ECONOMIC GEOLOGY RESEARCH UNIT

University of the Witwatersrand
Johannesburg

CRUSTAL DEVELOPMENT IN THE KAAPVAAL CRATON

PART I

THE ARCHAEAN

D. R. HUNTER

INFORMATION CIRCULAR No. 83

UNIVERSITY OF THE WITWATERSRAND
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by

D. R. HUNTER
(Senior Research Fellow, Economic Geology Research Unit)

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ABSTRACT

The relationship in time and space of the elements comprising the greenstone-granitic terrane in the eastern Transvaal and Swaziland is discussed. On the evidence derived from structural analysis, metamorphic style, geochemistry, and geophysics it is concluded that sialic crust (now represented by the Ancient Gneiss Complex in Swaziland) pre-dates the Swaziland Sequence. It is postulated that the sialic crust formed as a result of partial and total melting of hydrous basaltic lithosphere under tectonically metastable conditions. Limited sedimentation and volcanism in small basins on this early crust took place during periods of quiescence, following which deformation resulted in the tectonic interslicing of the early sialic crust and the sedimentary-volcanic sequences that were metamorphosed at high temperatures and low pressure (Abukuma-type), and included limited partial melting. The proto-continental crust so formed was distended along linear zones overlying sites of mantle upwelling. Rifting resulted from the distension and was accompanied by intense volcanism typical of greenstone belts. Following mantle withdrawal sagging was initiated in the linear zone leading to sedimentation that was initially of turbidite type. As greater stability was achieved, the style of sedimentation changed and cratonic-type, Moodies Group sediments were deposited. The cyclic nature of the volcanism and sedimentation is considered to be a response to, and a reflection of, the degree of distension and of the vertical adjustments along the bounding faults. Diapiric rise of tonalitic magma produced as a result of partial melting of the early sialic crust mixing with mantle material caused the deformation of the original linear geometry. Continued depression of the amphibolite facies of the sialic crust into the zone of partial melting gave rise to potassic granitic magma that spread at higher crustal levels at interfaces of low free energy to form hood-like sheets of granite flanking the original linear rift. It is concluded that the eastern Transvaal and Swaziland area attained a crustal thickness of ± 25 km prior to 3.0 b.y.

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PART I : THE ARCHAEAN

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CRUSTAL DEVELOPMENT IN THE KAAPVAAL CRATON

PART I : THE ARCHAEAN

INTRODUCTION

The Kaapvaal craton in common with equivalent areas elsewhere in the world consists of three fundamental elements :

1. the greenstone-granitic terrane constituting the shield;
2. the cratonic basins developed on the shield, and
3. the mobile belts that reflect, at least in part, the re-working of the shield and, in some cases, of the cratonic basins in linear zones.

Each of these elements is distinguished by characteristic styles of tectonism, metamorphism, sedimentation, volcanism, and plutonism. Earlier investigations of Precambrian terranes led to the proposal that the Precambrian could be divided into the Archaean and the Proterozoic to accommodate the shields and the cratonic basins respectively. Geochronologic studies have shown, however, that these terms have no chronostratigraphic significance, but they are retained here as convenient descriptive names to indicate contrasting stages in crustal development.

The Kaapvaal craton provides an almost unrivalled opportunity to study the three elements by virtue of their state of preservation and topographic expression, particularly in respect of the Archaean shield in the eastern Transvaal and Swaziland. Shield areas commonly have only moderate relief and lie close to mean sea-level, but the eastern Transvaal-Swaziland area lies astride a series of scarps that mark the descent from a high plateau standing at ± 2 000 metres above mean sea-level to a plain at ± 300 metres above mean sea-level. Major rivers flowing eastward have cut deep valleys that provide three-dimensional exposures through both the greenstone belt and the encompassing granitic terrane.

In Part I, the evolution of the shield area is traced, and it will become clear that there is an overlap in the style of the geological processes that operated during the latter stages of shield development and the beginning of the Proterozoic.

The distribution of the granitic rocks in the Kaapvaal craton is shown in Figure 1.

Various models have been proposed to account for the evolution of the greenstone-granite pair that constitute the oldest shield areas (Anhaeusser and others, 1968, 1969; Anhaeusser, 1973; Engel, 1968; Goodwin, 1968; Glikson, 1972; MacGregor, 1951; Ramberg, 1964; Stowe, 1971; Talbot, 1973; Viljoen and Viljoen, 1970; Windley, 1973; Windley and Bridgwater, 1971). As a consequence of their economic importance, the greenstones have generally been studied in greater detail than the areally more extensive granitic rocks in which the greenstone belts are preserved. The almost inevitable presence of intrusive granite around the margins of these belts obscures direct observation of the relationship between the greenstones on the one hand and the bimodal association of amphibolite and leuco-tonalitic gneisses on the other. In the Kaapvaal and Rhodesian shields it has been argued either that the latter antedate the development of the greenstone belts (Hunter, 1970a; Stowe, 1971) or that they represent the roots of greenstone belts that have been pervasively invaded by tonalitic magma (Viljoen and Viljoen, 1969d, and e; Anhaeusser, 1973). Similar lack of unequivocal evidence in other greenstone-granitic environments has led to the same divergence of opinion. Reconciliation of these opposed views is clearly fundamental to the problem of continental evolution.

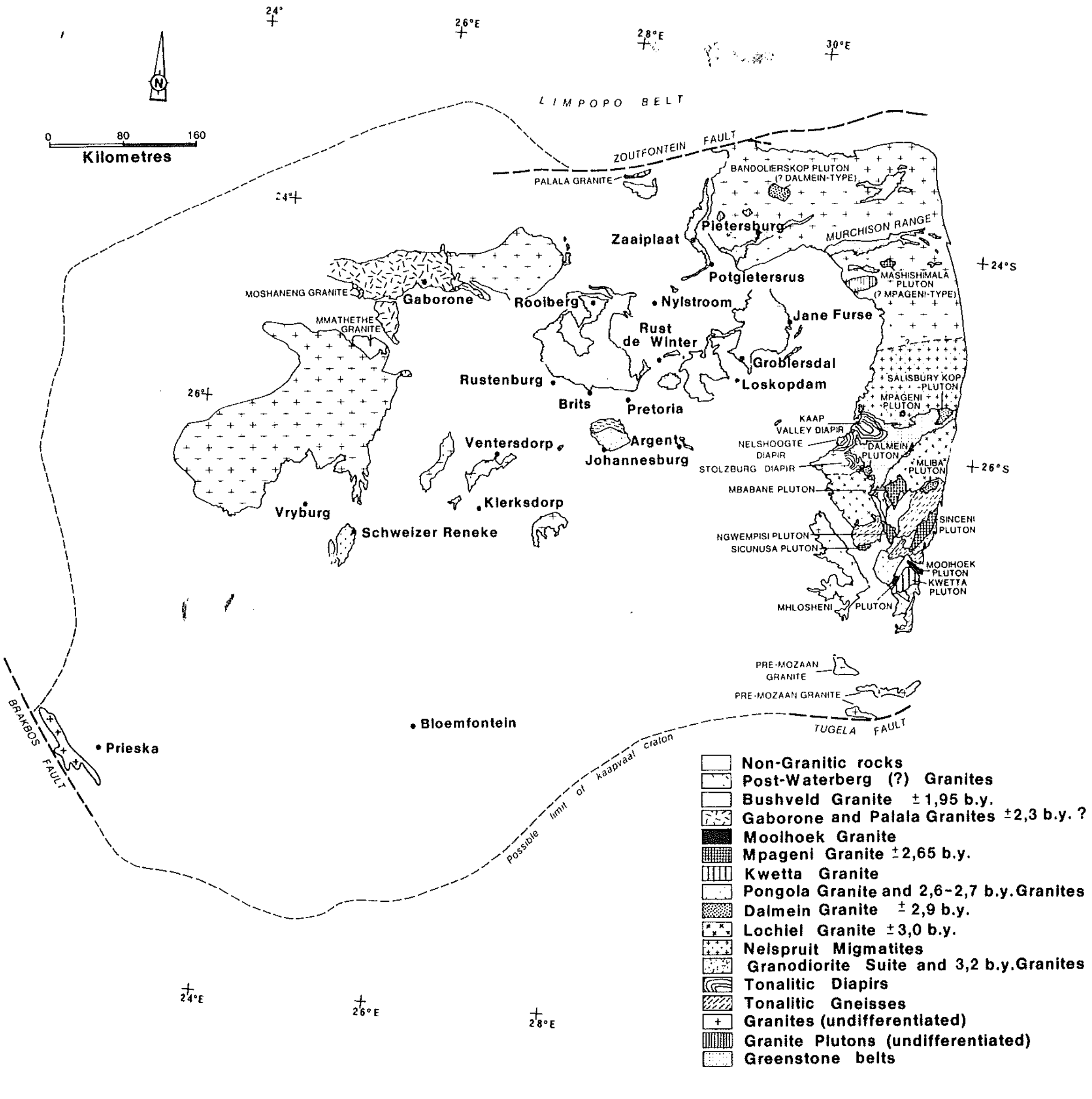


Figure 1 : The distribution of granitic rocks in the Kaapvaal craton

GEOLOGICAL SETTING

Swaziland Supergroup

The Swaziland Supergroup* comprises three major sub-divisions that are, in ascending order, the Onverwacht, Fig Tree, and Moodies Groups, described in detail by Anhaeusser and others (1968, 1969), Anhaeusser (1971a and b), Viljoen and Viljoen (1969a and b), Condie and others (1970), and Urie (1957 and 1965).

The cyclical nature of the volcanism and sedimentary successions is a dominant feature of greenstone belts (Anhaeusser, 1971b). Coupled with this pattern is the gradual decrease in abundance of ultramafic rock-types in the upper formations of the Onverwacht Group, accompanied by an increase in more felsic volcanics. The higher alkali content, particularly of K_2O, in the younger formations has been taken as evidence for an evolutionary development of a progressively thickening, sialic crust (Engel, 1968).

The ultramafic and mafic lavas have a major element chemistry characterised by high contents of MgO, low contents of alkalis (particularly K_2O), and high CaO/Al_2O_3 ratios which has led to the proposal that they constitute a unique class of igneous rocks to which the term komatiite has been applied (Viljoen and Viljoen, 1969a). The basaltic komatiites have been further sub-divided into three types based on their MgO and Al_2O_3 contents (see Table I). Viljoen and Viljoen (1969b) noted that the stratigraphically higher peridotitic komatiites in the Komati, Hooggenoeg, and Kromberg Formations contain more magnesium than do the Sandspruit ultramafics. McIver and Lenthall (1973) have suggested that this results from the settling of olivine from a magma having an initial composition similar to the Sandspruit ultramafics. The same authors also draw attention to the presence of nepheline normative basalts in the Hooggenoeg Formation, one of which has distinct alkali affinities.

The majority of the ultramafic and mafic rocks are regarded as subaqueous flows (Viljoen and Viljoen, 1969a), but sill-like intrusions have also been recognized in the lower three formations of the Onverwacht Group. The intrusions are layered, differentiated ultramafic to mafic bodies consisting of cyclic repetitions of dunite, peridotite, pyroxenite, gabbro, and anorthositic gabbro, or their metamorphosed equivalents. The major element chemistry of these intrusives is similar to that of the ultramafic and mafic rocks in which they occur. The layered complexes are located in a series of discrete bodies along the northwestern flank of the Barberton greenstone belt.

Small intrusions of quartz and feldspar porphyry are found in the Onverwacht Group, those invading the lower ultramafic and mafic formations having higher Na/K ratios than the porphyries in the upper formations (Viljoen and Viljoen, 1969a and b).

Sedimentological studies of the Fig Tree and Moodies Groups are lacking, but Condie and others (1970) have concluded that the immature graywacke textures in the Fig Tree Group indicate a limited degree of weathering and that the detritus was not transported distances greater than ± 100 km prior to deposition. These authors further suggest that the source area for the graywacke detritus was of diverse composition and included contemporary volcanic sources. The relative Sr-depletion in graywackes from the Sheba Formation, as compared to K, Ba, Ca, and Rb is taken as evidence for an abundance of Sr-depleted igneous rocks in the source area, that also included a significant, although not major, ultramafic component to account for the high Ni content in the Sheba graywackes. The Sr concentration in the overlying Belvue Road graywackes suggests that their source area contained more normal Sr-bearing igneous rocks (Condie and others, 1970). These authors conclude that the progressive compositional changes in the graywackes of the lower Fig Tree Group and continuing in the lower Moodies Group are indicative of progressive un-roofing of a granite-metamorphic terrane.

The basal conglomerate of the Moodies Group, particularly where it crops out in the Eureka syncline on the northern flank of the Barberton belt, contains granitic pebbles that are distinguished by graphic intergrowths between quartz and feldspar. This texture is not found in

* In the absence of a firm recommendation to use either Supergroup or Sequence in South African stratigraphic nomenclature, both terms have been used. Supergroup is used here in order to conform with the use of this term in, for example, the Transvaal Supergroup.

TABLE I

MEAN CHEMICAL ANALYSES OF ULTRAMAFIC AND MAFIC ROCKS IN THE SWAZILAND SUPERGROUP AND ANCIENT GNEISS COMPLEX

	Lower Ultramafic Unit						Mafic to Felsic Unit						
	1	2	3	4	5	6	7	8	9	10	11	12	13
SiO_2	44.72	41.61	52.73	52.22	47.37	52.13	49.86	49.95	50.07	51.12	54.61	52.04	54.20
TiO_2	0.52	0.31	0.85	0.56	0.46	1.09	0.70	0.69	1.22	0.17	0.49	0.80	0.75
Al_2O_3	3.25	2.70	9.83	5.42	6.79	13.33	14.25	13.48	13.34	5.92	16.10	15.37	12.63
Fe_2O_3	6.02	5.63	1.23	0.98	1.18	2.24	2.65	1.82	2.31	2.88	1.25	0.78	1.01
FeO	5.52	4.35	9.70	8.88	8.08	9.94	7.67	7.89	9.10	5.69	5.10	9.26	9.93
MnO	0.19	0.17	0.22	0.22	0.19	0.21	0.17	0.18	0.19	0.14	0.27	0.16	0.17
MgO	25.35	30.58	10.10	15.25	20.39	6.35	7.32	9.68	6.10	20.28	2.35	9.07	5.95
CaO	6.97	4.29	9.99	12.83	8.31	8.98	10.69	9.52	9.47	9.65	13.95	7.88	8.65
Na_2O	0.49	0.15	2.65	1.21	0.39	2.97	2.54	2.38	3.34	1.04	3.80	1.94	3.50
K_2O	0.05	0.03	0.46	0.09	0.06	0.26	0.16	0.77	0.54	0.19	0.37	0.34	0.62
H_2O^+	5.58	8.81	1.93	2.05	5.26	1.97	2.70	2.80	2.95	1.78	1.02	2.37	1.36
H_2O^-	0.21	0.22	0.16	0.09	0.25	0.11	0.11	0.09	0.06	0.06	0.14	0.07	0.10
P_2O_5	-	0.02	0.06	0.05	0.05	0.07	0.05	0.09	-	n.d.	0.07	0.06	0.71
CO_2	0.26	-	0.14	0.17	-	0.07	0.48	0.13	0.23	n.d.	0.32	n.d.	n.d.
No. of Analysis	3	8	3	5	4	4	5	5	2	1	1	1	1
Rb	-	1.0	6	1.4	-	-	-	-	-	-	-	35	3.60
Sr	-	15.3	108	51.3	-	-	-	-	-	100	200	132	385
Cr	3000	2700	-	-	2500	250	-	-	-	3100	500	-	300
Ni	1400	1800	-	-	600	850	-	-	-	1500	200	-	100
K/Rb	-	249	637	534	-	-	-	-	-	-	-	100	1430
Ca/Sr	-	2000	660	1784	-	-	-	-	-	69	497	426	160
Rb/Sr	-	0.06	0.05	0.03	-	-	-	-	-	-	-	0.26	0.009
Na/K	8.7	4.4	5.1	12	5.8	10.2	14.2	2.7	5.5	4.9	9.2	5.1	4.6

1. Peridotitic komatiite, Sandspruit Formation (Viljoen and Viljoen, 1969a).
2. Peridotitic komatiite, Komati Formation (Viljoen and Viljoen, 1969a).
3. Basaltic komatiite, Barberton type, Komati Formation (Viljoen and Viljoen, 1969a).
4. Basaltic komatiite, Badplaas type (Viljoen and Viljoen, 1969a).
5. Basaltic komatiite, Geluk type (Viljoen and Viljoen, 1969a).
6. Tholeiitic basalt, Lower Ultramafic Unit (Viljoen and Viljoen, 1969a).
7. Tholeiitic basalt, Hooggenoeg Formation (Viljoen and Viljoen, 1969b).
8. Mg-rich basalt, Hooggenoeg Formation (Viljoen and Viljoen, 1969b).
9. Tholeiitic basalt, Kromberg Formation (Viljoen and Viljoen, 1969b).
10. Tremolite rock, Ancient Gneiss Complex (Hunter, 1970a); Ba 100 ppm.
11. Diopside-plagioclase granolite interlayered with No. 10 (Hunter, 1970a); Ba 100 ppm.
12. Plagioclase amphibolite, Ancient Gneiss Complex (Hunter, 1970a).
13. Plagioclase amphibolite, Ancient Gneiss Complex (Hunter, 1970a); Ba 100 ppm. (Rb and Sr data for Nos. 12 and 13, personal communication, Barker, 1973).

presently exposed granitic rocks that could pre-date the Moodies Group. The pebbles have a high potassium content (Anhaeusser, 1973) which may be a reflection of the degree of sericitization of original plagioclase feldspar. Granitic pebbles have not been found to date in Moodies conglomerates in the southern outcrops in Swaziland. The Moodies Group in the most southerly outcrops in Swaziland rests disconformably on Fig Tree rocks (Urie, 1957), but overlaps in northern Swaziland onto the higher members of the Onverwacht Group.

The broad structure of the Swaziland Supergroup is that of a synform with a pronounced east-northeasterly to northeasterly trend. Within this broad structure, there is a series of tight synclinal folds with steeply dipping, often overturned limbs separated by major faults that have the effect of dividing the Swaziland Supergroup into a number of narrow, east-northeasterly-trending blocks, parallel to the regional grain (Roering, 1965). The bounding faults have been re-activated as right-lateral, transcurrent faults (Anhaeusser, 1965). In the southwest, the broad regional pattern has been disturbed as a result of the intrusion of diapiric, tonalite domes of varying sizes so that narrow arcuate zones of intensely deformed Swaziland Supergroup rocks trend in various directions around the domes. Flattening and stretching is marked adjacent to the tonalite domes. Elsewhere, however, the absence of pervasive deformational features such as cleavage and flattening is taken as evidence that little lateral compression was involved in the development of the broad regional structures (Viljoen and Viljoen, 1969f). Cross-folding about northwesterly-trending axial traces is a late-stage deformational event. A notable feature of the distribution of the various formations of the Swaziland Supergroup is that the lowest formations invariably form the outer rim of the broad synformal structure, except where late, potassic granites are intrusive.

The Swaziland Supergroup displays low greenschist metamorphism upon which has been superimposed dynamothermal metamorphism of low grade associated with the faulting, and contact metamorphism of amphibolite and pyroxene hornfels grades as a result of the emplacement of younger granites.

Ancient Gneiss Complex

Underlying the central area of Swaziland, to the southeast of the Barberton greenstone belt are a suite of gneisses consisting of two main types, namely, (i) a bimodal association of interlayered leuco-tonalitic gneisses and amphibolites, and (ii) metamorphites that include quartzites, quartzofeldspathic gneisses, siliceous and biotite-rich garnetiferous gneisses, quartz-diopside and diopside-plagioclase granulites, quartz-magnetite-grunerite gneisses, ironstones, and biotite-hornblende gneisses. All these rock-types are included in the Ancient Gneiss Complex (Hunter, 1970a).

The metamorphites attain their maximum development (underlying ± 200 km^2) in south central Swaziland, where they constitute a deformed, layered sequence. Smaller outcrops of quartzo-feldspathic gneiss, diopside-plagioclase and quartz-diopside granulites, and biotite-hornblende gneisses are interlayered within the tonalitic gneiss-amphibolite unit as isolated relicts. On the basis of their mineral assemblages it has been concluded that the metamorphites were formed at temperatures of at least 600°C and at pressures of 3 kb (Hunter, 1970a). Most significant in these assemblages is the coexistence of cordierite with almandine and potassium feldspar in the kinzigites, and the absence of garnet in the amphibolites. The latter feature could be the result of a lack of Al and an excess of Mg in the original rock, but inspection of Table I (columns 12 and 13) does not confirm this possibility. The quartz-biotite-microcline-cordierite ± garnet gneisses (kinzigites) provide no evidence that the cordierite and potassium feldspar formed as a result of the re-action biotite + sillimanite + quartz $\rightleftharpoons$ cordierite + potassium feldspar in the manner reported by Hietanen (1947). The stability of the assemblage in the Swaziland kinzigites is critical and implies pressures distinct from those in the almandine-amphibolite facies. The survival of calcite + quartz in the metamorphites imposes similar pressure and temperature constraints. The mineral assemblages are in accord with the cordierite-amphibolite facies (Winkler, 1967) within the Abukuma-type metamorphic series.

Banded metamorphites composed of quartz, plagioclase, biotite, hornblende, and diopside crop out in west central Swaziland and may represent retrograded granulite facies. The characteristic granulitic texture and the platy nature of the quartz are preserved, but no relict minerals diagnostic of granulite facies metamorphism have so far been identified. These meta-morphites occupy a zone 2 km broad and 5 km long interlayered with tonalitic gneisses and amphibolites; being closely associated with faults, that pre-date the 2.6 b.y. granite, striking in an east-northeasterly direction. Further evidence for the possible existence of granulite grade rocks lies in the discovery of central Swaziland of gneisses of charnockitic aspect (Edwards, 1970).

TABLE II

CHEMICAL ANALYSES OF METAMORPHITES IN THE ANCIENT GNEISS COMPLEX

	1	2	3	4	5	6	7	8
SiO_2	73.90	55.21	59.21	67.35	78.15	76.22	77.16	71.60
TiO_2	0.23	0.51	0.93	0.56	0.27	0.13	0.16	0.52
Al_2O_3	7.05	12.73	16.67	14.58	10.40	12.73	11.72	12.39
Fe_2O_3	0.31	0.39	1.79	0.78	0.61	0.55	1.90	2.07
FeO	2.33	9.46	4.80	3.29	3.91	0.83	0.70	3.18
MnO	0.38	0.12	0.13	0.07	0.05	0.03	0.03	0.08
MgO	4.04	15.01	1.39	2.20	2.34	0.58	0.16	0.42
CaO	7.75	2.45	3.72	4.73	Tr	0.60	0.55	2.02
Na_2O	2.17	0.42	4.73	3.82	0.54	4.01	3.76	3.12
K_2O	0.53	0.29	5.47	1.32	2.09	3.79	3.40	3.91
H_2O^+	0.59	3.45	0.96	0.79	1.00	0.66	0.28	0.36
H_2O^-	0.16	0.05	0.12	n.d.	0.08	0.03	0.03	0.05
P_2O_5	0.03	0.11	0.41	0.14	0.03	0.05	0.02	0.12
CO_2	0.03	0.10	-	0.27	n.d.	n.d.	0.01	0.03
Rb	-	-	-	-	-	-	80.5	129
Sr	200	100	-	1500	200	100	180	111
Ba	200	100	-	500	400	400	1000	-
Cr	2900	1200	-	50	<10	<10	<10	-
Ni	600	200	-	40	<30	<30	<30	-
K/Rb	-	-	-	-	-	-	350	251
K/Ba	22	24	-	22	43	78.6	28	-
Na/K	3.6	1.3	0.77	1.68	0.23	0.9	0.9	0.7
Ca/Sr	326	175	-	22.5	-	43	217	130
Ba/Sr	1	1	-	0.3	2	4	5.5	-

1. Quartz-diopside-plagioclase granulite.
2. Cummingtonite-cordierite gneiss.
3. Biotite-hornblende-feldspar gneiss.
4. Biotite-hornblende-diopside-quartz gneiss.
5. Quartz-biotite-garnet gneiss.
6. Quartzofeldspathic gneiss, Ngwempisi Valley.
7. Quartzofeldspathic gneiss (Mean of 2 analyses), Mkhondo Valley.
8. Quartz-microcline-biotite-hornblende gneiss (Barker, 1973).

The tonalitic gneisses are medium-grained, banded rocks, the banding being caused by the alternation of layers of different colour varying from dark to pale grey. These bands are conformable to the interlayered amphibolites that range from a few tens of centimetres to several metres in width. Less commonly larger bodies of amphibolite a kilometre wide are present. Individual amphibolite layers can be traced for considerable distances along strike where outcrops are good, in some cases up to 8 km. The effect of the banding is accentuated in the more migmatitic gneisses where biotite and hornblende-bearing quartz-feldspar gneisses are interlayered with the tonalitic gneisses. These gneisses retain in thin section the smoothly interlocking nature of the individual grains characteristic of the metamorphites, whereas in the tonalitic gneisses the grains have moderately to complexly involved margins. The heteroblastic texture arises from

(i) the development of larger grains of oligoclase and microcline in a finer grained groundmass;

(ii) mortaring which produces fine-grained areas;

(iii) the development of larger areas of quartz truncating the groundmass, and

(iv) the growth of myrmekite heads.

Accompanying these changes there is a sympathetic alteration of hornblende to hornblende + biotite + epidote and of brown biotite to green biotite + chlorite + epidote.

The tonalitic gneisses demonstrate the limited achievement of mobility by the disruption and slight rotation of amphibolitic skialiths as a result of the more plastic behaviour of the enclosing tonalite during deformation. Elliptical areas, 200 m wide and 1 km long, of more homogeneous, gneissic tonalite are found aligned with their long axes parallel to the surrounding banded gneisses. Chemical analyses reveal that the K content of the homogeneous tonalites is significantly higher than in the banded tonalite gneisses. When metamorphite relics are found within partially mobilized tonalitic gneisses, the metamorphites exhibit retrogressive metamorphic assemblages (Hunter, 1970a).

The contact between the Ancient Gneiss Complex and the Swaziland Supergroup is found to be faulted or obscured by the invasion of later granites. At faulted contacts, the Swaziland Supergroup, metamorphosed in the low grades of the greenschist facies, is in juxtaposition with banded tonalitic and amphibolitic gneisses. On the southeastern flank of the Barberton belt, the latter have been strongly deformed by at least three events, and are intersected by relictual mafic dykes of two ages, separating periods of pegmatite formation (Hunter, 1970a). If these gneisses do in fact represent the roots of the Swaziland Supergroup pervasively intruded by tonalitic magma (as has been proposed by Viljoen and Viljoen, 1969d, and Anhaeusser, 1973) the faulted boundary must reflect a vertical displacement of at least 5 km or it must be concluded that geothermal gradients were considerable, if smaller displacements are envisaged. An alternative view is that the Ancient Gneiss Complex is a pre-Swaziland event.

Structural studies (Hepworth, 1971; Hunter, 1970a) of the Ancient Gneiss Complex reveal a polyphase deformational history that is not yet fully unravelled. The regional trend of the foliation throughout central Swaziland is northeast to east-northeast, dips being directed southeastwards at between 30° and 60°. That more than one deformational episode is reflected in the tonalitic and amphibolitic gneisses can be inferred from the splay of lineations within single exposures, from the distribution of s-surface poles, and from the disparity between the strike of the foliation and the plunge of the lineation (maximum about southeast but lying in a girdle from northeast to northwest). If it is assumed that the lineations are related to major fold axes, it would be reasonable to deduce that the present disposition of the structural elements was caused by folding on northwesterly aligned axes followed by folding about northeasterly axes. In this case it may be inferred that at least some of the lineations plunging to the northeast are related to the second or northeasterly phase of folding. The only recorded second phase lineations in west-central Swaziland (north of Mankaiana) in fact plunge slightly north of east (Hepworth, 1971). Measurements of lineations and s-surface directions in the metamorphites in south-central Swaziland suggest that the early regional fold axes were aligned northeast and were subsequently refolded about northwesterly axes to produce more open folds (Hepworth, 1971). Northeast of Manzini plots of the poles of s-surfaces reveal a considerable scatter (Figure 2), but, if a distinction is drawn between gneisses with well-defined banding and foliation, and those with a more nebulitic gneissic structure it is seen that the latter contribute in the main to the departure from regularity of disposition of the s-surfaces and lineations. The fact that a large proportion of observations recorded from the nebulitic gneisses do still relate to the tectonic axes of the banded, foliated gneisses, provides support for the view that the nebulitic gneisses are partially re-mobilized portions of the tonalitic gneiss terrane, rather than magmatic intrusions.

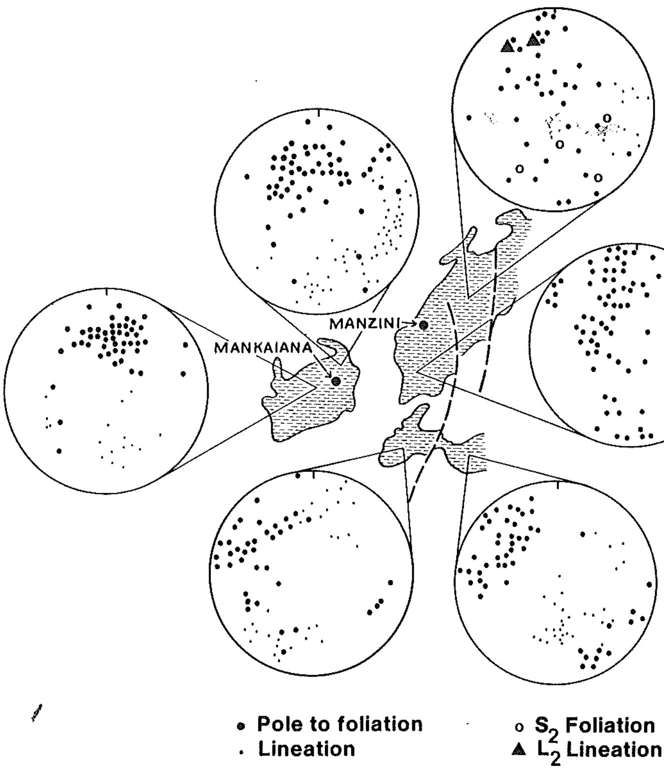


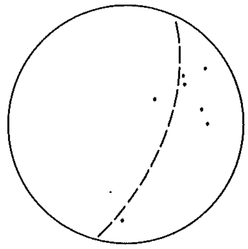
Figure 2 : The distribution of the Ancient Gneiss Complex in central Swaziland (shaded areas) and stereogram plots of foliation and lineation. Heavy dashed lines mark positions of mylonite or straightening zones. Structural data based on observations by Hunter (1968) and Hepworth (1971).

Small open folds with near vertical axes crenulate the foliation notably northeast of Manzini, and deform earlier tectonic axes. The folds plunge eart-northeastwards (Figure 3), but south of Manzini folds of a similar style plunge southwards.

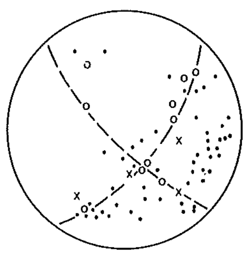
When the β-poles of the s-surfaces are plotted on a stereogram together with the plunges of the lineations, it can be seen (Figure 3) that they fall on two great circles trending northeast and northwest respectively. Similarly, the splay of the plunges of the minor open folds can be related to a northeasterly-trending great circle.

In addition to the fold structures, two major mylonite zones, striking generally northwards, form prominent features up to 80 km long, causing the re-orientation of the foliation and increasing deformation in the form of imposed folds, compressed and reclined about southeasterly plunging axes, that are brought into axial planar parallelism with the mylonite zones.

Within these zones intense milling has produced dense mylonite over widths of as much as 1 km. The final development of these mylonite zones post-dates the 2.6 b.y. granites. Hepworth (1971) considers that the straightening and re-folding associated with the mylonite represents an essential part of the regional deformation of the Ancient Gneiss Complex that is normally expressed as folds, but, where deformation is most intense, produces sheared and mylonitized rocks.



Plunge of minor folds



o Beta poles
· Lineations
x S_2 Foliations

Figure 3 : Stereograms showing plunge of minor folds and distribution of β-poles and lineations in the Ancient Gneiss Complex.

The foliation of the metamorphites in south-central Swaziland is parallel to the preserved bedding, but elsewhere the foliation is parallel to the compositional banding of the gneisses. Relict metamorphites in the tonalitic gneisses have their foliation parallel to that of the enclosing gneisses. South of Mankaiana an amphibolite layer, 45 cm thick, is deformed into a tight fold, the axial plane of which is parallel to the compositional banding and the foliation. These features suggest that the regional foliation results from intense deformation whereby the original layering is drawn out on the limbs of folds to produce the presently observed, compositional banding.

The Ancient Gneiss Complex differs from the Swaziland Supergroup in that its metamorphic and tectonic styles can be distinguished from those found in the Swaziland Supergroup.

Diapiric Domes

Medium- to coarse-grained, homogeneous tonalite builds a series of elliptical, discrete domes ranging in diameter from 40 km (Kaap Valley diapir) to 1.6 km (Doornhoek diapir) around the southwestern flank of the Barberton greenstone belt. The diapirs are intrusive into the lower formations of the Onverwacht Group, being transgressive in detail to individual stratigraphic horizons and causing metamorphism of the country rocks to the amphibolite grade. Narrow tongues of tonalite extend from the domes along and parallel to the foliation of the intruded rocks with the result that blocks of country rock with their original orientation preserved are eventually incorporated as xenoliths within the diapirs. Individual domes are separated from each other by screens of intensely deformed mafic and ultramafic rocks.

Around the flanks of the domes, the tonalite develops a conspicuous gneissic fabric that follows the elliptical shape of the individual domes. Foliation becomes less distinct towards the centre of the diapirs.

Banded foliated gneiss similar to the tonalite-amphibolite gneiss unit of the Ancient Gneiss Complex in Swaziland crop out southwest of the diapirs which occupy the interface between these gneisses and the lower members of the Swaziland Supergroup. The banding of the gneisses becomes increasingly deformed as the contact with the tonalitic diapirs is approached. Partial melting of the gneisses accompanies the deformation with the production of coarser grained homogeneous tonalite that occupies cores of folds and may also cross-cut the gneissic banding. The deformation and partial melting has been interpreted (Viljoen and Viljoen, 1969c) as marking the first stage in the production of the potassic, hood-type granites that build the Lochiel plateau immediately to the south. However, where the contact between the potassic granite and the underlying gneisses has been exposed in quarries in Swaziland no evidence of such intense deformation nor partial melting can be seen.

The Stolzburg, Theespruit, and Doornhoek domes occupy the core of an antiform deforming the lower Onverwacht formations and plunging steeply northeast. The diameter of the individual domes decreases from 19 km to 1.6 km down the plunge. The axis of the antiform is marked 2 km northeast of the smallest diapir by a large area of carbonatized Onverwacht lavas that is taken to indicate the presence of another, but hidden diapir (Viljoen and Viljoen, 1969c). The diapiric domes located in this northeasterly plunging antiform are elongated in the northwesterly direction.

The close resemblance in major element chemistry between the tonalitic diapirs and the banded gneisses in the Ancient Gneiss Complex (see Table IV) led to the proposal that both tonalites had a common intrusive origin (Viljoen and Viljoen, 1969c and d), but this emphasis on similarities in chemistry overlooks disparities in tectonic style and degree of homogeneity.

Granodiorite Suite

Coarse-grained, plutonic rocks ranging in composition from ultramafic to acid are intrusive into the Ancient Gneiss Complex in Swaziland, but no equivalents of this suite have so far been recognized in the Transvaal. The tonalitic members of this suite were included (Viljoen and Viljoen, 1969c) as a further expression of the invasion of tonalitic magma into the crust in post-Swaziland time. However, the demonstrably intrusive contacts with the Ancient Gneiss Complex, the lack of strong foliation, and the presence of quartz diorite and more mafic rock-types (see Table III) serves to distinguish this group of rocks from both the Ancient Gneiss Complex and the diapirs.

The gradational nature of contacts between the various members of the suite together with a paucity of outcrops in some areas renders it difficult to compute the proportions of each individual variety. The following generalized results were obtained by planimetric measurement :

(i)	Ultramafic rocks	0.6%
(ii)	Intermediate rocks mainly quartz diorite	29.0%
(iii)	Acid rocks (mainly tonalite)	70.4%

In earlier accounts (Hunter, 1968, 1971) a discrete body of granodiorite forming the Mliba pluton was included in this suite, but a recent geochronologic study (Davies, 1971) has shown that this pluton has an age of 2.9 b.y. and is therefore younger than the Granodiorite Suite which was intruded by 3.07 b.y. granite.

TABLE IV

MEAN COMPOSITION OF THE ARCHAEAN GRANITIC ROCKS IN THE EASTERN TRANSVAAL AND SWAZILAND

	Tonalitic Gneisses		Tonalitic Diapirs		Granodiorite Suite		Lochiel Granite
	1	2	3	4	5	6	7
SiO_2	71.16	65.44	70.96	64.84	56.22	67.67	71.32
TiO_2	0.34	0.43	0.18	0.49	0.77	0.49	0.32
Al_2O_3	14.84	15.23	14.93	15.44	19.73	15.92	14.43
Fe_2O_3	0.77	0.98	0.79	1.80	2.02	0.90	0.59
FeO	1.52	3.33	1.04	2.44	3.98	2.20	1.73
MnO	0.02	0.08	0.05	0.04	0.10	0.05	0.08
MgO	0.95	3.20	0.78	2.60	2.51	1.29	0.57
CaO	3.18	4.69	2.32	4.25	5.40	3.58	1.33
Na_2O	4.67	4.07	5.38	4.93	5.26	4.54	3.92
K_2O	1.64	1.95	1.92	1.53	2.41	1.72	4.59
H_2O^+	0.75	0.96	0.56	0.90	1.09	0.98	0.61
H_2O^-	0.07	0.09	0.13	0.20	0.09	0.50	0.06
P_2O_5	0.12	0.13	0.06	0.18	0.33	0.17	0.31
Rb	72.5	79	52	44	39	14	226
Sr	250	235	507	530	888	424	122
Ba	–	–	–	425	–	–	500
Li	–	–	–	23	–	–	44
Pb	–	–	–	9.7	–	–	41
Th	7.8	–	4.2	–	2.8	7.7	–
Na/K	2.5	1.8	2.5	2.9	1.95	2.4	0.76
K/Ba	–	–	–	30	–	–	74.0
Ba/Rb	–	–	–	9.7	–	–	2.2
K/Rb	187	205	306	290	513	1019	168
Ca/Sr	91	142	32.6	57.2	43.4	60.2	77
Ba/Sr	–	–	–	0.8	–	–	4.1

1. Leucotonalitic gneisses, Ancient Gneiss Complex. Mean of 6 analyses except for Na_2O (8 determinations); K_2O (14 determinations); Rb and Sr (7 determinations); Th (6 determinations).
2. Hornblende tonalitic gneisses, Ancient Gneiss Complex. Mean of 2 analyses except for Na_2O and K_2O (5 determinations); Rb and Sr (3 determinations).
3. Leucotonalitic diapirs. Mean of 3 analyses except for Na_2O (11 determinations); K_2O (12 determinations); Rb and Sr (10 determinations); Th (1 determination).
4. Hornblende tonalitic diapir (Kaap Valley diapir). Mean of 4 analyses except for Na_2O and K_2O (8 determinations); CaO (5 determinations); Rb and Sr (2 determinations); Ba, Li and Pb (1 determination).
5. Quartz diorite, Granodiorite Suite. Mean of 2 analyses except for K_2O (4 determinations).
6. Tonalite, Granodiorite Suite. Mean of 6 analyses except for Na_2O (7 determinations); K_2O (10 determinations); Th, Rb and Sr (3 determinations).
7. Lochiel granite. Mean of 6 analyses except for CaO (9 determinations); Na_2O and K_2O (17 determinations); Rb and Sr (8 determinations); Ba, Li and Pb (3 determinations).

Sources : Barker (1973); Davies (1971); Hunter, (1968); Kaye and others (1965); Viljoen and Viljoen (1969d); Visser (1956).

TABLE III

MINERALOGICAL AND COMPOSITIONAL DATA OF THE GRANODIORITE SUITE

	Ultramafics	Quartz Diorite	Tonalite/Granodiorite
Quartz	Absent	1.5 to 4% by volume	20 to 28% by volume
Microcline	Absent	usually present only interstitially but in hybrid quartz diorite ± 10% by volume	2 to 10% by volume
Plagioclase	present interstitially in peripheral parts of some hornblendites	andesine An_{40} ± 65% by volume	52 to 60% by volume
Amphibole	brown hornblende $2V = 80°$, $Z \wedge c = 20°$; green actinolitic hornblende $2V = 78°$, $Z \wedge c = 24°$	bluish-green hornblende $2V = 79°$, $Z \wedge c = 22°$; 3 to 8% by volume	bluish-green hornblende $2V = 77°$, $Z \wedge c = 21°$; nil to 8% by volume
Biotite	Absent	red-brown ($\beta = 1.660$) but often greenish and chloritized; ± 10% by volume	chloritized, greenish ragged laths; 2 to 10% by volume
Pyroxene	diopside augite $2V = 60°$, $Z \wedge c = 44°$; up to 45% by volume	diopside augite cores in amphibole; discrete grains in hybrid quartz diorite where up to 40% by volume	Absent

The Granodiorite Suite forms intrusive bodies that are elongated in a northeasterly direction, closely parallel to the synform of the Swaziland Supergroup in the Barberton greenstone belt. The ultramafic members are found as xenoliths up to 3 km^2 in area within the quartz dioritic and tonalitic rock-types, the latter carrying more abundant mafic minerals in the contact zone.

Lochiel Granite and Nelspruit Magmatites

A gently rolling plateau lies beyond the southwestern termination of the Barberton greenstone belt and extends into Swaziland where it forms the southeastern flank of the Swaziland Supergroup outcrops. The plateau is underlain by a massive, grey, medium- to coarse-grained granite composed of quartz, microcline, plagioclase, subordinate biotite and occasionally, hornblende. A complex stockwork of narrow pegmatites cuts the granite. The granite occupies an outcrop width varying from 30 to 60 km on the southern and southeastern sides of the Barberton greenstone belt. Its extension in a southwesterly direction is masked by a cover of younger formations.

The name Lochiel granite is proposed for the ± 3.0 b.y. potassic granite that has a distinctive horizontal disposition forming a hood or carapace over the Ancient Gneiss Complex. This granite has previously been referred to as the homogeneous hood granite (Hunter, 1968, 1971). In the more deeply incised valleys, the floors of which lie as much as 500 m below the plateau, the relationship between the underlying gneisses and the Lochiel granite is displayed. The Ancient Gneiss Complex is cut by granite, pegmatite, and composite granite-pegmatite dykes and sheets that increase in abundance and size until only blocks of gneiss are preserved. Passing onto higher ground, granite is predominant enclosing progressively fewer blocks of gneiss which are distorted and often ghost-like, until the granite becomes homogeneous. Where the present day erosion surface lies close to or within this zone of interdigitation of granite and gneiss, a complex apparently migmatitic terrane results.

The granitic terrane lying on the northern side of the Barberton greenstone belt consists of just such a complex of granite and gneiss to which the term Nelspruit migmatite is applied. The more homogeneous, potassic granite fraction in this migmatite terrane has isotopic ages closely similar to that of the Lochiel granite in the south. It is considered that the observed, involved relationships are a consequence of the present erosion surface lying within the zone of interdigitation of granite above and gneiss below. Preliminary reconnaissance indicates that this Nelspruit migmatite terrane extends for ± 70 km to the north of the Barberton greenstone belt.

GEOCHRONOLOGY

Rb–Sr ages from the Ancient Gneiss Complex tonalitic gneisses have a spread from 3.395 ± 0.086 b.y. to 3.138 ± 0.0006 b.y., the oldest age being from hornblende tonalite gneisses in southwestern Swaziland. The low initial ratio (0.7006 ± 0.0012) of the hornblende tonalite is indicative of little or no crustal contamination. The younger ages from the Ancient Gneiss Complex were obtained on gneisses invaded by dykelets of Lochiel granite or lying close to contacts with that granite. The higher primary ratios that range from 0.7022 to 0.7060 suggest that crustal contamination has influenced the ages. An apparent age of 3.203 ± 0.057 b.y. (R_o = 0.7048 ± 0.0011) was obtained (Davies, 1971) from the more homogeneous tonalite that builds elongate bodies within the banded tonalitic gneisses. This age is in close accord with the U/Pb ages determined on the Theespruit and Nelshoogte diapiric domes (Oosthuyzen, 1970, and see also Figure 4).

Apparent ages determined on rocks from the Swaziland Supergroup have a wide spread from 3.355 ± 0.070 b.y. for the Middle Marker at the base of the Hooggenoeg Formation (Hurley and others, 1972) to 2.540 ± 0.050 b.y. for felsic lavas in the upper formations of the Onverwacht Group (Allsopp and others, 1968). Fig Tree shales metamorphosed at low grades at the Consort Mine near Barberton are dated at 2.980 ± 0.020 b.y., and are intruded by pegmatite with an apparent age of 3.030 ± 0.040 b.y. (Allsopp and others, 1968) so that their age probably dates a metamorphic event related to the emplacement of the 3.0 b.y. Lochiel granite. If this is correct, the Swaziland Supergroup has an age >3.0 b.y. and it must be concluded that the younger apparent ages obtained from the Onverwacht felsic lavas cannot refer to their age of extrusion (Allsopp and others, 1969).

The lack of Rb–Sr geochronology on the diapiric domes places a constraint on direct comparison with the U/Pb ages that have been determined on these rocks and the Ancient Gneiss Complex tonalites. Furthermore, the apparent Rb–Sr age of the Middle Marker, although younger than the Ancient Gneiss Complex, is regarded as a minimum age (see discussion by Hurley and others, 1972), so that again there is no reliable evidence as to the relative ages of the Swaziland Supergroup and the Ancient Gneiss Complex.

Significant results have been obtained by Robertson (1969, quoted from Wilson, 1973) as a result of his isotopic analysis of some 80 Rhodesian galena samples, that provides evidence for the existence of sialic crust prior to the development of the greenstone belts. Robertson recognized two types of lead. The older Que Que type leads occur in gneissic and migmatitic areas that Stowe (1971) regards as being older than the greenstone assemblages and which are comparable to the Ancient Gneiss Complex in structural style and metamorphic grade. The Bulawayan leads are found in the typical greenstone sequence and in granites intruding these rocks. Wilson (1973) concluded that the isotopic study of the Rhodesian galenas provides support for the view that the main period of greenstone development in Rhodesia took place between 3.3 and 2.9 b.y. following a pre-3.3 b.y. event. This data is of value in indicating that older crust pre-dates the development of the greenstones in Rhodesia.

GEOPHYSICAL DATA

Burley and others (1970) have constructed a residual gravity map of Swaziland and a profile across the Barberton greenstone belt by removing the regional isostatic effect of the Karroo basalts and the Usushwana Complex, based on the 2 000 gravity stations in Swaziland and the gravity data from adjacent areas of the Transvaal (Smit, Hales and Gough, 1962). The anomalies on the residual gravity map display a distinct northeast trend, with an extensive negative anomaly over north and northwestern Swaziland coinciding with the mapped limits of the Lochiel granite. A positive gravity anomaly strikes across central Swaziland adjacent to this negative anomaly. The positive anomaly suggest that the presence in depth of rocks of greater density and it is significant that the main axis of this anomaly lies close to the outcrops of the presumed retrograded granulites within the Ancient Gneiss Complex and of the charnockitic gneisses reported by Edwards (1970).

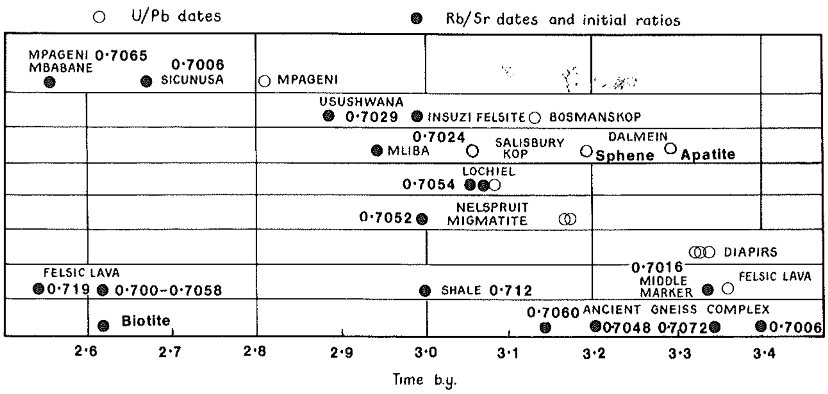


Figure 4 : Plot of radiometric ages for rocks and minerals compiled from Allsopp and others (1962, 1968 and 1972), de Gasparis (1967), van Niekerk and Burger (1969), Oosthuyzen (1970), Davies and others (1970), Davies (1971), and Hurley and others (1972).

A model to fit the observed residual gravity profile across the Barberton greenstone belt and the granitic terrane in Swaziland requires the presence of a major block 16 km deep, lowered in the centre to accommodate the Swaziland Supergroup anomaly (Burley and others, 1970). The anomaly produced by the Onverwacht Group can be provided for in this model by two blocks 2.8 km and 3.2 km deep respectively. The importance of this data lies in the contrast between these thicknesses and the calculated stratigraphic thickness of ± 15 km for the Onverwacht Group (Viljoen and Viljoen, 1970). Of interest in this connection is the observation (Hurley and others, 1972) that, despite apparently great depths of burial deduced from stratigraphic measurements, some parts of the Onverwacht Group (e.g. the pillow basalts in the Hooggenoeg and Kromberg Formations) are remarkably undeformed and show only mild effects of metamorphism. Despite this, however, in deep mines near Barberton steeply inclined to near vertical fold structures persist without signs of dips becoming flatter. The gravity data provides evidence for the presumed existence at no great depth beneath the Barberton greenstone belt of a floor of rocks of low density.

GEOCHEMISTRY

The major and minor element chemistry of the Ancient Gneiss Complex, the tonalitic diapirs and the Granodiorite Suite are given in Tables I, II and IV. The mole ratios of selected elements are presented in Figure 6. In respect to the mole ratios Ca:K:Na and Mg:Fe:(K + Na) the tonalitic members of the three groups are similar, while the amphibolites and mafic rocks inter-layered with the tonalites of the Ancient Gneiss Complex plot near to the average gabbro of Nockolds (1964). The fields of Fig Tree graywackes (derived from Condie and others, 1970) are also plotted on this diagram from which it can be seen that the graywackes have a higher content of potassium and higher Ca:Na ratios than the tonalites.

The K/Rb ratios of the various tonalites are shown in Figure 7. The plots of the Ancient Gneiss Complex have a wide scatter, but those of the tonalitic gneiss members cluster in

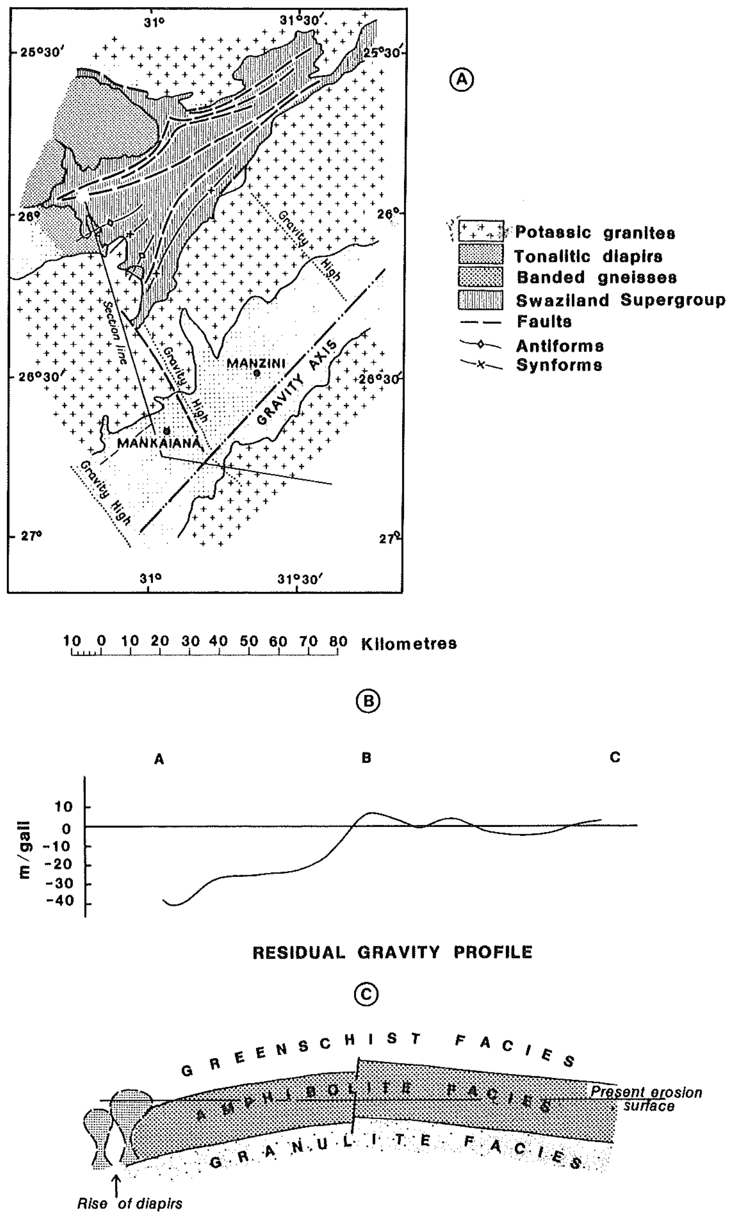


Figure 5 : A. Generalized geological map of the Barberton greenstone belt and adjacent areas of Swaziland showing location of residual gravity axis in Swaziland.

B. Residual gravity profile across the southern end of the Barberton greenstone belt and central Swaziland.

C. Provisional model to accommodate residual gravity data.

a more compact area lying above the field of the Fig Tree graywackes. These plots lie in a distinctly different field from those of the tonalitic diapirs which are in turn distinguished from the Granodiorite Suite. The three amphibolite plots in Figure 7 show a variable Rb content with a more uniform K content. The two amphibolites with K/Rb ratios of <200 are interlayered with tonalite gneisses in the Ancient Gneiss Complex, whereas the amphibolite associated with the metamorphite sequence has a K/Rb ratio of 1 280. Of significance is the fact that the interlayered amphibolites and tonalitic gneisses have K/Rb ratios that lie close to a mixing or unmixing line. The preliminary geochemical data suggests that amphibolites of more than one type are associated within the Ancient Gneiss Complex.

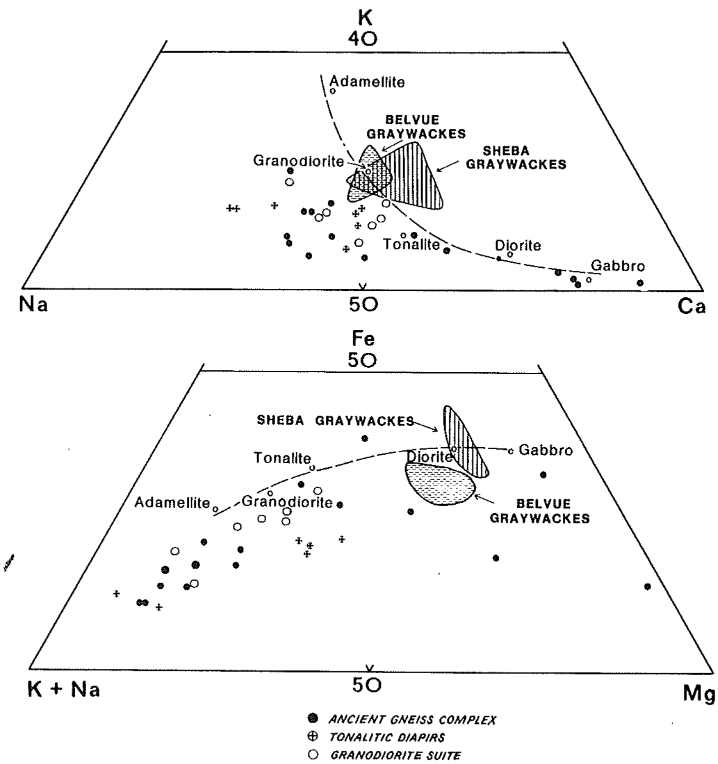


Figure 6 : Ternary diagrams showing mole ratios (upper) Ca:K:Na and (lower) Mg:Fe:(K + Na) for the Ancient Gneiss Complex, tonalitic diapirs, the Granodiorite Suite and the Fig Tree graywackes. Data from Hunter (1968), Viljoen and Viljoen (1969d), and Condie and others (1970).

The difference in trace element chemistry between the tonalites of the Ancient Gneiss Complex, the diapiric domes, and the Granodiorite Suite is further demonstrated in Figure 8.

Condie and others (1970) have concluded from the geochemistry of the Sheba Formation graywackes that their provenance area had an abundance of igneous rocks depleted in Sr relative to K, Ba, Ca, and Rb, and included an ultramafic component to account for their high Ni content. It has been suggested (Glikson, 1972) that the diapiric tonalites were emplaced prior to the onset of detrital sedimentation, and, as a consequence, could provide the source material of the graywackes. Inspection of Table V reveals that in Barberton the tonalitic diapirs are unlikely to have supplied the detritus because they do not satisfy the requirements of the graywacke geochemistry (see Table V columns 10 and 11). On structural grounds this is not

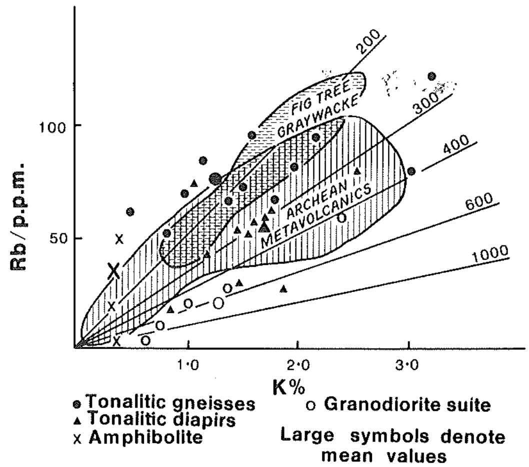
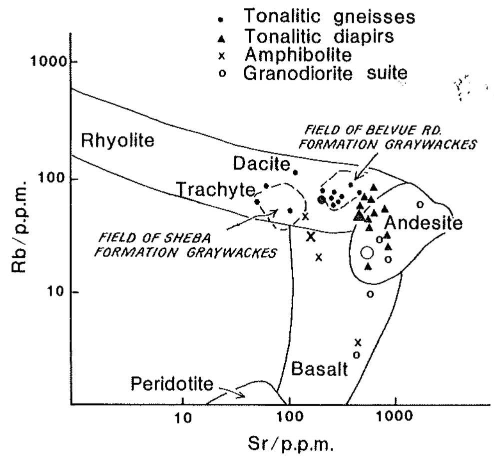


Figure 7 : Plot of Rb against K for whole-rock samples of the Ancient Gneiss Complex, tonalitic diapirs, and Granodiorite Suite. The mean amphibolite plot refers to the mean of amphibolite interlayered with tonalitic gneiss in the Ancient Gneiss Complex. The Fig Tree graywacke field is from Condie and others (1970) and the Archaean metavolcanic field is from Hart and Brooks (1970).

probable because the emplacement of the Kaap Valley diapir is reflected in the deformation of the Moodies Group. In general the rocks of the Ancient Gneiss Complex display a greater, relative Sr-depletion with respect to Rb, Ba, K, and Ca, than do the members of the Onverwacht Group and the tonalitic diapirs. The mafic and ultramafic rocks in the Ancient Gneiss Complex have Ni-contents ranging to 1500 ppm, so that in combination with the tonalitic gneisses, these rocks could have provided a suitable source material for the Sheba Formation graywackes in accord with the requirements determined by Condie and others (1970). On the other hand, it is apparent from Table V that neither the Onverwacht lavas nor the diapiric tonalites are significantly depleted in Sr with respect to Rb, K, or Ba. The Onverwacht lavas do, however, reflect Sr depletion with respect to Ca.

PETROGENESIS OF THE GRANITIC MAGMAS

Viljoen and Viljoen (1969c) postulated that the tonalites, the Ancient Gneiss Complex, the diapiric domes, and the Granodiorite Suite represent the products of a widely generated magma derived during a major differentiation event in the upper mantle. It was further proposed that this magma pervasively intruded the Swaziland Supergroup with the result that mafic and ultramafic rocks now preserved as interlayers in tonalite in the Ancient Gneiss Complex represent xenolithic remnants of a formerly more widespread crust of mafic and ultramafic volcanics. One of the results of this invasion, presumably largely lit-par-lit, into the Swaziland Supergroup would be a considerable volume increase that could be expected to produce a large horizontal component in steeply dipping rocks, and hence large scale deformation in those rocks on the periphery of magma intrusion. In this model the greenstone belts would represent such rocks,



Large symbols denote mean values

Figure 8 : Plot of Rb against Sr for whole-rock samples of the Ancient Gneiss Complex, the tonalitic diapirs, the Granodiorite Suite, and the Fig Tree graywackes. The fields of the igneous rock types are from Hedge (1966) and of the graywackes from Condie and others (1970).

and should consequently be expected to display evidence of compression. Specific reference is made to the lack of penetrative deformation in the Swaziland Supergroup (Viljoen and Viljoen, 1969f).

Hunter (1968) concluded that the intimately interlayered tonalitic gneisses and amphibolites of the Ancient Gneiss Complex originated as a result of the migration of superheated aqueous solutions, derived by partial melting at the base of a meta-sedimentary and volcanic pile, through the upper parts of the pile. In the light of the geochemical data on Precambrian graywackes that have a higher K-content than the tonalites, this hypothesis is not regarded as tenable. Derivation of a tonalitic magma from crustal sources requires that the source material has a lower potassium content than the tonalite and has sufficient water to depress the solidus temperature. Partial melting of sedimentary rocks of a composition similar to the Fig Tree graywackes would result in the production of a magma with a potassium content greatly in excess of that found in the tonalitic gneisses. Furthermore, the low primary Sr^{87}/Sr^{86} ratios in certain of the tonalitic gneisses (Davies, 1971) does not support a crustal origin. The postulate that sodium-rich solutions permeated a sedimentary-volcanic pile finds no support on field nor petrologic grounds. Partial melting of ultramafic or mafic rocks requires that the parent is silica oversaturated and includes garnet in its mineralogy in order to produce silica-oversaturated magma. None of the Lower Onverwacht rocks satisfy this requirement.

Bimodal associations of high silica, low-potassium gneisses and amphibolites have been described from several localities (Barker and others, 1969; Hanson and Goldich, 1972; McGregor, 1973; Stowe, 1971). Similarities have been noted between these sequences and the silicic volcanics of Saipan (Barker and others, 1969; Hanson and Goldich, 1972). The bimodal Twilight Gneiss of Colorado has been interpreted as being of volcanic origin, derived in either one or two stages from the mantle (Barker and others, 1969). Partial melting of eclogite or amphibolite has been proposed for the Northern Light Gneiss of Minnesota (Hanson and Goldich, 1972). Based on the experimental data (Green and Ringwood, 1968) a model has been proposed (Barker and Peterman, in press) by which the bimodal association can be derived. During the early de-gassing of the earth a basaltic crust and pyrolitic upper mantle containing hydrous minerals was produced. Depression of this hydrous crust and upper mantle into areas of higher temperature would cause dehydration of the lower parts, releasing sufficient water to prohibit the formation of andesitic magma. Dacitic magma and a residue composed of amphibole and silica-poor phases would be generated. Higher temperatures lower down the sinking slab would cause total melting and the production of tholeiitic magma. The Ancient Gneiss Complex bimodal association of tonalite and amphibole could be accommodated in this model as Barker and Peterman (in press) have already proposed.

TABLE V

ELEMENT RATIOS IN FIG TREE GRAYWACKES, ONVERWACHT LAVAS, ANCIENT GNEISS COMPLEX, AND TONALITIC DIAPIRS

	1	2	3	4	5	6	7	8	9	10	11	12	13
Rb/Sr	0.64	0.27	0.65	0.29	0.33	0.26	1.3	-	-	0.10	0.08	0.06	0.03
Ca/Sr	151	66	135	91	142	426	217	326	497	32.60	57.20	2000	1784
Ba/Sr	3.2	1.7	-	-	-	0.3	5.5	1	<0.5	-	0.8	-	-
K/Sr	136	55	144	54.4	68	9	156	22	15	31	24	16	14
K/Rb	216	204	219	187	205	100	350	-	-	306	290	249	534

1. Graywacke, Sheba Formation (Condie and others, 1970).
2. Graywacke, Belvue Road Formation (Condie and others, 1970).
3. Homogeneous tonalite, Ancient Gneiss Complex.
4. Leucotonalitic gneiss, Ancient Gneiss Complex.
5. Hornblende tonalitic gneiss, Ancient Gneiss Complex.
6. Amphibolite, Ancient Gneiss Complex.
7. Quartzo-feldspathic gneiss, Ancient Gneiss Complex.
8. Quartz diopside-plagioclase granulite, Ancient Gneiss Complex.
9. Diopside-plagioclase granulite, Ancient Gneiss Complex.
10. Leucotonalitic diapir (Viljoen and Viljoen, 1969d).
11. Hornblende tonalitic diapir, Kaap Valley (Viljoen and Viljoen, 1969d).
12. Peridotitic komatiite, Onverwacht Group (Viljoen and Viljoen, 1969a).
13. Basaltic komatiite, Onverwacht Group (Viljoen and Viljoen, 1969a).

During the development of the sialic crust in the manner described, brief periods of quiescence may be expected during which limited sedimentation accompanied by volcanism could occur. Deformation following the period of sedimentation, accompanied by metamorphism, would result in the association of metamorphites with the tonalite-amphibolite sequence. Partial melting in the deeper parts of the pile would be reflected in the heteroblastic texture of the tonalites produced by the presence of interstitial microcline and myrmekite, while some of the quartz-potassium feldspar pegamtites that are ubiquitous would be the other products of partial melting.

Tonalitic Diapirs

The restriction of the diapiric domes to the immediate vicinity of the Barberton greenstone belt is considered to be significant in the petrogenesis of the tonalitic magmas that constitute the domes. This coincidence implies a link between the generation of the magma and the deformation of the greenstone pile.

Rare earth element data is available for the Kaap Valley diapir (Goles, 1968). When this data is ratioed with that of chondrites, the pattern shows no Eu anomaly and a moderately steep curve for the heavy rare earths, and can be interpreted, in a partial melting model, as indicating that there was no plagioclase but garnet in the source regions. The magma would have to form at mantle depths where garnet, clinopyroxene and quartz are near liquidus phases or phases in the residuum after partial melting. The presently available data suggest that the Kaap Valley granite has a low Sr:Ba ratio which may be due to the melt being in equilibrium with amphibolite so that the melt is enriched in barium to a greater extent than strontium. The Kaap Valley tonalite would therefore have an origin involving partial melting at depth.

There is not sufficient data to clarify the origin of the leucotonalitic diapirs, but the field relations to be observed support the view that the leucotonalitic magma was in part, at least, derived by partial melting of sialic crust. It is probable that the leucotonalitic diapirs have an origin similar to the Kaap Valley tonalite with differences in depth and degree of melting, water content, and the partial involvement of crustal material being responsible for the variations in chemistry.

The leucotonalitic diapirs have an Ab/An ratio of 7.7 as compared to a value for this ratio of 3 in the Kaap Valley diapir. This high value provides some confirmation for the involvement of crustal material in the genesis of the leucotonalitic magma.

Granodiorite Suite

There is as yet inadequate data to clearly define the processes that give rise to this suite. It has been argued that the magmas were generated in the mantle (Hunter, 1968) variations in chemistry reflecting degree of crustal contamination, depth of melting, and, possibly, amount of differentiation.

Lochiel Granite and Nelspruit Migmatites

The Lochiel granite has an initial Sr^{87}/Sr^{86} ratio of 0.7054 (Davies, 1971) from which it is concluded that there is a strong crustal element in the genesis of this granite. On a Qz - Ab - Or diagram (Figure 9) of the plots of the Lochiel granite cluster around the minimum melt composition of a system with an Ab/An ratio of 2.9 at 7 kb. The Ab/An ratio for the tonalites in the Ancient Gneiss Complex is 3 and Figure 9 illustrates that their plots lie close to the cotectic line at 7 kb. A migmatite plot lies in an intermediate position between the Lochiel granite and the tonalitic gneisses. The conclusion is drawn, therefore, that the Lochiel granite magma was generated by partial melting at P_{H_2O} = 7 kb of the tonalitic members of the Ancient Gneiss Complex. The implication of this conclusion is that the crust must have attained a thickness of 20 to 25 km prior to 3.0 b.y. There is indirect support for this contention in the cratonic-type sedimentological style of the Moodies Group (Anhaeusser, 1971a) that immediately pre-dates the Lochiel granite, thus implying the existence of a thickening, more stable crust.

A MODEL FOR ARCHAEAN CRUSTAL DEVELOPMENT

The models that have been proposed to account for the features of the greenstone-granite terranes fall into two main categories, namely

(i) the ultramafic and mafic volcanic sequences overlie and post-date a sialic crust (Anhaeusser and others, 1969; Macgregor, 1951; Windley, 1973), or

(ii) the granitic rocks were a later addition to a simatic crust following oceanic or island arc volcanism (Anhaeusser, 1973; Glikson, 1972; Talbot, 1973).

Some models recognize that there must have been sialic crust available to provide the quartz-rich sediments, but these models primarily regard simatic crust as being fundamental (e.g. Goodwin, 1968; Talbot, 1973).

In the first group Macgregor (1951) attributed the greenstone-granite relationships to gravitional movements that find support in Ramberg's (1967) experiments, but Macgregor did not elaborate on how the inverted density stratification developed. Talbot (1968) invoked the effect of thermal convection cells in the granitic layer as the greenstones sank. Anhaeusser and others (1968) proposed that greenstone belts were located along fault zones and in associated downwarps developed on a thin sialic crust, the greenstone belts being deformed in response to a subsequent major period of granite addition. Windley (1973) pointed to the similarities between volcanism, ore deposition, and structure in greenstone belts and in the incipient stages of plate extension found in more recent environments. Greenstone belts in this model would be located in linear graben-like zones marking the sites of proto-oceanic ridge systems. Windley (1973) envisaged that there may have been all gradations from ensialic rifts to narrow, linear oceanic basins, depending on the amount of extension.

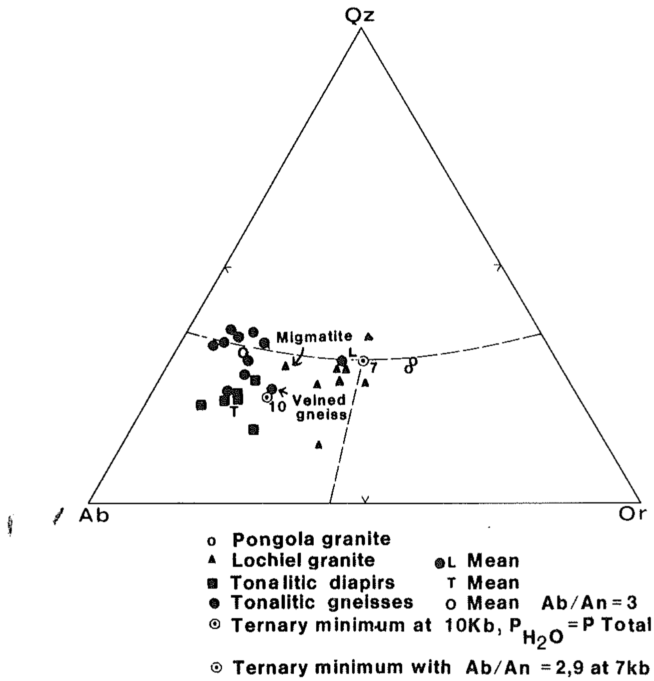


Figure 9 : Ternary Qz - Ab - Or diagram for the tonalitic gneisses of the Ancient Gneiss Complex, the tonalitic diapirs, and the Lochiel granite.

The second group of models deals with an essentially oceanic setting. Both Anhaeusser (1973) and Glikson (1972) postulated the development of undulations in a world-wide primitive oceanic crust. In Anhaeusser's model, subduction of parts of this crust results in the production of an island arc environment in which calc-alkaline volcanism and limited sedimentation are subsequently developed. Sodic acid magmas are generated at the base of downwarps of the simatic crust as a result of partial melting of this crust and by mantle differentiation, processes that lead ultimately to sialic underplating of the simatic crust and to diapiric swelling of the underplate. As the island arc develops above sea-level, more active erosion leads to increased sedimentation. Finally, additions of K, U, and Th from the mantle result in the production of potassic granites. Glikson (1972) invoked a two-stage process to generate sodic granites at the base of simatic crustal downwarps, resulting in early diapiric plutonism that accentuates the mega-ripples or undulations. Volcanism and sedimentation take place in the downwarps which are further depressed as a gravitational response so that the basal portions of the downwarps are depressed into zones of partial melting with the production of potassic granitic magma. Shield formation occurs during the cooling of the volcano-sedimentary troughs and the aggregation of the granitic nuclei.

Talbot's (1973) model is based on the assumption that small granitic masses accreted independently by separation from the mantle and became concentrated behind plate subduction zones in early Archaean times, while greenstone belt sequences developed in the oceanic environments. Collision of micro-continents preserved vestiges of oceanic crust (i.e. the greenstone belts) between the plates.

Development of the second type of model has been influenced by the analogous geochemistry of the lavas of greenstone belts and of recent island arc and oceanic volcanic rocks (Glikson, 1971). The presence of low potassium basalts and ultramafic intrusions are reported from cratonic environments in the Kaapvaal craton (see Button, 1973; Hunter, 1970b; McIver, 1972). The variation in the chemistry of basalts is probably more dependent on the depth of melting and the depth at which the melt equilibrates with the refractory residuum than on environment.

In the second group of models the association of tonalitic and amphibolitic gneisses is interpreted as the result of the invasion of sodic, silicic magma into mafic and/or ultramafic oceanic volcanic rocks. Attention has already been drawn to the volume increase involved in this mechanism and the lack of complementary structural features that would be expected in the remnants of the volcanic pile. A second aspect that is not adequately explained in these models is the source of the quartz needed for the considerable accumulations of graywackes and quartzites associated with many greenstone belts. Anhaeusser (1973) derives his initial graywackes by erosion of the island arc volcanic rocks (see his Figure 3, 1973), but the geochemical data provided by Condie and others (1970) requires a source material of a distinctive type that the island arc volcanics cannot wholly supply.

There is evidence from Rhodesia that a younger greenstone sedimentary succession rests unconformably on tonalite (Oldham, 1968) which indicates that at least some greenstone belt sequences did develop on sialic crust. The presence of andesites and rhyolites in other greenstone belts (Goodwin, 1968) points to the fact that volcanism evolved further than at Barberton where volcanic activity was largely aborted soon after the extrusion of the mafic phases. A model for the development of the greenstones must take cognizance of these facts.

In formulating a model for the evolution of the Archaean crust in the eastern Transvaal and Swaziland, the principles proposed by Shaw (1972), Barker and Peterman (in press), and Windley (1973) are employed and modified. During the development of the greenstones three phases are proposed involving

(i) distension and rifting accompanying mantle upwelling;

(ii) sagging of the rift accompanying mantle withdrawal, and

(iii) transcurrent faulting that may be strong or considerably suppressed.

Differences observed between greenstone belts (e.g. absence of thick sedimentary successions, greater abundance of andesitic volcanics as compared to the Barberton model) would be accounted for in this model as a reflection of the amount of spreading and distension of the rifts, preservation of junctions of rift systems, the life span and size of the mantle upwelling under the rift, and the extent of transcurrent faulting. The sequence of events is listed in Table VI and is illustrated in simplified form in Figure 10.

TABLE VI

PROVISIONAL CHRONOLOGY OF EVENTS IN THE DEVELOPMENT OF THE KAAPVAAL ARCHAEAN CRUST

1. (a) Degassing of earth accompanied by development of basaltic crust and pyrolitic upper mantle, forming a hydrous lithosphere.

   (b) Completion or near-completion of mantle solidification and rapid cooling of earth's surface. Non-uniform cooling is suggested by presence of ± 3.7 b.y. rocks in Greenland (Macgregor, 1973) and ± 3.4 b.y. rocks in Kaapvaal (Davies, 1971).

   (c) Development of proto-atmosphere and increasing development of lithosphere.

2. (a) Mega-undulation of crust or collision of crustal plates resulting in sinking or subduction of slabs of hydrous lithosphere.

   (b) Dehydration of lower parts of sinking or subducted slabs, release of water, formation of dacitic liquid and residue of amphibole and silica-poor phases.

   (c) Higher temperatures in deeper parts of slab cause total melting of basaltic crust with production of tholeiitic liquid.

3. (a) Explosive extrusion of dacitic liquids, partly as tuffs, contemporaneously with extrusion of tholeiitic basalts. Process continues until hydrous lithosphere consumed.

   (b) Metastable tectonic conditions cause deformation leading to production and accentuation of banding in dacitic-tholeiitic bimodal association. (First recognizable event in Ancient Gneiss Complex).

4. Emplacement of mafic dykes.

5. Formation of small depositional basins in which limited sedimentation and volcanism took place (represented by metamorphite sequence of Ancient Gneiss Complex).

6. Further deformation accompanying metamorphism of sedimentary-volcanic sequence deposited during Stage 5 and tonalite-amphibolite unit. Limited partial melting of metamorphites, particularly the kinzigite members. In deeper parts of bimodal tonalite-amphibolite unit partial melting resulted in development of heteroblastic texture (i.e. growth of interstitial microcline and new oligoclase; myrmekite formation) and production of potassic pegmatites. Deformation involves tectonic interslicing of metamorphites with tonalite-amphibolite unit.

7. (a) Crustal plate moves over a linear zone of high heat flow that causes doming and distension of continental crust accompanied by initiation of graben-like rifts. Continental crust at this stage had thickened to ± 20 km in order to accommodate partial melting of tonalite-amphibolite unit.

   (b) Active volcanism is initiated as doming and distension cause crustal thinning and rifts that tap magma sources in the upwelling mantle. The variations in the geochemistry of the ultramafic and mafic rocks reflect magma generation over a sizeable depth range. It is probable that the cyclic nature of the volcanism could be a response to resurgence of distension during the history of the rift. It should be noted that the highest mean Na/K ratio (see Table II) is found in the tholeiitic basalts of the Hooggenoeg Formation, well above the base of the Swaziland Supergroup. Note also the variations in Al-contents and the Na/K ratios of the basaltic komatiites in the lower formations of the Onverwacht Group (see Table I).

8. (a) Mantle withdrawal from beneath rift initiates sagging. Shoulders of rift actively eroded. Constant differential downwarp and uplift between the depositional basin and the source area, due to sagging in basin and movement along bounding rift faults, keeps the coastal areas steep and permits only temporary accumulation of sediment that slump and generate turbidity currents in response to tectonic movements (Walker and Pettijohn, 1971). Intermittent adjustment along the faults is reflected in the cyclic sedimentation pattern. Differential downwarping of the depositional basin gives rise to considerable variation in thicknesses of sediments accumulated in different parts of the basin.

(b) Downwarping, largely a gravitational response, produces vertical stretching of sedimentary and volcanic rocks, folding about near-vertical fold axes, and faulting longitudinal to the original graben.

(c) Depression of the pre-Swaziland Supergroup crust along flanks of graben accompanies the sagging with the result that conditions that simulate modern subduction zones are created, e.g. graywacke-chert sedimentary assemblages, andesitic volcanism in Fig Tree Group (Visser, 1956), and the rise of tonalitic diapirs.

(d) Tonalitic diapirs produced by reaction of lower crust and mantle rise diapirically deforming the original linear pattern of the graben and the volcanic-sedimentary sequence.

(e) Continued downwarping of rift initiates fracturing and faulting of original crust along the shoulders of original rift, thus permitting rise of magma that re-acts with crust through which it passes to give elongate bodies of differentiated Granodiorite Suite.

9. (a) Rise of tonalitic diapirs within graben coupled with the decreasing size of the depositional basin as a result of filling by earlier graywacke sequence and of collapse of rift causes retreat of seas in graben with the result that shallower water, cratonic-type sedimentation (i.e. the Moodies Group) is initiated.

(b) Disconformable and unconformable relations of Moodies Group to early sedimentary-volcanic sequence results from the differential downwarping of the rift and withdrawal of the seas in the rift.

(c) Some downwarping continues so that the sediments of the Moodies Group are deformed in a style similar to that in the lower formations.

(d) Re-activation of faults developed during deformation of volcano-sedimentary sequence as right-lateral wrench faults.

10. (a) As the downwarping proceeds, the original crust is sufficiently depressed so that portions of upper amphibolite grade become partially melted producing potassic liquids that rise in response to their lower density and spread laterally at sites of lower free energy adjacent to the site of the original graben to occupy a broad zone 150-200 km wide.

(b) Transcurrent movement along faults continues and affects stocks of Lochiel granite within the Swaziland Supergroup (e.g. at Wyldsdale and Kobolondo).

Where events in the preceding table have been subdivided into (a), (b), (c), etcetera, it implies that they are largely synchronous.

Two questions arise from this model concerning, firstly, the size and thickness of the original crustal plate, and, secondly, the dimensions of the Barberton graben.

Figure 1 illustrates that much of the granitic floor of the Kaapvaal craton is overlain by younger rocks, and that large areas of the exposed granite have not been mapped. Gneisses in the northern portion of the Johannesburg granite dome bear a close resemblance to the tonalitic gneisses of the Swaziland Ancient Gneiss Complex although Anhaeusser (1971c) regards them as post-dating the Swaziland Supergroup. Similar, interlayered, tonalite and amphibolite gneisses crop out to the east of Pietersburg in the Northern Transvaal. North of Vryburg, du Toit (1905) reported the presence of sillimanite-bearing schists, cordierite-quartz-muscovite-feldspar gneisses, and garnetiferous amphibolites associated with gneissic granites. Whether these rocks are equivalents of the metamorphites in the Ancient Gneiss Complex is uncertain. However, the presence of garnet in the amphibolites implies distinctly different metamorphic conditions. At the present time it is not possible to estimate the size of the original crustal fragments. Wilson (1973) has suggested that the pre-greenstone basement of Rhodesia was more extensive than postulated by Stowe (1971). If this is the case, the dimensions of the early crust must have approached the present size of the Rhodesian craton.

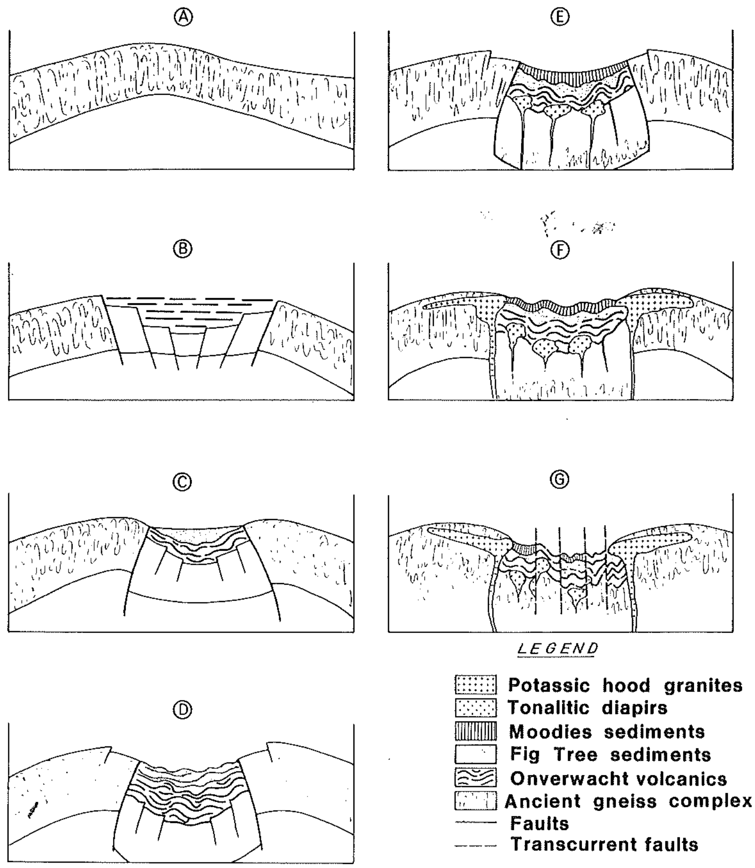


Figure 10 :

A. Mantle upwelling initiates crustal distension.

B. Continuation of upwelling and distension causes rift-faulting. Degree of distension will be determined by the magnitude of the mantle plume and its duration. Magma derived from mantle is intruded along fault plane.

C. Mantle withdrawal commences and sagging of rift zone results. The variations in the chemistry of the Onverwacht volcanics may be reflection of degrees of spreading and subsequent contraction (as a result of sagging). The presence of alkali basalt in the Hooggenoeg Formation (see McIver and Lenthall, 1973) could be synchronous with beginning of sagging. Erosion of shoulders of rift results in accumulation of piles of sediment that are unstable and subject to flow in turbidity currents due to intermittent movement along bounding faults in response to the sagging.

D. Continued sagging deforms volcano-sedimentary pile, and causes depression of lowest parts of the older sialic crust into zone of partial melting (such zones are likely to occur at relatively high crustal levels due to the steeper thermal gradient imposed by the rise of the mantle plume). Interaction of mantle and lowest crust produces tonalitic magma that starts to rise diapirically.

E. Transcurrent movement along faults in the volcano-sedimentary pile is initiated. (This process would cause formation of large boudins thus providing a mechanism for isolating the various layered ultramafic complexes located near the northwestern flank of the Barberton belt. These complexes may mark the site of rift faults or a median zone within the rift). The rise of the tonalitic magma disrupts the linearity of the faults and older structures. The rise of the diapirs coupled with the tilting of blocks of the Onverwacht

Continued on next page

There is no direct evidence to indicate the thickness of crust prior to greenstone formation. However, it is implicit in the conclusion regarding the genesis of the potassic Lochiel granite that the crustal thicknesses of at least 20 or 25 km existed prior to 3.0 b.y. (see also Saggerson and Owen, 1969).

Rocks of the Swaziland Supergroup are known, from isolated outcrops appearing as windows in the younger cover and from borehole intersections, to extend to the vicinity of Reitz (170 km south-southeast of Johannesburg) from which it appears that the Barberton graben extended at least 300 km in a southwesterly direction beyond its present limits. Granite dated at ± 3.0 b.y. (van Eeden, 1972) has been intersected in a borehole at Glen near Bloemfontein (350 km south-southwest of Johannesburg). If the 3.0 b.y. granites do occupy a broad zone peripheral to a greenstone graben, the probability exists that the graben extended for a further 250 km beyond Reitz. With the presently exposed length of the Barberton greenstone belt, the minimum length of the graben would be 700 km.

One hundred and sixty kilometres north of the Barberton belt, greenstone assemblages are located in linear belts in the Murchison Range and near Pietersburg. The Murchison belt has been the site of tectonism until, at least, the deposition of the lower members of the Pretoria Group (Transvaal Supergroup). Crockett (1971) has suggested that monoclinal folding in the Waterberg Supergroup (post-dating the 2.0 b.y. Bushveld Complex) in Botswana (southeast of Gaborone) is a reflection of adjustments along this tectonically unstable zone. This would imply that the Murchison belt has a minimum length of 650 km. Wilson (1973) has proposed that the sites of Rhodesian greenstone belts are tectonically controlled by faults and fractures in a pre-greenstone basement. He identifies strike lengths of 500 km for these faulted and fractured zones. The length of these graben suggests that the early crustal fragments were of considerable size.

Continued from previous page :

and Fig Tree Groups consequent upon transcurrent movement produces structural highs that restrict the size of the depositional basins of the Moodies Group that overlaps from Fig Tree onto Onverwacht.

F. Further sagging of the rift continues deformation of the volcano-sedimentary pile and causes depression of the amphibolite facies of the sialic crust into the zone of partial melting. Potassic granitic magma so produced rises along tensional zones in the shoulders of the rift thus forming linear zones flanking the graben. Some of the magma is intruded into the volcano-sedimentary pile some distance from the flanks so that small bosses result (e.g. Wyldsdale, Kobolondo).

G. Transcurrent faulting reaches a maximum intensity immediately following the emplacement of the initial pulses of potassic granitic magma (see Hunter, 1962). Transcurrent faulting produces a braided fault pattern and blocks that tilt with dips down the axis of the trough. Where this tilting is considerable, the upper parts of the sialic floor are brought to levels where they are exposed by subsequent erosion (e.g. the south-western end of the Barberton belt).

N.B. Initial transcurrent faulting is not shown in E in order to avoid over-complication of the diagram.

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