ECONOMIC GEOLOGY RESEARCH UNIT

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CRUSTAL DEVELOPMENT IN THE KAAPVAAL CRATON

PART II

THE PROTEROZOIC

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INFORMATION CIRCULAR No. 84

UNIVERSITY OF THE WITWATERSRAND

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by

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ABSTRACT

The distribution of the sedimentary basins, the granites and mafic complexes is illustrated and their essential features described. The Limpopo mobile belt that separates the Kaapvaal and Rhodesian cratons is briefly described. The generation of the granites in the setting of the craton is discussed and evidence is presented to support the conclusion that the granite magmas were, in part, mantle-derived and, in part, derived by partial melting of the Archaean sialic crust. The distinctive feature of the granites is that their locus of emplacement provides the source material for the sedimentary basins, the depositional axes of which migrated across the craton complementary to the northward migration of the locus of granite emplacement.

The parallelism of the chronology of crustal deformation and of magmatism in the Kaapvaal craton leads to an attempt to identify a concept that links responses in the crust to processes in the mantle. It is proposed as a working hypothesis that the proposals of Shaw and others (1971) can be applied to the Kaapvaal craton. This involves a complex interaction of heat exchange as a result of the dissipative energy of solid earth tides.

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CRUSTAL DEVELOPMENT IN THE KAAPVAAL CRATON

PART II : THE PROTEROZOIC

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CRUSTAL DEVELOPMENT OF THE KAAPVAAL CRATON

PART II : THE PROTEROZOIC

INTRODUCTION

In Part I the use of Archaean and Proterozoic was retained as convenient descriptive terms for particular stages in crustal development. The Proterozoic represents that period when heat flow had decreased, and, hence, temperature gradients were low enough to permit the survival of supracrustal rocks that are but little altered and deformed. No clear division between Archaean and Proterozoic is possible because the change in energy level was gradual with the result there is an overlap in geologic processes from Archaean to Proterozoic while regional variations in heat flow result in the boundary between Archaean and Proterozoic being diachronous.

In the Kaapvaal craton, a rigid, long-lived crustal plate capable of sustaining and preserving basins, containing gently dipping, largely unmetamorphosed deposits, developed at ± 3.0 b.y., at which time other crustal plates (e.g. Canada, Australia, and, possibly, Rhodesia) were still the sites of accumulation of greenstone-type volcanic rocks. It is probable that more rigid blocks existed in Greenland prior to 3.0 b.y. (McGregor, 1973) but these have been reworked by subsequent increase in heat flow. The arbitrary time-boundary between Archaean and Proterozoic in the Kaapvaal craton is taken at 3.0 b.y. and is marked by the onset of the first development of ensialic basins in which the products of sedimentation and volcanism accumulated.

THE SEDIMENTARY BASINS

The sedimentary and volcanic deposits occupy distinct basins and are grouped, in ascending order, into the Pongola, Dominion Reef - Witwatersrand, Ventersdorp, Transvaal, and Waterberg Supergroups. Pretorius (1966) considered that the basins developed under tensional conditions in an environment where vertical tectonics prevailed. In his model it was envisaged that a basin would remain active as long as the potential gravitional energy in the crust was sufficient to permit repeated elevation of the adjacent source areas around the basin after each period when the level of erosion approached the base-level of deposition. The maximum energy level represented in the basin-fill and the number of repetitions of volcanics, coarse and fine clastics, and non-clastics was taken to be a function of the intensity and number of cycles of waxing and waning of energy associated with periods of uplift and succeeding quiescence. Pretorius (1966) proposed that the life of a basin could be represented by a curve resembling a half sine wave on which were superimposed similar waves of smaller amplitude and periodicity that represent the alternation of active uplift and more passive erosion and deposition during the life of a basin. The resulting curve was defined in terms of the harmonics of wave forms. The first harmonic represents the overall life of the basin, while superimposed harmonics of higher orders reflect the number and intensity of resurgence of uplift and subsequent periods of erosion and deposition.

In the simplest case, where first and third order harmonics are superimposed, the stratigraphic column would ideally consist from the base up, of (i) coarse clastic and pyroclastics, (ii) volcanics, (iii) pyroclastics and coarse clastics, (iv) coarse clastics and fine clastics, (v) non-clastics, (vi) fine clastics and coarse clastics, (vii) coarse clastics and pyroclastics, (viii) volcanics, and (ix) pyroclastics and coarse clastics.

The stratigraphic columns of each of the five supergroups conform closely to the conceptual model, particularly now that some of the gaps noted by Pretorius (1966) have been filled (e.g. the inclusion of the Wolkberg Group in the Transvaal Supergroup [Button, 1973a], and of the volcanics cropping out in the Zoutpansberg in the Waterberg Supergroup [Coertze and others, 1970]). Uncertainty still surrounds the stratigraphic definition of the Ventersdorp Supergroup. Winter (1966) proposed that the lower division of the Ventersdorp Supergroup should be more properly regarded as the top of the Witwatersrand Supergroup, but other investigators (see Whiteside, 1970) recognized a major unconformity at the base of the lower division. The problem is compounded by the considerable reliance that has to be placed on borehole data, and by virtue of the fact that accumulation of the products of Ventersdorp sedimentation and volcanism took place on a highly irregular surface, and was controlled by the presence of fault-bounded troughs (Brock and Pretorius, 1964).

The validity of the Pretorius model is not seriously impaired by these apparent deviations, but may require refinement when the stratigraphic problems are resolved. The full complexity is illustrated, firstly, by the fact that superimposed on the first and third order harmonic patterns of the individual supergroups are half sine waves of even smaller amplitude and shorter periodicity within the constituent groups of each supergroup. Secondly, the supergroups themselves reflect a decrease in energy levels with time, that is demonstrated by the increase in the volume of finer clastics and non-clastics in successively younger basins and by the estimates of the rates of vertical movement (Table 1).

TABLE I

ESTIMATED RATES OF VERTICAL MOVEMENT

Supergroup	Maximum Thickness (km)	Time-Span (m.y.)	Rate (km/yr or mm/yr)
Swaziland	21.3	80	0.27
Pongola	10.6	70	0.15
Witwatersrand/ Ventersdorp	16.7	300	0.05
Transvaal	9	250	0.036
Waterberg	6.5	160	0.023

NOTE : Estimates of time-span based on following data :

(i) Swaziland Supergroup is taken to post-date the Ancient Gneiss Complex, dated at 3.39 b.y. (Davies, 1971) and to pre-date the Kaap Valley granite dated at 3.31 b.y. (Oosthuyzen, 1970).

(ii) Pongola Supergroup rests with a sedimentary contact on granite (Visser and others, 1947) that probably forms part of the Lochiel granite dated at 3.06 b.y. (Allsopp and others, 1962). The Dalmein granite dated at 2.94 b.y. (Davies, 1971) also probably pre-dates the Pongola Supergroup. The Usushwana Complex (2.87 b.y., Davies and others, 1970) intrudes the Pongola Supergroup.

(iii) Witwatersrand Supergroup rests with a sedimentary contact on granite dated at 2.72 b.y. (Allsopp, 1964). The Gaborone granite dated at 2.34 b.y. (McElhinny, 1966) intrudes the Ventersdorp Supergroup in Botswana (Hunter and Lenthall, 1973).

(iv) Transvaal Supergroup post-dates the Gaborone granite but is intruded by the Bushveld Complex dated at 1.95 b.y. (Davies and others, 1970). Ongeluk lavas in the Pretoria Group are dated at 2.22 b.y. (Crampton, personal communication).

(v) Waterberg Supergroup post-dates the Bushveld Complex but is intruded by a granitic dyke* dated at 1.79 b.y. (Oosthuyzen and Burger, 1964).

* Recent mapping by the South African Geological Survey has shown that the granophyric granite porphyry at Rust-de-Winter (dated at ± 1.79 b.y.) is an extrusive rock being part of early Waterberg volcanism. The minimum age of the Waterberg Supergroup, based on the date obtained from the syenite intrusive at Leeuwfontein, is then ± 1.42 b.y. The maximum life-span of the Waterberg basin becomes 0.37 b.y. indicating a subsidence rate of ± 0.01 km/m.y.

The estimates in Table I are probably too low. There are several reasons for this. Vertical movements are likely to be spasmodic so that periods of rapid movement will intervene between periods of quiescence in the basin. The length of the periods of observation largely obscures these more rapid variations (see Sutton, 1969). No allowance has been made for compaction of the sediments, so that the presently recorded thicknesses of the fill is not a direct function of the amount of vertical movement. The lack of precise geochronological data places a constraint on the estimation of the times when movements began and ended. For this reason the Witwatersrand and Ventersdorp supergroups have had to be considered as one event. Despite these inaccuracies, the rates of vertical movement do provide relative order of magnitude figures that illustrate the increasing stability of the Kaapvaal craton.

Pretorius (1966) estimated that the periodicity of the first harmonic in his model to be 300 b.y. The filling of a basin is taken as half a sine wave, which would then require 150 m.y. This figure compares closely with the mean time-span estimated in Table I for the cratonic basins.

The present distributions of the five supergroups (Figure 1) reflects an apparent migration of the basins across the craton from southeast to northwest (Pretorius, personal communication). Confirmation of this migration is not yet possible, but the sedimentological studies of the Witwatersrand and Transvaal supergroups (Brock and Pretorius, 1964; Button, 1972, 1973a) show that the depositional axis of the latter basin lies 150-200 km north of the Witwatersrand axis. The data from these two supergroups together with preliminary information from the Waterberg Supergroup (de Villiers, 1967) also reveals that the transport directions of sedimentation were consistently from the northward or northeastern sides of these basins in the Transvaal Province, although local deviations from this trend are found, due to the influence of basement highs (see, for example, Eriksson, 1971). Evidence from the Pongola Supergroup (Hunter, 1963) suggests that its provenance area lay to the north of the present outcrops.

A feature of the distribution patterns of the supergroups is the evidence for a constant interplay of axes aligned east-northeast and north-northwest. Both the Transvaal and Waterberg supergroups are arranged in belts that are curved about a broad north-northwesterly-trending arch that is the location of a number of domical basement windows (the Johannesburg, Devon, Vredefort, and other granite domes) that were positive features of varying magnitude at different times during the deposition of successive supergroups (see, for example, Eriksson, 1971; Visser, 1971). Although the lack of knowledge of the sub-surface geology may accentuate the linearity of the termination of the Ventersdorp Supergroup, it is noticeable that this termination is coincident with the eastern flank of the same broad arch. To the east of this arch, the basement features that influence sedimentation are arranged in linear, east-northeasterly-trending directions (see Button, 1972, 1973a).

The north-northwest and east-northeast directions that are apparent on a gross scale in Figure 1 are dominant in more detailed structural studies of the Pongola, Witwatersrand, Transvaal, and Waterberg supergroups (see Crockett, 1971; Brock and Pretorius, 1964; Hunter, 1963; Pretorius, 1964; Roering, 1968; Vermaak, 1970; Verwoerd, 1963). It will be recalled from Part I that these two structural directions are repeated in the Ancient Gneiss Complex and the Swaziland Supergroup.

MAFIC COMPLEXES

Mafic complexes were emplaced at various times during the Proterozoic evolution of the Kaapvaal craton. The Usushwana and Bushveld complexes post-date sedimentation in the Pongola and Transvaal basins respectively, while the Modipe gabbro possibly post-dates the Ventersdorp Supergroup (Kynaston and Humphrey, 1920). In the western Transvaal a mafic complex is intrusive into the lower members of the Dominion Reef-Witwatersrand Supergroup (von Backström, 1952), but its minimum age is not known. Certain mafic and syenitic intrusions in southern Botswana were regarded as being post-Waterberg in age (Crockett, 1971) but in a subsequent paper (Crockett, 1972) they have been restricted to post-Transvaal in age. The Losberg Complex is regarded as being co-genetic with the Bushveld Complex (Davies and others, 1970), with which mafic and peralkaline intrusives around the Vredefort dome are also correlated (Bischoff, 1972a and b, 1973). The Trompsburg Complex intrudes marbles that are tentatively correlated with the Transvaal Supergroup (Ortlepp, 1959) and has been dated at 1.372 ± 0.142 b.y. (Davies and others, 1970). It has been suggested (Smit, Hales and Gough, 1962) that the prominent isostatic gravity anomaly in the northwestern Cape Province is due to the presence of a body, denser than normal crust, lying at a depth of <20 km.

Certain of the mafic complexes have been emplaced along northwesterly-trending zones while others occur in groups aligned in the same direction. The Usushwana Complex has been interpreted (Hunter, 1970) as being located in two northwesterly-trending graben. The Bushveld Complex displays an elongation in that direction if the limits of the complex in the western Transvaal are restricted in keeping with the interpretations of Vermaak (1970) and Biesheuvel (1970). The latter author has identified a north-northwesterly trend intersecting an east-northeast trend from his gravity data in

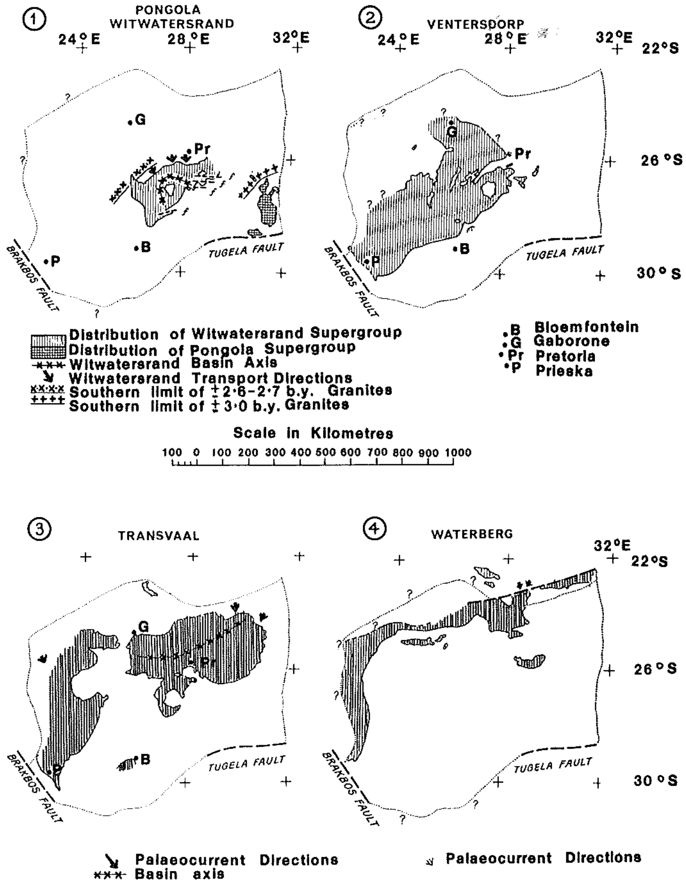


Figure 1 : Present distributions of the Pongola, Dominion Reef-Witwatersrand, Ventersdorp, Transvaal, and Waterberg supergroups on the Kaapvaal craton. The Shoshong Formation in Botswana is shown as part of the Transvaal Supergroup but this correlation is uncertain (see text).

respect of that portion of the Bushveld Complex near Goudini in the western Transvaal. The confinement of the felsic volcanics of the Bushveld Complex within a north-northwesterly aligned belt coincident with the elongate distribution of the mafic and acidic plutonic rocks of the Bushveld Complex has also been noted (Hunter, 1973a), and the isostatic gravity data (Smit, Hales and Gough, 1962) indicates a northwesterly-striking positive anomaly underlying the western lobe of the main outcrop of the Bushveld Complex.

The mafic intrusions around the Vredefort dome, the Goudini outcrop of the Bushveld Complex, and the Modipe gabbro all occupy a north-northwesterly-trending zone that also includes a distinct gravity positive located between Vredefort and Goudini. In Figure 2 the locations of the various mafic complexes are shown in relation to the fold axes of the Transvaal Supergroup, and it can be seen that complexes post-dating the Transvaal Supergroup are located along synformal axes; in particular at the intersection of major synforms.

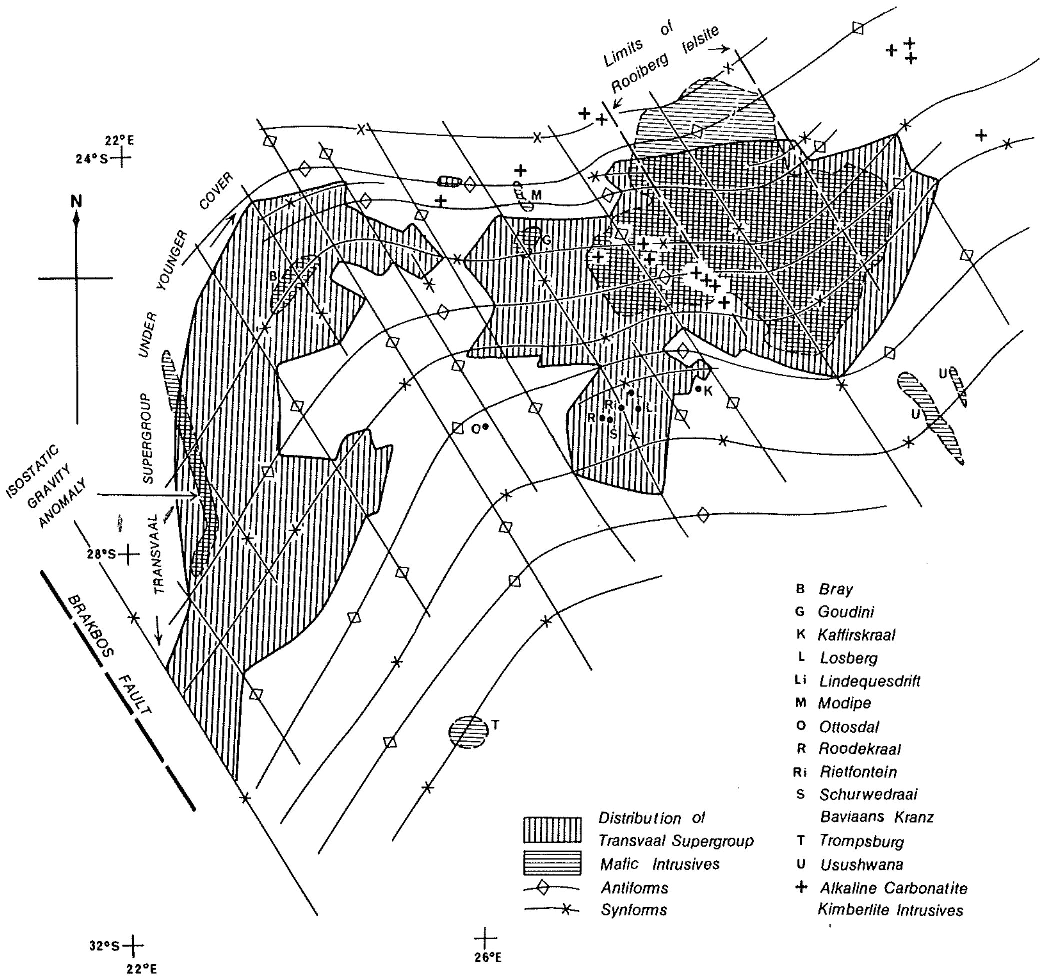


Figure 2 : Diagrammatic representation of the structure of the Transvaal Supergroup in relation to Precambrian mafic and alkaline complexes.

The dominance of the general northwesterly direction on the emplacement of mafic magma is further emphasized, particularly in the southeastern corner of the Kaapvaal craton, by the swarms of pre-Karroo dolerite (diabase) dykes that are aligned in that direction. Some dykes also strike east-northeast to northeast which is the dominant trend of the less abundant pre-Karroo dykes in the Murchison Range in the northeastern portion of the craton. Two notable exceptions are found, however. Dykes of pre-Transvaal age between the Barberton and Murchison greenstone belts trend eastwards, and post-Transvaal dykes in the eastern Transvaal build a prominent swarm trending north-northeast, which is parallel to the isostatic gravity anomaly underlying the eastern Bushveld Complex.

In Figure 2 the locations of alkaline, carbonatite, and kimberlite complexes of pre-Karroo age are shown. They are concentrated in a north-northwesterly zone, first recognized by Shand (1923), flanking the belt of felsites of the Bushveld Complex and are most prominent in the arch that causes the curvature of the outcrops of the Transvaal and Waterberg supergroups. Other complexes are located on the eastern side of the Kaapvaal craton that sedimentological studies (Button, 1973b) indicate to have been a structurally positive area during, at least, some of Transvaal times.

THE GRANITES

Granite emplacement occurred in the Kaapvaal craton following the deposition of the Pongola, Ventersdorp, Transvaal, and Waterberg supergroups, the granites post-dating the Ventersdorp through to Waterberg supergroups being distinguishable from the earlier granites on account of (i) their enrichment in Fe relative to Ti, Mg, and Sc (Hunter, 1973b), and (ii) their association with felsic volcanism.

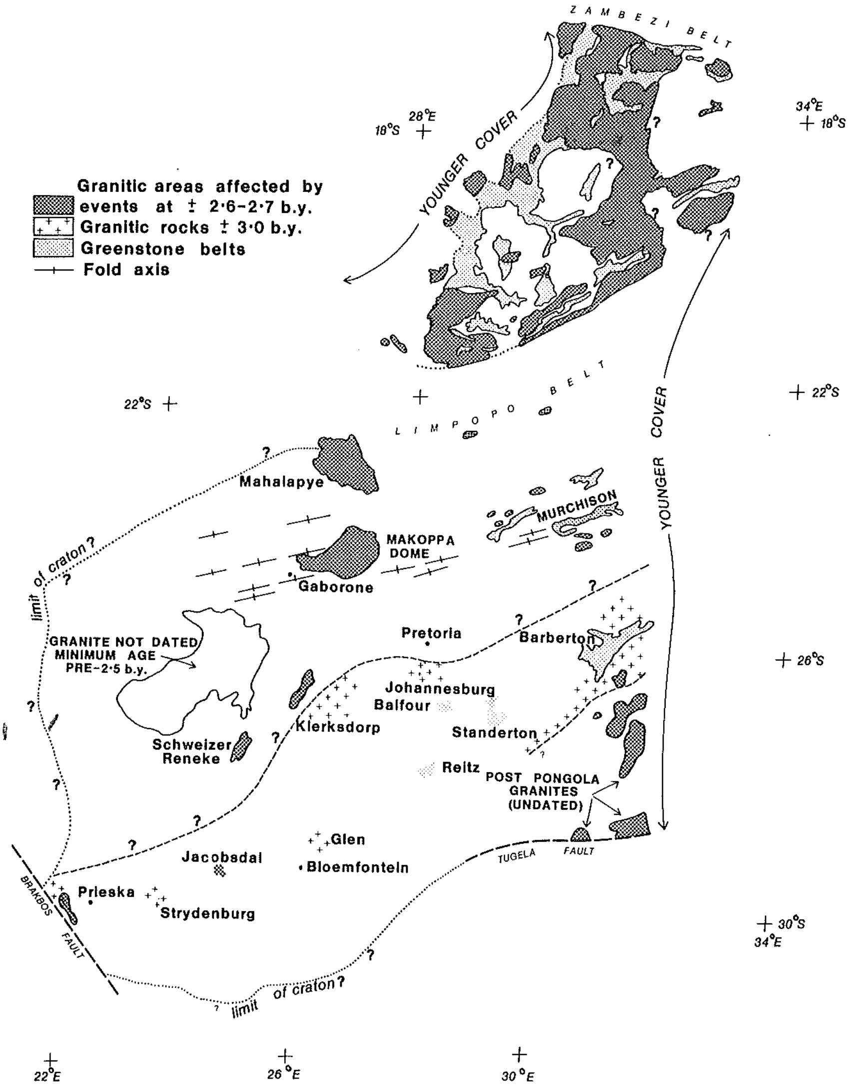
∿ 3.0 b.y. Event

In the eastern Transvaal and Swaziland the ∿ 3.0 b.y. event is represented by the Lochiel granite and the Nelspruit migmatite (see Part I), the former being the oldest recognizable potassic granite in that area. The Lochiel granite and Nelspruit migmatites occupy a belt ± 175 km wide lying astride the Barberton greenstone belt, the southwesterly continuation of this belt being obscured by younger cover-rocks. However, granitic rocks dated between 3.1 and 2.9 b.y. crop out on the Johannesburg dome (Allsopp, 1961, and personal communication), around the flanks of the Witwatersrand basin in the western Transvaal (Allsopp, 1964), and near Marydale on the southwestern side of the Kaapvaal craton (Burger and Nicolaysen, 1973). Boreholes have intersected granites of similar age at Glen and Strydenburg (van Eeden, 1972; Burger and Nicolaysen, 1973). In Figure 3 the presently known distribution of granites of this age suggests the existence of a crudely, east-northeasterly aligned belt on the southeastern flank of which are the only known outcrops of the Pongola Supergroup (see Figure 1).

Of the granites indicated in Figure 3 as occupying the ∿ 3.0 b.y. belt, only those on the Johannesburg dome have been mapped in detail (Anhaeusser, 1971). The northern half of the dome is underlain by banded, tonalitic gneisses that bear a close superficial resemblance to those of the Ancient Gneiss Complex. The southern half of the dome is composed of more massive, sometimes foliated, granodiorites and adamellites with which are found smaller outcrops of dark coloured tonalites. The latter are commonly found in close proximity to ultrabasic remnants that are equated with the Swaziland Supergroup (Anhaeusser, 1971). The granodiorites and adamellites are intrusive into the banded gneisses and have yielded ages of ± 3.1 b.y. (Allsopp, 1961; and personal communication).

In the eastern Transvaal and Swaziland, coarse-grained, porphyritic granites build three distinct plutons that have been dated at 3.06 ± 0.03 b.y. (Oosthuyzen, 1970) using U/Pb methods and 2.94 ± 0.045 b.y., R_o = 0.7024, (Davies, 1971) using Rb/Sr methods. These ages clearly suggest a close contemporaneity of these plutons with the Lochiel granite, although the chemistry of the granite (referred to as the Dalmein granite) building the plutons is distinctive (see Table 2).

The Lochiel granite can be traced southwestwards into the Transvaal province, where the Pongola Supergroup rests on it with a sedimentary contact (Visser and others, 1947). These authors also reported the presence in the same area of a coarse-grained, porphyritic granite that pre-dates the Pongola Supergroup. Re-examination of this granite suggests a provisional correlation with the Dalmein granite, which, if correct, would indicate a maximum age of the Pongola Supergroup of ∿ 2.94 b.y.



<u>Figure 3</u> : Distributions of granitic rocks that have yielded isochron ages of ∿ 3.0 and ∿ 2.7 b.y. in the Kaapvaal and Rhodesian cratons. The ∿ 3.0 b.y. tonalitic and adamellitic diapirs associated with the greenstone belts in Rhodesia are not shown.

On the basis of their isochron ages, geochemistry, and tectonic styles, the ∿ 3.0 b.y. granites were emplaced in at least three pulses that extended over a period of ± 160 m.y.

∿ 2.7 b.y. Event

Potassic granites have been recognized in the eastern Transvaal and Swaziland that intrude the Pongola Supergroup (Hunter, 1968), and that have ages of ± 2.65 b.y. (Allsopp and others, 1962; Davies, 1971). The granites form either sheet-like bodies (the Pongola granite) or grossly discordant plutons (the Kwetta, Mpageni, and Mooihoek granites, Hunter, 1973c).

The Pongola granite is indistinguishable in the field from the older Lochiel granite as regards lithology and mode of occurrence. Intrusive into the Pongola granite are a number of discordant plutons that have been grouped on the basis of their field relationships, petrology, and chemistry, into three classes, the most common being the Mpageni granite. The Mooihoek granite is intrusive into the Kwetta granite, but the field relationships of these two granites to the Mpageni type is not known. All three granites yield ages around 2.65 b.y. (Allsopp and others, 1962; Allsopp, personal communication; Davies, 1971). Like the Dalmein granite, the younger granite plutons are built of corase-grained, porphyritic granite that is devoid of pegmatite (Hunter, 1968).

Granites cropping out in the Schweizer Reneke and Ventersdorp 'windows' have yielded ages ranging from 2.64 b.y. to 2.82 b.y. (Allsopp, 1964). The Dominion Reef-Witwatersrand Supergroup rests with a sedimentary contact on these granites. Isotopic ages within this range are reported from the Prieska area (Burger and Nicolaysen, 1973), the Makoppa dome (Allsopp, personal communication), Mahalapye (Bennett, 1970), and within the Limpopo belt (van Breemen and Dodson, 1972). Pegmatites on the southern flank of the Limpopo belt have been dated at ± 2.57 b.y. (Burger and others, 1967). Granite closely resembling in lithology, petrology, and tectonic style the 2.65 b.y. Mpageni granite builds the Mashishimala pluton south of the Murchison greenstone belt. Post-Pongola granites crop out in the extreme southeastern corner of the Kaapvaal craton.

Granitic additions in the Rhodesian craton are relevant in considering the extent of the ∿ 2.7 b.y. event. Tonalitic gneiss domes (Stowe, 1970) and tonalite with granodioritic and adamellitic phases (Wilson, 1973) were emplaced into the Rhodesian greenstone belts ∿ 2.9 b.y. This period of tonalitic diapirism was succeeded by the intrusion of more potassic granites (largely adamellites) at ∿ 2.6 b.y. (Wilson, 1973) or between 2.7 and 2.3 b.y. (Stowe, 1970).

From the widespread distribution of granites dated ∿ 2.7 b.y. in the Kaapvaal-Rhodesian craton, it is apparent that this period represents a peak in the volume of granite added to the crust, the main locus of emplacement lying to the north of the 3.0 b.y. granites. Tonalitic diapirism in the Barberton greenstone belt terminated prior to ∿ 3.2 b.y., but in Rhodesia this stage of development attained its peak at ∿ 2.9 b.y. (Wilson, 1973). Thus when the Kaapvaal craton had achieved sufficient stability to sustain and preserve cratonic sedimentary basins, the Rhodesian part of the craton had yet to evolve from the greenstone environment. Significantly, the Limpopo mobile belt, wherein deformation and metamorphism reached a peak at ± 2.69 b.y. (van Breemen and Dodson, 1972), is located close to the interface between these environments. Cratonization was completed in Rhodesia ∿ 2.6 b.y., whereafter cratonic basins could develop. The diachronous nature of the boundary between Archaean and Proterozoic (these terms being used as defined in the Introduction) is demonstrated by the contrasting evolutionary histories of the Kaapvaal and Rhodesian cratons.

2.3 b.y. and 2.0 b.y. Events

The granites emplaced at 2.3 and 2.0 b.y. are confined to relatively restricted geographic localities, associated with felsic volcanism, and, in the case of the 2.0 b.y. granites, contemporaneous with mafic plutonism.

The Gaborone granite is located within the great crustal arch that extends north-northwestwards across the Kaapvaal craton. Its full extent is obscured by the Transvaal and Waterberg supergroups that overlie the granite, particularly along its northern and southeastern margins.

Around the flanks of the granite are found largely felsic volcanic rocks that have been correlated previously with either the Ventersdorp Supergroup or the Dominion Reef Group. Subsequently it was considered from field evidence that the lava succession included representatives of both Dominion Reef and Ventersdorp ages (Boocock, 1959). Preliminary geochronologic studies of the so-called Dominion Reef lavas gave Rb/Sr dates ranging from 2.39 to 3.41 b.y. (Snelling, 1965-67, quoted from Crockett, 1969). An age greater than ∿ 2.9 b.y. for the felsites was accepted because the intrusive Gaborone granite had yielded Rb/Sr dates of 2.98 and 2.88 b.y. (Snelling, quoted from

Crockett, 1969). As a consequence the lavas were given the local formational name of Kanye Volcanic Group that was provisionally regarded, in view of its extreme age, as being pre-Dominion Reef in age. However, Rb-Sr isochron ages of ± 2.3 b.y. have been obtained from the Gaborone granite (McElhinny, 1966; Crampton, personal communication) and felsites in the adjacent areas of the Transvaal have yielded similar ages. This data suggests that the emplacement of the Gaborone granite and the felsic volcanism were nearly synchronous events that took place at or near the termination of Ventersdorp volcanism. This data is pertinent to the petrogenesis of the Gaborone granite for Poldervaart (1954) suggested that the coarse-grained rapakivitic granite in the core of the Gaborone granite was the only truly intrusive phase, and that the marginal granophyres and granites were derived from pre-existing felsites unrelated to, and forming the country rock of, the granite by recrystallization *in situ*. With some modification this view was supported by Crockett (1969). Wright (1961) considered that the whole suite of granites, marginal granophyres, and felsites represented a single event during which the plutonic rocks intruded their own effusive roof, a view that is in accord with the geochronologic data (see also Hunter and Lenthall, 1973).

The relationships between granites, granophyres, and felsites in the 2.0 b.y. Bushveld Complex are equally uncertain. It has been variously proposed that the felsites represent : (i) the products of recrystallization of pre-existing rocks; (ii) volcanism terminating the filling of the Transvaal basin; (iii) volcanism, unrelated to the Transvaal basin; or (iv) volcanism associated with the final acid plutonic phase of the Bushveld Complex. A review of the geochemistry of the granites and felsites (Hunter, 1973b) led to the conclusion that the felsites represent the explosively extruded products of the partial melting of the pre-Transvaal granitic basement, the granitic rocks being derived, probably in a series of pulses, from the gradually fractionating partial melt. Implicit in this concept is the necessity for tectonically stable conditions to permit fractionation of the melt. Isotopic studies of the granite (Davies and others, 1970) are in accord with its derivation by partial melting. These conclusions do not resolve the age relationship of the felsites and the mafic phase of the Bushveld Complex, but do emphasize the fact that the felsites are genetically related to the complex.

The Bushveld granite was formerly believed to be a relatively thin capping to the mafic phase of the Bushveld Complex that had the structure of a great lopolith (Hall, 1932). On the basis of gravity data and field relationships, the mafic phase was considered to have been emplaced from a number of independent, though related centres (Cousins, 1959; Truter, 1955; Willemse, 1964). Although the granites have a sheeted form (Strauss, 1954) and have, in part, spread laterally, analysis of gravity, geochemical, and field data (Pretorius, personal communication; Lenthall, personal communication; Hunter, 1973b) points to the granites also being intruded from at least four centres.

The Palala granite that crops out near the northern flank of the Kaapvaal craton has not been dated but its similarities in lithology and chemistry with the Gaborone and Bushveld granites suggests that its emplacement occurred between 2.3 and 2.0 b.y.

? 1.8 b.y. Event

A granophyric granite porphyry intrusive* into the lower members of the Waterberg Supergroup (Glathaar, 1956) has yielded an age of 1.79 b.y. (Oosthuyzen and Burger, 1964). Crockett (1971) recognized post-Waterberg granitic intrusives in southern Botswana, about which uncertainty prevails for, in a more recent publication (Crockett, 1972), these are restricted to post-Transvaal on the maps although the text refers to their post-Waterberg age. Except for these Botswana intrusives, the volume of granite intruded at this time appears to be very small and may represent the final transfer to the upper crust of granitic magma that was generated during the 2.0 b.y. event.

GEOCHEMISTRY OF THE GRANITES

The mean compositions of granitic rocks in the eastern Transvaal and Swaziland, and of the Palala, Gaborone, and Bushveld granites are given in Table II. The available geochemical data of other Kaapvaal granites has been summarized elsewhere (Hunter, 1973b), and, in view of uncertainties of correlation with specific granitic events in the eastern Transvaal, are not included.

* Recent mapping indicates that this is probably an extrusive event at the onset of Waterberg sedimentation.

TABLE II

MEAN COMPOSITIONS OF GRANITIC ROCKS (3.0 b.y. AND YOUNGER) IN THE KAAPVAAL CRATON

	1	2	3	4	5	6	7	8	9
SiO_2	71.32	73.17	70.70	69.06	73.09	78.31	72.84	74.55	75.00
TiO_2	0.32	0.25	0.35	0.63	0.25	0.14	0.34	0.20	0.21
Al_2O_3	14.43	13.68	14.68	14.10	13.52	11.23	12.56	11.80	12.17
Fe_2O_3	0.59	0.85	1.05	1.88	0.83	0.92	1.49	1.39	1.41
FeO	1.73	1.68	1.18	2.23	1.48	0.83	1.44	2.08	1.79
MnO	0.08	0.10	0.04	0.25	0.04	0.06	0.04	0.07	0.05
MgO	0.57	0.29	0.89	0.94	0.59	0.30	0.41	0.53	0.23
CaO	1.33	1.03	1.92	1.99	1.59	0.57	1.24	1.34	1.01
Na_2O	3.92	2.88	4.69	3.14	3.35	2.54	3.42	2.56	3.23
K_2O	4.59	5.54	3.53	4.86	5.17	4.84	5.21	4.45	4.81
H_2O^+	0.61	0.64	0.69	1.06	0.45	0.38	0.39	0.55	0.65
H_2O^-	0.06	0.06	0.12	0.07	0.08	0.06	0.12	0.07	0.13
P_2O_5	0.31	0.08	0.14	0.20	0.08	0.01	0.14	0.15	0.14
Ba	500	260	–	–	570	–	550	1110	963
Hf	–	3.5	–	–	2.4	–	–	5.8	6.1
Li	44	15	–	–	28	–	39	–	20
Pb	41	49	–	–	68	–	58	–	53
Rb	226	380	109	–	295	–	350	277	215
Sr	122	59	488	–	132	–	65	141	66
Th	–	20.7	–	–	31	–	–	20.9	23.8
Zr	–	130	120	–	161	–	570	331	354
Ba/Rb	2.2	0.69	–	–	1.9	–	1.57	4	4.5
Ba/Sr	4.1	4.3	–	–	4.3	–	8.4	8	14.6
Ca/Sr	77	124	26.8	–	85.9	–	135	67.3	110
K/Ba	74	177	–	–	75.2	–	78.7	33.3	41.4
K/Rb	168	121	293	–	146	–	122	134	180
Na/K	0.76	0.46	1.12	0.57	0.58	0.47	0.58	0.51	0.58
Rb/Sr	1.9	6.2	0.19	–	2.2	–	5.4	1.96	3.26

1. Lochiel granite : mean of 6 analyses except CaO (9 determinations), Na_2O and K_2O (14 determinations), Rb and Sr (8 determinations), Ba, Li, and Pb (3 determinations).
2. Pongola granite : mean of 3 analyses except CaO, Na_2O, and K_2O (4 determinations), Rb, Sr, and Ba (2 determinations), Li, Pb, Th, Hf, and Zr (1 determination).
3. Dalmein granite : mean of 4 analyses except Na_2O, and K_2O (16 determinations), Rb and Sr (12 determinations), Zr (1 determination).
4. Kwetta granite : mean of 2 analyses.
5. Mpageni granite : mean of 4 analyses except CaO (6 determinations), Na_2O and K_2O (12 determinations), Rb and Sr (7 determinations), Ba (3 determinations), Li and Pb (2 determinations), Hf, Zr, and Th (1 determination).
6. Mooihoek granite : mean of 3 analyses.
7. Gaborone granite : mean of 11 analyses except Fe_2O_3 and FeO (14 determinations), Na_2O, K_2O, Rb and Li (16 determinations), Ba, Pb, Sr, and Zr (7 determinations).
8. Palala granite : mean of 2 analyses except trace elements (1 determination).
9. Bushveld granite : mean of 17 analyses except CaO, Na_2O, K_2O, Rb, Sr, and Ba (21 determinations), Hf and Th (14 determinations), Li and Pb (7 determinations). Mean excludes stanniferous Bobbejaankop granite stocks.

TABLE III

COMPARISON OF MEAN COMPOSITIONS OF LOW- AND HIGH-CA GRANITES

	High-Ca, Low-Si Granites		Low-Ca, High-Si Granites		
	Pre-2.3 b.y.	Turekian and Wedepohl	Pre-2.3 b.y.	Post-2.3 b.y.	Turekian and Wedepohl
Si%	32.3	31.4	34.8	34.8	34.7
Ca%	2.06	2.53	0.58	0.53*	0.51
Na%	3.35	2.84	2.79	2.30	2.58
K%	2.46	2.52	3.63	4.03	4.20
Ba ppm	785	420	500	868	840
Co ppm	9	7	5	2	1
Cs ppm	4.5	2	4	5	4
Hf ppm	3.5	2.3	3.8	6	3.9
Li ppm	36	24	24.6	30	40
Nb ppm	19	20	30	29	21
Pb ppm	25	15	29	55	19
Rb ppm	100	110	238	280	170
Sc ppm	3	14	3	2.6	7
Sr ppm	384	440	122	90	100
Th ppm	6	8.5	17	22	17
Tl ppm	0.9	0.72	1.4	1.0	2.3
Zn ppm	40	60	47	66	39
K/Rb	246	230	152	144	247
K/Ba	30	60	72	46	50
Ba/Rb	7.8	3.8	2.1	3.1	5
Ba/Sr	2	0.95	4	9.6	8.4
Ca/Sr	53	57	47	59	51
Rb/Sr	0.26	0.25	1.9	3.1	1.7

* Ca abundance adjusted to account for F content of these granites.

The rare earth element contents (Fourie, 1969) are shown in Figure 5. The undated Bandolierskop and the 2.6 b.y. Mpageni granites, both of which build discordant plutons, have slight negative Eu anomalies indicating only minor plagioclase in contact with their magmas in the source areas, where the presence of garnet is also suggested in the case of the Bandolierskop granite. The low initial Sr^{87}/Sr^{86} ratio reported in the Mpageni granite (Sicunusa pluton, Davies, 1971) is in accord with the REE pattern suggesting a deep source region. The granite from near Prieska has a similar REE pattern, but its tectonic style is now obscured by the faulting that affects the margin of the craton in that area. The Pongola granite has a strong negative Eu anomaly and a flat distribution pattern of the heavy rare earths, suggestive of the presence of plagioclase and an absence of garnet in the source region.

There is a close similarity between the patterns of the Bushveld granites and the Bushveld Complex felsites, that are distinguished from the western Bushveld granite pattern by the presence of a negative Eu anomaly. The Palala granite has a similar REE pattern to the western Bushveld granite, but has a steep heavy rare earths distribution. Whereas Davies and others (1970) have proposed an origin for the Bushveld granite by partial melting of a pre-Transvaal granitic basement, the REE pattern suggests that some of the granite may have been generated at greater depths.

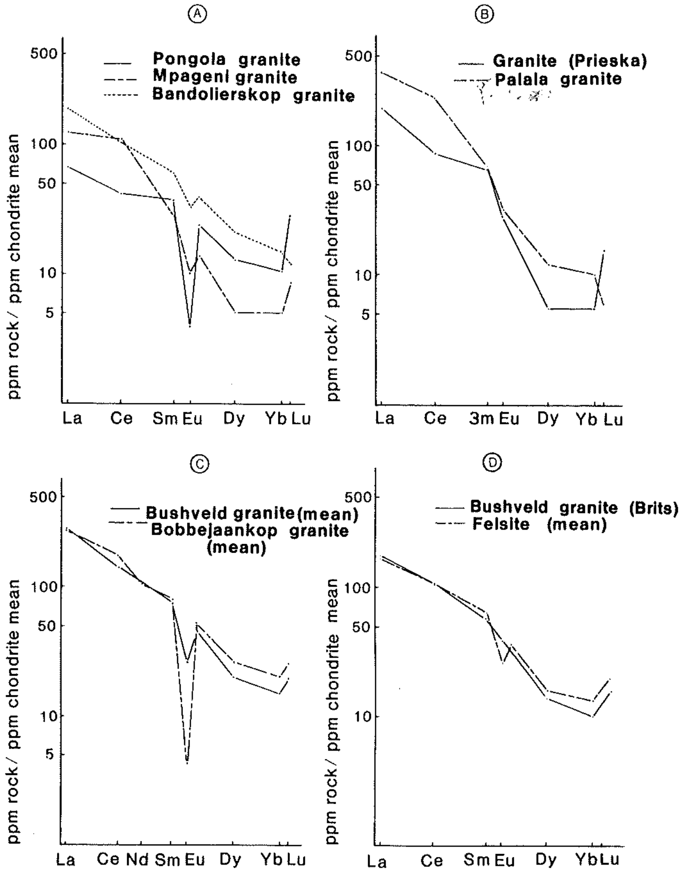


Figure 5 : Plots of rare earth element abundances in Kaapvaal granitic rocks normalized to abundances in chondrites.

The Qz-Ab-Or plots in Figure 6 reveal that most of the granites lie close to the thermal trough of the system for low An contents and H_2O pressures. The Dalmein granite lies on the plagioclase feldspar side of this trough, near the 5 kb isobaric eutectic, whereas the Pongola granite falls in the more potassic field. Both the Palala and Mooihoek granites lie on the quartz saturated side of the minima. This is interpreted as being due to the crystallization of these granites from more saturated, residual melts. It is concluded from Figure 6 that the Kaapvaal granites crystallized at pressures of 3 kb or less from magmas that had low or moderate H_2O contents. The shallow depths of emplacement of the majority of the granites suggests that volcanism may have been associated with them. In the case of the Gaborone and Bushveld granites, emplacement into their own effusive phases has been proposed. One of the problems of the Lochiel granite is the nature of its original roof. There is no evidence to suggest that there was a capping of rocks of the Swaziland Supergroup. The probability cannot be excluded that it had a roof of co-genetic volcanics that have now been stripped away by erosion.

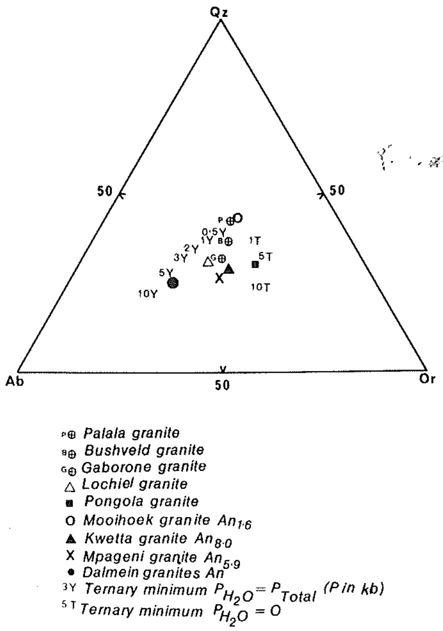


Figure 6 : Ternary Qz-Ab-Or diagram for the mean plots of the Lochiel, Dalmein, Pongola, Mpageni, Kwetta, Mooihoek, Gaborone, Palala, and Bushveld granites.

LIMPOPO MOBILE BELT

Resolution of the enigma of the Limpopo belt is fundamental to any model for the evolution of the Kaapvaal-Rhodesian craton. This belt, 240-320 km wide, has been divided into three major tectonic units (Cox and others, 1965; Mason, 1970). A complexly deformed central zone in which fold axes are disposed in general northeast or northwest (Bahnemann in Morrison and Wilson, 1971) is bounded by marginal zones of 'straightening', associated with dextral transform faulting. Metamorphism of granulite grade affected a granite-greenstone basement prior to the deposition of a distinctive sequence of sedimentary and volcanic rocks to which the local name of Messina Formation is applied. A renewal of metamorphism accompanied complex refolding of basement and cover. Cores of coarse-grained granite (Bulai and Singelele granites) are developed within the basement. A third tectonothermal event at $\sim$ 2.3 b.y. is considered to have affected these rocks following the emplacement of the Great Dyke of Rhodesia (Mason, 1973). The time-equivalence of the Messina Formation with supergroups on the adjacent Kaapvaal and Rhodesian cratons is uncertain (see Mason, 1970; 1973). If the 2.68 b.y. isochron for the Bulai and Singelele granites dates the reactivation episode that deformed the Messina Formation, its time-equivalence with the Pongola Supergroup is a probability (Mason, 1973), or it may be older (van Breemen and Bodson, 1972).

The Messina Formation is regarded by Mason (1973) as a predominantly metasedimentary sequence of semi-pelitic, psammitic, and calcareous rocks (meta-quartzites, magnetite quartzites, dolomite, marbles, quartzofeldspathic gneisses and amphibolites) intruded by semi-concordant anorthosite bodies.

The Messina Formation has close lithological similarities with the metamorphites in the Ancient Gneiss Complex of Swaziland and with the so-called Bushmanland Sequence in the $\sim$ 1.0 b.y.

Namaqualand mobile belt. More particularly these metasedimentary sequences together with the presence of anorthosites are typical of rock types encountered in granulite terranes. The question has not been resolved in the southern African examples whether the presently observed sequences represent the sedimentary response to a specific depositional environment (i.e. under tectonically unstable conditions) or whether they are the normal survivors of granulite grade metamorphism in which pelitic rocks are relatively rare, due to a pre-granulite history involving partial melting that would particularly affect and, hence destroy, pelitic rocks. The presence of carbon dioxide rich fluid inclusions in granulite facies minerals (Heier, 1973) suggests that granulite formation could take place at lower temperatures as a result of the increase in the percentage of CO_2 in the fluid reducing the water pressure. The distinctive calc-silicate rocks in these belts may result from the liberation of CO_2 by the reaction of melts, produced from pelitic rocks at lower P/T conditions, on calcareous rocks within the original metasedimentary sequence (Fyfe, 1973).

The north-northwesterly-trending Crystal Springs and Bubi dyke swarms assigned to the Great Dyke event (Robertson and van Breemen, 1970) cut the northern marginal zone of the Limpopo belt and display chilled margins with the high grade metamorphic rocks. The age relations of the Messina Formation and the Great Dyke are uncertain (see Mason, 1973). On the basis of isochron dates in the Mahalapye granite-migmatite complex and mineral ages within the belt, a third tectono-thermal event at $\sim$ 2.3 b.y. has been proposed (Mason, 1973), but the Great Dyke dated at 2.532 $\pm$ 0.089 b.y. (Davies and others, 1970) is not reported to be affected by this reactivation. It is certain that the Limpopo belt has remained a site of tectonic instability from early Precambrian to the present as evidenced by Mesozoic volcanism (Cox and others, 1965) and the higher heat flow values (Carte and van Rooyen, 1969).

Crustal thicknesses in the Limpopo belt appear to be attenuated. Green and Block (1969) report unusually early arrivals of the compressional wave refracted from the mantle (Pn) at distances of between 300 and 500 km north of Johannesburg, that would be broadly coincident with the site of the Limpopo belt. Early arrivals of Pn waves on an eastern traverse from Johannesburg have been interpreted as being due to thinning of the crust as the coastal plain was approached.

SOURCE OF THE GRANITIC MAGMAS

The association of granitic rocks with deformed, metamorphic terranes has influenced the formulation of concepts concerning the origin and source of granitic magmas. As a result of this association it has been considered that conditions prevail in the deep roots of orogenic belts that are favourable for the formation of acid magmas. Inherent in these proposals is the belief that the localization of granitic magmas is related to major downwarps where sialic crust is depressed to depths at which partial melting can be initiated. More recently the generation of acid magmas has been regarded as a response to partial melting along subduction zones where oceanic crust is in collision with and thrust beneath continental crust. Roering (1968) and Hunter (1968; 1971) have concluded that the granites emplaced between $\sim$ 3.0 b.y. and $\sim$ 2.6 b.y. in the eastern part of the Kaapvaal craton are anorogenic. There is a demonstrable lack of coincidence between the loci of emplacement of these granites and major downwarps in which sedimentary sequences accumulated in the Kaapvaal craton. In general, granite addition lies adjacent to these basins. An appeal to hypothetical subduction zones as the source of the granitic magmas is unlikely. The Limpopo mobile belt between the Rhodesian and Kaapvaal cratons provides the only locality that might be interpreted as marking the site of former plate collision, but serious objections to this have been raised (Mason, 1970), not least of which is the generation of granites synchronously on both sides of the Limpopo belt.

The initial strontium isotopic composition assists in the identification of the source regions of granites, but such data is as yet incomplete for the Kaapvaal craton. The initial Sr^{87}/Sr^{86} ratios listed in Table IV suggest that some of the granites incorporated only limited amounts of crustal material, or that any crustal material added was impoverished in radiogenic strontium. The isotopic data on the Bushveld granites has been interpreted (Davies and others, 1970) as indicating that these granites were derived from partial melting of Archaean basement. The REE patterns support this view with the exception of the western Bushveld granite that has no negative Eu anomaly.

Similarities in the rubidium and strontium contents of certain granites with felsic volcanics of closely comparable age can be seen in Figure 4 (e.g. the western Bushveld granite and the Bushveld Complex felsites; and the Dominion Reef felsic volcanics and the $\sim$ 2.9 b.y. Dalmein granite).

TABLE IV

MEAN RUBIDIUM AND STRONTIUM ABUNDANCES AND INITIAL STRONTIUM ISOTOPIC COMPOSITIONS OF SOME KAAPVAAL GRANITES

		Rb (p.p.m.)	Sr (p.p.m.)	Sr^{87}/Sr^{86}
Lochiel granite	3.0 b.y.	226	122	0.7054
Dalmein granite (Mliba pluton)	2.9 b.y.	82	523	0.7024
Granite (Schweizer Reneke)	2.7 b.y.	198	146	0.704
Mpageni granite (Mpageni pluton)	2.7 b.y.	272	154	0.7065
Mpageni granite (Sicunusa pluton)	2.7 b.y.	307	95	0.7006
Singelele granite (Limpopo belt)	2.7 b.y.	87	207	0.7038
Gaborone granite	2.3 b.y.	350	65	0.714
Bushveld granite	2.0 b.y.	215	66	0.7153

Sources : Allsopp (1964); Davies (1971); Davies and others (1970); de Gasparis (1967); McElhinny (1966); van Breemen and Dodson (1972).

The negligible negative Eu anomalies in the Mpageni, Palala, Bandolierskop and Prieska granites suggests that plagioclase was not abundant in contact with the magmas in their source area, implying that these magmas originated at depth, and, in the case of the Palala and Bandolierskop granite, in the presence of some garnet.

The available evidence suggests that Kaapvaal granites were derived from both mantle and crustal sources. It is noteworthy that the discordant plutons have characteristics suggestive of mantle origin whereas the chelogenic granites that precede them in time have high initial Sr^{87}/Sr^{86} ratios. This association could be interpreted as a reflection of partial melting of crustal material advancing ahead of a rising magma from the mantle. The observed variations in the geochemistry of the granites is a reflection of their subsequent fractionation, differentiation, and/or assimilation. High Rb concentrations in the majority of the granites may be due to their derivation from source areas enriched in Rb (phlogopite ?) and cannot wholly be attributed to derivation from higher crustal levels because the apparently mantle-derived granites are also enriched in Rb.

If the Kaapvaal granites have been derived from upper mantle and crustal sources, the mechanism whereby these acid magmas were generated requires consideration of environments other than those associated with geosynclines or subduction zones. It has been proposed in Part I that the Lochiel granite was derived from the products of partial melting of pre-existing sialic crust consequent upon the collapse of a rifted graben. An interval of $\sim$ 120 m.y. intervenes between this event and the emplacement of the greatest volume of granite into the Kaapvaal crust between 2.8 and 2.6 b.y. The generation of these granites is unrelated to downsagging of a geosyncline or of a linear graben associated with greenstone development. The same association of granites, in part, derived by partial melting of crustal material (i.e. Pongola granite) and, in part, from mantle sources (i.e. the grossly discordant plutons) is also found in the 2.8 and 2.6 b.y. granites. The emplacement of these granites that are largely confined to the northern part of the Kaapvaal craton took place following the cessation of greenstone development in the Rhodesian craton, and synchronously with the rise of the Bulai and Singelele granites within the Limpopo mobile belt. The coincidence of these events in time is suggestive of a common response to a widespread thermal event that affected the mantle and crust beneath the Rhodesian craton and large parts of the Kaapvaal craton.

The Gaborone and Bushveld granites have similar lithologic, geochemical and tectonic features. The high initial strontium ratios of the Bushveld granite have been interpreted as being indicative of an origin by partial melting of Archaean basement initiated by the rise of a large volume of mafic magma (Davies and others, 1970). The presence of the Modipe gabbro in association with the Gaborone granite, both of which may be nearly synchronous in view of their field relationships, suggests that the Gaborone granite was derived in a similar manner to the Bushveld granite, particularly as a considerable volume of basaltic magma was added to the crust during the immediately preceding Ventersdorp volcanism.

TOWARDS A MODEL

A provisional estimation of the increasing inundation of the Kaapvaal craton by shallow seas in relation to the peaks of magmatism and to the estimated rates of vertical movement in the sedimentary basins is illustrated in Figure 7. The estimates of percentages of the Kaapvaal craton inundated during successive depositional events can be regarded only as order of magnitude figures because it is not yet possible to reconstruct the palaeogeography of the basins. However, it is known that the original northern limits of the Witwatersrand basin were approximately coincident with the present outcrops of the Witwatersrand Supergroup that occupy the arc from Klerksdorp through, and 50 km east of, Johannesburg (Brock and Pretorius, 1964). Regression of this basin occurred during upper Witwatersrand sedimentation immediately preceding Ventersdorp volcanism.

Transvaal Supergroup sedimentation was initially restricted to a proto-basin approximately 200 km north of the Witwatersrand basin axis, but thereafter isopach maps of the succeeding sedimentary units indicate that large areas of the Kaapvaal craton were inundated. The northern limit of the Transvaal basin has not yet been defined. A rock sequence cropping out close to the Limpopo belt, known locally as the Shoshong Formation, has been regarded as a condensed equivalent of the Transvaal Supergroup (Boocock, 1961). On the basis of geochronological data, it has been argued that this formation cannot be older than ∿ 2.36 b.y. (Crockett, 1972), and that it may be much younger but there is no unequivocal evidence to support a correlation with the Transvaal Supergroup.

Episodic, temporary regressions during the close of Transvaal sedimentation herald the emplacement of the Bushveld Complex, while the Penge regression precedes the extrusion of the Ongeluk volcanics that occur near the base of the overlying and transgressive Pretoria Group of the Transvaal Supergroup.

Waterberg sedimentation was confined to more restricted proto-basins from whence stratigraphically higher units of this supergroup transgressed into southern Botswana and across the Limpopo mobile belt probably into southeastern and eastern Rhodesia where the Umkondo Supergroup in that country may be a time-equivalent of the Waterberg Supergroup (Vail and Dodson, 1969).

The greatest volume of granite was added to the Rhodesian-Kaapvaal craton between 2.8 and 2.6 b.y. (see Figure 4) by which time the Kaapvaal portion of the craton had closely attained a minimum rate of vertical movement, and inundation by shallow seas had already commenced, the peak of continental emergence having been reached between the close of deposition of the Moodies Group and the emplacement of the ∿ 3.0 b.y. granites.

Examination of Figure 7 reveals that on both the gross scale related to granite emplacement and the finer scale related to mafic plutonism and volcanism, regressions in sedimentary basins precede an igneous event, the peak of which lies on the falling limb of the asymmetric eustatic curve.

The mean abundances in the successive granites of the large heat producing cations are plotted against time in Figure 8. A sharp inflection in the curves is apparent at ∿ 3.0 b.y., which is interpreted as a reflection of the decrease to a steady state of the rate of heat flow. The lag between the curves in Figures 7 and 8 indicates that, whereas the rate of flow of large heat producing cations had become steady by ∿ 3.0 b.y., the lithosphere did not immediately respond by inverting from a level of high energy to one of low energy dissipation.

Additional facts pertinent to the evolution of Kaapvaal craton subsequent to ∿ 3.0 b.y. are :

(i) the pre-2.3 b.y. granites were emplaced in two major events each occupying ∿ 160 m.y. and each consisting of a series of pulses of emplacement;

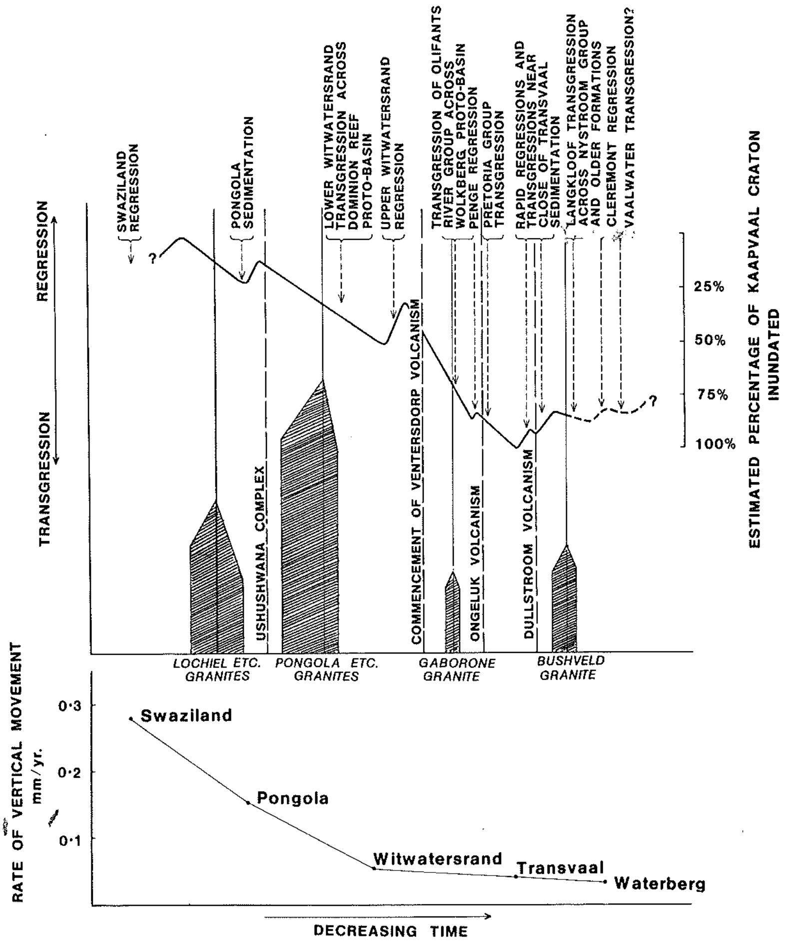


Figure 7 : Plots showing estimated percentage of Kaapvaal craton inundated between $\sim$ 3.0 b.y. and $\sim$ 1.8 b.y. in relation to igneous events. In the lower diagram, the curve for the rates of vertical movement in the sedimentary basins is plotted against time.

(ii) the migration of the sedimentary basin axes follows the northward migration of the loci of granite emplacement;

(iii) the successive loci of granite emplacement were the source areas for the sediments deposited in the basins;

(iv) the distribution of the granites is marginal to the downwarps occupied by the sedimentary basins;

(v) Sr isotope data suggests that some, at least, of the granites were generated in the mantle;

(vi) the granites were emplaced at relatively shallow ($\sim$ 10 km) depths;

(vii) the east-northeast linear distribution of the loci of granite emplacement is broadly parallel to the strike of the basin axes;

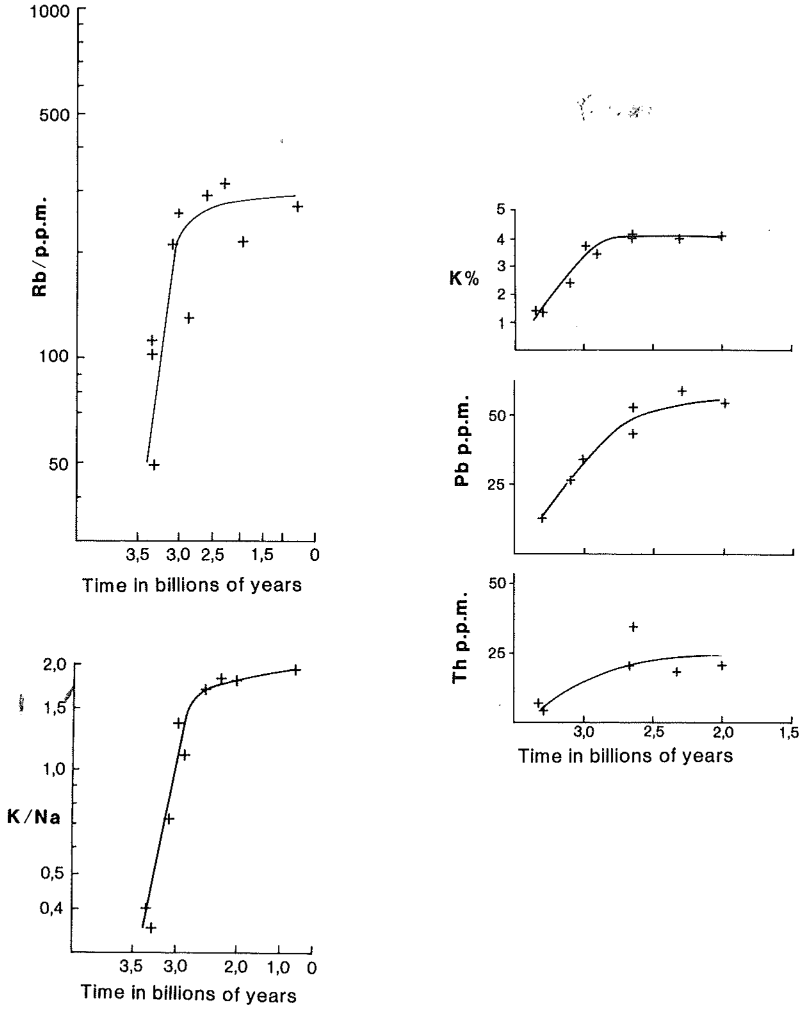


Figure 8 : Mean concentrations of Rb, K, Th, and Pb, and the mean Na/K ratios in Kaapvaal granitic rocks plotted against time.

(viii) mafic plutonism is commonly associated with north-northwesterly trends;

(ix) the fold patterns of the supracrustal rocks reflect the repeated interplay of the east-northeast and north-northwest axes.

These facts imply a connection between events in the mantle, crust, and depositional basins, pointing to a complex interaction of the parameters of energy (heat dissipation), of the volume of magmatic transfer to shallow (∿ 10 km) crustal levels, and of regressions and transgressions of epicontinental seas across the craton. The coincidence of the inflections of the eustatic curve with igneous events of an episodic nature further implies that events in the crust are responses to processes in the mantle and lower crust. Broad agreement between major transgressions of seas onto continents and peaks of igneous activity has been noted on a world-wide scale (Dearnley, 1966), and, in finer detail, during the Mesozoic era in North America (Kistler and others, 1971).

Shaw and others (1971) have proposed an hypothesis relating magmatic periodicities to orogenic-epeirogenic oscillations that, in its simplest form, envisages the production of a rapidly increasing accumulation of subcrustal heat that induces melting in the asthenosphere, causing a maximum of thermal expansion and magma storage in the subcrust beneath a continent, and continental emergence. Magmatic transfer to the crust depletes the subcrustal heat source, and continental deflation begins, being influenced by complex density distributions related to solid-solid and solid-liquid phase changes and by the vertical and lateral transfer of magma. The rate of dissipation of the thermal wave as surface heat flow and magmatic transfer of viscous components exceeds the rate at which heating in the asthenosphere returns to a peak level. When this occurs again the emergence or inflation of the continent precedes a second magmatic transfer to the crust. If the continent has drifted during this interval the new intrusive wave moving from the region of maximum melting will occupy a new locus of intrusion relative to the surface.

Complexity will be introduced by, amongst other factors, the more rapid crustal response to each heat pulse at the locus of most concentrated plutonism.

Shaw and others (1971), concluded, on reviewing the chronology of the Sierra Nevada plutonic cycle, that neither the geosynclinal nor subduction zone environments satisfactorily account for the observed spectrum of geological, geochemical, and geophysical data. In attempting to identify a process, entering both on the large and small scale, that is a common factor linking magmatic periodicities and orogenic-epeirogenic oscillations, these authors have "viewed the earth as a planetary body subject to persistently oscillating forces of tidal deformation". They have proposed that the dissipative energy of solid earth tides "is concentrated along oceanic ridge systems and in the asthenosphere by mechanisms of viscous dissipation involving shear melting", components of this energy entering "the continents as magmatic heat either where ridge type systems interact or where lateral motions induce shear zones and viscous dissipation within the continent". Periodicities of maxima of igneous intrusion and related epeirogenic oscillations are explained in terms of "periodic thermal instabilities in the process of shear melting in the mantle", longer term epeirogenic oscillations being induced by variations in proportioning of tidal energy dissipation between the solid earth and the epicontinental seas".

The application of this hypothesis to the Kaapvaal craton is not yet susceptible or rigorous testing but the following are pertinent :

(i) the proposal that the greenstone belts were generated over linear zones resembling oceanic ridge systems;

(ii) the major dextral transcurrent dislocation of the Limpopo mobile belt;

(iii) the migration of the locus of granite emplacement with a complementary migration of the sedimentary basin axes;

(iv) the existence of a zone of higher heat flow and thin crust beneath the linear Limpopo belt;

(v) the dextral wrench faulting in the Barberton greenstone belt.

These features within the Kaapvaal craton indicate that several of the elements that might be expected in the hypothesis of Shaw and others (1971) are present.

In Part I it was proposed that continental re-emergence began towards the close of the deposition of the Swaziland Supergroup when the Moodies Group was deposited in regressing basins. The peak of emergence was reached prior to the deposition of the Pongola Supergroup which marks the commencement of continental submergence and follows the transfer to the crust of the $\sim$ 3.0 b.y. granites. The bouyant rise of these granites would be expected, in the immediate vicinity of the axis of maximum intrusion, to cause deformation of the relatively strong lithosphere by elastic bending or by faulting or by a combination of both. The initiation of the Limpopo belt and the faulting that affect the Murchison greenstone belt could be seen as responses to this deformation along the northern flank of the rising granites. On the southern flank the depository in which Pongola sedimentation subsequently took place was prepared. Erosion of the axis intruded by the $\sim$ 3.0 b.y. granites would cause it to rise isostatically, thereby perpetuating the responses in the lithosphere initiated by the original emplacement of the granites. Meantime, to the north of the proto-Limpopo belt in Rhodesia, the greenstone environment still prevailed. As a result of the spreading of the original crust away from the greenstone graben, the Limpopo belt becomes the site of a complex interplay of deformation resulting from isostatic rise in the south and crustal spreading in the north. The locus of most concentrated plutonism subsequently is situated in the northern Kaapvaal craton causing a crustal response to the rise of a new wave of granitic emplacement, that exceeds the effects of the isostatic rise of the axis of the $\sim$ 3.0 b.y. granites, that would become progressively weaker as the level of erosion reached the base-level of deposition.

Further elastic bending and faulting of the lithosphere would be a consequence of the rise of the $\sim$ 2.7 b.y. granites, the subsequent erosion of this locus of emplacement causing a return to isostatic rise and a prolongation of the deformational history. Such a mechanism would account for the fault-bounded northern margin of the Witwatersrand basin (Brock and Pretorius, 1964), and for the regression of that basin. Coupled with the isostatic rise, there is a temporary increase in heat dissipated to the crust that heralds Ventersdorp volcanism. This thermal expansion causes distension and deformation at the locus of magmatism thereby accelerating the regression and, finally, death of the Witwatersrand basin.

Following the collapse of this thermal expansion, Transvaal sedimentation begins, influenced by the continuing isostatic rise of the far northern Kaapvaal and the Rhodesian cratons. The emplacement of the Bushveld Complex and of volcanism within the Transvaal Supergroup initiates similar regressions and deformation; their magnitude being a reflection of the amount of thermal energy dissipation and the proximity to the main locus of igneous activity.

It is apparent that cycles of varying periodicities have been active. There is the long cycle marked by the gradual submergence of the Kaapvaal craton that reaches its maximum during Transvaal times on which are superimposed cycles of shorter periodicity that cause temporary regressions. The emergence that followed the deposition of the Waterberg Supergroup implies in this model that there was again an accumulation of subcrustal heat causing continental inflation. The emplacement of granites, younger than those in the Kaapvaal craton, in northern South West Africa and the Kasai-Angolan craton may be the plutonic manifestations of this thermal event.

The parallelism of crustal deformation with igneous activity implies that the main loci of plutonism was associated with continental scale deformation which imposed regional stress distributions in both the mantle and overlying crust (see Shaw and others, 1971). This being so, the Limpopo belt may well be a crustal expression of a linear zone of shear and magma generation in the mantle. The concentration of granitic domes in the broad, northwesterly-trending arch across the Kaapvaal craton can be interpreted as a response to the interaction of isostatic rise and of the pattern of crustal deformation induced by the regional stress pattern. Pretorius (1964) has demonstrated that antiformal structures of differing wave-lengths produce structural culminations on a local scale. Superimposition of these structures onto antiforms of even larger wave-length, all of which reflect the regional stress pattern, could be expected to produce culminations of varying orders of magnitude. The broad arch across the Kaapvaal craton would then represent a major culmination that lies in juxtaposition with the elongation of the Bushveld Complex, the interface between these contrasting structural environments being the locus of later alkaline intrusive complexes. On the southwestern flank of this arch lies the North Western Cape gravity anomaly (Smit, Hales, and Gough, 1962) and the intense deformation associated with the Brakbos fault.

Economic implications flow from the concepts developed here. In Figure 7, it will be seen that deposition of the auriferous Witwatersrand Supergroup took place close to the inflection of the curve reflecting the rates of vertical movements in sedimentary basins, and that spatially this supergroup is preserved along the flank of a major locus of granitic emplacement, close to the site of an older greenstone graben.

In another environment, nickel mineralization is poorly developed in the Barberton greenstone belt but it is important in Rhodesian greenstones. The question must be asked in regard to both these aspects whether the mineralization is time-dependent or whether specific environments favoured the concentration of gold in the Witwatersrand Supergroup and nickel in the Rhodesian greenstones.

CONCLUSION

An attempt has been made in this paper to identify a concept whereby events in the crust are regarded as responses to a sum of a complex of processes in the mantle, and in particular, to relate the process-response model for sedimentary basins developed by Pretorius (1966) to magmatism in the Kaapvaal craton. The validity of this concept requires rigorous examination and its testing must await the accumulation of more geological, geophysical, and geochemical data.

It is not warranted to define a formal model for the crustal evolution of the Kaapvaal craton at this stage, but, following Shaw and others (1971), the parallelism of the chronology of crustal deformation, of magmatism, and of sedimentation in the Kaapvaal craton points to a process that has a common factor. Complexity stems from the interaction of large and small scale phenomena in cycles, the periodicities of which vary widely, and all of which are superimposed on the various stages of evolutionary history of the earth.

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