GRANITIC MAGMATISM IN THE DAMARAN OROGENIC BELT, NAMIBIA*

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ABSTRACT After the geosynclinal phase of the Damara Orogeny came to an end at about 700 Ma, numerous plutonic magmas intruded its sedimentary and volcanic rocks and its underlying Abbbis Complex basement. The igneous activity started with the intrusion of early, I-type, metaluminous, calcic, hornblende-bearing granodiorites to tonalites, which contain mafic enclaves. These rocks make up about 5% of the exposed plutonites. They probably originated in the upper mantle – lower crust level and their crystallization in the middle crust caused partial melting of sedimentary and possibly granitic and volcanic rocks. This resulted in the origin of a wide variety of petrographic different, but geochemically similar granitic rocks with S-type characteristics. These alkaline, peraluminous granites intruded higher levels of the crust and caused partial melting in the lower parts of the Damara Sequence. From these melts, the alaskites and leucogranites were formed. The peak of regional metamorphism coincided with the peak of granite intrusions at about 550-530 Ma and is probably caused by it.

INTRODUCTION The Damara Orogenic Belt of Namibia forms part of the late Precambrian to early Palaeozoic Pan African orogenic system (Kennedy 1964). It consists of three branches, of which the main one, situated between the Congo and Kalahari Cratons, extends in a northeasterly direction, whereas the northern and southern ones follow the Atlantic coast and continue into Angola and South Africa respectively.

The combination of stratigraphic, petrologic, structural, igneous and metamorphic data has led to the development of basically two contrasting subduction models for the evolution of the Damara Orogen: a continental (Ampferer) subduction model and an oceanic (Benioff) subduction model (summary in Martin 1983b).

Because most of the igneous rocks present in the area were emplaced during periods of deformation and metamorphism of the Damara Sequence and its basement, they are important for modelling the evolution of the Damara Orogen. Absolute age determinations have been carried out on many of these rocks providing a basis for an approximate absolute time scale for tectonic and metamorphic events (Martin 1983a).

THE GEOLOGY The main inland branch of the Damara Orogen has been subdivided into a Northern, Central and Southern Zone (Clifford 1967) (Fig. 1). This paper deals with the southwestern part of the Central Zone only.

At several localities Abbbis Complex basement rocks of pre-Damaraan age are exposed. They are between 1700-2000 Ma old (Jacob et al. 1978) and comprise augen gneisses, metasediments and metavolcanics.

The Damara Sequence was deposited between 900-720 Ma ago (Hawkesworth et al. 1981) upon a floor of these basement rocks and its estimated total thickness was some 10-14 km. Recent seismic investigations (Baier et al. 1983) indicate that the continental crust in the Central Zone has a thickness of about 40-45 km.

The lower part of the Damara Sequence consists of feldspathic quartzites, meta-arkoses and locally developed conglomerates, marbles and schists of the Etusis Formation, which together with the calc-silicate rocks and subordinate quartzites and schists of the Khan Formation, constitute the Nosib Group. This succession is overlain by the Swakop Group, from bottom to top including the Rössing Formation (dolomitic marble, quartzite, calc-silicate and conglomerate), the Chaos Formation (mixtite, meta-arkose and marble), the Karibib Formation (marble, calc-silicate and subordinate mixtite and amphibole schist), the Tinkas Formation (calc-silicate, schist and marble) and the Kuiseb Formation (mainly biotite schist).

TECTONICS The Okahandja Lineament, a zone of mainly vertical differential movement, strikes parallel to the trend of the Damara Orogen and separates the Central and the Southern Zone (Fig. 1).

Concomitantly with the Damaran period of igneous activity, three deformation phases took place in the Central Zone. On a regional scale, northeast-southwest-trending dome structures are the most conspicuous tectonic features. They are mainly due to interference of the second and third phase of deformation.

* Extended abstract
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METAMORPHISM

The second phase of deformation more or less coincided with the peak of regional metamorphism. The western part of the Central Zone is characterized by a high grade of metamorphism, and anatectic has occurred at some localities. P-T conditions of about 3-3.5 kbar and 650-710°C have been estimated here, while the metamorphic temperatures decreased to about 630-650°C in an easterly direction.

PLUTONIC ROCKS

The basement and Damara Sequence rocks of the Central and Southern Zone were intruded by over 300 plutons of the central Namibia granitic province. Granites are most abundant (95%), whereas granodiorites and tonalites (together up to 4%), quartz monzonites, quartz monzodiorites, quartz diorites, diorites, gabbros and syenites have been found less frequently (Fig. 2). The earliest plutonic rocks intruding the Damara metasediments have been dated at approximately 840 Ma, whereas the youngest ones have an age of about 460 Ma (summary in Haack & Martin 1983). The Damara igneous activity therefore extends over a period of about 380 Ma.

Based on criteria such as field appearance and relative ages compared to the deformation phases, eight groups of plutonic rocks can be recognised:

- the red inhomogeneous pre- or syntectonic granites; in many cases a very inhomogeneous rock with leucocratic and biotite-rich schlieren and occurring together with or occupying the stratigraphic position of the Nosib Group or basement rocks. They occur in the core of antiformal structures and are confined to the higher metamorphic southwestern part of the Central Zone and were probably derived by partial melting of Aababis Complex or Nosib Group rocks;
- the hornblendites and hornblende-bearing diorites, tonalites and granodiorites. These are early intrusives (before the main phase of deformation), which occur together with schists of the Kuiseb Formation and contain mafic, hornblende-rich enclaves. They are affected by the main phase of deformation but do not everywhere develop a planar fabric;
- the alkali complexes; porphyritic (K-feldspar) hornblende syenites, aplites and non-porphyritic syenites. Occurring near to the Okahandja Lineament, locally with a very strong regional planar fabric, one complex has been found in the Tinkas and two in the Kuiseb Formation;
- red and grey homogeneous syn- or post-tectonic biotite granites; not confined to any particular stratigraphic level or locality, locally a well-developed biotite foliation is present;
- the Salem-type granites; a group of grey, coarsely crystalline, porphyritic (K-feldspar) biotite granites, which comprises foliated and unfoliated members. Apart from a few exceptions, these rocks generally occur together with the Kuiseb Formation schists anywhere in the Central Zone and might contain enclaves of sedimentary or granitic origin;
- the post-tectonic granites; the Donkerhooch suite, Gawib, Achas and Bloedkoppe granite along the Okahandja Lineament and the Kubas granite further north belong to this group. Mainly biotite and biotite + muscovite granites. Contrary to the previous groups of intrusives this one is discordant in respect of the main trend of the Damaran rocks and structures and is clearly intrusive into the Aababis Complex and the Damara Sequence;
- the so-called alaskites; these syn- and post-tectonic Damaran intrusives do not form discrete plutonic bodies, but occur largely as sheets at various stratigraphic levels (Downing & Coward 1981). They occur mainly in the higher metamorphic western part of the Central Zone;
- the pegmatites, pegmatitic granites and late leucograniotes; most of these cannot be related to any of the Damaran granitoids, except for the ones associated with group c and f. They intruded after the peak of metamorphism and the third and last main phase of deformation and form relatively small, scattered bodies, not confined to a particular stratigraphic level or area.

This paper mainly deals with the groups b, c, d, e and f. During late Jurassic and early Cretaceous time, basement and Damaran rocks were intruded by late-Karoo Sequence dykes and sills of dolerite and dacite and at several localities of alkali complex, granites and lavas.

REVIEW DAMARAN GRANITOIDs

Early investigators of the Damaran granitoids were of the opinion that these rocks belonged to one magmatic event. Reunin (1922) collectively called them the “Hauptgranit” (Main Granite), while Gevers (1931) stated that “the great variety of different types of granite...all belong to one grand cycle of igneous intrusion”.

Probably the first intrusive to be named in the Central Zone of the Damara Orogen was a porphyritic biotite granite “the Salem granite”, which has scattered occurrences over 70,000 km². At present, all granites looking like this one are referred to as Salem-type granite. Gevers (1931) pointed out that this granite could be found mostly in synclinal structures together with schists of what is’ today called the Kuiseb Formation and that there is a very “intimate relationship” between the Salem-type granites and these schists. Smith (1965) also advocated an autochtonous character for the Damara intrusives. He stated that 70% of the igneous rocks, which consist of gneissose varieties, and part of the rest, are the result of in situ granitisation due to high-grade metamorphism. He proposed that the Damaran Kuiseb Formation schists were the major source for the granitic magma of the Salem-type granites, whereas the Kubas granite might have its precursor in Aababis Complex schists. Other granites are explained by “slight metamorphic differentiation of the autochtonous gneiss”. He could however not explain the difference in composition between the “Salem gneiss” and the “quartz diorite” in terms of a granitisation of the Kuiseb
Formation schists. Miller (1973) reported to have found evidence in the field, supported by melting experiments, for a derivation of the Salem-type granites from the Kuiseb Formation. The idea of partial melting of the schists to form the Salem-type granite was mainly inspired by the field observation that the granites occur almost everywhere in synclinal structures together with the schists or occupy its stratigraphic position.

For the Salem-type granites it was later found that:
- the $^{87}$Sr/$^{86}$Sr initial ratios vary widely (between 0.7056–0.7166 (Haack & Martin 1983);
- there is an age difference between Salem-type granites of up to approximately 140 Ma (Haack & Martin 1983);
- P-T conditions during regional metamorphism (3-3.5 kbar, on average 650–6700°C) are not favourable for initiating large scale partial melting of the schists;
- no regional-scale migmatites with the Kuiseb Formation schists do occur on surface, and the schists do probably not extend very far in depth;
- the Salem-type granite has intrusive relationships with and also occurs in underlying stratigraphic sequences and contains enclaves of these formations;
- the enclaves in the Salem-type granite mainly consist of biotite schist and granitic rocks, whereas those of the hornblende-bearing intrusive rocks are more mafic in composition. It is therefore unlikely that the Salem-type rocks and the hornblende-bearing plutonites are related;
- some of the granitic rocks have a foliation, others do not. This might indicate pre-, syn- or post-tectonic members of the Salem-type granite group.

THE PRESENT STUDY In the present study 302 samples (totalling about 7500 kg) of several plutonic bodies of granitic composition have been collected, mainly in an area south of Karibib (Fig. 1).

Govers (1931), and others, emphasize the fact that the Salem-type granite occurs with the Kuiseb Formation schists in synclinal structures. It should however be pointed out that in most antclines, the schists, which are locally associated with Salem-type granite, have been eroded away to such an extent, that only the core of older metasediments is exposed. Damara granites in antclines are therefore scarce. That almost all the Damara granitoids (the exception are the red inhomogeneous granites) can be found associated with the Kuiseb Formation seems therefore more important than its apparent restriction to synclines. It can be explained by a sheet-like intrusion of the magmas into the upper crustal levels of the Kuiseb Formation. The largest group of granitic intrusives consists of a variety of granites (in the sense of Streckeisen 1976) and occupies about 90–95% of the surface underlain by Damaran plutonic rocks. The rest comprises alkali complexes (less than 1%) and hornblende-bearing granodiorites, tonalites, quartz monzodiorites and quartz monzonites (Fig. 2). Apart from the inhomogeneous granite, most intrusives occur together with Kuiseb Formation schists, the highest Damaran stratigraphic unit in the area. Intrusive relationships with such occurrences in metasediments of lower stratigraphic units have however been found as well as enclaves of these rocks.

Mineralogically the granites mainly consist of feldspar, quartz and biotite. Some granites are characterised by large K-feldspar phenocrysts (Salem-type granite), by the presence of muscovite (Donkerhoek granite), or by the occurrence of garnet (especially when there is a large schist content in the form of enclaves or at the granite-schist contact). The hornblende-bearing intrusives are characterised by hornblende, plagioclase, biotite and up to a few percent sphene.

The enclaves are the single most important indication in the field that there is an essential difference in composition between the granites and hornblende-bearing plutonites. The former contain rock-fragments of metasedimentary rocks such as pelitic and arkosic schist (95% of the cases), calc-silicate and marble. In the hornblende-bearing intrusives enclaves of these rock-types have only been found sporadically, but hornblende-rich, more mafic ones predominate. The most obvious type consists almost completely of finely to coarsely crystalline hornblende.

Locally K-feldspar phenocrysts have been found in a schist bordering a Salem-type granite. There are indications that the schist represents a strongly deformed (sheared) granite similar to that mentioned by Vernon (1986), but at other places schist enclaves with K-feldspar porphyroblasts might be due to K-metasomatism. The occurrence of the last phenomenon is supported by thin sections showing a second phase of microcline, overgrowing (with a reaction rim) an earlier sericitised one.

GEOCHEMISTRY Several cluster analyses, measuring the degree of similarity between the different samples, support the distinction of two groups. Within each group however there are subgroups which might contain samples of different plutons, indicating the subtle geochemical difference between the plutons. In some cases, the subgroups show approximately parallel magmatic trends (e.g. $V$ versus $TiO_2$, Fig. 3).

Figure 3 – $V$ (in ppm) versus (in wt.%) diagram of several $TiO_2$-granitic Damaran rocks. Regression line 5 represents 14 samples of six plutons of tonalitic - granodioritic composition. The lines 1-4 represent four plutons of Salem-type granite (153 samples). The double lining indicates the distribution of the samples when projected onto their regression lines

Geochronologically the alkaline peraluminous group of granites and calcic metaluminous group of hornblende-bearing plutonites (Fig. 2 and 4) can be distinguished in that the granites have on average more $SiO_2$, $Na_2O$, $K_2O$, Rb, Li, F,
Ce and La and their Rb/Sr ratio is 1, and the hornblende-bearing plutonites contain more TiO₂, Al₂O₃, total Fe, MnO, MgO, CaO, P₂O₅, Sr, Ba, Sc, Cu, Zn, Ni, V, Cr and Co and their Rb/Sr ratio is about 0.2.

The hornblende-bearing plutonites have I-type, the granites S-type characteristics (as specified in Chappell & White 1974). Both groups are more mafic in character, have less K₂O, more CaO and MgO and the granites more Na₂O than the average of Cox et al. (1979). Originally these differences might have been somewhat larger because they are partly reduced by a slight sericitisation of feldspar which is apparent in most rocks. The increased CaO content is possibly the result of the intrusion of the granitic rocks through marbles of the Karibib Formation.

**TECTONIC SETTING** The AFM diagram in figure 5 indicates the fields for type compressional (C) and type extensional (E) plutonic suites (Petror et al. 1979). The granites and hornblende-bearing plutonites of the Damara Orogen clearly follow the same well-defined trend, but take up different positions along the trend. The field of the Damaran plutonic rocks (including the syenites) resembles that of a compressional suite, but there is a definite shift away from the total Fe corner of the diagram towards a higher MgO percentage, which is in agreement with the more mafic character of the Damaran granitic rocks as mentioned before. The granites do only partly fulfil the other criteria for compressional suites as mentioned by Petror et al. (1979). They do have normative plagioclase and a unimodal frequency distribution of the differentiation index, but their calc-alkaline index is not in the range of 60-64, but lower than 50 (Fig. 4). Figure 5 does not show a change from extensional to compressional tectonic regime during the intrusion of the Damaran plutonic rocks.

The discriminant diagrams as proposed by Pearce et al. (1984) do not give a unique answer either to the question of the tectonic setting of the Damaran plutonic rocks, possibly because these diagrams are strongly based on different processes of magma formation and differentiation, which might vary within one tectonic setting or during one orogenic cycle. The hornblende-bearing intrusive rocks plot in the "volcanic arc" field of several of the diagrams. The granites fall in the "within plate", "volcanic arc", or "syn-collision" fields.
It is evident that the different plutonic rock-types plot in different fields of tectonic regime (all of them compressional) and it would be very important to define the sequence of intrusive events. A chronological sequence of events involving pre-plate collision, syn-collision and late orogenic intrusives is not supported by absolute age determinations. The pre-collision hornblende-bearing plutonites (field 2 in figure 6), syn-collision granites (field 1) and late-orogenic syenites (field 3) have according to available age determinations (see Haack & Martin 1983, Haack et al. in press) ages of respectively 650, 550 and 570 Ma. The interpretation of the geochronological data has been hampered by the occurrence of inherited isotopic systems in most of the Damaran plutonic rocks, which have not been fully understood yet.

**CONCLUSIONS**

Field and geochemical data suggest that the Damaran plutonic rocks can be subdivided into two major groups, i.e. a minority (less than 5%) of early I-type calcic metaluminous hornblende-bearing plutonites with an average Rb/Sr ratio of primary sialic crust (0.2) and a majority of later S-type alkalic peraluminous granitic rocks with much higher Rb/Sr ratios (1), representing reworked continental crust material. The members of especially the granite group represent a wide range of petrographic different but petrogenetic similar multipulse intrusions.

Combining isotopic data (Haack & Martin 1983) with geochemical, mineralogical and field observations it has been possible to locate the origin of most of the Damaran plutonic rocks (Fig. 7). The hornblende-bearing plutonites (tonalites etc.) have I-type characteristics and were probably formed from melts generated in a mafic lower crust. Large scale anatexitis of the middle crust might have been initiated by the intrusion and crystallization of these magmas, resulting in melts crystallising into typical S-type granites. On surface today, migmatites have been found of leucocratic granites and rocks of the Abbabis Complex basement or the lower Damara Sequence, indicating the origin of such granites in upper crustal levels.

**REFERENCES**


