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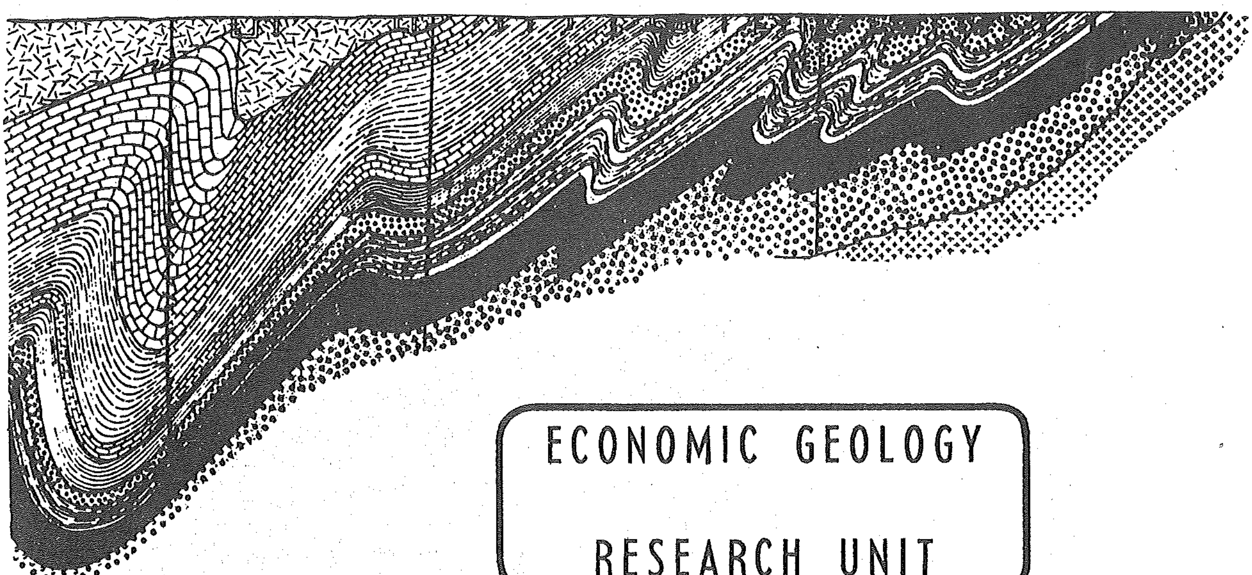

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NON-OROGENIC GRANITES IN THE ARCHEAN GEOSYNCLINE OF THE BARBERTON MOUNTAIN LAND

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by

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ABSTRACT

The Early Precambrian supra-crustal rocks of the Barberton Mountain Land are remarkably similar in type and sequence to those found in the classical geosynclines of much younger age. These rocks were laid down on a basement which was granitic in certain areas, indicating that granitic cycles probably existed in the very distant geologic past (+ 3000 million years). Intrusive into the supra-crustal rocks are granites which could not have been formed in accordance with currently accepted processes of metamorphism and orogenesis in geosynclines. It is suggested that these intrusive granites were derived from a fractional process in the mantle, and that the Archean crust formed from cyclic additions of granitic material of this type.

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NON-OROGENIC GRANITES IN THE ARCHEAN GEOSYNCLINE OF THE BARBERTON MOUNTAIN LAND

CONTENTS

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NON-OROGENIC GRANITES IN THE ARCHEAN GEOSYNCLINE OF THE BARBERTON MOUNTAIN LAND

THE BARBERTON MOUNTAIN LAND AS A POSSIBLE GEOSYNCLINAL REMNANT

A. THE PROBLEM

In examining the Precambrian, it would appear that the linear orogenic belt, such as the younger Alpine and Hercynian orogenies of Europe, among others, does not exist. Several lines of reasoning have been employed to explain this, the most frequently mentioned being that the ancient granitic shield areas actually comprise a number of juxtaposed root zones of orogenic belts, in accordance with the continental accretion hypothesis. It has also been argued that the Earth's crust was much thinner in Precambrian times, a phenomenon acting against preservation of ancient linear belts. Brock (1959) has suggested that the size of orogenic belts increases with time. The validity of this hypothesis hinges on the significance of the associated granites. The apparently smaller size could be indicative either of the existence of less extensive geosynclines and orogenic belts, or of the preservation of small remnants of larger orogenic belts in vast masses of mobile and intrusive granite.

The examination of any map of an ancient shield area reveals that granitic rocks account for a major portion of the exposed crust. The problem of the apparently smaller Precambrian orogenic belts can, possibly, be considered from another equally important, and genetically related, point of view — instead of the emphasis on the small size of the Archean belts, attention should be shifted to the very large masses of associated granitic rock. Because of its age in excess of 3000 million years, and its unique state of preservation, the Barberton Mountain Land is believed capable of providing an important insight into the problem of the development of relatively small orogenic belts and of vast expanses of granitic material in Archean times.

B. GEOSYNCLINES AND OROGENESIS

The term 'geosyncline', as used in this paper, refers to an elongated basin filled with a relatively thick accumulation (kilometres) of sediments which have been strongly folded. Geosynclines develop in mobile zones in the Earth's crust, between, or surrounding, the stable zones (cratons). In their most elementary form (Aubouin, 1965), they are made up of a series of ridges and furrows. Thus, passing from the continent, or craton, the miogeosynclinal furrow, the miogeosynclinal ridge, the eugeosynclinal furrow, and the eugeosynclinal ridge are successively encountered. These ridges and furrows may, in fact, represent submarine horsts and grabens. The miogeosynclinal ridge and furrow are referred to as 'external' (Externides of Stille, 1940), while the eugeosynclinal ridge is described as being 'internal' (Internides of Stille, 1940). Two fundamental features distinguish the miogeosyncline from the eugeosyncline. Firstly, the eugeosyncline is characterized by the presence of ophiolites, while the miogeosyncline does not act as host to this rock assemblage. Secondly, there is a progressively younger age of flysch development from the interior to the exterior of the chain (Aubouin, 1965).

Geosynclines are frequently located at the margins of continents, and have their modern analogues in the island arcs (Engel, 1963). The development of these large depositories, although not completely understood, results in a certain order of characteristic rock assemblages. The earliest rocks to form in the eugeosyncline are characterized by the greenstone - radiolarite association, also known as the ophiolite assemblage. The greenstones comprise igneous rocks, amongst which volcanics are the most common. Basalts and albitized basalts (spilites) predominate, although keratophyres and, less commonly, rhyolites are found. Pillow structures are particularly characteristic of the basic lavas (de Sitter, 1964; Kundig, 1956). Other common igneous rocks are peridotites, serpentinized peridotites, dunites, diorites, and gabbros. The frequent association of peridotite and gabbro has led Thayer (1960) to conclude that gabbroic rocks should be included as an "..... integral and important part of the alpine-type peridotite problem".

Aubouin (1965), in describing ophiolites from geosynclines, supports the view of numerous other investigators that they "..... well out in the shape of an enormous submarine flow", and are built up of an outer shell of microlitic rocks (spilites, basalts, pillow lavas), followed inwards by a shell of medium-grained dolerite, and a central differentiated core consisting of peridotite, at the bottom, followed upwards by pyroxenite, gabbro, and diorite, with quartz diorite at the top. Such an idealized arrangement of rock-types is not common, and Kundig (1956) states that the tectonic style of ophiolite belts is characteristically complex, presenting the almost universal problem of not being able to establish when the rocks were emplaced with respect to one another.

The sediments associated with these ophiolites are somewhat variable, but are generally described as being "pelagic" or "bathyal". Unbedded shales, clays, and phyllites, of a bathyal facies are found as the "schists lustre" of the Pennine Alps and the "argille scagliose" of the northern Appenines (de Sitter, 1964). Other sedimentary rocks are siliceous limestones of deep-water type and microbreccias formed by turbidity currents but distinguishable from similar flysch material by not containing any terrigenous material. The radiolarities are siliceous rocks formed from the accumulation of radiolaria fragments.

The initial stage of the geosyncline is followed by the flysch period during which an appreciable thickness of deep-water turbidites fills, first, the eugeosynclinal furrow, and then the miogeosynclinal furrow (Aubouin, 1965). The postulated structural environment giving rise to these rocks is the paroxysmal stage in prelude to the main orogeny (de Sitter, 1964). The major requirement for the onset of flysch formation is the development of a rapidly rising cordillera in the eugeosynclinal ridge zone. A monotonous sequence of dirty sandstones (greywackes, microbreccias) and shales are then deposited in the eugeosynclinal furrow by turbidity currents which remove detrital matter from the inner flank of this furrow by gravity slides. According to Aubouin (1965), the flysch shows a characteristic pattern of development. Its formation is essentially "pre-tectonic", preceding the orogeny in time and space from the internal zones towards the external zones. The migration of the flysch is somewhat spasmodic, filling first the eugeosynclinal furrow (which thus acts as a barrier to the migration) and, only after this, the miogeosyncline furrow. The flysch facies is developed throughout the region, between the cordillera producing the material and the neighbouring (more external) furrow. It therefore results from the erosion of a zone siutated to the interior of that receiving the sediment.

The main features of these deposits, according to Aubouin (1965), are :

(a) sedimentary characteristics of distinctly marine origin, in which there is a mixture of pelagic and land-derived material, regular alternations of sandstone and pelitic clay beds, rhythmic layering, graded bedding, and sole markings;

(b) a high degree of concordance with sediments of the pre-flysch period, in general, but an occasional transgression towards the external portions of the geosyncline; and

(c) the youngest pre-tectonic age, particularly with respect to flysch deposits in the eugeosyncline, since those in the miogeosyncline may show merely a transgression.

Flysch material, therefore, has a very close time-space relationship to the orogeny which occurs when the geosyncline is subjected to the main paroxysm. Orogeny also reveals a migratory tendency, starting first in the internal zones and moving gradually outwards in time. Various rock-types become folded according to different styles, depending on which section of the orogenic belt is undergoing deformation. Metamorphic and granitic phenomena are closely linked with the orogenic pulse, the metamorphic effects often being post-major folding, or late tectonic (Wenk, 1956; Chatterjee, 1961; Sutton, 1965). Granitic phenomena show a broad time-range of development, being both syn- and post-tectonic, the latter probably being the anatectic products of processes of regional metamorphism, which have a tendency to behave diapirically.

The granitic phenomena tend to be confined to the internal zones of the geosyncline (de Sitter's, 1964, axial zone; Aubouin's, 1965, eugeosynclinal ridge and furrow). North American examples of granitic emplacement with respect to geosynclinal zones are particularly impressive. King (1959) has shown that the distribution of siliceous plutons is clearly confined to the eugeosynclinal zones in North America, which are younger than 1000 million years. Eardly (1962) has stated, with reference to the Western Cordillera of North America, that the batholithic belt coincides almost exactly with the previous eugeosyncline. Aubouin (1965), however, has suggested that, "in the course of time", there is a retreat of granitic plutonism towards the eugeanticlinal ridge. Within the Hercynian belt of Europe, plutonism is confined to the eugeanticlinal zone, while in the Caledonian chain it reaches the eugeosynclinal furrow, and in the Sveccofennian of Finland the miogeosynclinal zone.

With regard to the sequence of flysch deposition, plutonism, and metamorphism, Sutton (1965) has suggested that there is an overlap in time between the period in which plutonism continued and that during which the flysch was deposited. He has suggested that regional metamorphism may be occurring at present, near island arcs and oceanic trenches, where heat flow is known to be unusually high, and where flysch-like deposits are being laid down. Takeuchi and Uyeda (1965) have also put forward the possibility of active present-day regional metamorphism in the Japanese island arc area.

Molasse deposition is generally accepted as marking the end of the period of active folding, and takes place as a result of isostatic readjustment in the Earth's crust where the orogen is characterized by regional uplift. Sutton (1965) has stated that the molasse facies also marks the end of the metamorphic cycle. Using geochronological data, he has indicated that, in many of the larger fold belts, the end of metamorphism and the start of post-orogenic molasse formation cannot be readily distinguished. Molasse deposition is frequently referred to as being post-orogenic (de Sitter, 1964). However, Aubouin (1965) prefers to relate molasse formation to a late-orogenic, or late-geosynclinal, period, because molasse troughs are often themselves subjected to deformation, though this is generally of a much lower degree than that of the preceding geosynclinal period. Certain molasse troughs are marginally overlain by older superficial rocks which have attained such a position by gravity sliding. Molasse troughs can be classified as (i) back-deeps, occurring behind the eugeosynclinal ridge, (ii) fore-deeps, situated close to the craton, and (iii) intra-deeps, or intermontane basins, situated in the heart of the chain. The Meso-Hellenic Furrow (Aubouin, 1965), filled with molasse-type sediments, occurs in the eugeosynclinal zone, in fact over the original eugeosynclinal furrow.

The molasse sediments are generally those of a fresh-water or continental environment. They are characterized by sandstones and conglomerates. Cross-bedding is often developed. According to de Sitter (1964), there is a rapid change in facies in a direction perpendicular to the mountain chain. On the internal margin of the basin there can be a considerable accumulation of conglomerates, interstratified with sandstones and shales, and often with evaporites.

In many molasse basins, there is an association of magmatic activity, expressed by the outpouring of andesitic and rhyolitic lavas, as well as by the emplacement of granitic plutons. This igneous activity may be associated with anatexis at deeper levels during the previous stage. As Sutton (1965) states, "..... regional metamorphism and thus (andesitic and rhyolitic) volcanicity may be associated in space ....."

Read (1957), in relating his Granite Series to various types of geosynclinal sediments, has pointed out that the molasse and Red Sandstone-type sediments are intruded by small granite bodies "..... emplaced by mechanical contrivances, such as cauldron subsidence or graben faulting". He also put forward that "..... the post-orogenic sediments are clearly the wrong setting for granitization; they are too distant in time and place from the source of all granite". In Aubouin's (1965) opinion, the formation of the molasse, the extrusion of andesites and rhyolites, and the formation of granodiorites and diorites are all part of the late-geosynclinal stage. De Sitter (1964) has proposed that intrusive stocks, which are directly connected with ring dykes and cauldron subsidence, form a transitional type between the late-tectonic intrusive batholiths and the post-tectonic volcanic phase. They are later, in relation to the orogeny, than the normal batholiths, and are often intrusive into the molasse.

It thus appears, from studies of younger orogenic belts, that metamorphism and large-scale granitic phenomena precede molasse formation, and that volcanic phenomena (andesitic and rhyolitic extrusion), as well as the emplacement of smaller granitic stocks and plutons, are post-molasse in age.

The final stage in the development of a geosyncline is represented by a period of essentially vertical movements (deep-seated tensional faulting associated with broad regional arching) which are more-or-less independent of the earlier zonal development. These movements produced the land forms as seen today in the younger geosynclinal belts. This final stage is also accompanied by an important igneous phase, Stille's (1940) "final magmatic phase" comprising mainly basalts, although less basic lavas may also occur.

C. THE ORIGIN OF THE BARBERTON MOUNTAIN LAND

De Sitter (1964) has stated that "in the Precambrian orogenies the dominance of magmatic and volcanic phases during the whole history of their structural development tends to obliterate the facies differences between the geosynclinal, flysch and molasse phases". This, as shown below, is certainly not true as regards the Barberton Mountain Land. It has been suggested by Anhaeusser (1964) and Viljoen (1964) that the Onverwacht Series at the base of the Swaziland System, which comprises the main mass of rocks of the Mountain Land, represents the initial magmatic phase of a geosyncline, that the overlying Fig Tree Series represents a flysch facies, and that the Moodies Series at the top of the succession represents a molasse facies. Outside of the Onverwacht Series, only two lava bands are present in the Swaziland System — one in the Fig Tree Series, and one in the Moodies Series. The former is controversial, and may be a greywacke. However, including that rock as a lava, the amount of volcanic material represents less than 3 per cent of the total thickness of Fig Tree and Moodies sediments. In certain portions of the Mountain Land these volcanic rocks are not even developed.

Concerning the ophiolite assemblage of geosynclines and the Onverwacht Series of the Mountain Land, A.E.J. Engel (personal communication, 1965) has identified a considerable development of pillow lavas in the Onverwacht group of rocks. These lavas are essentially basaltic, and are interlayered with ultrabasic rocks and more acid lavas (M.J. Viljoen and R.P. Viljoen, personal communication, 1965). The upper acid volcanic phase of the Onverwacht Series is also open to doubt, since the large mass of quartz porphyry occurring just south of the Stolzburg Syncline may, in fact, be a greywacke. A sample of the so-called quartz porphyry has revealed the presence of at least four different populations of zircon, and analysis has shown that the chemical composition of the rock does not allow it to be classified as igneous (C.B. van Niekerk, personal communication, 1966).

Cherty-looking horizons have also been identified in the Onverwacht Series. Under the microscope they consist of an equigranular mosaic of quartz, with scattered mica flakes. They are metamorphic quartzites. Cherty rocks are always associated with the ophiolites of younger geosynclines, and consist of a residue of radiolarian tests. The Onverwacht chert bands may be of similar origin, since the remains of primitive life forms have been established in these ancient rocks (Pflug, 1966). Alternatively, the siliceous material may have been precipitated by chemical means.

The presence has not been established in the Mountain Land of either albitized basalts or of glaucophane, jadeite, and lawsonite which are commonly derived from the metamorphism of basic rocks in younger post-Palaeozoic fold belts (Eskola, 1929; de Roever, 1956). The absence of these essentially high-pressure minerals has been explained by de Roever as the result of a secular decrease in the geothermal gradient in the Earth's crust. This might have resulted from a "stiffening" of the crust with time, favouring conditions for the "high pressure - low temperature facies" of regional metamorphism (Miyashiro, 1961) in which these minerals form. A.E.J. Engel (personal communication, 1966) has pointed out that the non-development of a blueschist facies favours a thin crust and a steep thermal gradient in Early Precambrian times.

The problematic absence of spilites may be linked with the unusual contact metamorphism observed in the Mountain Land. Another influencing factor may have been the fact that the chemical environment of this very ancient depository differed from that of its younger equivalents, since the chemical activity of entrapped and connate sea water, squeezed up from deeply buried sediments, possibly influences the evolution of spilites.

To justify classifying the Fig Tree rocks as a flysch facies, the greywackes and shales should have been tectonized before the deposition of the overlying molasse. The unconformable relationship between Fig Tree and Moodies sediments is difficult to establish, largely because of faulted contacts between syncline and syncline — a structural feature characteristic of the area. However, pronounced unconformities can be seen north of the Princeton Mine, where the basal beds of the Moodies Series rest on schistose rocks of the Zwartkoppie Horizon (Lower Fig Tree and Upper Onverwacht) or on shale, banded chert and greywacke of the Fig Tree Series, and on the farm Amo 298 where a well-defined grit band occuring in a sequence of thinly-bedded pelitic sediments of the Fig Tree Series disappears under the basal conglomerate of the Moodies Series. On the Swaziland side of the Mountain Land, Urie (personal communication, 1965) has observed that the predominantly arenaceous Moodies Series rests unconformably on the Fig Tree Series in the northwestern part of the territory. Urie (1957) has described a pronounced angular unconformity between Fig Tree and Moodies sediments in the southern extremity of the Mountain Land, and has reported a degree of folding in the Fig Tree Series appreciably greater than in the Moodies Series.

The evidence for the Moodies Series representing a molasse-type deposit is not abundant, since most of the orogenic belt is missing and only a small portion can be examined. There is, however, a striking contrast between the Moodies and Fig Tree sediments. The Moodies rocks are of a distinctly shallow-water origin. An assemblage of conglomerates, sandstones, and shales show cross-bedding, ripple-marking, and mud cracks. The cross-bedding is often of the festoon-type, while occasional conglomerate bands show very poor sorting, with boulders up to 3 feet in diameter lying next to small pebbles. If the Moodies Series is a molasse-type accumulation, then no important volcanic stage was developed with it, at least not within the limits of the Mountain Land.

In general, it can be concluded that there is a marked similarity between the rock-types, and their order of super-position, of the Barberton Mountain Land, and those found in younger, typical geosynclines. The problem still remains as to whether the rocks of the Mountain Land were deposited in a geosyncline which underwent orogeny, since such an orogenic belt, if it existed, cannot presently be identified. The supra-crustal rocks comprising the area are intruded on all sides by granitic material. It is impossible to define the original cratonic area (if such existed), the miogeosyncline, and the eugeosyncline. Most of the geosyncline has been obliterated by the appearance of post-Moodies granitic masses which have removed all traces of the original regional zonation. The rocks occurring in the Mountain Land could be eugeosynclinal, and the Moodies Series could represent an intermontane molasse basin (ultra-deep). Alternatively, they could represent portion of a miogeosyncline, if ophiolitic activity in Early Precambrian times extended beyond the eugeosyncline. The folding observed in the area is post-Moodies in age, and thus post-molasse. This deformation is intense (isoclinal folding, ubiquitous thrust faulting), having the appearance of a "second orogeny" in the geosyncline, and being intimately related to the emplacement of the surrounding granitic rocks.

THE HIERARCHY OF THE GRANITIC ROCKS

A. THE PRE-ONVERWACHT BASEMENT

The recognition of the basement on which the Swaziland System was deposited is of major significance in regard to the development of the ancient crust. Since no sedimentary or unconformable contact between the Onverwacht Series and the underlying rocks can be identified, indirect methods of analysis have to be employed.

Examination of Fig Tree sediments gives certain clues as to the composition of the source material. The greywackes are sedimentary microbreccias made up of such rock fragments as shale, banded ironstone, and quartzite, and of the minerals quartz, potash felspar, plagioclase, carbonates, chlorite, muscovite, zircon, apatite, and serpentinite. Of interest is the potash felspar which averages 2.5 volume per cent, the highest value value thus far recorded being 5.3 volume per cent. The potash felspars are generally microcline, and reveal perthitic and micro-pegmatitic textures. The plagioclase is generally of andesine composition. A chemical analysis of one such rock revealed a K_2O content of 1.44 per cent and an Na_2O content of 2.90 per cent. These minerals certainly would suggest that at least part of the material contributing to the greywackes could have been derived from granitic rocks.

The Moodies Series provides more definite evidence of having been derived from granitic rocks. Pebbles of granite and quartz porphyry occur in the basal conglomerate. Many of the quartzites are felspathic, containing fresh microcline and albite. C.R. Anhaeusser (personal communication, 1966) has found numerous granite pebbles which have a micro-pegmatitic texture of microcline and quartz, and quartzites containing significant amounts of microcline perthite and oligoclase grains.

If the Moodies Series represents a molasse facies, then the granitic material could have been derived from the orogenic axis in which granitic and metamorphic phenomena occurred. The granitic material would then be of orogenic derivation, and would not represent crustal material. However, in many cases it has been suggested that granitic rocks of this type may be palingenic equivalents of earlier granitic basement material. If, on the other hand, the Moodies Series is not a molasse facies, then exposed granitic masses must have supplied detritus with the characteristics described above. Either model is suggestive of there having been a granitic basement close to the present occurrence of supra-crustal rocks in the Mountain Land.

C.E. Wegmann (personal communication, 1963) observed the presence of highly deformed dykes in some of the migmatites surrounding the Mountain Land. These dykes have been folded, and the axial planar structure of the migmatites is identical to the axial plane of the dykes. Dykes which had an orientation more-or-less parallel with the axial planar trend of the folded migmatites are not folded, but are elongated and boudinaged. Furthermore, the dykes are locally cross-cut and injected by the granitic matrix into which they at one time intruded — examples of the "Sederholm effect". This implies palingenesis of the surrounding migmatitic and gneissic material. The dykes, presumably of an initial basaltic composition, now consist of biotite, hornblende, and felspar. They have thus undergone an alkali-metasomatism during the palingenetic period. That these bodies are dykes is shown by the fact that, even in the case of many of the folded varieties, they are often distinctly discordant with the folded gneissic layering in the migmatites.

There are several ages of dykes. Some have been involved in folding and palingenesis, while others have not. The youngest dykes in the area are all post-folding in age, and cut across the supra-crustal rocks and granites of the Mountain Land in a northwesterly direction. No folded dykes are known in the supra-crustal rocks of the Mountain Land, rendering it unlikely that those migmatites containing deformed dykes immediately adjacent to the supra-crustal rocks represent granitized portions of the latter. It is more reasonable to assume that the migmatites represent crust on which the supra-crustal rocks were deposited, and through which the dykes acted as feeders to overlying lavas of a pre-Onverwacht cycle. The present exposures of granite possibly contains remnants of this early crust.

A striking example of this phenomenon has been found in northwestern Swaziland by Hunter (personal communication, 1965). Here, in the "Ancient Gneiss Complex", at least two distinct ages of dykes can be recognized. An earlier dyke has been disturbed by a period of folding which also affected the gneisses. A younger set of cross-cutting dykes shows no deformation, yet both ages of dykes have been involved in palingenesis, the final stage of which process must have been of a passive nature, without folding. These gneisses are veined and cut by the G.4 granite which intrudes and metamorphoses the supra-crustal rocks of the Mountain Land. The ancient gneisses and associated dykes were possibly reactivated during the G.4 granitic cycle which has been dated at 3070 $\pm$ 60 million years (Allsopp et al, 1962). These data must thus suggest a cycle of : consolidated rock — injection of dyke — gneissification, granitization, and folding — consolidation — injection of younger dyke — re-granitization by G.4 granite. Since none of these dyke groups is known in the adjacent supra-crustal rocks, the gneisses must be taken as probably representing an ancient basement with a complex history involving at least one earlier period of granitization. Thus, a granitic basement to the rocks of the Barberton Mountain Land probably exists at certain localities.

B. THE RELATIONSHIP BETWEEN GRANITES AND SUPRA-CRUSTAL ROCKS

Along all the mapped contacts, granite intrudes and metamorphoses the supra-crustal rocks of the Barberton Mountain Land. The northwestern contact with the Nelspruit Granite has been described by Viljoen (1964) and Anhaeusser (1964) as revealing both intrusive relationships and a well-defined contact metamorphic aureole. The Kaap Valley Granite, on the southwest, is also clearly intrusive, containing enclaves in a high state of digestion in the central part of the pluton, and features of injection and brecciation along the margins. The Badplaas granite, at the southwestern extremity, shows intrusive relationships, while in Swaziland the intrusive nature of the G.4, or "late-orogenic", granite has been described by Hunter (1961). Here, the supra-crustal rocks have also suffered contact metamorphism. The Salisbury Kop granite, towards the northeastern limit of the Mountain Land is also intrusive (M.J. Viljoen and R.P. Viljoen, personal communication, 1966).

Recent structural investigations have shown that the main period of deformation in the Mountain Land is intimately related to the metamorphism of the granite contacts. Thus, folding was essentially synchronous with the metamorphism which must have been initiated by an energy source from the intruding granites, the bulk of all varieties of which may possibly have been emplaced more-or-less simultaneously. That some granites actually are later than the main period of deformation could mean either that there are, in fact, younger granites in the area, or that the cooling history of the large intrusive granitic masses was complex, with younger fractions being removed from the main mass after the major tectonic event.

C. THE REGIONAL STRUCTURE OF THE INTRUSIVE GRANITES

The most striking feature of the contact along the northwestern segment of the Mountain Land is that the actual intrusive material consists of an homogenized phase, with associated pegmatites and aplites, of the mobilized Nelspruit granite (Viljoen, 1964; Anhaeusser, 1964). Proceeding away from the supra-crustal rocks, this contact zone, several thousand feet wide, gives way to migmatites and gneisses. The Kaap Valley Granite, is, itself, an homogeneous massif, showing a mineral orientation at its margins. The intrusive granite in the Badplaas locality also consists of an homogenized phase in the contact zone, which shows similarities with the Kaap Valley Granite (M.J. Viljoen and R.P. Viljoen, personal communication, 1966). Hunter (1961) has suggested that the homogeneous G.4 granite of Swaziland, which intrudes the supra-crustal rocks, represents a large hood, or sheet, which gives way vertically downwards to a zone of nebulites, that is, in turn, underlain by gneissic granites.

The varieties of granite described above possibly constitute large diapiric masses, surrounded and covered by hoods of mobilized magmatic granite which intrudes the supra-crustal rocks. As suggested previously, portions of the migmatitic terrain could well represent the ancient basement rendered mobile (rheomorphic) during the main period of diapirism. The fact that the overlying granite within these masses is homogenized in the form of a hood may be explained through the mechanism suggested by Kennedy (1954). Within a magma chamber (which may apply to a highly migmatitic or partially magmatic mass) there will be a tendency for equilibrium of the vapour pressure or the partial vapour pressure of water. In colder areas, such as those where the assumed migma encounters wall-rocks or supra-crustal rocks at lower temperatures, the drop in the vapour pressure is compensated by an addition of more vapour in order to maintain equilibrium in the entire chamber. The same effect will be brought about in areas where the vapour phase is able to escape, such as through cracks in the country-rock. More vapour will migrate to the low pressure areas. Both phenomena will thus bring about a migration of vapour to the margins of the mass, and this could well lead to a concentration, in the upper zones of the granitized crust, of the mobile magmatic granitic material from the unconsolidated migmatite, with the resultant formation of a magmatic hood.

The significant feature of these ancient granites is that their zonal distribution is the complete reverse of that found in regions where anatectic granites are developed. In the latter, the sequence from the contact rocks to the granitic core is as follows : (i) felspathic gneisses, in which are often preserved planar structures and layered zones of earlier sedimentary rocks, (ii) a zone showing nebulitic structures with a tendency towards homogenization, and (iii) the anatectic granite zone (Raguin, 1965). This reversal of zonal structure is important, and emphasises the intrusive nature of the Archean Barberton granites, with their associated contact aureoles, in contrast with anatectic granites generated in situ.

D. THE TIME AND MODE OF EMPLACEMENT OF THE GRANITIC ROCKS

It is a well-established fact that a major granitic event in the history of the Barberton Mountain Land is of post-Moodies age. This event includes the almost synchronous development of phenomena represented by the emplacement of the Kaap Valley granite, by the intrusive phase of the Nelspruit and Badplaas granites, and by the G.4 granite in Swaziland. Typical orogenic granites, and in particular the large siliceous batholiths, are late-tectonic. Post-molasse granitic activity is considered to be confined to smaller stocks, ring complexes, cauldron subsidences, and similar phenomena associated with graben faulting, so that these post-orogenic granites are generally of a sub-volcanic nature, being often intimately related to volcanism. Therefore, if the Barberton Mountain

Land represents a geosynclinal sequence, the extensive invasion of post-molasse granitic material into the geosyncline and its surroundings is anomalous, when compared with younger equivalents.

If it is not possible to employ a uniformitarian geosynclinal orogenic model in explaining the development of these very ancient rocks, an unique mechanism of granite generation is required to account for granites encroaching on, and obliterating most of, an Archean volcanic-sedimentary depository. A reassessment of present concepts of granite generation is indicated.

Another fundamental aspect of the Barberton granites is that their emplacement appears to be the direct cause of the "orogeny", or, rather, much of the folding observed in the supra-crustal rocks. The granites are not the result of, nor are they intimately associated with, the orogeny of a geosyncline in the classical sense. If they are related to a geosynclinal cycle at all (a point that requires proof), then they must have made their appearance in virtually the last stages of such a cycle. This implies that either current knowledge of the geosynclinal cycle is incomplete, or granites have very little to do with it, and were derived from some other fundamental process.

It has been suggested that the granites of the Barberton Mountain Land were intruded in a diapiric fashion. The outcrop pattern of the supra-crustal rocks and associated granites reveals that the latter commonly develop rounded embayments into the former. The Kaap Valley granite has a rounded outline, and the orientation of the planar fabric of the supra-crustal material is parallel to the granite contact. The same features have been observed in two rounded embayments in the Onverwacht Series in the Steynsdorp Valley. On a regional scale, it is apparent that the supra-crustal rocks are draped around the granite bodies, as the lowermost members of the Swaziland System almost invariably lie in contact with the intrusive granites.

The G.4 granite clearly intrudes the supra-crustal rocks in the northwestern part of Swaziland (Hunter, 1961). Age determinations employing the rubidium-strontium method indicate that this granite was emplaced about 3000 million years ago (Allsopp et al, 1962). It has been put forward that most of the granitic material was emplaced at this time, but there are indications that certain granitic phenomena post-date the major structural event which is associated with the emplacement of the 3000 million year-old granites (Viljoen, 1964).

THE POSSIBLE EXISTENCE OF NON-OROGENIC GRANITES

The more significant aspects of the geology of the Barberton Mountain Land which the present paper has attempted to define include the following :

(a) The supra-crustal rocks are remarkably similar in composition and sequence to those found in a typical geosyncline.

(b) These rocks were laid down on a basement which in certain areas, at least, was granitic. The great age of this basement (+ 3000 million years), and the fact that it does not differ much in character from younger granitic terrains suggests that comparable cycles of granitization and gneissification existed in the Archean.

(c) Granitic detritus contributed to sediments of the Fig Tree and Moodies Series.

(d) The large expanses of intrusive granitic material have removed all traces of the original zonal distribution pattern of the depository and adjacent areas.

(e) The granites are not of an orogenic type.

The intrusive bodies of granitic material surrounding the Barberton Mountain Land cannot be fitted into the sequence of events established for more recent geosynclines. In the geosynclinal-orogenic model for this area, a major granitic event is post-molasse in age, which is obviously anomalous with respect to the models for younger orogenic belts. If the granites were emplaced immediately after the deposition of the Moodies Series, then they would be related to the development of the geosyncline only in some obscure manner. Such a process would have to permit the generation of granite after the major diastropic and metamorphic events, when a high state of stability and equilibrium had been attained within the confines of the geosyncline. If such an explanation is not acceptable, then the possibility exists that the granites are associated with another cycle, and were developed well beyond the eugeosynclinal environment of that cycle. A third hypothesis is that granitic material was added to the crust in very Early Precambrian times from a differentiative process in the upper mantle, without reference to any orogenic zones. Irrespective of the mechanism, the fact remains that the granites are not orogenic in the classical sense.

The idea that granites are derived from, and associated with, processes of orogeny has been championed by Read (1957) who has stated that "the granitic and plutonic rocks belong to the orogeny, the basic and volcanic rocks belong to the geosynclinal phase". From this postulate, the theory has been advanced that large granitic shield areas represent the exposed roots of adjacent orogenic belts. Ramberg (1964), in proposing a theory for the origin of continental blocks, stated that "the present structure of the continental blocks bears witness to numerous periods of reworking of the sialic material since it originally rose from depth, a reworking chiefly effected within orogenic belts of various ages".

However, it is known that certain granites are not orogenic, among which can be included the Rapakwi granite of Finland, the granites of the Bushveld Igneous Complex, and subvolcanic granites of the type described by Korn and Martin (1954) from South West Africa. It is put forward here that another group of granites be added to the above established types. These granites are primary, although they may affect and rework existing crustal material. Their source is "somewhere below", and it is suggested that, in the Early Precambrian, the mantle was directly responsible for the addition of granitic material to the crust on a large scale. Continental nuclei were possibly formed by this process of granite addition. The crust was probably thinner in Archean times, and granite addition was rendered visible because of its intrusive nature. This process of granite addition may have ceased to operate in younger geologic times, possibly from the Cambrian (?) onwards.

Another example of large-scale granite formation exists in the Sveccofennides of Sweden. A sequence of acid lavas, limestones and dolomites progresses upwards into a group of greywackes, shales, and conglomerates, with intercalated spilites (Geijer and Magnusson, 1944). These rocks were subjected to orogeny and syntectonic granite invasion (urgranit). A period of quiet crustal stability followed in which dykes (meta-diabases) were intruded. These dykes do not penetrate a younger granitic cycle (sensvioniska) which affected the entire Sveccofennides. Fragments of the basic dykes have been found in these younger granites. These later granites have been attributed to regional, "epeirogenic" sinking of the area, associated with weak folding, as was produced with the early syntectonic granites. The result was a regional migmatisation by upward-migrating granite solutions. Locally, large plutons of granite resulted from homogenization. This later granitization followed a period of crustal stability, when fractures developed in the crust which permitted the ascent of basaltic magma. This period of dyke invasion has been interpreted as intra-orogenic, so that both granitic events are classified as "orogenic". However, the epeirogenic nature of the younger granite period, following after the dyke invasion, detracts from such a straightforward interpretation.

In the Eastern Transvaal, Natal, and Swaziland, the Pongola System is intruded by G.4 granite (Hunter, 1961). The sedimentary rocks are typical of a cratonic depository, the sequence beginning with a basal, cross-bedded quartzite overlying granite, as can be seen in the Amsterdam area. The quartzite is followed by an assemblage of andesites, often amygdaloidal, and more acidic felsites, with intercalated shales and quartzites. This sequence is approximately 19,000 ft. thick (Humphrey and Krige, 1931). It is overlain by a group of continental-type sediments, some 16,000 ft. thick, made up of well-sorted conglomerates, quartzites, and shales. Along its eastern margin, in Swaziland, it is intruded by G.4 granite which is responsible for the intense folding and contact metamorphism of the sediments. This large body of granite, correlated with the 3000 million-year old granite which intrudes the Barberton Mountain Land (Hunter, 1961; Allsop et al, 1962), has therefore encroached right on to the craton. The intrusive contact granite has, as yet, not been dated, but it, in turn, is intruded by a younger granite which is at least 2540 million years old (Allsopp et al, 1962). This extensive mass of Archean granite is far removed from an orogenic environment, and must have been generated by some other fundamental process. If the correlation with the G.4 granite intruding the Barberton Mountain Land is correct, then the Pongola System may well represent the cratonic equivalent of the geosynclinal sediments of the Barberton Mountain Land. If, on the other hand, the granite which intrudes the Pongola System is not 3000 million years old, but somewhere between this age and 2540 million years, it still points to the fact that in Archean time granites invaded the crust on a scale which extended the limit of their development as far as the stable craton.

It would appear that, in the remote geological past, similar geological processes operated as in younger environments (cratonic and geosynclinal depositories), but that an anomalous situation existed with regard to granite-forming processes.

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