the felspar content is too low for such an origin, even allowing for much of the felspar to have been transformed into sillimanite. They were hence finally identified as felspathic quartzites, interbedded with biotite schists, of the kind, also containing sillimanite, that around the Waldau ridge dome can frequently be seen to grade into the adjacent schists.

To confuse the issue, two up to 10 feet thick bodies of this nature can quite clearly be seen on the steep cliffs of the Gross Waldau River, a few hundred yards to the north of the main swarm, to cut across the dip of the biotite schists. At least these bodies must therefore represent intrusive sheets of sugary aplite. Their sillimanite content as well as highly sheared nature, features absent in the late tectonic intrusive pegmatites and aplites of this region, indicate an earlier stage of injection prior to the last intense phases of tectonism.

G. Kaoko (Karroo) Dolerites

Though not present in profusion as in the area farther west, particularly in the elongation of the great post-Karroo Waterberg fault (6, 14, 18, 31), dykes of this
rock are nevertheless not rare. Usually they cut across the strike of the Khomas schists. Only two very thick dykes, striking N-S to NNE-SSW and both transecting Donkerhoek granite, are shown on the map (Plate I) on Sneyrivier and to the northeast of Otjimbingwe. The rather massive dyke along the southern banks of the Swakop River on Ravensberg, as well as the narrower dykes in the southern portion of Gross Barmen and in the vicinity of the Klein Barmen and Okandu thermal springs, have already been mentioned in the previous paper (19).

Under the microscope they show the usual ophitic texture of calcic plagioclase and augite; olivine is present in some. Roughly 6-7 miles southwest of the Onjossa farmhouse a several hundred yards thick body of basic rock, containing considerable amounts of olivine, has been injected into the northeastern fringe of the Otjua brachyanticline between Donkerhoek granite and para-amphibolites and amphibole-pyroxene granulites of the Marble (Hakos) Series.

The nearest large body of intrusive late Kaoko (lowermost Jurassic) basic rock occurs some 25 miles to the north of Gross Barmen in the Omibutosu hills. The nearest outcrops of basic Kaoko lavas (Jungfrau and Sargdeckel) are located on Okongava Ost, 3-4 miles west of the northwestern boundary of the map (Plate I). Some at least of these dykes therefore probably represent feeding fissures for a now eroded eastward extension of these lavas.

VIII. TECTONICS
A. General Tectonic Pattern

On several previous occasions the writer has drawn attention to the striking difference in tectonic style between the Khomas Highlands and the regions adjoining it on both sides (12,13,16,17). The Khomas and Windhoek Highlands represent a tightly folded, 80-60 miles wide, synclinorium within which a monotonous succession of dark garnetiferous biotite schists and biotitic quartz schists (meta-greywackes) strikes between NE-SW and ENE-WSW and dips NW to NNW with equal regularity and persistence. The folding is largely isoclinal; owing to uniformity of rock types, details are difficult to make out. Photo 6, Plate V, represents one of the few instances where such can be seen.

Apart from isolated sheets of intrusive, possibly also extrusive, ortho-amphibolite in the southern portion of the Highlands, igneous rocks are entirely absent. There are no granites and related rocks; quartz veins, however, are ubiquitous.

Both to the northwest and the southeast the tectonic pattern is radically different, being characterised by highly complex folding, as well as, in the northwest, by a host of granites and subordiuate, only local, dioritic rocks.

The structurally diversified belt along the southeastern margin of the Damara geosyncline is comparatively narrow, being only some 30 miles wide. Recent unpublished work by Martin and Schalk appears to have shown that gneisses and granites assigned by Gevers to post-Damara magmatism (13), are largely pre-Damara in age, though extensively re-mobilised during the Damara orogeny.

Within the more interior portion of the orogen, to the northwest of the Khomas Highlands, the Damara sediments are intimately mingled with a profusion of gneisses and granites, partly autochthonous and formed by granitisation processes in the manner already described, and partly intrusive.

Though a general tectonic trend between NE-SW and ENE-WSW, parallel to the regular isoclinal folding in the Khomas Highlands, is still evident, folds very frequently deviate from it to a marked extent. The extremely regular design of the
Khomas Highlands is replaced by a pattern of brachyanticlines and domes, exposing the lower members of the Damara System and to the southwest of Karibib even the floor of older rocks (Abbabis metasediments, metalavas, and gneisses). While extremely irregular, the closed upfold (antiform) structures are not uncommonly strung out along the general NE-SW trend, as commented on also by Smith (31).

The geological map (Plate I) demonstrates the two highly divergent patterns particularly clearly. The dip signs along the margin of the Khomas Highlands have been purposely inserted in such profusion to draw attention to the extremely regular strike and dip of the biotite schists and biotitic quartz schists (metagreywackes) that build up this mountainous tract. The striking change of tectonic style comes in suddenly, as indicated by the Lievenberg and Waldau ridge domes and the small, distorted upfold northeast of the latter, which are all strung out parallel to the strike of the schists, still in contact with the latter in the northeast but already detached by the Donkerhoek granite in the southwest. The Waldau dome is already more distant from the edge of the schists; its NE-SW elongation is apparent. Also the several brachyanticlines and domes in the northwestern portion of the map show clear elongation in the general NE-SW tectonic trend, though the Kaliombo ridge anticline strikes E-W in its central section.

Under the impression that all granites were syntectonically intrusive, and therefore mostly concordant, Gevers and Frommurze likened the pattern in northwestern Damaraland to “a skeletal framework of sediments, the interstices between which are filled by granitic magma” (6, pp.50-52). The newer concepts first put forward by Smith (31, 32) and substantiated in the present paper, which regard a large portion, if not the majority, of granites as of stratigraphically determined transformation origin, invalidate this simile, except for the large Donkerhoek granite sheet.

To explain the pattern of brachyanticlines and -synclines and domes and basins, whose cores and troughs are filled with granite, and the frequent “meandering” of marble bands separating granite “phacoliths”, as well as the frequent “bewildering” irregularity of the folds, Gevers and Frommurze assumed the operation of multilateral stresses (6, pp.50-52.) Though subjected to a dominant stress from the SW, as indicated by the frequent overfolding to the NW in northwestern Damaraland, “the sediments were not entirely free to yield laterally, but experienced considerable resistance also at right angles to the dominant stress” (6, p.50).

This greatly oversimplified explanation was modified in 1935 by H. Cloos (2) on the basis of the maps previously published by Gevers and Frommurze. He made the following points. “The more the irregularly distributed plutons recede, the more undisturbed and regular becomes the folding. Along the Ugab, northwest of the Brandberg, as well as elsewhere outside the region depicted by the maps, the type of folding in its primary features resembles that of the Appalachians and “Schiefergebirge” (slate mountains) of the Rhineland. The folds are long and parallel. Their axes rise and fall gently”. “With increasing participation of syntectonic plutons, however, the anticlines and synclines become shortened along their strike. Their slender, pointed ends become broader and steeper, move closer together, and the dominant fold trend is more and more modified by oblique and transverse folds; the pattern of elongate folds passes over into one of domes.”

Cloos went on to stress that the latter pattern exhibits the “highest possible degree of concordance of plutons and their sedimentary environment”. His observation that the granites preferentially emplaced themselves in the cores of brachy-
anticlines and domes, more rarely in the troughs of synclines, but are also met with in all horizons of the rock-succession, however, does not fit the facts as outlined in the previous chapter.

Cloos concluded that "we are dealing with a type of folding in which magmatic melts participate equally with the sedimentary framework which guides the movement and emplacement of the magma". In this "mixed" pattern the vertical stress component, indicated also in the more normal fold pattern by axial culminations and depressions, comes into increasingly active operation proportional to the amount of magma involved, while the horizontal stress component proportionately recedes and cross-folding becomes more and more conspicuous. Cloos regarded this type of tectonic pattern as "proof of the provision of space for the plutons on a purely tectonic basis, practically without assimilation or mechanical removal of pre-existing rocks". He considered the level of formation of the dome cum pluton pattern to be intermediate between an upper level of normal folding, without magmatic injection, in which the lateral stress-component dominates, and a very deep level in which plutonic activity is completely dominant. He finally used his deductions as arguments against lateral compression (shrinkage of earth and continental drift) as the primary cause of orogenesis and in support of Ampferer's "Unterstromungstheorie", i.e. lateral drag by magmatic flow.

On the basis of detailed mapping and analysis of minor structures, according to the techniques evolved by Ramsay and others, in the Khan Canyon region, Smith recently came to the conclusion that the Damara orogeny was marked by at least two major phases of folding (31 and 32). The first phase produced well-defined folds trending NW-SE, locally isoclinal and overturned to the SW. Early metamorphism of amphibolite facies grade is attributed to initial deep burial of the sediments and to this early tectonism which was of considerable intensity. The second, stronger phase, directed from the southeast and northwest, produced NE-SW fold trends and almost obliterated the earlier folds, altering their shapes substantially and leaving only local areas relatively unaffected. Metamorphism continued during this later phase. The formation, by granitisation of suitable sediments (Chuos-Etusis arkoses and felspathic quartzites below the Marble (Hakos) horizon and Khomas schists above the latter), of "vast bodies of gneiss, the foliation of which conforms to this fold movement, must have begun during this phase, as is shown by porphyroblast orientation of many of the gneisses." "Metamorphism and granitisation, resulting in the production of magma locally, continued after the second phase of folding died out. This is evident from the abundant development of porphyroblasts in suitable rock types which show little or no orientation due to crystallisation under conditions of no directed stress." This feature is conspicuous in all intrusive granites. A third, very weak fold phase, for which evidence is claimed to exist in the Khan Mine area, may have occurred during the final and strongest phase of metamorphism (31, p.57 and 58).

A more detailed structural analysis, based on the same techniques, by Roering of the deformation of crystalline limestones and associated rocks in the Albrechtschôhe-Kaliombo area (northwest portion of Geol. Map, Plate I), some 80-90 miles to the northeast of the area examined by Smith, gave somewhat similar results. The first period of folding was about axes trending WNW-ESE and in places gave rise to isoclinal folds; a second phase produced N-S trending structures. A minor third phase can be deduced from "rather weak" evidence. Roering is careful to state that "without more detailed knowledge of the regional geology it is impossible to de-
termine whether these three phases of folding are part of one act or are related to definitely different ages of folding.” (28, pp.24-26).

The emplacement of zoned, mineralised pegmatites in the neighbourhood of Karlsbrunn (northwestern portion of Geol, Map, Plate I) is closely related to the stress-field of a wrench-fault that displaces the folds. Roering found that in general the mineralised pegmatites of this area were emplaced along zones of tension that post-date the folding (28, pp.26-27). The late-stage nature of the mineralised pegmatites and their smallish parent bodies of generally pegmatitic granite, already commented on in the previous chapter, is thus well documented. The observations of Smith also support the comparatively late-stage emplacement of the great Donkerhoek granite sheet.

The rather divergent trends of the two major phases of folding ascertained by Smith and Roering in two small portions of the great Damara orogen serve to show that local conditions cannot be generalised. The orogen itself is by no means a simple one. It is true that its approximately 230 miles wide branch that trends more or less NE-SW through central South West Africa is comparatively rectilinear; but on nearing the Atlantic the folds in the north (Kaokoveld) swing into parallelism with the NNW trending coast-line. In the area of the Tinkas flats, west of Donkerhoek, the maps of Gevers (15, 16) quite clearly show the beginnings of a swing to the southwest. South of the Kuiseb River, below the great escarpment, the folds have turned even more south. The vast sea of sand dunes that characterises the Namib Desert south of the Kuiseb then completely buries solid rock. But a flight by the writer over the coastal Namib and a journey by jeep through Diamond Area No.2 demonstrated quite clearly that in the White Mountain west of Sossus Vley, and in the rock outcrops at Sylvia Hill, Spencer Bay and Saddle Hill, north of Lüderitz, the tectonic trend of rocks, very probably belonging to the Damara System, is strictly parallel to the coast, viz. NNW-SSE. Martin has already depicted these features on his provisional tectonic map of South West Africa (24).

It is obvious that in such an orogen, showing a practically right angle virgation, both north and south, in the coastal region, the stress-field must have been variable not only in space, but also in time. World-wide investigations have quite clearly demonstrated that, contrary to the rigid pigeon-holing time-scheme of Stille, not only the development of great geosynclines but also their subsequent deformation are very complex and proceed in diverse stages over considerable periods of time. The time and intensity of individual pulses of deformation may vary widely from place to place.

The importance and frequent strong local influence of the geosynclinal foundation has been conclusively demonstrated in many orogens throughout the world. Geanticlinal swells differentiating the Tethys geosyncline of the Mediterranean region into a number of separate basins of deposition are the very backbone of the Alpine nappe-structure. In reply to Haughton, Martin has already drawn attention to the geanticlinal ridge separating the Damara eugeosyncline in the north from the Otavi miogeosyncline. The Okatjira anticline, projecting into the eugeosyncline, appears to represent a spur of the main geanticlinal ridge (24, p.95).

A considerable body of sedimentological evidence suggests the existence of a median geanticline in the Karibib region. It represents the only known outcrop within the great eugeosyncline of the pre-Damara foundation, the metasediments, metalavas, and gneisses of the Abbabis System. It may hence be referred to as the Abbabis swell. Massive conglomerates and arkoses at the base of the Chuos (Nosib)
Series occur in greatest distribution and thickness along the flanks of this tectonic "window". The only comparable development of such coarse, basal, rudaceous rocks, known to the author, is along the southern margin of the geosyncline to the south of Windhoek. Northwards of the Abbabis swell the entire thickness of arenaceous *Chuos* (*Etusis*) sediments appears to decrease rapidly, there being no outcrops in the cores of marble anticlines between the Kudukuppe, a few miles north of Usakos, and the northernmost boundary of the area so far mapped in detail towards the Ugab River (5, 18). The psammitic rocks appear to be replaced by semipelitic and pelitic sediments. Quartzites and conglomerates, however, reappear along the northern margin of the *Damara* eugeosyncline in the area of Fransfontein. They are also widely distributed at the base of the miogeosynclinal *Otavi System* (*Nosib Formation*) (33).

Westwards the reddish *Chuos* (*Etusis*) quartzites thin very greatly or even disappear, to be replaced by the calcareous sands (quartzose calc-granulites) and interbedded clayey sands (biotite-quartz schists) of the *Khan* facies. The latter continues also far to the southwest, though locally thick quartzites are still present along the Swakop River as far south as the northern edge of the Tinkas Flats, west of Donkerhoek.

Pure crystalline limestones are particularly well developed in the Karibib area, decreasing in purity and thickness towards the west, south, and east. The purer forms of dolomitic limestone quite probably may represent shallow-water deposits in the formation of which algae took a part, as already suggested by Smith (31, p.60). Such pure dolomitic limestones often fringe shore lines where the water is clear. At this stage the *Abbabis swell* must already have been submerged below shallow water far from the margins of the geosynclinal basin.

The isolated outcrops, projecting through Kalahari sand, of thick, in part coarse and felspathic, quartzites and rather pure marbles with which manganese ores and itabrite schists are interbedded at Otjosondu, northeast of Okahandja, may represent an eastward prolongation of the *Abbabis swell*, perhaps another axial culmination of the latter. A geanticlinal ridge in this area is all the more likely since Roper claims that some of the gneisses there are definitely of pre-*Damara* age (30, p.20).

In an orogen virgating both north and south in the coastal area, practically at right angles to its inland branch, stress conditions must have been extremely complex. If movements in both coastal and inland sections were contemporaneous, these must have been very involved indeed. If the main movements, or at least a major pulse, in the coastal branch preceded the main deformation of the inland branch, it would not be surprising to find its effects in the latter most marked towards the Atlantic. The fact that in the Khan Canyon region, only some 30 miles distant from the coast, Smith found evidence for a well-marked initial phase of folding trending NW-SE can perhaps be used as evidence for orogenic deformation having begun first in the coastal branch of the *Damara* geosyncline and that the main movements in the inland branch began at a later stage. Roering's evidence in the Karibib area, much farther inland, of an initial phase of folding trending WNW-ESE, if taken at its face value, already represents a southward rotation of the coastal trend. It should be noted that Smith's Khan Canyon area is already to the west of where, in the south, the fold-trends swing southwest and southwards and, in the north, northwest and north northwestwards. It is of interest that the fold trends depicted on Martin's generalized tectonic map of South West Africa (24)
to the north and northwest of the Brandberg indicate something akin to the oblique folds of the Cape Fold syntaxis, where the E-W trending folds swing sharply into a NNW direction.

While Smith's structural analysis of the Khan Canyon area is no doubt correct for that locality, it seems to the writer completely unlikely that his explanation of the brachyanticline and dome structures as being largely due to successive tectonic phases of radically differing trend, viz, cross-folding, can receive general application throughout the geosyncline. It would be necessary to envisage the NW folds produced by the first major phase to extend right up the entire exposed length of the inland branch of the orogen, for several hundred miles, at right angles to its margins, like tidal waves running up a river estuary. This does not appear likely.

Martin, in a private communication to Roering, has already drawn attention to the fact that all fold-belts show plunging folds; and that the explanation of their being due to a subsequent phase of folding, produced by stresses at right angles to the initial one, is in most cases wrong. Laboratory experiments simulating natural conditions have shown axial plunges already to appear in the initial stages of folding and to become progressively more pronounced with increasing compression. Under conditions of high metamorphism and a consequent high degree of plasticity not only vertical, but even overturned fold axes can be produced. "Such cogenetic cross-structures have recently (1960) been described by Saggerson et al. from the Basement System of Kenya. They are characteristic of most highly metamorphosed areas. Where the metamorphism became high enough to produce granitisation, this deformation may become intensified to such an extent that some of the larger anticlines (domes) became diapirs." (28, pp.30-31.)

In the same communication Martin points to the frequently marked effect on fold trends and patterns produced by basement structure and cites examples both from the northern and the southern margins of the Damara geosyncline. He concludes that the sequence of differently oriented deformations, established by Roering's detailed analysis of the area immediately to the east of Karibib, was not caused by changes in the direction of the regional stresses, but are due to a purely local stress field. With this the present writer wholeheartedly agrees.

Regarding the late tectonic* intrusion of the mineralised pegmatites along tension-fractures, Martin advances the following possibility. "In the development of an orogenic belt the cessation of the folding stresses is, as a rule, followed by the beginning of 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 available. 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." (28, p.32).

In the writer's opinion the intrusion of pegmatites and their parent granites need not be delayed as late as final isostatic uplift of an orogen. Their injection in the general area under review is far too much structurally controlled to envisage a state of universal tension. This is particularly true in the case of the great Donker*

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* Martin uses the term post-kinematic. The terms tectonic and kinematic are used more or less as synonyms by many authors. It has recently been suggested, however, that the term kinematic should be reserved for metamorphic processes in orogens. Since folding and metamorphism are so often closely related, the two terms are in fact frequently synonymous. If, however, differentiation is made between orogenic processes at different depth levels, e.g. within supra- and infrastructures, they cease to be synonymous, if the term kinematic is restricted to processes of metamorphism.
hoek granite sheet which, although also late-tectonic, is of enormous size; the dis­tribution of its vast swarms of pegmatites clearly indicates the “opening up” of the fissile Khomas schists, i.e. tension produced in the roof and along the flanks by the upward push, viz. doming effect, of the granite magma itself. All that appears to be necessary is a state of sufficient rigidity in the neighbouring rocks to respond to the local stress-field by “cracking up” in zones of tension.

After the introduction of detailed mapping and statistical analysis of minor structures, cross-folding has come in for much discussion. Reference should be made to De Sitter’s summary of the 1960 symposium on this specific feature (4, pp.195-197). In some of the papers presented, the variation of trends, e.g. in the “Schiefergebirge” of the Rhineland and in the Pyrenees, is attributed to local developments in a constant stress-field. In others, some cross-folds are regarded as contemporaneous and others as due to a secondary stress-field derived from the main one. Elsewhere, as done by Smith for the Khan Canyon region, successive separate stress impulses belonging to one and the same orogeny are invoked. The deformation of long antecedent structures by very much later orogenic movements is not at issue in this connection.

De Sitter concludes: “Much work has still to be done in order to arrive at a better understanding of the interaction between the infra-structure and the supra-structure, between the stress-field and the metamorphosing factors. The relative intensities of the successive tectonic and metamorphic phases determine the final shape and character of an orogen, but we have still to learn how to determine and formulate this relationship satisfactorily.” “An attempt to summarise the evidence presented . . . would point out that in a complete orogen with a well-developed syntectonic regional metamorphism, non-metamorphic border-zones must be distinguished from a central metamorphic complex on the one hand, and a supra-structure from an infra-structure on the other. In the central infra-structure cross-folding accompanies the gradual development of the regional metamorphic stages from synkinematic to granitisation. In the border-zones a precursory phase of simple folding is followed by cleavage-folding in at least two stages. Vertical movements possibly connected with the granitisation phase, in some cases leading to migmatitic doming, are clearly demonstrated by tilting of the cleavage in the border-zones. The final stage . . . seems to be a dilatation phase with knick zones in the border-zones, probably followed or accompanied by faulting, further vertical movements and an intrusive magmatic phase” (4, p.197).

De Sitter considers it reasonable to suppose that the intermediate stage of cross-folding in the infra-structure had its repercussions in cross-folding also in the supra-structure. His general scheme is summarised in the following table (4, p.196).

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| **Initial Stage** | Supra-structure  
| Folding and vertical axial-plane cleavage. | Infra-structure  
| Synkinematic regional metamorphism, horizontal schistosity, b-axis crystal growth. |
| **Intermediate Stage** | Parallel folding and several kinds of cross-folding; fracture-cleavage.  
| Late kinematic parallel folding and symmetric cross-folding; granitisation. |
| **Final Stage** | Dilatation. knick zones. faults. granite intrusion.  
| Rheomorphism. granite sheet intrusion. granite plutons. |
From the preceding discussion it is obvious that the region to the northwest of the Khomas Highlands, as depicted on the geological map (Plate I), is a typically developed infra-structure. All characteristics listed by De Sitter are well represented. Although the early (1928) explanation by Gevers and Frommurze of the brachyanticlines and dome structures being due to multilateral stresses, in retrospect appears rather naive, it nevertheless, through the implied confinement of plastic rocks at the relevant depth level, indirectly emphasises an active vertical component in the stress-field. Further, in spite of the fact that the mainstay of Cloos’ deductions, viz. molten magma, must now be largely replaced by plastic granitised material formed in two main stratigraphic horizons below and above the rocks of the Marble (Hakos) Series, his general concept of the vertical component of the general stress-field increasing in effectiveness with depth and with the degree of plasticity and mobility of transformed material, still remains valid. This is implicit in Martin’s emphasis on the relationship between degree of metamorphism and extent of granitisation, and the steepness of plunge of elongate folds grading gradually into more and more shortened structures and finally diapiric domes.

Had successive phases of folding, as suggested by Smith, been the major factor involved, evidence for marked cross-folding should be found also in the immediately adjacent, incompetent schists of the Khomas Highlands. No detailed structural investigation of the latter has as yet been carried out; but a glance at the map (Plate I) suffices to show that south of Otjimbingwe and the Lievenberg there is no such evidence, unless the slight and, if one wishes to call it that, broad undulatory bending of the margin of the Khomas schists around the Lievenberg dome be interpreted in this way. It is also true that the crystalline limestones, para-amphibolites and amphibole-pyroxene granulites, as well as intercalated schists, of the Upper Marble horizon bend into the gap between the Waldau ridge dome and the small eastward distorted upfold. This, however, would be a normal consequence of dome formation. In any case, within a mile or two upwards into the Khomas schists, the latter, standing vertical, run practically dead straight ENE-WSW for many miles and maintain this rectilinearity also south of the Swakop, with gradually flattening dip, right across the Khomas Highlands.

In this particular area there is no intervening granite and, as will be shown presently, the rectilinear, isoclinal folds of the Khomas Highlands are separated from the region of dome structures merely by a 2 miles wide belt of irregular, more open folding, in places showing enormous contortion in the horizontal plane. The frequently radically different fold-pattern of infra- and supra-structure, of course, immediately comes to mind; but this is no way of escape from Smith’s assumption of the general presence of successive fold phases, affecting both deep and shallow levels of the orogen.

Final conclusions must be withheld until detailed mapping and analysis of minor structures has been carried out, or at least attempted, in the monotonous, poorly differentiated, schistose rocks of the Khomas Highlands.

B. THE NORTHWESTERN MARGIN OF THE KHOMAS HIGHLANDS

The radically different fold-pattern of infra- and supra-structure in any orogen obviously implies differential movements in a zone of mobility or of shearing between the two, depending on the degree of plasticity and rigidity of the lower portion of the supra-structure. For the margin of the Khomas Highlands west of
Klein Barmen the emplacement of the wide sheet of Donkerhoek granite would offer a ready means for the accommodation of differential movements.

That this granite, in the main, actually does represent intrusive magma is indicated by the marginal, often deep, injection of *highly aplitic* granite tongues into the adjacent schists. Also the vast swarms of pegmatites, often in direct linear projection of such intruding tongues, definitely represent injected material whose boundaries against the invaded schists are strikingly sharp. Though in the vast majority of cases strictly concordant, several thick cross-cutting pegmatites also occur. Although the elongation of this granite sheet is largely concordant, definitely cross-cutting contacts occur over long sections, particularly where, in the far west, the granite, together with the folded Damara sediments, swings into a southwesterly trend. In the Donkerhoek mountains, where the granite, as already noted, is particularly highly aplitic, long strips of schists finger out into the granite, many eventually to be cut off across their strike. Finally, any transformationist view would have to show how a mostly highly aplitic granite, often composed to over 99% of potash felspar, with quite subordinate sodic, and quartz, could be derived isochemically, or with the addition of *normal* amounts of K and SiO₂, from pelitic or even semi-pelitic sediments. The usually marked dearth of biotite has already been stressed in this connection.

While this large mass of granite, extending along the entire northwestern margin of the Khomas Highlands, could easily have accommodated, when still liquid or mushy, differential movements between the two radically different patterns of tectonic deformation, it has already been shown that the dome structures bordering or engulfed by it must already have been in existence at the time of its intrusion, though probably further deformed and modified at this stage and possibly also by still later phases of orogenic development. The general lack of deformation of the component minerals, however, indicate the Donkerhoek granite to have been emplaced at a very late stage.

De Sitter states (3, p.195) that in the Pyrenees the zone separating the two structural units (infra- and supra-structure) "is determined in the first place by the metamorphic front but may be influenced by the lithology of the strata. Where the metamorphism rose very high, to the top of the Cambro-Ordovician, the incompetent black shale horizon of the Silurian became the separating horizon. But when it stopped lower down in the little differentiated rock sequence of the upper thousand metres of the Cambro-Ordovician, then the separating zone is independent of the lithology and strongly discordant to the stratigraphy."

Before proceeding to the discussion of the tectonic nature of the northwestern margin of the Khomas Highlands and to where in the general orogenic structure the latter belongs, it is as well to summarise briefly the main characteristics of the two juxtaposed structural units.

On the one hand, to the northwest, the fold-pattern is one of brachy-anticlines and domes. Some of the latter, e.g. the Lievenberg dome, are highly symmetrical; others, e.g. the Otjua dome, are complex and distorted. Within the upfolds (antiforms) of this particular region, metamorphism is intense (its degree, however, greatly influenced by lithology) and granitisation widespread; also rheomorphism as well as more extensive mobilisation are much in evidence. Granitisation of Khomas schists to form Salem-type granites, so widespread more deeply into the core of the orogen, is not marked in this particular area, the intrusive Donkerhoek
granite sheet having largely lifted the Khomas schists off and up from the underlying lower Damara sediments.

The general "softening up" of the latter, as well as of residual patches and strips of highly altered schists, is most striking, resulting in a high degree of plasticity of most rock types, both primary and transformed. Plastic flow within the crystalline dolomitic limestones often reaches astonishing proportions. The rocks most resistant to coherent plastic deformation are highly siliceous quartzites and especially the massive para-amphibolites and pyroxene-rich granulites, which in areas of particularly high deformation on the flanks of domes often assume a disrupted pattern of their own, discordant to the intercalated marbles and sillimanite schists or adjacent intrusive granite.

Except on a minor scale involving these particularly competent and unassimilable rocks, faulting is conspicuous by its absence. The Karlsbrunn wrench-fault, described by Roering from the western portion of the Kaliombo limestone ridge, is a very isolated instance and of very late-to post-tectonic age.

On the other hand, in the Khomas Highlands, remarkably regular isoclinal folding is the keynote; and in the northward extension of the Khomas schists, on Rüdenau and Gross Barmen, shearing in more or less rigid rocks, with strikingly developed fracture-cleavage, occurred pari passu with metamorphism, viz. growth of myriads of andalusite porphyroblasts.

In this area the boundary between infra- and supra-structure appears to be a marked shear zone, several hundred yards wide, more or less in direct continuation of the southwestern margin of the Donkerhoek granite sheet. To what extent the schistose rocks of the Khomas Highlands in their entirety belong to the supra-structure cannot be debated here; much more work is still necessary. In the only area so far examined in detail along its northwestern margin, viz. that described in the present paper, many of the features listed by De Sitter in Table I are present, a notable exception being cross-folding, at least on any readily visible scale. Since this particular region obviously represents a boundary-zone between the two units, it is not surprising to find also certain features of the infra-structure, such as bedding-schistosity and b-axis crystal growth, well developed.

The latter two features, as far as orientation of biotite flakes is concerned, as well as meso-grade regional metamorphism, (garnetiferous biotite schists), are characteristic of the entire Khomas and Windhoek Highlands. While no doubt for the most part representing an isoclinally folded deeper portion of the supra-structure, the Khomas Highlands definitely do not represent a border-zone of the Damara orogen. More highly metamorphic rocks, with evidence for mobilisation of the pre-Damara foundation, again outcrop over a 25-30 mile wide belt to the south. Whilst it is true that phyllites and not highly recrystallised limestones are in places already much in evidence in the southernmost belt of the inland branch of the Damara eugeosyncline, many features found here suggest that the infra-structure once more rises to the surface southeastwards of the Khomas Highlands. Folding is once more complex, with the development of brachyanticlines and -synclines, domes and basins. Metamorphism is frequently high, though often rapidly varying in intensity.

A typical border-zone, however, is well-marked along the northern margin of the eugeosyncline, where the more highly metamorphic sediments of the latter grade into the much less altered and tectonically deformed sediments of the Otavi System (Outjo Facies of Damara System). If all the rock groups now considered to
be older than the sediments of the Damara System formed also a southern border-swell, then its northernmost portion must have sunk to sufficient depths during the Damara orogeny to have assumed many features of the infra-structure.

The absence of a well-defined uniform border-zone within the Damara sediments themselves along the southern margin of the Damara orogen, perhaps lends some support to Martin's and Söhne's view that the sediments of the Nama System, whose northernmost outcrop lies some 40 miles to the south of the southernmost outcrops of highly deformed Damara sediments, represent a shallow-water foreland facies of the latter. That their northernmost outcrop area exhibits folds trending parallel to those of the Damara orogen (24), as well as their intense deformation involving nappe structure in the Naukluft region, within the southern virgation arc of the Damara orogen, appear to lend further support for this view. The strong influence of basement "grain" and the structure of closely neighbouring older fold-belts on later deformation of younger sediments cannot, of course, be left out of account in this connection.

It should be noted, however, that there must have existed a closely adjacent upland region subject to erosion along the southeastern margin of the Damara eugeosyncline at least during the initial stages of deposition within the latter. The very thick and coarse conglomerates at the base of the Chuos (Nosib) Series (Kamtsas Member), as well as the fact that the majority of the faceted erratics in the overlying tillite horizon were derived from pre-Damara quartzites outcropping to the south, clearly prove this (13). In a communication to the author Martin points out that, as indicated by stromatolitic and oolitic limestones as well as ripple-marked quartzites, very similar to rocks found in the northeasternmost outcrops of the Nama System farther south, the Marble (Hakos) Series must have transgressed at least parts of the southern borderland as a shallow-water facies. The existence of a well-defined geanticlinal (Rehoboth) swell is indicated, whose general development parallels that of the Abbabis swell and which, with reference to its structural position, is a mirror-image of the Kamanjab inlier within the northern virgation.

The southeastern margin of the Khomas Highlands presents several features strikingly different from the northwestern. Beginning with a medium (40-55°) northwestward dip in the Auas mountains, the dip soon shallows to between 15 and 25° in the same direction. Marked undulation of quartzite bands intercalated in the biotite schists of the lower Khomas Series immediately south of Windhoek [Map I, (13)] may possibly indicate a small measure of cross-folding in the sense of De Sitter. In the uniform biotite schists farther north this feature becomes unrecognisable. This comparatively low northward dip persists for a considerable distance across the strike of the Khomas Highlands. Gradually steepening, it reaches 45°-50° NW in the southeastern corner of the map accompanying this paper (Plate I). From here on it steepens more rapidly, reaching 70° close to the margin of the Donkerhoek granite; at the actual contact the schists are often even more steeply inclined. In the northeast the increase in dip of the schists is somewhat more rapid, finally reaching a vertical position over a 2½-3 miles wide belt stretching from Klein Barmen through Rüdenau and Gross Barmen towards Okahandja. (Geol. Sections, Plate II). Along the southeastern margin of this vertical belt reversals of dip steeply to the south are sometimes seen. In its southern portion there is a zone of marked lateral shear accompanied, over a width of several hundred yards, by the development of extensive minor (drag-) folding in the vertical
plane and intense vertical fracture-cleavage. Otherwise the general strike of the schists remains extremely regular ENE-WSW within this vertical zone.

Beyond this vertical belt, still with regular rectilinear strike, the dip of the schists gradually lessens to progressively lower angles. Then, as indicated by frequent reversals of dip, a roughly 2 miles wide zone of irregular folding supervenes, on the whole rather “open” and of no great amplitude. This zone is well exposed on the rocky cliffs of the Gross Waldau River in the vicinity of the cattle post in the northern portion of Gross Barmen (Geol. Section, Plate II). The anisotropic zones in the rock succession, containing narrow bands of light grey to whitish, fine-grained quartzite interbedded with mostly “sandy” biotite schists, are usually intensely crumpled, sometimes to an astonishing extent. (Photos 3-5, Plates IV and V). Many minor folds lie flat or nearly so. Strong differential movements must have taken place in this zone; sometimes miniature “nappes” with digitating fronts have been produced (Photo 5, Plate V). Overturning of minor folds appears to be directed mostly towards the SSE. One gets the impression of a “squeezed” zone that did not fold isoclinally as the more uniform schists farther south, but, possibly due to its greater anisotropy, viz. the abundance of narrow layers of quartzite, marble and extremely tough para-amphibolite and amphibole-pyroxene granulite intercalated in the incompetent schists, responded by more differential movement to form folds of greater irregularity and lesser amplitude. The folding in individual lithological units is often strongly disharmonic.

Below the Waldau ridge the strike again becomes more regular and the dip uniformly north at comparatively low angles (30°-40°) (Geol. Section, Plate II). Although the rocks are still strongly diversified, highly competent para-amphibolites and amphibole-pyroxene granulites now make up a greater proportion of the rock succession, while highly incompetent sillimanite-(muscovite) schists and “sandy” biotite schists recede in volume. The former competent rocks also dominate over the flow-prone crystalline limestones. Furthermore, the great mass of the core-rocks of the Waldau ridge dome, strongly overfolded to the SSE at angles of 30°-40° (to the horizontal), may have exerted a stabilising effect. The extremely disharmonic contortions of the very thinly banded rocks within the Main Marble horizon have already been mentioned. This, however, may in part at least be a primary feature due to slumping of chemically precipitated colloidal material (metamorphosed banded cherts, jaspilites and ironstones). In one well-exposed outcrop the minor folds in these contorted rocks reach isoclinal proportions, with axial planes practically horizontal.

The Waldau ridge dome, elongated parallel to the regional strike of the adjacent Khomas schists, is thus a recumbent one, strongly overturned to the SSE, as is the major portion of the great synclinorium of the Khomas Highlands (Geol. Section, Plate II). Also the Lievenberg dome is slightly overturned to the SE. (Geol. Section, Plate II). The southeastern flank of the Otjua brachyanticline exhibits a higher degree of overturning (60° in horizontal plane); also the southeastern flank of the Okandura dome has a steeper dip (70°) than the northwestern (60°). The tightly compressed Kaliombo ridge anticline exhibits much subsidiary folding. Farther to the southwest, beyond the western boundary of the map (Plate I), quite a number of dome structures are either actually overturned to the SE or have steeper flanks in that direction. Roper’s section through his geological map of the manganese-bearing Otjosondu area, roughly 100 miles to the NE of Okahandja.
TRANSACTIONS OF THE GEOLOGICAL SOCIETY OF SOUTH AFRICA

(30), also shows clear overfolding to the SE. To the north of the Abbabis swell overfolding is frequently in the opposite, viz. NW, direction.

The Abbabis swell and its northeastern continuation in the Otjosondu area thus appears to have had a noticeable effect on the folding during the Damara orogeny, directing any overfolding that exists away from itself into the adjoining geosynclinal troughs. This is a common feature of geanticlinal ridges within geosynclinal basins in whose deformation the dominant stress directions have not been too strongly unilateral. It is most easily explained by geanticlinal swells, dividing geosynclines into separate basins, during subsequent tectonic compression rising into the sediments deposited on them when, with progressive overall deepening of the geosyncline, they were more or less deeply buried.

The northwestern margin of the Khomas Highlands, both morphologically and geologically conspicuous, has played a considerable rôle in early discussions of the structure of central South West Africa. In the absence of detailed geological maps and basing their deductions mainly on incompletely known general features, several geologists in previous times came to consider the "rigid block" of the Highlands to be a horst, i.e. an upfaulted block bounded by strong continuous faults. In 1927 Stahl (34) even extended the latter westwards into the Atlantic Ocean and eastwards through the Kalahari as far as the Okavango swamps and Zambesi River.

Among his evidence for a very extensive major fault along the northwestern margin of the Khomas and Windhoek Highlands Stahl (34, p.59) not only cited the rectilinear nature of a marked morphological escarpment and of the schist-granite contact, but also the presence of a Thermenlinie (line of hot springs). Krenkel (21, p.648) further added in 1928 that "so far no contact-effects had been observed along the schist-granite contact", thus indicating its faulted nature.

Already in 1933 Gevers disputed the validity of these deductions and drew attention to the erroneous nature of much of the evidence on which they were based (12). It is apparent from the results of detailed work presented in this paper, that few of these arguments are actually based on fact. A more or less rectilinear escarpment is a well-marked feature only in the southwestern section after the Swakop River, beyond Tugab and the Lievenberg, has left the Khomas schists and entered the wide sheet of Donkerhoek granite. The schist-granite contact is anything but straight, approaching rectilinearity again only in the southwest. The evidence for the contact being an intrusive one is legion: numerous intrusive tongues of granite projecting into the schists; myriads of marginal pegmatites extending for miles into the bordering schists (Photo 7, Plate VI); and, at least in the Gross Barmen section, some of the most striking contact-metamorphism in all South West Africa.

There remains the Thermenlinie. At best, when considered over the entire relevant distance of well over 100 miles, it is very short, the thermal springs of Gross and Klein Barmen being only 7½ miles apart. Furthermore, they are not in the same line of strike, relative to structure, and have different geologic environments. Any major fault connecting them would show up clearly in dislocations within the intervening belt of pegmatites on farm Rüdenau. The warm spring of Okandu, another 13 odd miles, as the crow flies, from Klein Barmen, is not in the line connecting Gross and Klein Barmen, but widely offset to the south.

Over more than 120 miles between Okahandja and Donkerhoek no evidence of a continuous major fault has been found. But quite obviously such an extensive
zone of marked discontinuity, not only between radically different styles of folding but also between a thick, up to 30 miles wide, sheet of massive granite and well-bedded, fissile schists, must represent a potential line of weakness during subsequent periods of crustal stress. The fact that this structural and petrologic discontinuity is parallel to the general "grain" of a wide region further adds to potential instability.

It is not surprising, therefore, to find indications of tectonic disturbance, albeit of a comparatively minor and local nature, at least in connection with the Hot Springs on Gross Barmen. Both at the Okandu and the Klein Barmen thermal springs there is surprisingly little surface-evidence of any sort of structural control. The surrounding aplitic granites show no abnormal degree of fracturing; the latter is no greater than at many localities elsewhere. The mostly well-exposed banded and laminated Khomas schists in the surroundings of the Hot Springs on Gross Barmen, on the other hand, provide a wealth of minute detail indicating structural disturbance, to which brief reference has already been made in the previous paper (19).

C. Structural Detail on Gross Barmen

The broader features have already been outlined in the previous chapter. The main aspects are a gradually steepening dip of the Khomas schists until, in a 2-3 miles wide belt, they stand vertical, the strike remaining amazingly rectilinear and conforming to the general ENE-WSW trend of this region. Northwards the dip shallows again to pass into a 2 miles wide zone of more open, non-isoclinal, extremely irregular folding within which anisotropic, lithologically inhomogeneous zones show strong distortion (Photos 3-5, Plates IV and V). A narrow belt of more regular folding then fringes the Waldau ridge dome, strongly overfolded to the SSE. (Geol. Section, Plate II).

In the irregularly folded zone to the north of the belt of vertical dip, many of the minor structures indicate a strong southwards directed stress component, as well as features that suggest an upward push. It has already been stated that most likely the granite cupola of Klein Barmen extends with eastward plunge under this zone. It is, however, devoid of numerous pegmatites; these are, in fact, distinctly rare. They come in with a vengeance as concordant bodies in the northern portion of the belt of vertical dip ["Chinese Wall" pegmatite swarm, (Air Photo (19)].

No detailed examination of minor structures, outside strongly contorted zones, has been carried out in the northern belt of non-isoclinal folding. Except on the rocky banks of the Gross Waldau river, exposures are nothing like as good as in the surroundings of the Hot Springs. Here a large number of readily recognisable minor structures reveal displacement not in the vertical, but in the horizontal plane.

As pointed out in the previous paper (19), the Hot Springs of Gross Barmen are located along the southern margin of the belt of vertical dip in an area of strong fracturing and shattering where a wide zone of horizontal shearing, parallel to the strike of highly banded schists, is crossed by a number of faults of small throw.

(a) Banding of Schists

A striking sedimentological feature of the rocks in this horizon of the lower Khomas schists is their marked differentiation into rapidly alternating layers of more purely pelitic material (biotite-rich schists) and semi-pelitic "sandy" biotite-quartz schists (Photos 17, 19, 26, 33, Plates XI, XII, XV and XIX). The thickness
of individual bands varies from less than an inch to several feet. As already men­tioned, the “sandy” biotite-quartz schists are often thinly laminated in a fashion akin to varves: thicker, more sandy layers, poorer in biotite, up to more than an inch, sometimes several inches wide, alternating with thinner and darker, more biotite-rich laminae measurable often only in millimetres (Photos 8, 9, 11, 14, 17, 19, Plates VI to IX, XI and XII). Biotite flakes are usually parallel to the bedding and general ENE-WSW strike of the schists.

Under the microscope gradation in the size of the mostly angular quartz grains and of the biotite content, from lighter to darker layers, can often be seen, indicating the differentiation into bands of varying thickness to be in part at least a primary sedimentological feature. But the strong evidence for differential bedding-shear in these rocks, as well as the frequent presence of millimetre-wide films of biotite along abundantly developed fracture-cleavage planes, with biotite flakes oriented parallel to the latter, indicate bedding-slip banding also to be involved. Segrega­tion-banding due to ionic migration during metamorphism may also be represented.

The strike of the banded schists is mostly regularly ENE-WSW; locally bending into an almost E-W trend is evident. This, however, manifests itself quite irregu­larly and is probably connected with the drag-folding to be discussed presently. The dip of the banded schists is vertical; but along the southern margin of the drag­folded zone steep dips, up to \(70^\circ\), to the south, viz. opposite to the general northward dip of the sediments outside the vertical belt, is often seen, particularly along the rocky floor and banks of the lowermost Gross Waldau River. At a few points in this locality slight southward overturning of the normally vertical axial planes of minor folds and of associated fracture-cleavage appears to have taken place. Crenulations on bedding planes of the schists, oriented parallel to their strike, i.e. fold axes, indicate differential movements along bedding planes in the direction of transport. This feature, as well as the general orientation of biotite flakes in the a-b plane, in this case parallel to the bedding and thus inducing bedding-schistosity, is no doubt connected with the regional isoclinal folding of the schists.

(b) Boudinage

The abundance in certain zones of narrow lenticular layers of very fine­grained white quartzite, often speckled with small flakes of biotite particularly in their marginal portions, as well as of usually thicker (up to 1 foot) layers of amphibole-pyroxene-garnet granulite, has already been mentioned. These narrow intercalations, together with the universal banded and laminated nature of the enclosing schists, are of great utility in determining minor structures.

As would be expected in such anisotropic sediments, comprising more compe­tent beds interbedded with less competent, boudinage is often strikingly developed, particularly in the granulite layers. This varies from mere alternate thickening and thinning down to complete disruption. These features are particularly well exposed in the Gross Waldau River and along the northern rocky bank of the Swa­kop near the boundary of Gross Barmen with Rüdenau. Very common are discs in which one dimension (b) greatly exceeds the other (a). While often tapering gradually (Photos 10, 11, Plates VII and VIII), some ends of boudins are rounded and blunt. The distortion reaches its highest degree in the form of long spindles of ellipsoidal, and “torpedoes” of practically circular outline. Their elongation is parallel to the strike, i.e. fold axes. They can only be accounted for by stretching and disruption both along strike and down dip being accompanied by “rolling out”
movements operating up and/or down dip, viz. compression perpendicular to the bedding resulting in strong differential slip along bedding planes.

Quite obviously distortion must have taken place prior to, or more probably \textit{pari passu} with metamorphism, for concentric mineral banding is a marked feature of most discs, spindles and “torpedoes”. An outer, dark border composed predominantly of hornblende grades inwards into a zone of light minerals (quartz, twinned plagioclase and variable calcite) speckled with varying amounts of greenish pyroxene and pink garnet, the latter in particular increasing inwards to form a garnet-rich core. This sometimes weathers more rapidly to form a groove in outcrop sections across the disc-like \textit{boudins} or a central pit in ellipsoidal spindles or round “torpedoes”. Presumably this is due to a higher calcite and sphene content of the core in such cases.

Less frequently the mostly much narrower biotitic quartzite bands have also been rolled out into spindles, whose ends are usually pointed (Photo 9, Plate VII). Occasionally, however, also very blunt terminations occur. Biotite is most abundant in the marginal portions of these bodies.

The general orientation of these discs, spindles and “torpedoes” indicates \textit{boudinage} deformation to have occurred during the tight isoclinal folding that produced the regional ENE-WSW trend.

The later period of stress resulting in differential shearing movements in a horizontal direction, parallel to the strike of the already tightly compressed, vertically dipping schists, however, gave rise to additional \textit{boudinage} effects within the minor folds to be described presently. It should be noted, however, that in many of the numerous chevron-type minor folds, the granulite bands, though often kinked into right angle bends, show surprisingly little change of thickness, often none at all (Photos 15 and 16, Plate X). Sometimes, however, they have thickened by flow into the axial plane portion of the minor folds (Photo 17, Plate XI).

\textit{(c) Zones of Horizontal Shear.}

As already briefly outlined in the previous paper (19), the entire outcrop zone around the Hot Springs of Gross Barmen shows pronounced effects of strong shearing movements parallel to the strike and the dip of the vertically standing schists. A several yards wide zone of intense shearing is exposed over several hundred yards [Air Photo and photos 9 and 10 (19)]. Within it the schists have been reduced to an almost slaty cleavage. The full lateral extent of this shear-zone is not known. Eastwards towards Okahandja its line of strike is completely obscured by surface-deposits. Westwards it disappears in the sandy bed of the Swakop River, whose straight course for 2-3 miles in line with this shear-zone perhaps indicates incision along the latter. Where the river again loops to the south exposures are very poor and a continuation could nowhere be traced.

This main shear-zone is not the only one at Gross Barmen. It is merely the most evident and most persistently exposed of a number of parallel zones of shearing, exposed intermittently over a belt several hundred yards wide across the strike of the schists and probably present over a total width of roughly one mile (Geol. Section, Plate II).

\textit{(d) Minor (Drag-) Folds.}

These are a striking feature of the exposed area of lateral shear, within which their number is legion. In amplitude they vary from mere kinks, viz. a few inches, up to 4-5 feet. (Figs. 1-4 and Photos 12-17, Plates VIII-XI, and 29-31, Plates XVII and XVIII). A minor drag-fold, after flattening out, may show several more,
Mostly knotted "sandy" schists
Fracture cleaved more micaceous schists
Coarse micaceous border with muscovite
Massive quartz
Narrow undulating quartz veins
Joints

usually of lesser amplitude, in the prolongation of its axial plane over a distance of several dozen yards. Fig. 3 illustrates this on a somewhat smaller scale. The usual pattern, however, is one of random distribution, one fold, or a small series oriented along the same axial plane, being replaced by another in a different position in closely adjacent zones. A width of several dozen yards, or even a few hundred feet, across the strike of the schists may be more affected by drag-folding than the intervening zones. Also along strike in the same zone its abundance is variable.

All the features indicate differential slip, in the horizontal plane, between layers of schists of differing competence.

The degrees of curvature of the minor folds vary from fairly tight (Photo 29,
FIG. 2

LEGEND

- Fracture-cleaved andalusite-biotite schist.
- Narrow bands of biotitic quartzite.
- Thinly laminated sandy biotite schist.
- Fracture-cleaved biotite schist.
- Massive Quartz.
- Coarse muscovitic border.
- Narrow undulating quartz veins.
- Joints.
Plate XVII) (not common) to very open. Chevron-folds are very frequent, often with right-angle bends (Photos 15, 16, Plate X).

Similar to the dip of the banded schists, the axial planes of these minor folds are all vertical and make angles of 30°-40°, sometimes 45°, with the strike of the schists. The minor folds are thus all vertical and all point in one direction only, viz. NE to NNE. When a plunge could be discerned, e.g. along the Swakop River on Rüdenau, this was always towards the WNW, but invariably at very steep angles, practically nowhere less than 80°.

Commonly there is a marked fracture in the axial plane of the larger minor folds (Figs. 1-4); often there are two, along the axial plane of each "kink" (Fig. 2). Sometimes in a small fold the fracture crosses from one "kink" diagonally across the fold to the other. Where thicker competent layers of granulite are involved, axial-plane fractures are often absent (Photos 14, 15, 16, Plates IX and X). Where there is a series of minor folds along one and the same axial plane, the fracture joint may extend through several folds (Figs. 2-4). Usually, however, also in such cases they are intermittent, in general short. The main fracture, or pair, bisecting the folds are often accompanied by short subsidiary parallel joints over a lateral distance of several feet (Figs. 1 and 4). Owing to the effect of adjacent folds of different degrees of compression, these joints are not always strictly parallel. Sometimes a fan arrangement is displayed when folds of different amplitude and degrees of compression are closely spaced.

Quartz veins are very commonly emplaced along axial plane fractures (Figs. 1-3, and Photos 29-31, Plates XVII and XVIII). Rather frequently, instead of open fractures in the axial planes, there occur narrow welts, varying in width from a few millimetres to 2 centimetres. They appear to be due to a slight degree of silicification of narrow zones of dilatation and hence stand out on weathering (Photo 12, Plate VIII). Where a chevron-type fold of small width occurs in laminated "sandy" schists between two rather closely spaced fractures, the lamina­tions on right-angle bending have been "opened up" to a marked degree [Photo 11 in previous paper (19)].

The fact that the fabric of laminated layers is distorted by these drag-folds together with intercalated bands of amphibole-pyroxene-garnet granulite and biotitic quartzite (Fig. 2), clearly indicates that the lamination of different bands of varying biotite content, as already described, is in the main a primary sedimentational feature, modified perhaps by segregational banding during metamorphism. The metamorphic fabric, mainly indicated by narrow biotite-rich laminae and the orientation of biotite flakes, must for the most part have been formed during the main phase of tectonic deformation that produced the regional ENE-WSW fold trend.

(e) Fracture-cleavage

The intense development of fracture-cleavage in these banded schists is one of the most striking features within the belt of lateral shear. Its well exposed features represent a veritable textbook example of this particular structural phenomenon. It is most pronounced in the biotite-rich bands, in which it is often so closely spaced as to impart to them a secondary cleavage-schistosity that has largely destroyed the original bedding-schistosity fabric, the biotite flakes now being oriented parallel to the fracture-cleavage planes (Photos 17, 18, Plate XI). In other instances it is more widely spaced, leaving the pre-existing fabric intact except for the re-orienta-
Strike of axial planes of droplets: 12-17° E.

- Thinly banded "sandy" biotite schists
- More micaceous schists with fracture cleavage
- Ditto, with abundant spindles of andalusite + muscovite along fracture cleavage
- Ditto, with more sparing spindles
- Sparring andalusite-muscovite spindles // to bedding
- Thin bands of light-colored granulite in schists
- Bodies of quartz emplaced mostly along axial plane joints.
- Narrow contorted veins of quartz
- Joints

Fig. 3
tion of biotite flakes into parallelism with the fracture-cleavage planes in a marginal zone a few millimetres wide (Photos 19 and 33, Plates XII and XIX).

It may stop dead against the more competent, comparatively biotite-poor "sandy" layers (Figs. 1-4, and Photos 17, 18, 20 33, Plates XI, XII and XIX); where the latter, however, are somewhat more biotitic, viz. originally more clayey and therefore less competent, it may extend with wider spacing some distance into, or even right through, such bands (Photo 17, Plate XI). Sometimes fracture-cleavage is indicated in the more "sandy" types merely be extremely thin, macroscopically barely visible, dark lines of biotite concentration.

This extension of fracture-cleavage on a reduced scale into the more "sandy" layers is most often seen in more uniform, less laminated bands. In the case of the more highly and thinly laminated bands exhibiting very distinct "varving", i.e. narrow bands of gradational biotite content or sharply demarcated very biotite-rich laminae, the fracture-cleavage in the more uniformly biotite-rich bands usually stops abruptly at the bedding contact. It is astonishing to see the effectiveness in this respect even of quite narrow laminated layers, no wider than a few inches. This feature suggests that bedding-shear may have been operative either contemporaneously, thus enforcing a biotite fabric parallel to the bedding-slip movements, or subsequently, again destroying whatever fracture-cleavage had previously developed. The fracture-cleavage never extends through the narrow intercalated bands of biotitic quartzite and amphibole-pyroxene-garnet granulite of high competence. In addition to the frequent boudinage, already described, these merely show occasional, at times more closely spaced, cracks oriented at right angles to their bedding elongation, viz. tension- or rotation-joints (De Sitter, 3, p.100).

The fracture-cleavage in the less competent biotite-rich bands throughout is parallel to the axial planes of the ubiquitous minor folds. When developed, usually with wider spacing, in the more competent, less biotitic, bands it may steepen somewhat with reference to the bedding planes. This feature sometimes results in curving (Photos 17 and 18, near pencil, Plate XI). Photo 19, Plate XII, shows markedly curved, very steep and widely spaced fracture cleavage in banded schists with laminae of varying competence. (Compare De Sitter, 3, pp.94-101).

Except in the isolated locality in the Gross Waldau River, already mentioned, where slight subsequent southward tilting appears to have taken place, the fracture-cleavage planes are vertical, similar to the axial planes of the minor folds with which they conform.

The formation of minor folds and fracture-cleavage is obviously closely connected. Both features are confined to the approximately one mile-wide belt exhibiting strong horizontal shear. Analysis of their strikingly consistent pattern indicates the operation of a couple, viz. strong differential movements involving shear within an anisotropic zone of vertical, closely banded schists of different degrees of competence, between two blocks moving more or less horizontally in opposite directions, the northern being shifted to the ENE relative to the southern (Khomas Highlands).

(f) Stress-oriented Andalusite Porphyroblasts.

The enormous development of andalusite porphyroblasts is the most striking feature within the mile-wide zone of horizontal shear (Photos 16-26, Plates X-XVI). Andalusite is a common mineral in contact-aureoles. Universally it has hitherto been regarded as an "anti-stress" mineral. The most astonishing feature, however, in this locality is not so much the profuse development, but the strikingly stress-
oriented growth of this mineral. Only very locally, where drag-folding and fracture-cleavage are inconspicuous, is random orientation occasionally found.

By far the bulk of andalusite porphyroblasts, either in the form of elongate flat plates or anhedral rods, up to 8½ inches long, have grown within fracture-cleavage planes. They are most abundant and closely spaced within the most highly fracture-cleaved biotite-rich bands (Photos 16-18 and 20-24, Plates X-XIV). Where the fracture-cleavage stops abruptly against more sandy layers, the deve-
lopment of andalusite stops as abruptly (Photos 17, 18, 20, 21, Plates XI-XIII). When the cleavage extends with wider spacing into the less biotite-poor "sandy" layers, then also andalusite may continue into these bands in much more sparing development, as long as the original clay content is high enough for its formation (Photo 19, Plate XII). Rather puzzling at a first glance is the occasional paucity, almost absence, of andalusite in narrow, rather highly fracture-cleaved layers adjacent to similarly cleaved layers in which it is present, though seldom profusely in such cases (uppermost part of Fig. 3). On closer examination, however, the quartz content of the former is found to be higher than in the latter.

Usually in the absence of fracture-cleavage there is no andalusite at all in the "sandy" layers even when these show distinct lamination with reference to biotite content. Not infrequently, however, andalusite porphyroblasts are developed comparatively sparingly in laminated bands, of high enough biotite content, that show signs of strong bedding-slip shear. In such cases their elongation is parallel to the latter (Photo 25, Plate XV and left-hand bottom of Fig. 3.)

As stated, the axial planes of the minor (drag-)folds and orientation of the fracture-cleavage parallel to them is entirely in one direction only, viz. NE to NNE. But, to drive home the stress-orientation of andalusite growth, the writer came across one single instance of a shear-fracture oriented at right angles to the axial plane direction; and it too had numerous andalusite porphyroblasts elongated in the trend of the fracture (Photo 26, Plate XV).

In this description of the mode of occurrence of andalusite porphyroblasts, the author has been careful to use the term stress-oriented and not stress-controlled. Throughout the entire length and breadth of the magnificent exposures there is no evidence whatsoever of the reorientation of random growth into one preferred direction; nor of bodily rotation of pre-deformation porphyroblasts into the trend of axial-plane cleavage or bedding-slip shear.

Under the microscope the andalusite porphyroblasts not infrequently enclose residuals of quartz and biotite. In a few large specimens the biotite borders of the fracture-cleavage planes, with biotite flakes oriented parallel to the latter, were seen to extend intermittently through their entire length. This would indicate crystal growth subsequent to the formation of the fracture-cleavage. This phenomenon, however, was observed in only a few instances. From some of the photographs (20 and 21, Plates XII and XIII) it can be seen that andalusite has developed along fracture cleavage planes not as single long plates or anhedral rods, but as aggregated bands of linked-up individuals.

Whatever the actual shape of the porphyroblasts, whether euhedral or anhedral, growth took place along zones of tectonic shear. It is a well-known fact that also under unconfined conditions prismatic crystals tend to grow faster in the direction of the C-axis. All features described, however, indicate quite clearly that growth took place under the influence of a marked gradient of chemical potential. Among the factors determining such gradients in metamorphic diffusion or differential migration of the component ions of the metamorphic system are differences in non-hydrostatic stress. Whether growth took place within fracture-cleavage or, much more rarely and sparingly, along bedding-slip shear, the elongation of the andalusite porphyroblasts is in the direction of minimum stress. Most certainly there is no evidence of growth having taken place during a subsequent stage of stress relaxation. To this extent then the growth of andalusite porphyroblasts is not only stress-oriented, but definitely stress-controlled.
In a recent private communication to the author Professor J. B. Thompson jnr., of Harvard University, writes: "I have long felt that the classic view of andalusite as an "anti-stress" mineral is untenable. It is widely developed in northern and eastern New England (Appalachian orogen) not only in contact aureoles, but also on a regional scale in highly deformed mica schists. I believe that andalusite owes its abundant occurrence there to a relatively light load-pressure during metamorphism. In southwestern New England (also in central and southern Vermont) its place is taken by kyanite, suggesting that the metamorphism there occurred at greater depth... The New England andalusites are frequently as abundant and in several occurrences larger than those you describe. I do not, however, remember as marked a preferred orientation or as pronounced a tendency to develop along cleavage planes. It does not surprise me though, that this should develop under favourable circumstances."

It has already been stated earlier on that the shear-zone, within which the andalusite porphyroblasts on Gross Barmen and Rüdenau occur, represents the boundary, involving differential movements, between the radically different tectonic patterns of infra- and supra-structure of the Damara orogen. As already mentioned, no kyanite schists were noted anywhere, sillimanite taking the place of andalusite lower in the stratigraphic succession and generally in the infra-structure. This appears to conform with Prof. Thompson’s idea of a lesser load-pressure for the formation of andalusite. Its prolific development along fracture-cleavage planes associated with a late-tectonic phase, involving the "lifting off and up" of the schists of the Khomas Highlands from the infra-structure by the vast sheet of Donkerhoek granite, lends further support to Professor Thompson’s view.

On Gross Barmen the largest (up to 8½ inches long) porphyroblasts of andalusite were found in the rocky banks of the Gross Waldau River towards the "Chinese Wall" swarm of pegmatites. In the immediate neighbourhood, however, of these pegmatites and in between the miles-wide swarm of closely spaced pegmatites on Rüdenau and elsewhere, there is no marked development of andalusite. Its much more sparing occurrence in mere knots along the contact of the Khomas schists with the vast mass of Donkerhoek granite farther to the west has already been mentioned. Also around the Klein Barmen cupola of aplitic granite and within the innumerous xenoliths within the Donkerhoek granite, there are no readily visible signs of andalusite. Its profuse development, with striking stress-orientation, is confined to the mile-wide belt of strong lateral shear abounding in drag-folds and fracture-cleavage. The two smallish, up to 3 feet wide, pegmatites on the north bank of the Swakop River, west of the Gross Barmen boundary, which occur right within the andalusite-rich, drag-folded and fracture-cleaved belt, show not the slightest effect on all of these features. The main portions of these pegmatites clearly demonstrate pure dilatation subsequent to the formation of the minor structures, which are utilised for emplacement by minor offshoots.

While it is clear, therefore, that this profuse distribution of andalusite is situated in the general area of a high degree of late-tectonic magmatic injection, which was probably responsible for raising the temperatures high enough for the formation of andalusite to be able to take place, the specific site of development and orientation of the growth of andalusite porphyroblasts are strikingly stress-controlled.

Their widespread subsequent muscovitisation, however, is definitely linked with solutions derived from the pegmatites and with the emplacement of innumerable quartz veins.
(g) Quartz Veins.

The emplacement of these also shows marked control by the local tectonism. It has already been stated that the vast majority of pegmatites are concordant and that there is evidence of the “opening up” of fissile schists by the upward “push” of the Klein Barmen granite cupola and its probable, concealed, ENE-ward plunging extension under Rüdenau and Gross Barmen. Many of the numerous quartz veins are also concordant, e.g. the several feet wide vein of glassy quartz at the old Police Fort ruins. Farther to the east, on the western side of the small fault on which the hot farm bore-hole is located, there is a zone some ten feet wide in which the schists are heavily interleaved with concordant quartz veins up to 1 foot wide. The schists are somewhat bent, apparently due to drag by the cross-cutting fault. Here the thicker quartz veins contain marginal slabs of schists, a rare phenomenon.

Most striking is the structural control of the innumerable minor (drag-) folds on the emplacement of quartz veins. The number filling axial plane fractures is legion. Details are shown by Figs. 1-3, and Photos 29-31, (Plates XVII and XVIII). It may appear strange that axial planes of folds, oriented at right angles to the dominant stress at the time of their formation, should act as host for quartz veins sometimes nearly a foot thick (Figs. 1 and 2). Subsequent relaxation of stress or “opening up”, when the dominant stress had once more changed and possibly returned to the regional NNW-SSE directed trend, comes to mind. There is, however, little or no evidence of this. The axial planes of the minor folds and the associated fracture-cleavage and joints in the vast majority of cases show no subsequent deformation.

De Sitter (3, p.97) has shown that in the formation of such folds in thinly banded or laminated rocks (he likens them to rows of bricks in Fig. 67), slip takes place along closely spaced bedding planes resulting in step-like open spaces along the axial planes, to put it crudely. In fairly uniform bands showing only closely spaced, very thin biotite-rich laminae within more “sandy” material, the open spaces would be very minute, macroscopically simulating a straight line. In such cases there is usually nothing more than a very thin, often only millimetre-wide, film of quartz that stands out on weathering. The formation of the peculiar welts produced by mere silica-impregnation, in the way already described, also belongs to this category (Photos 12, Plate VIII, and 31, Plate XVIII). Under more anisotropic conditions, involving layers of differing competence, the open spaces along the axial-plane cleavage would be wider, but of varying width. Figs. 2 and 3 quite clearly show variations in thickness of the quartz veins not only dependent on lithology and spacing of fracture-cleavage, but to some extent also due to flow of the quartz into folds and boudinage along the cleavage planes, viz. at right angles to the dominant stress. This latter feature rather negatives the idea of final permanent stress-relaxation, though, in view of the considerable thickness of some of the veins, this probably was intermittently operative as well.

In a private communication Martin has put forward the following simple and plausible explanation. Varying degrees of competence within an anisotropic succession of banded rocks would seem to be the main cause of the formation of the minor (drag-) folds. Each minor fold affects only a limited thickness of rock. The deformation is therefore not evenly distributed through adjacent beds. This means that portions of the successive beds have moved varying distances. If this dif-
ferential movement cannot be accommodated by plastic thickening, it must cause rupturing. This is rather well shown by Photo 31, (Plate XVIII).

Not infrequently the quartz veins become "stumpy", mushroom-shaped, or split up on leaving a highly fracture-cleaved band and encountering a non-cleaved layer or one that shows only bedding-slip shear (bottom of Fig. 3). In the latter case they often send out branching veins parallel to the latter. Saddle-reefs of quartz, parallel to the contorted bedding and superimposed lens-like along the axial plane of a fold, are quite common. Their emplacement is easy to explain by slip along the bedding planes resulting in "opening" up in the zones of maximum bending.

Very often the thicker quartz veins emplaced along the axial planes of minor folds, and also those parallel to the bedding, send off very narrow, but frequently quite long, veinlets into the adjacent rocks. These often show strong crenulation due both to the higher degree of competence of already consolidated veins during folding or bedding-slip shear, and emplacement *pari passu* with deformation.

Figs. 1 and 3 show several such narrow veins. The two upper in Fig. 1 exhibit contortion increasing in intensity towards the main body of quartz emplaced in the axial plane of the minor fold. The two lower veinlets and all those of Fig. 3 merely exhibit strong crenulation on a small scale. In the drawings these veins are simply shown as wavy lines. In detail, however, it is most interesting to note that when crossing fracture-cleaved bands the axial planes of the crenulations, viz. minute folds, are the fracture-cleavage planes of the host-rock (Photos 32 and 33, Plates XVIII and XIX). Within the laminated rocks, however, particularly those showing thin, closely spaced biotite-rich layers, the axial planes of the crenulations are often oriented parallel to the bedding schistosity. Since the crenulations and their axial planes stand vertically, the primary bedding schistosity produced by the main phase of ENE-WSW folding, with a dominant NNW-SSE directed major stress, cannot be responsible, but rather the later horizontally directed bedding-slip shear associated with the minor folds and fracture-cleavage.

Photo 34, Plate XIX, demonstrates that even in the less well laminated "sandy" schists some measure of bedding-slip shear must have occurred, since the axial planes of the crenulations are mostly parallel to the bedding indicated in the upper left hand corner and by two boudins of biotitic quartzite. A just visible "feather" cleavage, parallel to the general axial-plane cleavage of adjacent more biotite-rich bands, has been developed along the quartz vein; this also appears to have influenced the shape of the crenulations, indicating that bedding-slip shear and fracture-cleavage went on *pari passu*. When quartz veinlets cut more obliquely across such more massive "sandy" biotite schists, a secondary feather cleavage, parallel to the general axial plane cleavage, is often much more strongly developed and frequently forms the axial planes of the crenulations.

It is clear that most of the crenulated veins of quartz shown in Fig. 3, though affected in detail by both fracture-cleavage and bedding-slip shear, partake in the minor folding, thus further strengthening the evidence for the close time relationship of all of these movements.

Photo 27, Plate XVI, shows a quartz veinlet cutting at right angles across the strike of vertical laminated "sandy" schists. Its upper surface is markedly crenulated; apparently this is an effect of weathering due to the more ready removal of granulated zones produced by vertical bedding-slip shear. The pronounced "feather" cleavage along its lower margin, however, would appear to indicate also
some measure of horizontal bedding-slip shear. The crenulations visible in places, particularly along the upper vertical wall of the vein, would seem to support this.

The quartz vein depicted in Photo 28, Plate XVI, cutting horizontally across vertical “sandy” schists, quite definitely indicates deformation by lateral compression, viz. by the dominant NNW-SSE directed stress. Not only does the deformation of the vein assume isoclinal proportions, with in part completely parallel limbs, but disruption and boudinage are also in evidence. This particular quartz vein must thus either be earlier than those affected by, and related to, the later horizontal shear movements parallel to the strike of the schists after they had already been tilted into vertical position by the major stress of the main phase of folding, or the latter must subsequently again have resumed its operation, at least locally. It is perhaps significant that this vein occurs closely adjacent to the area where the vertical attitude of the schists changes to a steep southerly dip, opposite to the general northward dip of the southerly adjoining area.

A common feature around the more massive quartz veins emplaced along the axial cleavage planes of minor folds, i.e. the late bodies of quartz, is a “contact aureole” of muscovitisation, up to a few inches wide, within which the marginal biotite has been replaced more or less completely by muscovite (Figs. 1 and 2). In the case of fairly thick bodies of quartz, the latter is often quite coarse. This alteration must have entailed the addition of some K and removal of most of the iron and magnesium in biotite. Sometimes a dark, particularly biotite-rich border, in which this mineral is coarser than normal, can be observed adjacent to the muscovite aureole. It is of interest in this connection that several offshoots of the two already mentioned muscovite-bearing pegmatites, occurring within the belt of shearing on the north bank of the Swakop River, within 6-8 feet begin to lose their felspar content and change into quartz veins. Around the latter the biotite again is largely replaced by muscovite, as well as having recrystallised to larger flakes in the border zone.

(h) Later Faults and General Fracture and Joint Pattern.

The main features of the fracture pattern around the Hot Springs on Gross Barmen have already been depicted schematically on Maps 2 and 3 of the previous publication (19). Many hundred measurements of strike were made with the intention of plotting the poles of the joints on a point diagram. Since, however, they are practically all vertical and the majority follow a few well marked trends, the labour involved in such a pictorial presentation was finally not considered worthwhile.

In addition to the innumerable, usually short, vertical joints in the direction of the axial planes of the minor folds, trending between NE and NNE, another prominent vertical group trends between slightly west of N and NNW. A subordinate vertical set trends approximately NW (Figs. 1-4).

Several NNE, N and NNW trending joints, however, can be traced over longer distances, a few over the entire width of the exposures, i.e. several hundred yards. These show up quite clearly on the aerial photograph accompanying the previous paper and are depicted on Map 2 (19).

These longer fractures are often accompanied by a good deal of shattering (Photo 36, Plate XX) and sometimes show small lateral displacement. Two closely adjoining NNW trending fractures displace the large pegmatite near the old Mission ruins. Since the pegmatite stands vertical, these must be dip-slip or wrench faults. Also the more or less N-S trending fault running from the Gross Waldau River
up to the hot farm-borehole [Photo 8 (19)] is shown by an amphibole-pyroxene-garnet granulite band to be a dextral wrench fault of small displacement. A seepage on the banks of the Gross Waldau River, the warm well, hot farm borehole, and elongation of the dozen hot springs are more or less in a straight line, when allowing for the slight changes in strike shown by some of the continuously exposed major fractures. This line may therefore be another major dislocation. The outcrop positions of the large vertical pegmatite on the banks of the Missions River behind the old Mission ruins may be construed as a slight displacement.

Where exposed over a height of a few feet, as in the shallow gully formed by the N-S fault on which the hot farm bore-hole is located, the surfaces of the joints trending between NE and NNE, parallel to the axial planes of the minor folds, are often rather rough, as would be expected from their mode of origin (De Sitter 3, p.97). The N to NNW trending joints along or close to the faults are by comparison often smoother; in view of the slight lateral displacement along them, this is perhaps to be expected. In the area south of the hot farm bore-hole, they not infrequently possess narrow greenish borders within which the marginal biotite has been chloritised to varying degrees. This suggests the circulation along them of thermal waters, as also does the presence in this locality of narrow films of fine-grained silica (Photo 35, Plate XX). The breccia produced by the adjacent fault is in places strongly cemented by in part drusy silica. All these features may be connected with the formerly more extensive circulation of the present day thermal waters. The massive cementation by chaledony of fault-breccias associated with the two westernmost faults near the old Mission ruins was already referred to in the previous paper (19).

(i) Structural Analysis

Aerial photographs of the hilly terrain made by the vast swarm of pegmatites cut through almost at right angles by the Missions river show up linear features, sometimes continuous for several hundred yards, oriented more or less at right angles to the regional strike of the schists [Air Photo (19)]. These and some of the similarly oriented joints in the area around the Hot Springs may therefore be tension-fractures parallel to the initial dominant NNW-SSE regional stress. Only very occasionally were joints noted striking parallel with the vertical schists, but dipping at 40-50° N. These would be shear-fractures produced by the same regional stress. Photo 36, Plate XX, showing two conjugate shear-fractures cutting obliquely across the strike of the schists near the farm bore-hole fault, is included not on account of any imagined novelty of the phenomenon, but because it provides a textbook example of absolute symmetry, the acute angle between the two shear-joints being neatly bisected by the direction of maximum stress.

The major longer fractures and faults of small throw do not fit into the tectonic picture as readily. In part they are parallel to the axial-plane trend of the minor folds, formed by horizontal shear subsequent to the tight isoclinal folding and vertical dip produced by the major regional compressional stress. In part they trend parallel, or almost so, to the fractures assumed to be due to tension in the initial dominant stress-field. Their swinging from this direction into the minor fold axial-plane trend, however, militates against this view, as also does the strike-slip shift along them and the frequently marked shattering and brecciation.

There is evidence that they are later than the horizontal shearing movements so pronouncedly marked by minor folds and fracture-cleavage. As stated, the two smallish pegmatites on Rüdenau were injected after the latter features had already
come into existence. On the other hand two, possibly three, of the NNW trending faults in the Hot Spring area displace pegmatites. Furthermore, in Fig. 4, the major set of NNW joints quite clearly cuts across the minor fold at the bottom. To have produced the minor folds and the fracture-cleavage parallel to their axial planes, the dominant stress in this locality must have swung from the general regional NNW-SSE direction into one at right angles to the axial planes of the ubiquitous minor folds. The NNW and N trending joints, major fractures and faults would then be shear-fractures in relation to this new, local, dominant stress. Under these conditions any major NNW tension fractures produced by the initial main regional stress would become subjected to compressive shear, thus enabling lateral movement with shattering and brecciation of the wall-rocks.

Since the striking metamorphism, viz. formation of andalusite porphyroblasts, went on pari passu with the second phase of deformation and the temperatures must have been high enough for their growth, it is rational to assume, as has already been done, that the late-tectonic intrusion of the Donkerhoek granite sheet, with its vast swarms of pegmatites, contributed substantially towards the required temperature conditions. There need not have been a great time interval between intrusion and consolidation of the pegmatites, injected in any case for the most part outside of the main zone of manifestation of the later stress-field localised within a belt only approximately one mile wide. There is no valid objection for the latter to have continued until after the consolidation of the pegmatites, thus enabling faulting on a minor scale of the most closely adjacent bodies. This speculation need not be carried farther. It is more than likely that tectonic deformation of this portion of the Damara geosyncline did not cease altogether with the intrusion of the great sheet of Donkerhoek granite that lifted the more rigid supra-structure of the Khomas Highlands off from the infra-structure with its widespread granitisation and mobilisation phenomena. Settling movements due to crystallisation of the vast mass of Donkerhoek granite and consolidation of softened-up and mobilised material at lower levels, can readily be envisaged, quite apart from the effects of final isostatic uplift.

If the mile-wide zone of horizontal shearing is projected to the southwest, it is more or less continuous with the southern margin of the Donkerhoek granite sheet and with the long tongue of granite injected into the adjacent mass of steeply dipping Khomas schists (Geol. Map, Plate I). As already mentioned, the arc-like swing of schists on the northern and western side of the enclosed small body of granite on Klein Barmen, as well as the fingerling out of the schists on its eastern side, suggest an upwelling effect; the particularly high degree of metamorphism of the lower Khomas schists and associated sediments on Rüdenau and Gross Barmen, furthermore, make plausible the idea of the Klein Barmen granite continuing with northeastward plunge underneath this area.

There is thus a distinct possibility that the shearing movements in question are connected with the mechanism of intrusion of this vast late-tectonic mass of Donkerhoek granite. It appears quite feasible that in turning northwards around the Waldua ridge dome, it pushed the comparatively narrow lowermost portion of Khomas schists (turned into a sharp flexure and updomed on Klein Barmen) somewhat to the northeast, as deduced from the analysis of the structural pattern of drag-folding and fracture-cleavage on Gross Barmen. On structural and mechanical grounds it is not surprising that this lateral movement should be effected in the narrow belt of vertically standing schists in more or less direct continuation of the southwestern
margin of the granite which, after intense disruption of the Khomas schists, continues more or less rectilinearly for more than sixty miles southwestwards (Geol. Map, Plate I.)

The author wishes to emphasise that he considers this late-stage change in the dominant regional stress to be local. After surmounting the obstacles of the Waldau ridge and the neighbouring dome structures and once more turning into a concordant contact with the schists, there is no mechanical reason for lateral shear by a stress emanating from the granite to the west and northwest to continue. As already stated, the extensive sand cover towards Okahandja makes it impossible to ascertain how far these differential lateral movements continued northeastwards. Though not examined in detail, minor structures similar to those described from Rüdenau and Gross Barmen were not noted in the pegmatite-invaded hills to the northeast of Okahandja.

IX. ORIGINAL DEPTH OF EXPOSED TECTONISM AND METAMORPHISM

Although the author has emphasised the effect of the vertical component in the stress-field within the infra-structure of brachy-anticlines, domes and extensive granitisation, there is no doubt, notwithstanding the views of Beloussov, Carey, and others about the relative unimportance of horizontal movement in geosynclinal tectonics, that lateral compression has been intense in this part of the Damara geosyncline. The author has already referred to the possibly very considerable effect of the Abbabis geanticlinal swell rising upwards, during geosynclinal deformation, into the thick sediments deposited on top of it after complete burial.

The degree of crustal shortening involved in the tight isoclinal folding of the Khomas schists within the Khomas Highlands and the area along the Swakop River must have been very considerable. In the absence of marker-horizons the details of folding are at present unknown, except in the limited region described in the present paper. Even here the absence of identifiable marker-horizons, except in the lowermost portion of the Khomas schists, makes it impossible to assess the amount of crustal shortening, except to say that in the 3 mile wide belt of vertical dip lateral compression reached the mechanically possible maximum.

The depths of burial of sediments during geosynclinal development and deformation regarded as possible by some authors in recent publications, basing their views on the work of Wyllie, Tuttle, and others, are indeed startling. Thus Smith, "assuming the not unreasonable geothermal gradient of 30°C per Km (31, p.228) to have been present in this (Damara) orogen", considers a total depth of burial of the infra-structure of the order of 18 to 24 Kms (11-15 miles) not to have been unlikely (31, p.109). Smith came to this conclusion on the basis of all gneisses and granites, with the exception of scattered bodies of limited distribution and size, being of transformation origin.

The demonstration, in this paper, of the injection at a comparatively high level, viz. the boundary between infra- and supra-structure, of a vast mass of truly intrusive granite, the largest individual body of igneous-type rock so far known in the entire Damara orogen, appears to make necessary a revision of the geothermal gradient assumed by Smith. Whatever its ultimate origin, whether anatectic or syntectic, temperatures below the exposed level of the infra-structure must have been high enough, over a very large area, for such vast masses of granite to be generated and kept fluid until late-tectonic times. Further detailed mapping may prove the existence of more large masses of intrusive granite in other parts of the orogen.
Martin has suggested to the author that stability conditions of the $\text{Al}_2\text{SiO}_5$ minerals may allow of a better estimate of the depth of burial than a hypothetical temperature gradient. From experiments with this system, R. D. Schuiling (Proc.Koninkl.Nederl.Akad.V.Wetensch., Vol. 60, 1957, pp.220-226) draws the conclusion that kyanite is stable between 10 and 14 Km at temperatures of 410°-580°C and low vapour pressure. Above this temperature sillimanite should be stable at this depth and andalusite at depths less than 10 Km. A considerable measure of uncertainty, however, still attaches to the stability range of andalusite.

The depth of burial must have been sufficiently great to have reworked the original fabric of the Abbabis System (metasediments, metalavas and gneisses) into complete conformity with that of the overlying deformed and metamorphosed Damara sediments, unless complete “posthumous” renewal, in the sense of Stille, of an earlier orogenic trend be assumed for the later.

**LITERATURE INDEX**

No. 15—Right-angle chevron-type minor fold in laminated "sandy" biotite schists with bands of amphibole-pyroxene-garnet granulite. Note parallelism of limbs and displacement to the right of upper "kink" in top fold. Axial plane of lower "kinks" makes angle of $\pm 30^\circ$ with regional strike of schists. Note that granulite bands, though competent, bend into right angle without fracturing. North bank of Swakop River on Rüdenau.

No. 16—Chevron-type minor fold in laminated biotite schists. Note that competent granulite band is bent into right angle without fracturing, but disappears through boudinage. The thinly laminated biotite-rich schists have flowed into fold lower down and developed an axial-plane cleavage ($\pm 35^\circ$ with regional ENE-WSW strike of schists) visible below two narrow lenticles of white quartz emplaced in lower "kink" of fold. Abundant elongate porphyroblasts of andalusite have grown along axial-plane cleavage, which does not cross granulite band; it also does not bisect symmetrically the right-angle "kink" of the granulite band, but the more inclined fold within the underlying biotite-rich schists. Same locality.
SECTION THROUGH WALDAU RIDGE AND GROSS BARMEN INTO KHAMAS HIGHLANDS

SECTION FROM NORTH OF KALIOMBO RIDGE THROUGH LIEVENBERG INTO KHAMAS HIGHLANDS

HORIZONTAL SCALE 1:500,000  VERTICAL TOPOGRAPHIC SCALE 1MM = 100 FEET

DESIGNATIONS THE SAME AS ON GEOLOGICAL MAP EXCEPT THAT KHAMAS SERIES IS DASH-LINED TO INDICATE DIP
GEOLOGICAL MAP OF AREA BETWEEN OKAHANDJA AND OTJIMBINGWE, SOUTH WEST AFRICA

REFERENCE

THERMAL SPRINGS. KB = Klein Barmen OK = Okandu

KARROO DOLERITE.

Li ZONED PEGMATITES: with Lithium Minerals, Beryl, Columbite-Tantalite, etc.

PEGMATITES: often with Muscovite, Black Tourmaline and Almandine Garnet.

GRANITES: Mostly massive medium grained Biotite Granite, in part leucocratic, but also including coarse porphyritic varieties.

Hornblende-Biotite Quartz DIORITE.

UPPER MAIN KHOMAS SERIES: Biotite-Schists, often garnetiferous, and Quartz-Biotite Schists.

LOWER KHOMAS SERIES: Biotite-Sillimanite Schists, Biotite-Andalusite Schists, Biotite-Staurolite Schists, "Sandy" Quartz-Biotite Schists, in part thinly laminated; in basal portion with numerous layers of Quartzite, Para-Amphibolite, Amphibolite-Pyroxene Granulite, Marble, etc.

UPPER MARBLE HORIZON: Crystalline Limestone, Para-Amphibolite and Amphibolite-Pyroxene Granulite.

MARBLE SERIES: Crystalline Limestones, Para-Amphibolites, Amphibole-Pyroxene and Amphibole-Pyroxene-Garnet Granulites and banded Quartzite-Amphibolite.

CHUOS TILLITE: Unsorted Facetted Erratics in Biotite Schist Matrix.

QUARTZITE SERIES: Pale red felspathic Quartzites, Grits and Arkoses, often with Sillimanite, and abundant pegmatite schlieren, grading into reddish Gneisses and red Granite, mostly aplitic or pegmatitic, in part with intrusive contacts and off-shoots outside domes.


SCALE 1:300,000
• GEOLOGICAL MAP OF AREA BETWEEN OKAHANDJA AND OTJIMBINGWE, SOUTH WEST AFRICA •

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- **DARMA SYSTEM**
  - **UPPER MAIN KHOMAS SERIES**
  - **LOWER KHOMAS SERIES**
  - **UPPER MARBLE HORIZON**
  - **MARBLE SERIES**
  - **CHUOS TILLITE**
  - **QUARTZITE SERIES**

**SCALE 1:300,000**

- **Dip.**
- **Vertical Dip.**
- **Roads.**
- **Railway.**

**MILES**

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**KILOMETERS**

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SECTION THROUGH WALDAU RIDGE AND GROSS BARREN INTO KHMAS HIGHLANDS

SECTION FROM NORTH OF KALIONBO RIDGE THROUGH LIEVENBERG INTO KHMAS HIGHLANDS

HORIZONTAL SCALE 1:500,000 VERTICAL TOPOGRAPHIC SCALE 1MM = 100 FEET

DESIGNATIONS THE SAME AS ON GEOLOGICAL MAP EXCEPT THAT KHMAS SERIES IS DASH-LINED TO INDICATE DIP
No. 1—Intensely contorted rock of alternating bands of quartzite and narrow para-amphibolite layers. Main Marble Horizon, Northern Rüdenau.

No. 2—Banded rock composed of alternating layers of boudinaged pyroxene-garnet granulite and fine-grained "sandy" biotite schists. Main Marble Horizon. Northern Rüdenau.
No. 3—Disharmonic folding, overturned towards SSE, in laminated "sandy" biotite schists with intercalations of narrow biotitic quartzites and thicker white quartzites. Lowermost Khomas Series. Gross Waldau River, northern Gross Barmen.

No. 4—Highly contorted alternating layers of "sandy" biotite schists and fine-grained white quartzite. Note "rolled" boudinaged thicker quartzite layer. Minor folds slightly overturned towards SSE. Very white rock on left is aplite. Lowermost Khomas Series. Gross Waldau River, northern Gross Barmen.
No. 13—Chevron-type minor fold in same rock types. Note axial-plane fracture, in line with pencil, making angle of 40° with regional strike. North bank, Swakop River, Gross Barmen.

No. 14—Chevron-type minor fold in thinly laminated “sandy” biotite schists with boudinaged bands of amphibole-pyroxene-garnet granulite. Axial plane at 45° to regional strike. Same locality.
No. 5—Digitating front of fold overturned towards SSE. Same rocks and locality as Photo 4.

No. 6—Example of very rarely seen tight folding of Khomas schists. Photo at right angles to strike. Western escarpment of Khomas Highlands near Donkerhoek.
No. 7—Intrusive contact between Donkerhoek granite, in foreground, and Khomas schists, south of Otjimbingwe, showing innumerable parallel pegmatites and aplitic granite offshoot on top of hill on right. Dip of schists and concordant pegmatites steep to vertical.

No. 8—Thin layers of boudinaged white biotitic quartzite in drag-folded thinly laminated, "varved", biotite schists of lower Khomas Series. Some joints along axial plane direction of drag fold; others more or less at right angles to bedding. Lower Gross Waldau River. Gross Barmen.
No. 9—Numerous boudinaged bands of biotitic quartzite in thinly laminated “sandy” biotite-schists of lower Khomas Series. Lower Gross Waldau River, Gross Barmen.

No. 10—Heavily boudinaged bands of amphibole-pyroxene-garnet granulite in “sandy” biotite schists of lower Khomas Series. Note darker, garnet-rich core of boudins. Same locality.
No. 11—"Torpedo" boudin of same rock at same locality as No. 10. For scale note pencil.

No. 12—Chevron-type minor fold in thinly laminated biotite schists with intercalated, boudinaged narrow layers of light, biotite-speckled quartzite. Note welt, due to slight silica-impregnation in axial plane, making angle ±45° with ENE-WSW regional strike of schists. North bank, Swakop River, Gross Barmen.
No. 15—Right-angle chevron-type minor fold in laminated "sandy" biotite schists with bands of amphibole-pyroxene-garnet granulite. Note parallelism of limbs and displacement to the right of upper "kink" in top fold. Axial plane of lower "kinks" makes angle of $\pm 30^\circ$ with regional strike of schists. Note that granulite bands, though competent, bend into right angle without fracturing. North bank of Swakop River on Rüdenau.

No. 16—Chevron-type minor fold in laminated biotite schists. Note that competent granulite band is bent into right angle without fracturing, but disappears through boudinage. The thinly laminated biotite-rich schists have flowed into fold lower down and developed an axial-plane cleavage ($\pm 35^\circ$ with regional ENE-WSW strike of schists) visible below two narrow lenticles of white quartz emplaced in lower "kink" of fold. Abundant elongate porphyroblasts of andalusite have grown along axial-plane cleavage, which does not cross granulite band; it also does not bisect symmetrically the right-angle "kink" of the granulite band, but the more inclined fold within the underlying biotite-rich schists. Same locality.
No. 17—Alternating bands of non-laminated biotite-rich schists and "sandy" biotite schists, with interbedded narrow bands of light-coloured biotite quartzite (bottom and top) and speckled amphibole-pyroxene-garnet granulite, have been deformed into drag-folds. Note contortion, boudinage and disruption of both; particularly the biotite quartzite bands have been disrupted. Note how strong, closely spaced fracture-cleavage, marked by thin biotite lines, has been developed throughout in the non-laminated biotite-rich layer immediately below the granulite band. Where the biotite-rich layer has been thickened by flow, on the right, the fracture-cleavage extends also into the layer immediately below, right up to the first appearance of bedding-lamination; it here also shows a slight "fanning out" upwards. Where, on the left, this layer has been less deformed the fracture cleavage bisects the major "kink" in the granulite layer approximately symmetrically, viz. is oriented parallel to the axial plane. Note that no andalusite has been developed in this particular, highly fracture-cleaved layer, but makes its appearance lower down, oriented parallel to the main axial-plane cleavage direction. Note intermittent fracture along axial plane of main drag-fold. North Bank of Swakop River on Rüdenau.

No. 18—Fracture-cleavage developed in poorly laminated band below amphibole-pyroxene granulite layer in middle of photo. Granulite band is not fracture-cleaved but shows two right-angle tension- or rotation-joints. Abundant andalusite developed in non-laminated band, near top, parallel to axial-plane fracture-cleavage. Quartz vein parallel to bedding in upper left corner of photo. Same locality.
No. 19—This photo should be viewed upright in direction of white pencil.

Boudinaged aggregate of amphibole-pyroxene-garnet granulite bands at bottom. Widely spaced, slightly curved, fracture-cleavage indicated by lines rich in biotite, in crenulated laminated schists. Fracture-cleavage not, or barely, developed in layer higher-up, with thicker “sandy” bands. Fracture-cleavage again well developed and more closely spaced in poorly laminated biotite-rich zone higher up, with long andalusite porphyroblasts parallel to fracture-cleavage. No fracture-cleavage at all in uppermost thinly laminated (“varved”) “sandy” biotite schists. Lower curved fracture-cleavage steeply inclined to bedding; upper andalusite-bearing fracture-cleavage at ± 35-50°. North bank of Swakop River on Rüdenau.

No. 20—Minor fold with long andalusite porphyroblasts developed along axial-plane fracture-cleavage at ± 30° to bedding within un laminated or very thinly laminated biotite-rich bands. Distorted quartz vein parallel to bedding. For scale note pencil in direction of fracture-cleavage. Gross Barmen.
No. 21—Laminated "sandy" biotite schists overlain by fracture-cleaved, non-laminated band with abundant elongate andalusite porphyroblasts developed along fracture-cleavage at ± 40° to bedding. Lower Gross Waldau River, Gross Barmen.

No. 22—Masses of andalusite porphyroblasts developed along fracture-cleavage in biotite-rich schists. Note narrow separating layers of thinly laminated "sandy" biotite schists. Hot Spring Area, Gross Barmen.
No. 23—Abundant andalusite porphyroblasts developed along fracture-cleavage in biotite-rich schists at angle of 45° with bedding. Note sparse, narrow, thinly laminated layers of "sandy" biotite schists in upper portion. Hot Spring Area, Gross Barmen.

No. 24—Elongate porphyroblasts of andalusite developed along fracture-cleavage in biotite-rich schists. Gross Barmen.
No. 33—This photo should be viewed upright with andalusite porphyroblasts, oriented in strongly developed axial-plane cleavage, at bottom. Note narrow vertical quartz vein whose crenulations are controlled by axial-plane cleavage. Note absence of the latter in laminated "sandy" biotite schists near top. White specks in upper right portion of photo are loose small quartz fragments. North Bank of Swakop River, Gross Barmen.

No. 34—Narrow vertical quartz vein cutting at high angle across "sandy" biotite-schists whose lamination can be seen in top left corner of photo. Two vertical boudins of biotitic quartzite parallel to bedding. Note that axial planes of crenulations of quartz vein are oriented parallel with bedding (slip); also note cleavage, whose trend is indicated by pencil, developed around quartz vein in direction of general axial-plane cleavage of area and that right-hand limbs of crenulations are mostly parallel with it. Lower Gross Waldau River, Gross Barmen.
No. 25—Elongate porphyroblasts of andalusite developed comparatively sparingly parallel to bedding-lamination of more "sandy" biotite schists. Gross Garmen.

No. 26—Elongate porphyroblasts of andalusite developed abundantly along fracture-cleavage in upper, more biotite-rich layer, and much more sparingly and less elongate in underlying, more "sandy" biotite schists showing bedding-lamination. Though in part randomly distributed, alignment of porphyroblasts along fracture-cleavage direction is indicated. Note development of andalusite along single shear-fracture oblique to bedding lamination and crossing normal fracture-cleavage direction. Lowermost Gross Waldau River, Gross Barmen.
No. 27—Vertical quartz vein, cutting at right angles across strike of lower Komas schists, crenulated in direction of vertical bedding-schistosity. Note oblique “feather” joints on left side, (Photo should be viewed upright with pencil pointing to right). Lower Gross Waldau River, Gross Barmen.

No. 28—Horizontal quartz vein, cutting at right angles across dip of laminated lower Komas schists, deformed into isoclinal folds on right, and boudinaged and disrupted on left, individual boudins lying in strike of bedding-schistosity. Lower Gross Waldau River, Gross Barmen.
No. 29—Thick, lenticular, vertical quartz vein emplaced along axial plane of minor fold in laminated schists with sharply demarcated biotite-rich layers probably due to bedding-slip shear. Axial plane of fold $\pm 45^\circ$ to bedding. North bank of Swakop River, Gross Barmen.

No. 30—Vertical quartz veins emplaced along axial planes of two adjacent minor folds. Note narrow offshoot quartz veins parallel to bedding, indicating bedding-slip at time of drag-folding. Same locality.
No. 31—Vertical quartz vein of irregular thickness emplaced along axial plane of drag-fold making angle of $40^\circ$ with bedding; petering-out quartz vein replaced by silicified welt on lower left; thin offshoot quartz veins, of same age, parallel to bedding. Comparatively small andalusite porphyroblasts developed within biotite-rich bands showing, at least in part, orientation along axial-plane cleavage. North Bank of Swakop River, Gross Barmen.

No. 32—Narrow vertical quartz veins cutting obliquely across bedding, crenulated by axial-plane cleavage developed in non-laminated biotite-rich layers. Note isolated small andalusite porphyroblasts oriented parallel with bedding in lower right. Other small white specks on banded schists are not andalusite but small loose fragments of quartz. For scale note white pencil placed parallel with axial plane cleavage. Same locality.
No. 35—Laminated “sandy” biotite schists, with boudins of amphibole-pyroxene-garnet granulite, crossed at right angles by numerous joints, in part filled with fine grained silica, trending parallel with adjacent hot farm bore-hole wrench-fault. Gross Barmen.

No. 36—Symmetrically intersecting shear joints in vicinity of closely adjacent hot farm bore-hole wrench-fault, the main ± NNW stress direction neatly bisecting acute angle. Note brecciation of banded and laminated schists; breccia cemented by finegrained silica. Photo should be viewed with loose white pebbles at bottom. Compass needle is fixed and does not indicate strike directions. Gross Barmen.
Discussion

G. Söhnge

Professor Gevers has made yet another very valuable contribution to the over-all picture of the great Damara geosyncline, and the superb close-up photographs that accompany his paper deserve the highest compliment. It is now possible to compile a reasonably detailed map from published as well as unpublished sources, embracing the area between the northwest border of the Khomas Highlands and the Ugab River catchment from the Atlantic Coast as far inland as Kalkfeld and Okahandja. A striking feature of this map is the zone, 25 miles wide, of partly granitized quartzite brachy-anticlines, bounded on the north by marble and schist formations (intruded by Salem granite) and to the south by the belt of uniform quartz-biotite schist of the Khomas Series. If Prof. Gevers' structural term "Ababbis swell" does not include all of this broad zone of early Damara sedimentation, then the accumulation of quartzites and conglomerates as a depositional feature may be given a special name such as the "Chuos belt" considering that it has so markedly influenced the structural style, the degree of regional metamorphism, granite emplacement and character of mineral concentration within the eugeosyncline. Everyone acquainted with the area knows that tin-tungsten deposits are widespread north of this belt; lithium-beryllium pegmatites and contact-metamorphic copper deposits are typically located within it; and the uniform quartz-biotite schists of the Khomas Highlands to the south are host to comparatively few metallic ore prospects, mainly copper. Inasmuch as the pegmatites and the epigenetic mineral deposits in the folded formations have in the past been ascribed directly or indirectly to igneous intrusion, the economic geologist is keenly interested in the interpretation of field evidence bearing on the origin of the plutonic rock masses. The writer has on numerous occasions observed the varied structural form, the mineral composition and texture of the granites in the Chuos belt, and agrees with Smith, Gevers, Roering and others that they are very largely products of ultrametamorphism. In the present paper attention is drawn to a vast sill of "undoubtedly intrusive granite" reaching from Okahandja to Donkerhoek, with the tentative suggestion that it may have played a part in the evolution of the lithium-beryllium-bearing pegmatites of the area to the north. I wish to refer to certain structural and petrographic aspects that have made me believe that also the Donkerhoek granite is essentially autochthonous, like the red granites and the Salem granites, all of which developed local mobility and injection-relationships.

(A) Structure in the Khomas Series

The map (Plate I) and sections (Plate II) give the impression that the dip of the Khomas beds steepens progressively to the north until it is practically vertical at Gross Barmen. This is supported by the author's description on pp. 230, 351, and expanded to stress the southward over-folding displayed still farther north in the Waldau Ridge area. It may be confusing to the reader who does not realize that half of the northward-dipping beds are upside down and that such dips per se give no indication as to whether the over-all dip of the schist formation is to the north or to the south. Worse still, the intense schistosity is accompanied in places by parallel banding from metamorphic differentiation, and where the bedding and the schistosity do not coincide it may be most difficult to distinguish between them. To demonstrate the point I include a photograph (looking west) taken on Auuanis 306, about 30 miles south of I itjimbine, showing isoclinally overfolded Khomas beds on which dip measurements range from 20° S to 50° N (to the right), whereas the formations as a whole are tilted 20° S (to the left). The net effect is that the Hakos Series and the Nosib quartzites logically appear in the broad anticlinorium north of the Swakop River, and there seems little need for postulating major differential movement between these formations and the overlying Khomas schists, or, as suggested tentatively by the author, accommodation of décollement thrusting in the liquid sheet of Donkerhoek granite.

(B) Structural Features of the Donkerhoek Granite

In describing the contact-relationship between this allochthonous granite and the folded Damara formations Professor Gevers puts much emphasis on tongues of granite invading the sediments and on the abundant xenoliths of schist preserved in the granite. Such evidence loses force if we compare with it the contact-features and tongue-and-xenolith pattern of the autochthonous Salem granite as displayed e.g. in the Okombake Reserve northwest of the Erongo Mountains. As no intrusive contact of Donkerhoek granite against Salem granite has so far been established in the Wilhelmstal area one wonders whether further work will not indicate a transition from one type of granite into the other. The structural evidence that the floor of the Donkerhoek granite conforms to the fold structure of the underlying bedded rocks would fit well into the hypothesis that the "intrusive sheet" represents a stratigraphic zone of granitized meta-sediments.
The numerous veins of granite and pegmatite in the roof of the Khomas schist may be regarded as evidence that the steep foliation of the latter offered optimum conditions for the ascent of heat and granitizing solutions. The myriads of simple pegmatites associated with the Donkerhoek granite may be explained, following T. T. Quirke and W. H. Collins (1930, 1949), in their interpretation of the Killarney granite (Canada), as generated in the schists and forming the advancing front of granitization. The aplitic granite body of Klein Barmen would in this frame of thought represent not a magmatic intrusion through the schist but a cap of transformation-granite hiding yet another dome of marble and meta-quartzite in the floor.

These remarks prove nothing but indicate how equivocal the evidence can be in a metamorphic terrain. To distinguish between a transgressive contact caused by magmatic injection and one resulting from granitization usually involves subjective reasoning and a modicum of uncertainty. In order to solve the problems of form and petrogenetic history of the Donkerhoek granite it would be necessary to map the whole "sheet" in sufficient detail (granite tectonics) to establish the development and meaning of flow-structure, schlieren, textural and mineral variations, as well as of contact-features. This may even have to include evaluation by process-response models based on heavy mineral content, as advocated by E. Whitten (1941). Such investigation may determine whether this vast mass of granite represents some 4,000 cubic miles of magma that broke through the marble-quartzite succession to spread out as a sheet (to the northeast?), notwithstanding the lack of evidence of such disruption anywhere in the present exposures of floor formations. It would also assess to what extent flow-structure is primary (magmatic?), or inherited from sedimentary banding in the schists, or taken from metamorphic banding parallel to the schistosity. Thus the writer has observed a gross dip of "rifting" in the granite of 10°—20° NW just west of Otjimbingwe, and about 40°—50° SE few miles to the southwest; yet local biotite-rich schlieren (with flow-puckering) are nearly vertical and could well represent zones of metasomatic, ferromagnesian concentration along the axial-plane foliation. Finally, such structural analysis may support or invalidate the view that the Donkerhoek granite "lifted the Khomas schists off and up from the underlying lower Damara sediments", and by lateral push developed a zone of horizontal shearing, a mile wide, in the vertical schists on Gross Barmen.

(C) Petrographic Aspects of the Donkerhoek Granite

In many localities this granite is aplitic and partly granophytic, as stated by Professor Gevers. These textures cannot be regarded as diagnostic of crystallization from a magma; the writer submits that full-fledged granitization can produce the very same features, e.g., Bushveld granophyre of the Transvaal. In the transition zone from granite to schist some ten miles south of Otjimbingwe all stages of metamorphic change are displayed, the final product being the even-grained Donkerhoek granite. The uniform character of this rock derives possibly from the circum-stance that the Khomas schist parent-formation is likewise relatively uniform in texture and mineral make-up, and the redistribution of elements during granitization attained virtually complete equilibrium. In the case of the Salem-type granite these processes did not reach the end-stage because the sedimentary rocks were probably more heterogeneous, the granitizing fluids less pervasive, and ionic migration more restricted.

The point has been made that the reddish granite of the quartzite domes and the Salem-type granite above the marble of the Hakos Series formed by isochemical ultrametamorphism. There--against it is claimed that the Donkerhoek granite diverges too far in chemical composition from the quartz-biotite-sericite schists to have been formed in like manner. I wish to refer to the following reactions presented in textbooks:

\[ \text{muscovite} + \text{quartz} = \text{andalusite} + \text{orthoclase} + \text{water}. \]
\[ \text{muscovite} + \text{biotite} + \text{quartz} = \text{orthoclase} + \text{garnet} + \text{water}. \]

The abundance of andalusite and sillimanite in the Khomas schists near the granite contact means that potash was eliminated (from the mica) and probably went to form microcline in the granitization front. Almandine garnet, which is not uncommon in the Donkerhoek granite, may be a product of ultrametamorphic transformation instead of contamination in granite magma by inclusions of schist. The water liberated in the above reaction may have helped to bring about local mobility of the granitized mass, perhaps accounting also for the peripheral aureole of quartz-feldspar pegmatites. The claim that there was less chemical transfer in the generation of the reddish "dome" granites and Salem-type granites than of the Donkerhoek granite needs substantiation by extensive sampling and chemical analysis of the plutonic masses as well as their host- (or parent-) rocks.

Finally, if all three kinds of granite were formed essentially in place by ultrametamorphic transformation of Damara sediments then no igneous intrusive of deep-seated origin remains to account for the introduction of tin, tungsten, lithium, beryllium, copper, lead and zinc ores in this part of the great eugeosyncline. The understanding of ore genesis in this province therefore depends very largely on the detailed study of stratigraphic units, with due regard for secondary structure and metamorphism.
Isoclinally overfolded quartz-biotite schist of the Khomas Series on Amanis 306, looking west. The bedding dips 20° N (normal) to 50° N (inverted), axial-plane foliation about 35° N, and fracture-cleavage at intermediate angles. The ink line joining the crests of anticlines dips 20° S, which is the average inclination of the Khomas Series as a whole in this part of the geosyncline.
Reply to Dr. A. P. G. Söhnge

I am grateful to Dr. Söhnge for his constructive criticism of certain aspects of my paper. With the perspicacity born of long experience he has put his finger on what I know to be its weakest points, viz. the lack of detailed structural mapping within the Khomas Highlands and adequate structural, mineralogical, and chemical analysis of the Donkerhoek granite. It had not been my intention to publish the paper on the present extent of investigation. On two occasions I suggested further detailed work in the region to research students; unfortunately, however, lack of funds negatived not only these efforts, but also further field work by myself. Dr. E. Lubbert, the generous benefactor of scientific endeavour in South West Africa, is alas! no longer among the living.

I have stressed that in some aspects my work must be regarded as being of a reconnaissance nature only. From Dr. Söhnge’s comments, I should have stressed more strongly the generalized nature of the dip signs within the main mass of schistose rocks building up the Khomas Highlands (Map, Plate I, and Sections, Plate II). The dips shown on my map are meant to represent the average within the major folds of the Khomas synclinorium. They are based on sedimentary features, viz. well marked bedding planes of flaggy or more thickly bedded biotitic quartz schists (metagreywackes). To my mind, there is in their case little danger of bedding being confused with fracture-cleavage and axial-plane schistosity, or even pure metamorphic differentiation-banding. I have made specific and detailed reference to such features in my description of the Gross Barmen-Rüdenau area.

The photo, appended by Dr. Söhnge from 30 miles south of the Otjimbingwe, showing details of folding and his remarks concerning dip of bedding and actual tilt of the formation as a whole, are certainly most noteworthy. But this method of deducing the actual tilt can only be valid if the measurements are made not only on one plane, which on the photo is a steep erosion slope more or less at right angles to the strike, but if the plunge of the fold axes is also taken into account, i.e. if the structural analysis is made in three dimensions. The over-all tilt line drawn by Dr. Söhnge on this photo can only be valid if the fold axes are absolutely horizontal.

Furthermore, the three-dimensional analysis should cover an extensive enough area. Application of the method used by Dr. Söhnge to the folding shown on Photo 6, Plate V, of my paper, would give a different angle of over-all tilt, i.e. practically none at all, for that particular locality, a few miles east of the schist-granite contact at Donkerhoek. The necessity for prior demonstration of the absence of additional tilting by faulting is obvious, but probably need not be considered in this region.

Outcrops showing such details of folding within the great Khomas synclinorium are rather rare in these areas visited by me; a complete three-dimensional picture is thus mostly not readily available. Since Dr. Söhnge speaks of the average inclination of the Khomas Series as a whole, he presumably must have been more successful in locating suitable outcrops.

Dr. Söhnge’s argument in this connection is that the lower members of the Damara System, on his interpretation of the structure south of Otjimbingwe, appear logically in the broad antiform north of the Swakop River, without the need for major differential movements between these formations and the overlying Khomas schists, or “accommodation of décollement in the liquid sheet of Donkerhoek granite”.

I would like to point out that my representation (Map, Plate I) of the area south of the Waldau ridge dome, where the Donkerhoek granite is absent, at least on surface, also shows the appearance of the lower Damara sediments within the dome and brachyanticlinal structures to be quite logical, as emphasised in the detailed description of the stratigraphic succession. Yet there can be no doubt here of the actual presence of differential movements within the schists.

The vertical dip of the rocks over a 24—3 miles wide belt is based on what most definitely is bedding in lithologically well differentiated sediments. The photo’s should make clear that confusion with fracture-cleavage or axial-plane schistosity is out of the question. The accentuation of the strongly marked banding by metamorphic differentiation is specifically mentioned by me.

I would also like to point out that my account does not postulate differential movements between formations, but between rocks affected by most strikingly dissimilar styles of deformation. The boundary zone between the two highly contrasting tectonic styles, viz. infra- and suprastructure of the orogen, is relatively so sharply delineated, that I have difficulty in envisaging a mechanism not involving differential movements.

Besides, if in the Otjimbingwe area the over-all tilt of the schists in the Khomas Highlands is to the south and the dome and brachyanticlinal structures in the north are en masse overfolded to the south, often strongly so, how is this to be explained without some measure of differential movements in the separating zone occupied by the Donkerhoek granite?
**Décollement** is too "strong" a term to use for the differential movements envisaged by me between infra- and supra-structure. I certainly did not have in mind thrusting of great magnitude. The boundary zone would, of course, be a favourable *locus* not only for widespread injection of granitizing melts but also for the ready ascent of granitizing solutions.

Whatever its origin, the vast body of Donkerhoek granite, does in fact separate the two highly contrasting styles of deformation, except in the area south of the Waldau Ridge dome. Here, however, the strikingly high degree of metamorphism over a wide belt and other features listed by me lend some measure of support to my suggestion of a concealed granite offshoot.

Such arguments, however, mean little, or nothing, to confirmed transformationists. Not that I consider most points raised by Dr. Söhng in his effort to show that also the vast body of Donkerhoek Granite could largely be of metasomatic origin, to be invalid. Having mapped the main areas of Salem Granite, which I too now consider to be largely autochthonous with boundary features caused by partial mobilization. I myself have pointed out (p. 215) that also the Donkerhoek Granite, when viewed *in toto* over its outcrop distance of 180 odd miles, largely conforms with the broad structural features, i.e. is to a very considerable extent concordant.

To Dr. Söhng the local, but frequent, cross-cutting relationships stressed by me, are merely the result of local mobilization. Tongues of granite invading the adjacent schists and myriads of pegmatites within the latter, of radically different composition and usually possessing knife-sharp contacts, are seen as products of "optimum conditions for the ascent of heat and granitizing solutions".

Dr. Söhng is, however, an eminently fair critic. He plainly states that his remarks on contact-relationships prove nothing, but serve to indicate how equivocal the evidence can be in a metamorphic terrain and that the interpretation of boundary-features usually involves subjective reasoning. With this I wholeheartedly agree. This is where conditioning by range of experience and familiarity or otherwise with mechanics, thermo-dynamics, chemical equilibria, etc., etc., play a determining rôle. Even mere temperament is an important factor. My own mental make-up induces me to seek variety and shun uniformity.

Dr. Söhng freely admits that he has not proved the vast body of Donkerhoek granite to be of metasomatic origin and largely autochthonous in nature. I admit as freely that I have not proved it to be an intrusive sheet, injected in more or less fluid state. But I incline that way, at least for its bulk. I have already outlined my reasons and need not repeat them here.

I wish to state, however, that I fully support the program outlined by Dr. Söhng for establishing more securely the form and petrologic history of one of the largest bodies of granite in South West Africa. If Dr. Söhng's criticism of my conclusions should serve to stimulate anyone experienced in the necessary techniques to undertake this work, I shall give enthusiastic support.

Among other things, it will be necessary, as pointed out by Dr. Söhng, to establish the precise relationship of the Donkerhoek Granite to the Salem Granite so abundantly distributed to the west and northwest. I myself prefer to speak of Salem *type* granites. I have already pointed out (pp. 217-218) that the Donkerhoek granite *does* indeed locally, and sometimes over considerable areas, grade into a Salem *type* of granite. For the reasons outlined in my paper, I regard the development of these rocks as being due to the incorporation and digestion by normal leuco-granite of xenolithic bodies of schists crowded with *dents de cheval* felspars produced by prior permeation of the schists by solutions emanating from the surrounding magma. Dr. Söhng would no doubt reverse the process. To him the biotite-rich, frequently porphyritic, types would represent initial stages and the highly leucocratic and even-grained main phase the end-product of "full-fledged" granitization.

Only the results of the detailed procedures listed by Dr. Söhng will enable interpretation on a more precise basis.

Dr. Söhng's suggestion that "the uniform character of the Donkerhoek Granite derives possibly from the circumstance that the Khomas schist parent formation is likewise very uniform in texture and mineral make-up", does not appear to fit the facts very closely. The lowermost Khomas sediments, which on the basis of *in situ* transformation *disappear* to the west of Gross Barmen and Rüdenau, and around the western and northern flanks of the Waldau ridge dome, represent the lithologically most diverse portion of the entire Khomas succession. Contrary to the suggestion of Dr. Söhng, the schistose rocks from which Salem types of granite were developed farther to the northwest and west are frequently much more uniform.

Other noteworthy points in this general discussion are the following. The stress-oriented nature of the abundant andalusite porphyroblasts along the shear zone in the Gross Barmen—Rüdenau region indicates metamorphism to have proceeded *pari passu* with this particular phase of deformation. No shear zone of similar marked development was noticed in the granite to the southwest; admittedly its effects would be much more difficult to pick up in the massive rock. If granitizing solutions on a scale vast enough to form the enormous body of Donkerhoek Granite were able to stream through the underlying "marble-quartzite succession", why should fluid magma as such not have been able to effect a break-through?
In conclusion, I wish to refer briefly to Dr. Söhnges final statement, viz. "if all three kinds of granite were formed essentially in place by ultrametamorphic transformation of Damara sediments, then no igneous intrusive of deepseated origin remains to account for the introduction of tin, tungsten, lithium, beryllium, copper, lead and zinc in this part of the great eugeosyncline".

No matter what its origin, the Donkerhoek Granite, though by far the largest mass of granite, appears to have been of little significance in this respect. As stressed in my paper, no important pegmatite mineralization appears to be connected with it; the spodumene-tantalite-beryl-aquamarine-bearing pegmatites on Donkerhoek, those carrying beryl farther to the north-northeast on Komuanab, and the isolated beryl-bearing pegmatite on Tugab, southwest of Klein Barmen, are so far about the only occurrences that can definitely be linked with this granite. Dr. Söhnges appears to have misunderstood my remarks on p. 219. I in no way suggested that the lithium- and beryllium-bearing pegmatites in the Karibib area were directly connected with the Donkerhoek granite. I merely put forward the tentative idea that "possibly the emplacement of such a vast mass of granite helped to raise the thermal gradient in its floor sufficiently for ultrametamorphic and magmatic processes to be once more stimulated".

With reference to Dr. Söhnges initial remarks, I prefer to retain the designation Abbabis swell. Since this pre-Damara topographic feature directly controlled the areal deposition of quartzites and conglomerates, the additional term Chuas belt suggested by Dr. Söhnges would appear to be superfluous.

The outline of economic mineral distribution relative to the Abbabis swell given by Dr. Söhnges, certainly holds in broad outline. It must be pointed out, however, that the occurrence of lithium-beryllium-bearing pegmatites in the Karibib area is very local only, when the great extent of this swell is considered.

Furthermore, the extensive lithium-beryllium Van der Made pegmatites in the Erongo Schlucht are located right within the Southern Tin Belt and contain subordinate amounts of cassiterite. Tinschmann's pegmatite on Dawib Ost, rich in beryl, too is situated within this tin belt. Beryl also occurs in the Sandamap pegmatite farther to the northwest.

The well-known lithium- and beryllium-rich Karlsbrunn pegmatite in the Karibib area was initially worked for cassiterite. The main Donkerhoek pegmatite contains appreciable amounts of spodumene.