



UNIVERSITY OF THE WITWATERSRAND
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ASPECTS OF THE GENESIS AND CRYSTALLIZATION SEQUENCE OF
THE KARIBIB PEGMATITES, SOUTH WEST AFRICA

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ABSTRACT

Several of the more important lithium- and beryllium-bearing pegmatites of the Karibib area have been studied in detail with regard to their mode of emplacement, internal zoning, and mineralogy. They reveal a fairly uniform zonal arrangement which is often developed in a vertical, as well as a horizontal, direction. An idealized arrangement of zones is given, and an attempt is made to explain the fractionation. Vertical fractionation is considered to be the result of the development of a gas phase in the crystallization of the pegmatite magma.

It is shown that these complex pegmatites are related to late-kinematic granites of the Damara Orogeny. A "pegmatite series" is suggested, broadly relating the complexity of pegmatites to time and space in orogenic belts. Simple pegmatites are thought to be of a local secretion origin, forming at a fairly early stage in the metamorphism, and being related to the first stages of mobilization of granitic material. Complex pegmatites are genetically related to late-tectonic granite plutons intruded into environments of moderate- to high-grade metamorphism. Similar mobilized granites, emplaced at higher crustal levels in the form of high-level granite plutons, crystallize at a relatively quicker rate, with resulting wide dispersion of unusual elements in the normal granite-forming silicates, and of fluxing agents. The notable exception to this appears to be tin mineralization associated with high-level orogenic granites, as well as anorogenic granites.

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ASPECTS OF THE GENESIS AND CRYSTALLIZATION SEQUENCE OF
OF THE KARIBIB PEGMATITES, SOUTH WEST AFRICA

INTRODUCTION

During the period 1959-1963 the Economic Geology Research Unit was engaged in a research project involving studies of the nature, origin, and regional setting of the economically mineralized pegmatites in the vicinity of Karibib, South West Africa. These bodies constitute one of the most important sources of beryllium and lithium in Southern Africa. The main objective of the investigations was the determination, if possible, of the factors responsible for the development and localisation of the mineralization in the hope that such knowledge might assist in the search for further ore-bodies and the extensions of known pegmatites.

The exploited occurrences are present in rocks of the Damara System which is of late Precambrian age, and were formed during an orogenic cycle which took place about 500 million years ago. The general geology of the area, which represents the southwestern part of the Damara geosyncline, has been described by Smith (1962) in Information Circular No. 8 issued by this Unit, and entitled "Metamorphism, Granitization, Structure and Mineralization between the Khan and Swakop Rivers, South West Africa". The actual pegmatites investigated are located, for the most part, within a radius of 20 miles from the town of Karibib which is approximately 120 miles by rail from Walvis Bay on the Atlantic coast. They include the bodies known as Rubicon, Helicon, Karlsbrunn, Brockmann's (on Albrechtshöhe), Becker's (on Otjua), Koliombo, Henckert's (on Dernburg), Van de Made's (in the Erongoschlucht). The more important of these have been reported on by Roering and Gevers (1962) in Information Circular No. 9 : "Lithium- and Beryllium-bearing Pegmatites in the Karibib District, South West Africa". The manner in which the pegmatites were emplaced in the Damara rocks, and the role which structure played in the process, were dealt with by Roering (1961) in Information Circular No. 4 : "The Mode of Emplacement of Certain Lithium- and Beryllium-bearing Pegmatites in the Karibib District, South West Africa".

The regional setting, the mechanics of emplacement, and the composition of the pegmatites having been discussed, it remains for consideration to be given to the manner of generation of the bodies, and to the cooling history which has resulted in the observed structures and textures. Attempts have been made to answer the following questions : (a) are complex pegmatites products of in situ crystallization of pegmatite magmas injected into structurally-controlled sites, or do they represent the results of secretion-diffusion processes?, (b) if pegmatites do crystallize from a magma, what can be deduced from field observations about their crystallization history?, and (c) what conclusions can be drawn about such a pegmatite magma, if it exists?

It is hoped that the discussions and speculations which follow will contribute to a more complete understanding of the pegmatites in the Karibib area, in particular, and to the knowledge of pegmatite genesis, in general, which topic has already received considerable attention from a large number of investigators (Jahns, 1955).

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ASPECTS OF THE CRYSTALLIZATION SEQUENCE OF THE PEGMATITES

A. SUMMARY OF FIELD OBSERVATIONS ON THE KARIBIB PEGMATITES

In order to present a synopsis and tentative synthesis of the information gathered in the field, Fig. 1 has been constructed. All the zonal units have been assembled according to the sequence of from oldest to youngest, in order to show that certain members tend to recur systematically from pegmatite to pegmatite. Certain shortcomings of the figure should be mentioned. For instance, owing to frequently rapid variations, it is often difficult to establish the overall relative proportions of the major mineral constituents in a particular zone, such as that of albite-perthite-quartz-muscovite. The Karlsbrunn pegmatite shows a continuous lateral variation from an albite-quartz-muscovite zone to a perthite-albite-quartz-muscovite rock. Where several large perthite crystals are fairly closely aggregated, perthite quantitatively dominates the other constituents, while immediately adjacent exposures may reveal a single perthite crystal only in a mass of albite-quartz-muscovite. In fact, when considering this zone, the assemblage should be regarded as indicating the most important minerals only, and not necessarily the complete sequence of minerals, from the most to the least important, excluding the accessories. In the Van de Made pegmatite there is a certain amount of doubt as to the true location of the cleavelandite-topaz zone which is probably a replacement unit, the more usual position of which is closer to the core margin.

The zonal pattern described by Cameron et al (1949) for North American pegmatites is, from the margins in towards the core, as follows :

1. plagioclase-quartz-muscovite
2. plagioclase-quartz
3. quartz-perthite-plagioclase with or without muscovite and biotite
4. perthite-quartz
5. perthite-quartz-plagioclase-amblygonite-spodumene
6. plagioclase-quartz-spodumene
7. quartz-spodumene
8. lepidolite-plagioclase-quartz
9. quartz-microcline
10. microcline-plagioclase-lithium micas-quartz
11. quartz

Those of the above zones which can be satisfactorily correlated with units in the Karibib pegmatites are listed in Fig. 1. Differences and discrepancies should be considered in the light of the following points :

- (i) the classification of Cameron et al (1949) does not contain a petalite-rich unit; North American lithium-pegmatites appear to be mainly spodumene-amblygonite-lepidolite-bearing types, in contrast to the Karibib pegmatites which often carry abundant petalite, but are notably deficient in spodumene.
- (ii) a late-stage sugary albite unit which is well developed as independent masses in several of the Karibib pegmatites, e. g. Karlsbrunn and Van de Made, is included.
- (iii) a core margin zone in which many of the economic minerals are found is introduced for the Karibib pegmatites; this zone is believed by Heinrich (1948) to be a variation of the intermediate zone, while Brotzen (1959a) considers it to be a diagnostic member of his pegmatite classification.

- (iv) in the Karibib pegmatites a cleavelandite-rich unit is very often developed immediately before the lithium-bearing zones
- (v) a mixed core zone is introduced for those narrow pegmatite dykes in which the lithium ore zone, the quartz core, and the core margin mineralization are telescoped into a single unit.

Other reasons for the lack of complete correspondence between zonal patterns and for divergences from their eleven dominant mineral assemblages have been given by Cameron et al (1949) as :

- (i) a given lithologic unit might occur at two places in the sequence
- (ii) two or more zones might be telescoped (see also Hanley, Heinrich and Page, 1950)
- (iii) the mineral assemblage might be slightly different from the norm.

It was first pointed out by Cameron (1955) that, despite the differences mentioned above, there is a marked degree of similarity between the zoning patterns in the pegmatites of South West Africa and North America. The major difficulty in a precise correlation of the two sequences is provided by the presently proposed albite-perthite-quartz-muscovite group and Cameron et al's (1949) Group 3, consisting of quartz-perthite-plagioclase with or without muscovite or biotite. This rock-type, as it is developed in pegmatites of the Karibib district, is common in late-tectonic intrusive massifs of pegmatitic granite, and consists essentially of a very coarse variety of such granite, with phenocrysts of microcline perthite embedded in a matrix of albite-quartz-muscovite that often shows corrosive relationships with the perthite. It resembles closely that described by Page et al (1953) from the Black Hills area. In his Zone 3, in which perthite, quartz, muscovite and plagioclase are the major constituents, he found that concentrations of perthite are characteristically confined to the upper part of the pegmatite body, and that the perthite content "decreases from the outer to the inner contact, and also down dip". Furthermore, "textures indicate that the uniform intergrowth of albite, quartz and muscovite, which forms the groundmass throughout the zone, formed later than the perthite". It would appear, therefore, that the Karibib albite-perthite-quartz-muscovite rock-type is, in fact, a variety of Cameron et al's (1949) Group 3.

From the detailed study of each individual pegmatite, and from the summarized tabulation of the data, the following idealized zonal arrangement and sequence of mineralization are taken to be typical of the pegmatite deposits found in the Karibib area :

(a) The outer pegmatite zone, of variable thickness, is essentially a very coarse-grained granite consisting of large perthite phenocrysts lying in a matrix of albite, quartz and muscovite. The inner portions of this zone sometimes reveal an enrichment of perthite which may grade into a giant perthite zone, as in the main Rubicon ore-body, and the Karlsbrunn pegmatite close to the lithium ore zones. This outer portion of the pegmatite may be sub-divided, in some instances, into two distinct units ; an outermost one of albite-quartz-muscovite, and an inner one of albite-perthite-quartz-muscovite.

(b) This sequence of essentially granitic crystallization is often abruptly broken by the appearance of a zone consisting mainly of cleavelandite, with minor quartz and muscovite, and characterized by the presence of numerous accessory minerals, often in economic quantities, which include beryl, columbite-tantalite, frondellite, topaz, and apatite. The zone is generally of the order 1 - 5 feet wide, depending on the original size of the pegmatite and the degree of fractionation. That it is not a late replacement unit is confirmed by observations at Rubicon where corroded crystals of beryl belonging to this zone are found lying in a matrix of lepidolite and albite comprising the next unit to form. The lepidolite-albite zone, in fact, replaces the beryl-bearing zone. The striking symmetry of the Rubicon body testifies to this zone preceding the lithium ore zones in the sequence of crystallization (Roering and Gevers, 1962). Significantly, this zone marks a distinct break in the crystallization history of the pegmatite - a change from the crystallization of essentially granitic

components to the formation of late-phase constituents (lithium-bearing and associated minerals). It possibly indicates the transition from magmatic crystallization to late-magmatic conditions, when pneumatogenic, and even hydrothermal, processes begin to operate.

(c) The succeeding group of minerals are rich in lithium, and are frequently associated with sugary albite. The more important minerals are petalite, lepidolite, and albite, while minor amounts of amblygonite also occur. There is a definite spatial arrangement and a definite time sequence in the formation of these minerals. Petalite crystallizes first, and collects in the upper part of the unit, generally forming a hood. Amblygonite, albite, and quartz may form at the same time. Immediately below this petalite hood, and at a somewhat later stage, fine-grained lepidolite is developed, together with albite and minor quartz. The final phase is represented by sugary albite which collects at the bottom of the portion of the magma chamber which has not yet crystallized. The sugary albite phase behaves diapirically in some instances, and intrudes, brecciates, and replaces earlier zonal constituents. Each successive stage can corrode previously consolidated units. During the entire process of complex diffusion and crystallization silica is apparently concentrated in the residual fractions of the pegmatite magma.

(d) The next zone which forms contains a cleavelandite-rich rock, located along the margin of the quartz core. The cleavelandite can vein, brecciate, and corrode the immediately adjacent lepidolite. It is often associated with beryl, columbite, tantalite, tourmaline, topaz, and apatite. Amblygonite may also form during this stage of mineralization though, in general, it tends to be associated with the petalite stage.

(e) The final stage of the crystallization sequence produces the quartz core. Quartz veinlets emanating from the core cut across adjacent lepidolite-rich and amblygonite-albite zones. Euhedral crystals of columbite and beryl at the core margin are completely surrounded by quartz. These observations suggest that quartz, although concentrated in the centre of the dyke, probably existed in some unconsolidated stage, such as a gel (Brotzen, 1959). The narrow veinlets of lithium mica transecting the quartz core in the Van de Made pegmatite indicate that this mineral may form after the consolidation of the quartz core. In general, however, the quartz core is the last zone to form, though not all pegmatites accumulated sufficient residual silica to produce a well-differentiated central body of massive quartz.

B. COMPARISON WITH OTHER PEGMATITE AREAS

One of the most thoroughly investigated lithium-bearing pegmatites is that of Varuträsk, in Northern Sweden (Quensel, 1955). Two main stages of crystallization exist. The first is the pegmatitic stage, when the border, wall, intermediate, and quartz core zones formed. The intermediate zone consists of an outer unit composed of perthite, quartz and muscovite, and an inner unit of the same constituents plus spodumene and montebrasite in considerable amounts. The quartz core is made up essentially of milky white quartz. The pegmatitic stage is followed by a pneumatogenic stage, the minerals of which show a replacement relationship with the previous zones. In this latter stage an earlier lithium replacement unit comprises lepidolite, petalite, and a second generation of spodumene, the two last-mentioned being contemporaneous. A cesium replacement unit composed of pollucite follows, and the later age of the unit is indicated by this mineral's replacement of petalite. The youngest unit consists of almost pure albite, developed mainly in the form of cleavelandite, though fine-grained albite also exists. The albite replaces and cuts across all earlier mineral assemblages.

There are certain similarities between the above sequence and that found in the Karibib pegmatites where some of the albite post-dates the formation of lepidolite, and the main sodium-rich phase can be subdivided into an earlier sugary albite stage and a later cleavelandite stage. The main difference is that the quartz core of the Varuträsk body predates the lithium and sodium mineralization.

Heinrich (1948) proposed an essentially similar model of pegmatite crystallization for the Eight Mile Park pegmatites of Colorado. An initial magmatic stage gave rise to the border, wall, intermediate, and quartz core zones, and these were followed by later secondary units in the form of fracture-fillings, fracture- and contact-controlled replacements, and other more irregular replacement masses. The major minerals belonging to the secondary units are quartz, sodic plagioclase (sugary albite and/or cleavelandite), lithium micas, beryl, phosphates, and columbite-tantalite. The quartz core is believed to have crystallized before the lithium and sodium mineralization.

Similar sequences are indicated by Jahns (1952) for the pegmatites of the White Pichacho District, Arizona - zones (border, wall, intermediate, and core), replacement bodies, and fracture fillings. Lepidolite occurs in replacement bodies in the wall zones, outer intermediate zones, and the more central parts of the pegmatites. The quartz core is replaced in places by post-zonal albite. The Pidilite pegmatite, New Mexico, consists of border, wall, intermediate, and quartz core zones, and several "composite units" which owe their origin to a certain amount of replacement. Minerals due to replacement processes are albite (mainly cleavelandite), lepidolite, and muscovite. It is thought that the actual amount of replacement is quantitatively small.

In his description of the crystallization sequence of Namaqualand pegmatites, Gevers (1936) stated that the magmatic and epimagmatic stages were followed by a number of replacement phases - "albitization began earlier than muscovitization or lepidolization, was in part contemporaneous with these, but ceased before the latter two processes were complete". This trend differs somewhat from that found in the Karibib pegmatites.

Page et al (1953) concluded from their investigation of the Black Hills pegmatites in South Dakota that most of the plagioclase and lithium minerals are not related to a hydrothermal stage, as thought by previous investigators, but belong to a magmatic stage, though "like other pegmatitic minerals they may also occur in units formed primarily by hydrothermal solutions". Crystallization is considered to have taken place in an orderly sequence from the walls inwards, the last two zones to form being microcline-plagioclase-lithium micas-quartz, and the quartz core. This general pattern, ending with the quartz core, is similar to that of the Karibib bodies.

Brotzen (1959b) discussed the crystallization sequence of pegmatites on the basis of numerous literature references and his own observations, and concluded that :

- (i) lithium and sodium mineralization may precede or post-date the quartz core.
- (ii) similarly, the sodium mineralization (essentially cleavelandite) may precede or post-date the lithium mineralization.
- (iii) in the very complex pegmatites the formation of lepidolite follows on that of spodumene and petalite, while cleavelandite persists beyond lepidolite.
- (iv) the quartz core becomes brittle at about 270°C , before which alkali replacement and core margin mineralization take place.

Several of these observations can be applied to the pattern of development of the Karibib pegmatites.

The order of crystallization of granitic pegmatites, as envisaged by Ginsbourg (1960), is essentially controlled "by the part played by alkalis at differing stages of the process and the appearance of volatiles during the last stages". The proposed sequence, from oldest to youngest unit, is : calcium - sodium (plagioclase), potassium (microcline), lithium (spodumene), sodium (albite), and late lithium and potassium (lepidolite). Here again, the period of albitization precedes the lepidolite stage.

The above review brings to light considerable differences of opinion with respect to either the actual sequence of crystallization in the various pegmatites, or the interpretations of similar features. The disagreements mainly concern the degree and extent of replacement of earlier by later phases. While some investigators (Gevers, 1936, and Quensel, 1955) assign a major role to this process, others, particularly Page et al (1953), consider it to play an insignificant role only. It would appear, however, that while a broad overall pattern seems fairly well established, there actually do exist distinct differences between the various pegmatite areas, not only with regard to the perfection and symmetry of mineral zoning, but also in respect of late-stage processes. The general sequence in the Karibib bodies conforms, in many ways, with that suggested for other areas, except for the differences in the relationship between the sodium and lithium stages of mineralization. The cooling history of the pegmatites studied in South West Africa resembles strongly that suggested by Brotzen (1959a and b).

C. CONDITIONS OF CRYSTALLIZATION WITHIN PEGMATITE BODIES

In most syntheses it is accepted that pegmatite formation takes place during processes ranging between magmatic crystallization and hydrothermal mineralization. This range is possibly a rational deduction for magmatic pegmatites, but the assignment of rigid temperatures to various stages of mineralization can only be regarded as highly speculative. However, as Jahns (1955) has pointed out, some of these overall temperature limits have stood up well against new geothermometric data.

Selected examples of these estimates of temperature and environment are given below, as they serve to illustrate the impression of most investigators that pegmatite mineralization covers a wide range of processes :-

(a) Fersman (1931) :

800 - 700°C - epimagmatic	}	equilibrium between silicate-melt and crystalline phases
700 - 600°C - pegmatitic		
600 - 500°C - pegmatoid	}	essentially coexistence of crystalline, liquid, and gas phases
500 - 400°C - hypercritical		
400 - 300°C - high hydrothermal	}	essentially equilibrium between crystalline, aqueous liquid, and aqueous gas phases
300 - 200°C - middle hydrothermal		
200 - 100°C - low hydrothermal		

(b) Gevers (1936) :

above 600°C	-	epimagmatic and late magmatic replacements
about 600 - 500°C	-	early pneumato-hydrotogenic stage; replacements at high temperature with the formation of schorl, spessartite, beryl, fluor-apatite, columbite- tantalite, and spodumene

- about 500 - 400°C - late pneumato-hydatogenic stage; processes of albitization, muscovitization, and lepidolization take place
- about 400 - 269°C - initial hydrothermal stage; vein formation; formation of quartz, tourmaline, and apatite; muscovite continues to form
- 269°C and below - late hydrothermal stage; formation of phyllosilicates essentially by replacement

(c) Quensel (1955):

- around 800 - 600°C - pegmatitic stage, with the formation of border, wall, intermediate, and quartz core zones
- around 600 - 400°C - pneumatogenic stage in which lithium and cesium replacement units represent a higher temperature stage, while sodium replacement takes place during a lower temperature
- around 400 - 100°C - hydatogenic stage; numerous secondary minerals form, e.g. kaolin, montmorillonite, cookeite.

In later pegmatite investigations the trend is towards fewer, less precisely defined stages which include: (i) a magmatic stage, (ii) a pneumatolytic stage where the residual fluids contain a considerable enrichment of volatile constituents, and the vapour pressure reaches a maximum, and (iii) a hydrothermal stage starting near the critical temperature of water. The assignment of individual rock-types to these main stages is somewhat speculative. The most significant criteria are the sudden appearance of numerous hydrous minerals, and the texture which comprises, essentially, replacement features.

Among North American investigators (Heinrich, 1948; Cameron et al, 1949; Hanley, Heinrich and Page, 1950; Page et al, 1953; Jahns, 1955), there is a tendency against differentiation into definite temperature groups. Jahns (1955), in his summary of the literature on pegmatites, pointed out that replacement processes, in general, have been attributed to one or more of the following:

- (i) rest liquid of progressively changing composition
- (ii) vapours and their condensates derived from a rest liquid undergoing resurgent boiling
- (iii) hydrothermal solutions formed by direct descent from the rest liquid
- (iv) hydrothermal solutions immiscible with the rest liquid
- (v) liquid or gaseous solutions derived from sources outside the pegmatite body

Replacement as a result of the activities of condensed vapours formed by resurgent boiling of the rest liquid is the process favoured by Jahns (1955). Some 75 per cent of the Pidlite pegmatite was considered by Jahns (1952) to have consolidated prior to the major period of replacement. The minerals of the latter stage formed partially from the replacement of pre-existing consolidated material, and partially from direct crystallization of the residual fluid.

Brotzen (1959b) has divided pegmatite crystallization into the following series of mineralogical assemblages representing the order of formation and the significant genetical stages of the whole pegmatite process :

- (i) granitoid border zone
- (ii) graphic granite zone
- (iii) pegmatoid zone formed of microcline crystals
- (iv) core margin
- (v) alkali replacements
- (vi) core margin products
- (vii) alteration products

The quartz core is not included because its true position is difficult to assess. It is believed that quartz ceases to crystallize in the graphic granite zone, but later reappears as interstitial quartz of the pegmatoid zone and core margin, and as the quartz core. This is explained by the "ability of silica to polymerize and to form inert 'noncrystalline' matter, such as glass and a silica gel". Carbon dioxide is considered to play an important part in this process.

Jahns (1955) concludes that pegmatites are formed in the range $700 - 250^{\circ}\text{C}$, and that internally zoned pegmatites begin to crystallize at temperatures not greatly in excess of about 550°C . Brotzen (1959b) suggests that most pegmatites are emplaced at temperatures well above 600°C (graphic granite), that feldspar and the earliest beryl crystallize at about 600°C (pegmatoid zone), that muscovite starts to form at about 500°C (core margin ?), that spodumene commences to form below 500°C (alkali replacement and core margin), that beryl and muscovite continue to form up to 300°C (the higher range about 500°C representing core margin and equivalent assemblages, and the lower range about 300°C later groups including cavity fillings), and that finally the quartz core becomes brittle at about 270°C .

Recent laboratory experiments have thrown considerable light on pegmatite crystallization. Burnham and Jahns (1962) have shown that pegmatitic melts can dissolve as much as 20 per cent water at 675°C and 10,000 bars. The influence of water on the crystallization processes has always been considered an important factor by pegmatite investigators. This water, however, is probably concentrated in the residual pegmatite fluids, the percentage thus steadily increasing with the time of crystallization, assuming a closed system. The relative water content leaves its imprint on the minerals formed at successive stages. A considerable amount is incorporated in the hydrous silicates of which micas are the most important. Some water is required to keep the final residual fractions in a non-crystalline state, and this will be released only after crystallization. Numerous vugs, druses, etc. indicate the presence of water. No quantitative data are available for an estimate of the amount of water finally released. If the system is not a completely closed one, some of the water may escape into the country rock.

A problem that remains is the mechanism of maintaining quartz in a non-crystalline state at low temperatures of about 300°C , as estimated by Brotzen (1959b), who suggested that increased activity of carbon dioxide may play an important role.

Jahns and Burnham (1961) have suggested a model of crystallization for granitic pegmatites based on the following threefold sequence :

- (i) crystallization from a crystalline melt, yielding granitoid pegmatite
- (ii) crystallization concomitantly from a silicate melt and from a co-existing gas phase, yielding giant-textured pegmatite and fine-grained, even aplitic, aggregates; segregations of these products vary enormously; partitioning of constituents between the two fluid phases, rapid diffusion of constituents through the gas, and gravitational rising of this gas to form pods and zones of unusual composition
- (iii) crystallization in the absence of a silicate melt, yielding a wide variety of late-stage products

It is contended that the second stage is vital to all truly magmatic pegmatites. Processes included in the second and third stages can satisfactorily account for metamorphic pegmatites.

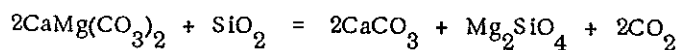
From the above interpretations the following generalizations can be made : (i) magmatic pegmatites are emplaced at a temperature of about 700°C; (ii) crystallization generally begins with a magmatic stage which is followed by stages in which volatiles, mainly water, but also fluorine, chlorine, and carbon dioxide, play a more important role; (iii) during later processes a gas phase probably co-exists with the residual silicate melt.

D. CONCLUSIONS CONCERNING THE CRYSTALLIZATION SEQUENCE OF THE KARIBIB PEGMATITES

The complex lithium- and beryllium-bearing pegmatites are crystallization products of a magma, and represent fractionates of late-tectonic intrusive granites emplaced in a region of moderate- to high-grade metamorphism (Roering, 1961).

These pegmatites appear to have crystallized under closed- or restricted-system conditions. Many of the bodies occur in dolomitic marbles, and, at the level of exposure, reveal very little wall-rock alteration. It is noteworthy that two incompatible phases, such as a silicate magma and a dolomitic marble, reveal only very narrow zones (inches in width) of reaction skarn (tremolite, scapolite, diopside). Furthermore, the calcium content of the plagioclases does not approach even that of oligoclase, indicating that very little exchange took place.

The phenomenon of restricted skarn formation is a useful guide in estimating the depths at which the pegmatites were emplaced. The following reactions are possible (Turner and Verhoogen, 1960) :



Assuming a temperature of 700°C for the pegmatite emplacement, and taking into consideration that the carbonate phases remain essentially stable means that the depth at which the partial pressure of carbon dioxide was equal to the partial pressure of the fluid was equivalent to about 10 - 20 kms.

Another feature in favour of closed- or restricted-system conditions for the pegmatite crystallization is the fact that rocks containing lepidolite, petalite, pollucite, almost pure albite, spodumene-quartz, etc. are confined to the pegmatite bodies themselves. Had any material been

able to escape in significant amounts, then some of the minerals, or their characteristic elements, would have developed within the enclosing country rocks.

There appears to be a direct relationship between the size and shape of a complex pegmatite and the degree to which it fractionates. Large lensoid bodies often attain a high degree of fractionation (e. g. the main Rubicon ore-body, Helicon I, Karlsbrunn), while narrow dyke-like bodies are not well fractionated, particularly with respect to the lithium-bearing zones and the quartz core (e. g. Rubicon West, Dernburg, sections of Helicon II). The crystallization of a magmatic pegmatite is greatly dependent on the rate of cooling and the final proportion of volatiles in the residual melt. It is to be expected, therefore, that size, in comparable environments of temperature and pressure, will have a strong influence on the rate of cooling and consequent fractionation. It is appreciated that this is not the only factor governing fractionation.

The crystallization sequence of the Karibib pegmatites, which is repeated from one body to the next, indicates a fairly uniform set of thermodynamic conditions. Furthermore, fractionation, particularly of the later lithium and sodium stages, might also have taken place in a vertical direction. The following conditions are thought to have controlled the development of these pegmatites :

(a) The first stage of crystallization is represented by coarse-grained granite of which the main constituents are feldspar (albite and perthite), quartz, and muscovite. Crystallization probably was "magmatic", in that the mineral components crystallized directly from a silicate melt. Locally, in some pegmatite bodies, subtle interplay of thermodynamic conditions - variations in initial partial pressure of water, in temperature, and in pressure - resulted in fractionation of the minerals. This stage closed with special conditions represented by the increased stability of perthite (developed as an independent unit in places), the greater activity of potassium, the formation of giant crystals concentrated on the hangingwall side of dipping ore-bodies, e. g. Rubicon, Karlsbrunn (Page et al, 1953, state that perthite is often concentrated in hooded zones). The formation of giant perthite crystals in the upper sections of unconsolidated pegmatites was probably due to the appearance of a gas phase in the higher levels of the residual chamber and the high diffusion rates of the component perthite ions.

(b) The above stage was followed by a definite break in mineralization. Cleavelandite was the main mineral to form, and was accompanied by quartz, muscovite, and numerous accessory minerals. On the outer margin of this unit reniform nests of muscovite formed from which narrow, tapering, radiating spines of the same mineral project corewards. The tips of the spines are often made up of pink lepidolite. This texture is considered to owe its origin to the fact that the residual pegmatite fluid was enriched in lithium, since the lithium micas tended to form instead of muscovite, and to the fact that the micas were unable to develop as crystallization proceeded, because their components were polymerized and concentrated in the residual fluids. The subsequent zones were lithium-bearing, indicating that the concentration of lithium was achieving critical proportions. Silica was also being concentrated, and beryl, columbite-tantalite, iron-manganese phosphates, and topaz were being precipitated with the cleavelandite. These unusual minerals were unable to form stable complexes with the alkalis in the residual fluids, and were thus eliminated under the prevailing critical conditions, while the alkalis were being stabilized. During the whole of this stage components of the cleavelandite zone were able to react and replace pre-existing consolidated phases.

(c) The next stage marked the appearance of lithium- and sodium-bearing minerals showing a systematic spatial relationship about the quartz core. Whatever the actual state of the latter, it must have been fairly well segregated at this stage. It is envisaged that a complex series of fractionations took place. The essential element diffusions are illustrated in Fig. 2. Although a certain amount of overlapping might

have taken place in the crystallization sequence, it is quite clear that petalite was among the earliest minerals to form, and was accompanied by amblygonite, minor albite, and quartz. The petalite and amblygonite tended to develop giant crystals, also requiring rather specialized conditions for fractionating these components from the residual system. Possibly a gas phase was involved, since the earliest petalite formed in the hood of this zone. It appears that, under ideal conditions, lepidolite post-dated the petalite, and itself was followed by the main portion of albite, commonly found in massive units below the lepidolite. This vertical fractionation poses certain problems. Liquid immiscibility could possibly have been involved, but, in general, the lepidolite ores contain a certain amount of albite which probably crystallized together with the mica. Lepidolite is slightly heavier than albite, making it difficult to account for its collecting mainly above the latter, if both were crystallizing from an undisturbed silicate melt. Possibly, much of the lepidolite may have been derived from the replacement of petalite. After petalite (anhydrous) had formed in the hood portion through the aid of a gas phase, the residual system must have become progressively enriched in water and other volatiles. With a steadily mounting vapour pressure, conditions for replacement would have been enhanced. The increasing water and potassium contents, of the latter of which certain quantities must have been taken up by the residual fractions in the replacement of microcline perthite by albite in the earlier formed zones, then converted the anhydrous petalite to lepidolite. (The footwall of Rubicon contains very little petalite, probably due to its conversion to lepidolite, and at Helicon I a small isolated body of petalite occurs within the lepidolite-albite zone). After this stage the residual fraction of the pegmatite consisted mainly of albite, silica (already segregated), and volatiles. Another build-up of vapour pressure probably enabled the albite residual fraction to behave diapirically, intruding surrounding consolidated rock-types, as at Karlsbrunn (Roering and Gevers, 1962). When the vapour pressure was rapidly released the under-cooled albite fluid crystallized into a sugary albite rock. During this stage of extremely high vapour pressure, previously consolidated units, especially the adjacent lepidolite ores, were brecciated. This fracturing brought about a rapid drop in vapour pressure of the residual system. In some cases lepidolite and albite separated out so closely in time that the lepidolite mush became permeated with albite. It is impossible to estimate exactly when a gas phase was liberated in the pegmatite system. The rates of cooling and consolidation no doubt varied in individual bodies, depending on the temperature and pressure of the surrounding rocks, and on the size of the particular body. Consolidation lead to a build-up of volatile constituents in the residual fraction, and of its vapour pressure until this reached equilibrium with the surrounding rock pressure, thereby allowing boiling. The rate of consolidation and vapour pressure build-up were possibly reduced by the rate of cooling tending to condense a gas phase. Latent heat of crystallization probably extended the duration of this phase. Because of the numerous components within the whole of the system, a second, or even third, period of boiling might have occurred.

(d) As shown by the sodium-rich core margin mineralization, the precipitation of albite usually continued well beyond that of lepidolite. Instead of sugary albite, however, the final product was cleavelandite. The residual sodium-rich fluid contained elements which were not incorporated in silicates formed during previous stages, or which were able to form minerals of their own, e.g. columbium, tantalum, tin, cesium, beryllium, and boron. These crystallized as specific minerals, together with cleavelandite which replaced and veined the lepidolite zone. Fig. 1 suggests that this stage is particularly well developed in pegmatites where these elements were not stabilized at an earlier period preceding the lithium- and sodium-mineralization. A basic difference in the behaviour of the unusual elements thus existed from one pegmatite to the other, as can be seen from a comparison of the Rubicon and Helicon I bodies. It seems that very slight changes in the pegmatite system determined

whether the unusual elements were concentrated with the alkalis of the residual system which ultimately give rise to the lithium and sodium units, or whether, unable to form complexes with the alkalis, they produced minerals of their own. Slight variations in pH, as suggested by Ginsbourg (1960), have been a deciding factor in the formation of mineral assemblages before or after lithium and sodium mineralization.

(e) The quartz core was probably the last unit to form, although it is difficult to envisage quartz remaining unconsolidated at low temperatures around 300°C. Small amounts of fluids available, in portions of the pegmatite after final consolidation of the quartz core gave rise to veins of lithium mica, bismuth, and associated minerals.

REGIONAL ASPECTS OF PEGMATITE GENESIS

In descriptions of pegmatite areas the close relationship between particular types of pegmatites and their parent granites has often been neglected. Read (1957) has synthesized various granite types into a genetic sequence - the granite series - which is intimately associated with events in an orogenic cycle. This sequence attempts to relate both time and place in the genesis of the plutonic rocks. From a relatively deep-seated early ancestor are derived the later high-level members of the series. The earliest and deepest members of the series are the autochthonous granites and granitization granites which are surrounded by extensive aureoles of migmatites and metamorphic rocks. Parautochthonous granites are "higher and later in the series. By mobilization, certain of the autochthonous granites begin to part company with their genetic setting and move higher in the crust, or more usually, into tectonic domains of lower pressure". With continued movement the "genetic ties are completely severed and true intrusive granites emplace themselves into higher levels of the crust, maybe as magma, but more likely as migma". The final members of the series are high-level plutons "intrusive into non-plutonic regions, late in the history of the orogen concerned".

Possibly the main difficulty in establishing a "pegmatite series" is the fact that most granites, at different crustal levels, have various pegmatitic types of their own, and that these migrate into different environments. Pegmatitic "disperse phases" (gaseous, magmatic, or diffusive flow of ions) are generally the most mobile in any metamorphic-metasomatic terrain, making it possible for complex additions and mixing of these phases in horizontal or vertical directions in an orogen. Another complicating factor is that granite formation and injection under syntectonic conditions result in the most mobile fraction being squeezed out of the area of granite generation, while post-tectonic magmatic granites are not necessarily associated with similar suitable conditions for the removal of pegmatitic fractions.

A. SUMMARY OF CURRENT IDEAS ON THE REGIONAL CLASSIFICATION OF PEGMATITES

Gevers and Frommurge (1929) noted specific variations in the size, shape, composition, and abundance of pegmatites with distance from the parent body in the Erongo tin fields of South West Africa. A systematic classification of pegmatite distribution and mineralization, with reference to a particular granite body, was presented by Gevers (1936) and Gevers, Partridge and Joubert (1937) in descriptions of Namaqualand pegmatites. Interior pegmatites of simple undifferentiated composition, situated well within the parent body, and marginal pegmatites injected outside the parent body into surrounding country rock were recognized. The interior pegmatites are characterized by a quartz-felspar base, and are generally devoid of late concentrations of economic minerals. There is little evidence of pneumatolytic (post-magmatic) action. Accessory minerals are schorl, garnet, and muscovite. Marginal pegmatites, where of large size, are often highly mineralized, and exhibit considerable evidence of post-magmatic processes. Minerals formed by the latter are albite, muscovite, beryl, tourmaline, lithium-bearing minerals, columbite-tantalite, monazite and other rare earth minerals, native bismuth, and sulphides.

Heinrich (1948) found that a classification of pegmatites into interior, marginal, and exterior types was valid for the Eight Mile Park area, Colorado. The interior pegmatites are well zoned, consisting of microcline, quartz, oligoclase, muscovite, biotite, and schorl, but showing no evidence of hydrothermal alteration. The marginal pegmatites reveal a rude zonal structure, and are composed chiefly of microcline, quartz, muscovite, biotite, and graphic-granite. Post-magmatic mineralization is revealed by replacement

action which resulted in the production of albite, muscovite, beryl, tourmaline, and triplite. Exterior pegmatites, occurring in schist, are well zoned, and often show evidence of extensive post-magmatic replacement formation of albite, muscovite, schorl, apatite, beryl, triplite, columbite, lepidolite, alkali-tourmaline, and natromontebrazite.

Heinrich (1953), on the conclusion of later investigations, stated that "in numerous pegmatite districts the size, shape, external and internal structure, texture, and mineral content of an individual pegmatite can be shown to be functions of the distance of the body from its batholith source". In explanation of these phenomena he suggested that the location and the composition of a pegmatite depend upon (i) the chemical character of the source batholith, (ii) the stage of crystallization of the batholith at the time of withdrawal of the pegmatite material, and (iii) the penetrability of the rock around the pegmatite hearth.

Jahns (1955) considered it an established fact that "this well-documented (regional) zoning constitutes one of the strongest arguments for a genetic relationship between intrusive masses and associated bodies of pegmatite".

A basic differentiation of pegmatites, from simple to complex types, has been proposed by Brotzen (1959a). This grouping portrays variations in the mineralogical composition which can be correlated with the "order of crystallization of the pegmatite minerals, with the position of the pegmatites in zoned pegmatite districts, and with the complexity of the deposits" (Brotzen, 1959b). The four main types are :

- (i) first-type pegmatites : these are essentially granitic in composition, and contain biotite as the dominant mica; they generally reveal the "normal" zonal pattern, i.e. an outer granitoid zone followed inwards by a zone of graphic granite, a pegmatoid zone, and a quartz core.
- (ii) second-type pegmatites : these are nearly granitic in composition, but contain muscovite as the dominant mica; as a rule they reveal the "normal" zonal pattern, although the granitoid zone may be lacking and "reversed" zoning may occur; in the "reversed" zonal arrangement, set out by Cameron et al (1949), the outer zones are represented by mineral assemblages generally found near the core in Brotzen's (1959a and b) more simple pegmatite types
- (iii) third-type pegmatites : these are characterised by late plagioclase, mainly "albite"; the dominant mica is muscovite; the composition of the pegmatite may deviate from that of granite by having a higher silica content and a higher proportion of sodium to potassium; "reversed" zoning is frequent
- (iv) fourth-type pegmatites : these are characterised by the appearance of lithium phases; muscovite and lepidolite are the dominant micas; the composition may be far from granitic; "reversed" zoning is the rule.

Brotzen (1959a and b) suggested that a filter-press action may be an important mechanism in producing these types in zoned pegmatite districts. The most primitive pegmatite stage in the above sequence is localized in the central portions of pegmatite districts, and there is the suggestion of a systematic "pegmatite series" which increases in complexity with distance from a central region of simpler types.

In Russia, the early classic work of Fersman (1931) has been modified by the recent investigations of Ginsbourg (1960) who has suggested the existence of a "depth facies of granitic pegmatites". Deep-seated pegmatites have an approximate depth of formation in excess of 6 - 7 km. The associated granitic rocks are "large intrusions" of biotite-hornblende granite-gneiss. Migmatitic pegmatites are the usual type, though

well-zoned bodies occasionally occur. Albitization processes are absent, but quartz and quartz-muscovite replacement is common. The group of pegmatites is generally rich in calcium, magnesium, titanium, and iron which might have been derived from assimilation processes. Sometimes uranium, thorium, and niobium occur as trace elements, but beryllium is much rarer. Potentially economic constituents are feldspar, muscovite, and rare-earth minerals.

Pegmatites of average depth are found between 3.5 and 7 km, below the surface, and are usually associated with biotite, and biotite-hornblende, granites, or banatite, or granodiorite. This group is generally well zoned internally. Mirolitic cavities might be developed in the central portion of the pegmatite. Replacement processes are locally intense. Microcline is a major constituent, and typical elements are cesium, rubidium, boron, lithium, beryllium, niobium, tantalum, and tin, of which the last five might be present in economic quantities.

Shallow-seated pegmatites are formed at depths of 2 - 4 km., and are commonly associated with small domes of fine-grained alaskite granite. Pegmatites are developed as schlieren bodies with numerous mirolitic cavities. This group is rich in the volatiles boron and fluorine. Beryllium and lithium are characteristic, and gemstone deposits might occur.

The "depth facies" concept is an important contribution to the understanding of pegmatite genesis on a regional scale, proposing that the most complex types of pegmatites occur in the intermediate depth zones, and are not associated with high-level granites. Previously it was accepted that, in pegmatite districts, the exterior pegmatites (the most mobile type) are the most complex, and that high-level magmatic granites of Read's (1957) "granite series" represent the accumulation of the most mobile constituents of metamorphic and ultrametamorphic processes, and give rise to fractionates rich in the uncommon suite of elements so characteristic of complex pegmatites.

A recent contribution by Wiles (1961) on the Miami mica field, Southern Rhodesia, reveals certain features identical with those found in the Karibib area. Two origins are considered for pegmatites in the Miami area, one magmatic, and the other metamorphic or metasomatic. The distribution of the economic mica-bearing pegmatites shows a definite metamorphic control, "whereas the beryl-bearing ones are clearly of igneous origin and are related to intrusive plugs of late kinematic biotite-granite".

In the Daberas area of the Kenhardt District, Cape Province, Hugo (verbal communication) has found that a large lens-like, non-foliated biotite granodiorite has numerous pegmatites containing gadolinite, monazite, allanite, and fergusonite more or less symmetrically arranged around the margins of the massif. The pegmatites are generally zoned as follows: granodiorite - graphic granite - perthite - quartz core. There appears to be a definite genetical relationship between the pegmatites and the granodiorite. The same relationship, though not clearly illustrated, was also found on the farm Styrkraal in the same district. In the Kakamas area Hugo (verbal communication) has established that the pegmatite swarms in the "grey gneisses" are essentially of the simple type, and may cross-cut the foliation, while in the adjacent metamorphic rocks ("pink gneisses") more complex pegmatites occur, but to a lesser extent. Further away, in the schistose metamorphic rocks, hardly any pegmatites are present. The more complex pegmatites cross-cut the foliation more frequently than the simple types. The pegmatites appear to be genetically related to the grey gneisses, and provide another example of regional pegmatite zoning.

B. IMPLICATIONS OF THE KARIBIB INVESTIGATION

From the combined results of an investigation by Smith (1962a) on the regional geological environment, and by the author on the smaller-scale relationships of complex pegmatites to their environment certain preliminary conclusions pertaining to the genesis of these complex bodies can be drawn. It is appreciated that a great deal more work is required on a regional scale over larger areas of the Damara orogenic belt before a complete picture can be obtained. More data are required of the sequence of structural, metamorphic, and magmatic events in particular areas.

Smith (1962a and b) has shown that, although a great variety of granitic rocks occurs within the western portion of Damaraland, the two most widely distributed types can be related to particular lithological environments, and are therefore products of in situ granitization and gneissification. In addition, a small group of intrusive granites and pegmatitic granites has been recognized in almost all stratigraphic horizons. These non-foliated granites are distinctly transgressive with regard to the meta-sediments. The complex, internally zoned, economically mineralized pegmatites are related to such bodies.

The pegmatites are of varying ages with regard to structural and metamorphic events (Smith, 1962b). Three main types can be recognized, ranging from syntectonic to post-tectonic. The simpler types are early and by far the most abundant, while the complex types are late-tectonic, similar to their parent bodies, and much more sparsely distributed. Locally intrusive relationships are revealed by the earlier types, although they are generally directly derived from the meta-sediments of their immediate environment. An intermediate group of intrusive pegmatites is considered to originate from secretion processes.

Roering (1961) has provided further evidence in support of the late-tectonic behaviour of the pegmatites, and of their relationship to late intrusive granites. The granites and pegmatites sometimes clearly cross-cut the fabric and fold trends of the meta-sediments, and in places are related to post-folding faults. Some of the mineralized pegmatites lie in late-tectonic granite and pegmatitic granite massifs, e.g. Rubicon and Brockmann's pegmatite in the Albrechtshöhe-Kollombo area. The pegmatites show no evidence of internal deformation.

From the field evidence the following major conclusions can be drawn :

- (i) the complex pegmatites are clearly magmatic
- (ii) they are related in time and space to late-tectonic intrusive granites
- (iii) they occur in a high-grade metamorphic environment, amphibolite grades increasing until localized melting and mobilization of rocks occur
- (iv) earlier pegmatites, generally simple types, are often syntectonic.

C. TOWARDS A REGIONAL SYNTHESIS OF GRANITIC PEGMATITE GENERATION

One of the major difficulties of trying to bring pegmatites into line with Read's (1957) plutonic processes of orogeny is the paucity of data with respect to the relative times of formation. It has been postulated for some regions that interior pegmatites are earlier than the exterior types. Another problem concerns the relationship of pegmatites to the various igneous and metamorphic rock-types in the

so-called "batholithic" regions. Mobilized and homogenised granites may develop as relatively small belts at the margin of batholiths. This phenomenon is well seen in the contact region of the Nelspruit granite in the Barberton area of the Transvaal. Complex pegmatites, often exterior types, may be associated with this type of granite.

It is emphasized again that high-level intrusive granites are known to contain pegmatites which are usually of the simple type. Gevers (1936) concluded that "depth appears to be an important factor in the development of residual melts rich in volatiles" The non-orogenic Erongo granites of South West Africa solidified at very shallow depths of only a few thousand feet, and in these granites pegmatites are rare, although small lenticular vugs and lenses of pegmatite minerals and gemstones occur. Black schorl in nests and lining fractures is widely distributed in the Erongo granites. Volatiles were, therefore, present in considerable quantity, but the absence of typical pegmatites is probably to be explained by the shallow depths of solidification, the volatiles being rapidly distilled off and dissipated into the roof and the atmosphere. This environment is identical with that proposed for the shallow-seated gem pegmatites of Ginsbourg's (1960) classification. In Southern Africa other examples of high-level granites, also notably poor in the large complex type of pegmatites, are the Bushveld granite in the Transvaal, the Cape granite plutons (Scholtz, 1946), and the late Karroo granites of Southern Rhodesia and the Lebombo Mountains.

From the above, therefore, it would seem that a direct correlation between Read's (1957) granite series and the transition from simple to complex pegmatites is not directly applicable - high-level granites do not, in general, give rise to the most complex pegmatites. Tin and niobium-tantalum mineralization may be associated with high-level granites either of the late-orogenic or the anorogenic type. Examples of the latter are the Bushveld granites and the younger granite province of northern Nigeria. The Cornish tinfields are related to the high-level Hercynian granites.

The composition of the parent source plays an important role in determining the nature of the pegmatites. If a particular region is enriched in certain elements entirely by an effective sedimentary "differentiation", then, providing conditions are suitable for their formation, complex pegmatites will be characterized by a particular mineral suite. The extreme case might exist where conditions for the formation of pegmatites were ideal, but for some reason there was no enrichment of characteristic elements in the particular portion of the earth's crust. Under such circumstances simple pegmatites could well appear in an environment where complex pegmatites would normally develop. When viewed in terms of orogenic events the nature of the rocks undergoing simple melting, metamorphism, granitization, and mobilization must have a profound influence on the composition of the derived granite magmas, and may be responsible for differences in pegmatite-types in different mineral provinces.

Jahns (1952), from the bulk composition of the complex Pidlite pegmatite, was able to show that it did not differ much from the average composition of granite. In contrast, Brotzen (1959a) suggested that there might be differences in bulk composition of his four pegmatite types. Orville (1960) has studied the modal and chemical composition of several simple pegmatites occurring in quartz-mica schists peripheral to the Harney Peak granite in the Keystone District, Black Hills, South Dakota. The pegmatites have similar compositions close to that of the Harney Peak granite. The Li_2O content in the pegmatites is 0.02 - 0.05 per cent, while that of the granite is 0.06 per cent. Jahns (1952), however, found a much higher Li_2O content (0.7 per cent) in the Pidlite pegmatite. Inherent variations in the bulk composition of different pegmatites are to be expected, and this is particularly true of the unusual elements.

Questions that remain to be considered with respect to the bulk composition of pegmatites are :

(a) Is there any marked variation between the bulk chemistry of pegmatites and their parent granite masses? For simple pegmatites it would appear that there is none (Orville, 1960). However, it is anticipated that the complex lithium-bearing pegmatites in the same district differ in bulk composition from the simpler pegmatites and from the Harney Peak granite. Jahn's (1955) employing Daly's average granite composition for comparison is not conclusive in demonstrating a close similarity in bulk composition between the Pidlite pegmatite and its actual parent body. There are no satisfactory data to suggest that the unusual element content of granites and pegmatites is identical. Where it can be established that pegmatites are clearly related to granitic bodies, the bulk chemistry of the two can be compared to establish whether the pegmatitic fractionate is different.

(b) Are there real differences in chemistry between simple and complex pegmatites? Brotzen (1959b) suggested a true progressive difference in composition from his first-type pegmatites to his fourth-type. The depth facies of pegmatites, as suggested by Ginsbourg (1960), runs parallel with a difference in the content of unusual elements. The same interpretation is suggested by Orville (1960) for pegmatites of the Keystone area. At present it would appear that true differences in unusual element content could possibly distinguish simple from complex pegmatites, but a large amount of more detailed chemical data is required.

Heinrich (1948) has made the suggestion that the mechanism of concentration of uncommon elements in pegmatites may not have come into operation, and that these elements are distributed widely in the ordinary pegmatite minerals. Therefore, "It may be possible that the differences between some complex and simple pegmatites are more mineralogical than chemical, and more apparent than real". However, considering previous arguments, it would appear that basic differences in bulk chemistry might, in fact, exist between simple and complex pegmatites.

With regard to the regional aspects of pegmatite genesis and relationship to parent granitic rocks, the laws of Goldschmidt (1930 and 1937) suggest that fractionation should, in fact, take place in the case of those elements which are rejected during the crystallization of granite minerals, and which might be enriched in pegmatites. This requires that the cooling history of the magma is sufficiently slow for these elements to concentrate in the pegmatite magma. Therefore, in considering the generation of pegmatites, the formation and the cooling history of the source rocks are also of prime importance.

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GENERAL CONCLUSIONS

Regarding the generation of pegmatites, it is known that, at the various levels of present-day erosion, different types of pegmatites occupy definite zonal positions with respect to associated granitic rocks. In the central regions of pegmatite development simple pegmatites are found. If the parent source contained unusual elements, these are frequently concentrated in more complex pegmatites which are usually marginal to the parent granite, often extending for many miles beyond the latter. The greater degree of migration is due to the greater mobility of the final residual fractions which are rich in volatiles. Generally, complex pegmatites are the youngest, and in the Karibib area it has been possible to demonstrate their direct relation to late- or post-tectonic granites. In many regions such a relationship is unproved, either because of insufficient structural work or because such granites are not exposed at the level of erosion. In other areas, however, a direct time-space relationship between complex pegmatites and late-tectonic granites is quite clear. These regions generally display a high grade of metamorphism, usually of the amphibolite facies or higher, and frequently contain gneisses, migmatites, and granites. Late- or post-tectonic, or non-orogenic high-level, granites not associated with complex pegmatites, might give rise to tin and columbium-tantalum mineralization.

Certain geologic terrains have revealed that secretion-diffusion mechanisms are also responsible for simple pegmatite formation (Ramberg, 1952 and 1956; Reitan, 1958 and 1959a and b). In general, such pegmatites are formed in metamorphic grades varying from the epidote-amphibolite facies up to the granulite facies. They represent local "sweats" of a mobile pegmatitic "disperse phase", and are usually concentrated in areas of low pressure, leaving behind a zone enriched in ferro-magnesian minerals. It is thought that pegmatites which are of such local origin, with respect to their surrounding metamorphic rocks, can be regarded as the oldest and simplest types developed during processes of metamorphism and folding. They would then establish a definite starting point in pegmatite genesis. Localisation of these pegmatites, and the non-development of complete melting of the surrounding metamorphic rocks are considered the essential factors in the formation of these bodies.

In the metamorphic rocks around simple granitic pegmatites, the rarer elements, such as lithium, may act proxy for bivalent atoms occupying the octahedral sites in the micas. Columbium and tantalum may be widely dispersed in minerals like sphene and zircon, while beryllium may go into a variety of silicates, replacing silica in such minerals as alkali feldspar, mica, tourmaline, muscovite, and biotite (Rankama and Sahama, 1956). In this case there is no effective means of fractionation of these elements.

Complex pegmatites require a granite magma which cools slowly enough to give rise to complex fractionates. A melt is probably one of the most important factors in the mechanism of concentrating unusual elements in the pegmatitic fractionate. Under non-melting metamorphic conditions, the actual distance of diffusion of an individual unusual element is probably very small as it is incorporated into new phases almost in situ. This state contrasts with truly magmatic, or at least partially magmatic, conditions where significant diffusion and migration of unusual elements, aided by the movement of water and other volatile compounds, can take place into low temperature and pressure regions (Kennedy, 1955).

The most suitable environment for the development of complex pegmatites is that where granitic magmas are injected into, or generated within, zones of active high-grade metamorphism. Much of this magma would possibly owe its origin to the partial melting of geosynclinal sediments and underlying basement rocks. Because this magma cools in a moderate- to high-grade metamorphic zone, it is given

sufficient time to fractionate, and the unusual elements which are rejected from the common rock-forming minerals are concentrated together with the volatile phases (water in the main) and the other pegmatitic constituents (granite).

High-level granites do not give rise to complex pegmatites, though their composition may not differ appreciably from that of the bodies already described. Gevers (1936) suggested that the rapid cooling of these granites was responsible for this phenomenon. According to Marmo (1958), post-kinematic granite contains orthoclase, while syn-kinematic and late-kinematic granites contain microcline. Where cooling takes longer, the lower is the degree of symmetry of the K-felspar, and the more ordered is the lattice. Recent work, however, by Mathias (1962) on various South West African disharmonious granite plugs has shown that the K-felspar is microcline-perthite. In the case of porphyritic magmatic granites such as the high-level granites of Spitzkop, Erongo, and Brandberg in South West Africa, and the Cape granite, the phenocrysts may have formed at a late pegmatitic stage, indicating that the pegmatitic action itself was fairly evenly dispersed, and that the degree of fractionation of the volatile material was poor. The absence of marked concentrations of volatiles may be due to these high-level granites cooling comparatively rapidly, thereby preventing diffusion to sites of low pressure and temperature. Instead, the volatiles, together with associated rarer elements, were trapped in the ordinary granitic minerals.

In conclusion, it may be stated that the generation of complex pegmatites can be related to plutonic processes associated with orogeny. One of the factors essential to the formation of such pegmatites is an intermediate- to high-grade metamorphic environment. The complexity of pegmatites increases with the degree of mobilization of the disperse phase (granitic material ultimately becoming a magma) of the active metamorphic zone. This increased mobilization may occur marginally, or externally, to large areas of granitic rocks, resulting in intrusive granitic and pegmatitic relationships, or it may occur within the central area of granitic rocks developed as homogenized granite plutons and associated pegmatites. Late-tectonic granites will fractionate to give complex pegmatites only where the grade of active surrounding metamorphism is high enough to ensure slow cooling. High-level intrusive granites tend to be devoid of complex pegmatites, but may contain scattered gem-bearing pegmatitic druses and small lenses. Complex mineralized pegmatites will form only if the rocks from which the mobile disperse phase is derived do, in fact, contain a significant amount of unusual elements.

There would appear to be a continuous "pegmatite-series" associated with metamorphic and orogenic events. The simplest types are formed by in situ "secretion" or "sweating out" of the most mobile constituents. The complex pegmatites are derived from granitic magmas of which they represent true volatile-rich fractionates in the classical sense. Simple pegmatites, however, may also be derived from these granitic magmas if unusual elements are not present - Brockmann's pegmatite reveals both simple and complex types in the same pluton. The simple pegmatites of this type are generally well fractionated and zoned. Between these two extremes there probably exists a series of pegmatites of varying complexity. Pegmatites injected into less intensely metamorphosed environments, or generated directly by secretion-diffusion may be added to, or have added to them, mobile pegmatitic material derived from the adjacent metamorphic rocks. With increased metamorphism and development of palaeogenic granite, the pegmatites are possibly more likely to be developed from residual fractionates of the granite magma.

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KEY TO FIGURE 1

ORDINATE (mineral assemblages of zones and units) :

ab	: albite	B-pe	: blocky perthite
am	: amblygonite	G-G	: graphic granite
ap	: apatite	K-fel	: potash-felspar
be	: beryl	Li-mica	: lithium mica
cl	: cleavelandite	M. C. A	: mixed core zone - Li-mineralization + quartz + albite
co	: columbite	S-ab	: sugary albite
fr	: frondelite	1	: possibly a replacement unit
ga	: garnet	2	: a composite unit
mu	: muscovite	3	: a composite unit
pe	: perthite	++	: mineral occurs in more than accessory amounts
pt	: petalite		
qu	: quartz		
sc	: schorl		
sp	: spodumene		
to	: tourmaline		
tp	: topaz		
u	: uraninite		

ABSCISSA (individual pegmatite sections with zones and units found within the body; asterisk indicates presence of zones and units; symbols represent common accessory minerals) :

I	: Rubicon (main ore-body)	XII	: Albrechtshöhe (Brockmann's pegmatite)
II	: Rubicon (B ore-body)	XIII	: Albrechtshöhe (Berger's Claims, Type 1)
III	: Rubicon (C ore-body)	XIV	: Albrechtshöhe (Berger's Claims, Type 2)
IV	: Rubicon (D ore-body)	XV	: Dernburg (eastern part)
V	: Helicon I	XVI	: Dernburg (central part)
VI	: Helicon II (eastern part)	XVII	: Dernburg (western part)
VII	: Helicon II (central part)	XVIII	: Kaliombo (Berger's pegmatite)
VIII	: Helicon II (western part)	XIX	: Van de Made's pegmatite (eastern part)
IX	: Otjua (Becker's pegmatite)	XX	: Van de Made's pegmatite (central part)
X	: Karlsbrunn	XXI	: Van de Made's pegmatite (western part)
XI	: Karlsbrunn (northeastern lens)		

	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	XIII	XIV	XV	XVI	XVII	XVIII	XIX	XX	XXI	Number of occurrences	Corresponding assemblage given by Cameron et. al (1949)	Main stages of crystallization found in Karibib pegmatites
pe, qu, ga																						1		
pe, ab, qu																						2		
ab, qu, mu																						7		
qu, mu, ab																						4		
ab, qu, mu																						4		
mu, ab, qu																						1		
ab, qu, mu, pe																						3		
ab, pe, qu, mu																						11		
qu, mu																						1		
pe, qu, mu																						2		
cl, tp																						1		
G-G																						1		
B-pe																						6		
B-pe, ab, qu, mu																						1		
cl, qu, mu																						11		
pt, am, qu																						4		
Li-mi, ab, K-fel, qu																						11		
S-ab																						1		
am, ab, qu																						2		
cl																						2		
ab, ap, co, be																						3		
M C Z																						1		
qu																						6		
																						14		

Figure 1 : SUMMARY OF ZONAL ARRANGEMENT IN KARIBIB PEGMATITES

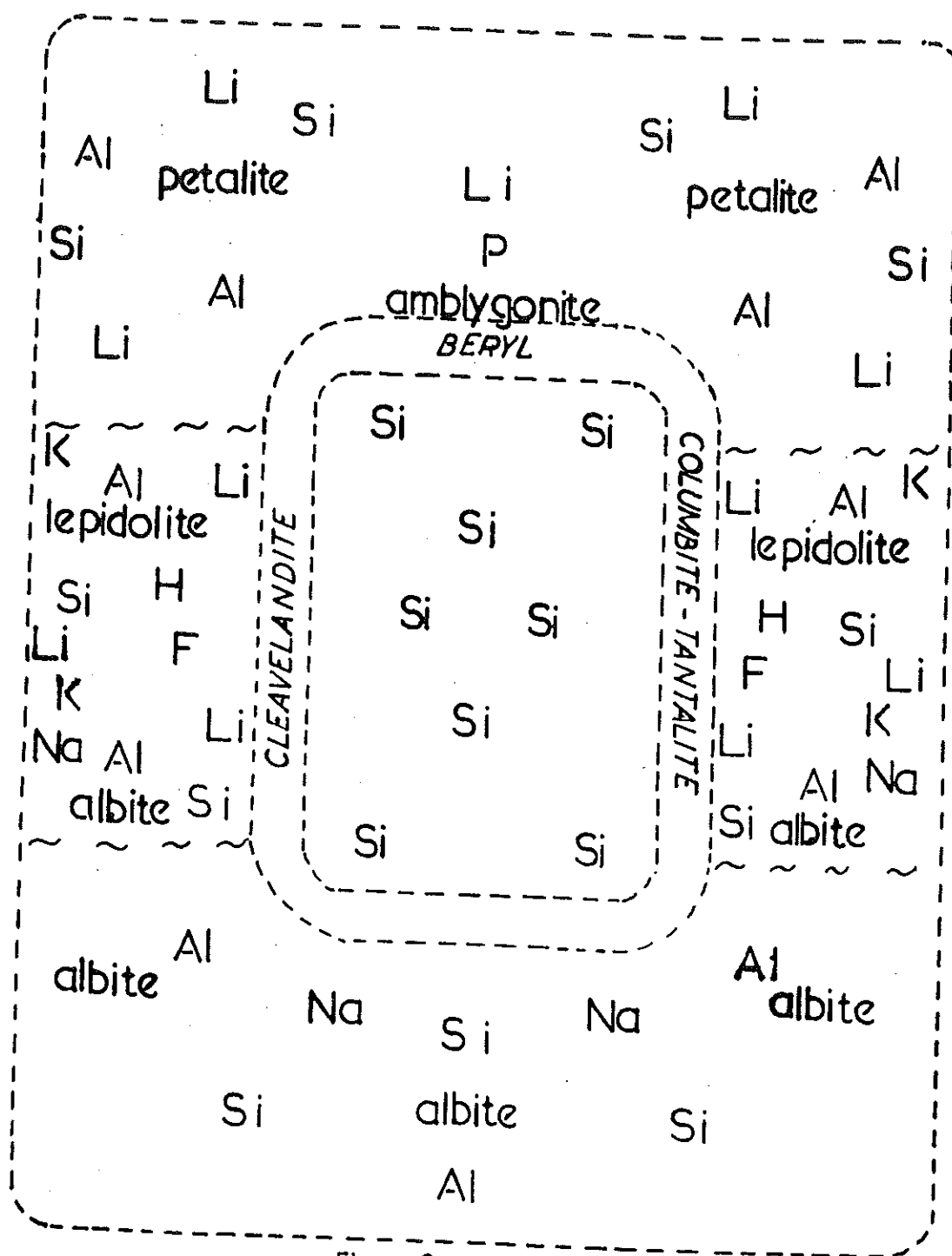


Figure 2