

IS THE VENTERSDORP RIFT SYSTEM OF SOUTHERN AFRICA RELATED TO A CONTINENTAL COLLISION BETWEEN THE KAAPVAAL AND ZIMBABWE CRATONS AT 2.64 Ga AGO?

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ABSTRACT

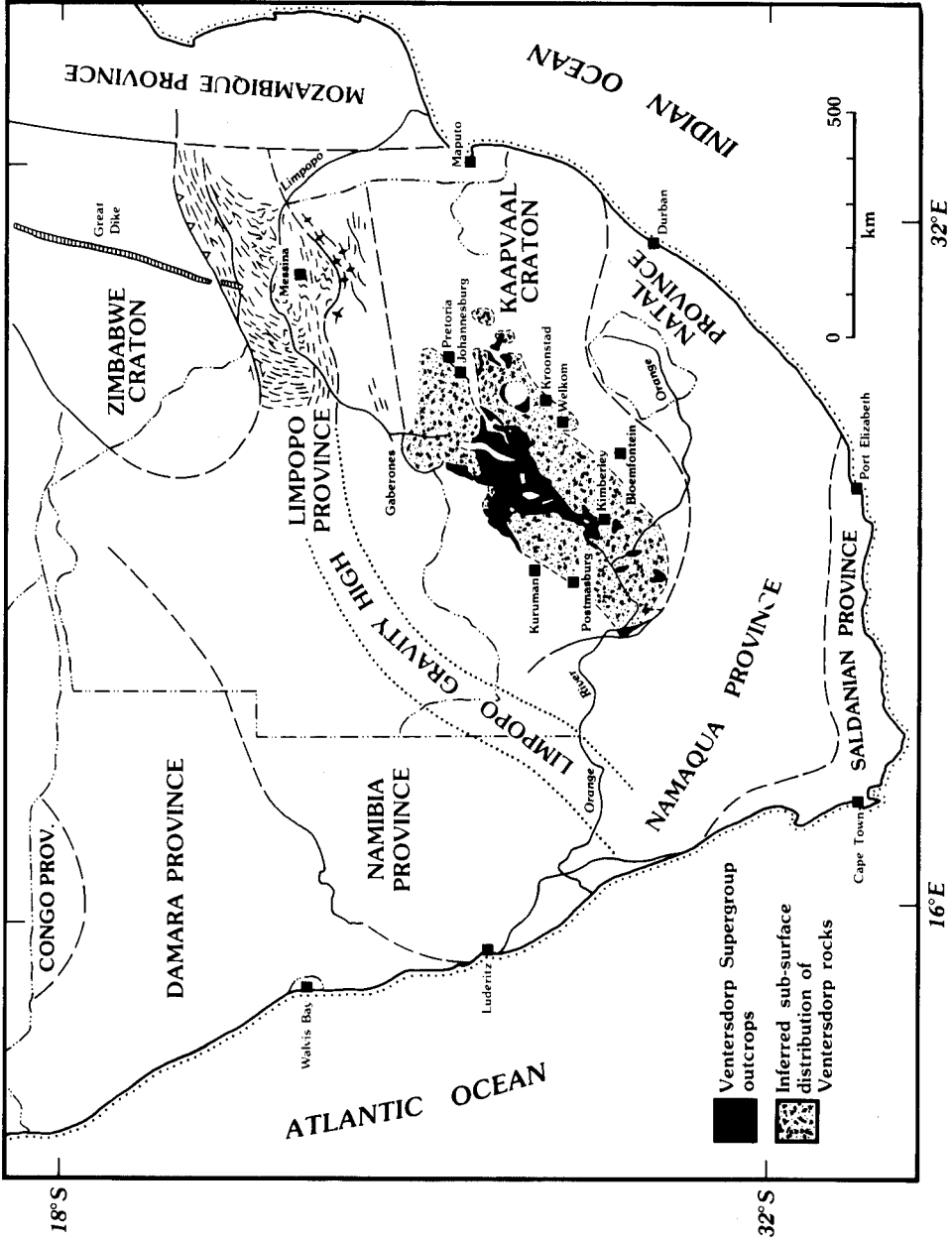
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Rocks of the Ventersdorp Supergroup were deposited in a system of northeast trending grabens on the Kaapvaal Craton approximately 2.64 Ga ago contemporary with a continental collision between the Kaapvaal and Zimbabwe Cratons. We suggest that it was this collision that initiated the Ventersdorp rifting. Individual grabens strike at high angles toward the continental collision zone now exposed in the Limpopo Province where late orogenic left-lateral strike-slip faulting and anatectic granites are recognized. We relate the Ventersdorp rift province to extension in the Kaapvaal Craton associated with the collision, and see some analogy with such rifts as the Shansi and Baikal Systems associated with the current India–Asia continental collision.

INTRODUCTION

Sedimentary and volcanic rocks of the Ventersdorp Supergroup were deposited in north to northeast trending grabens that define a broad elongate belt on the Kaapvaal Craton of southern Africa (Fig. 1). Ventersdorp rifts are estimated to extend over 200,000 km², although much of this is covered by more recent strata (Tankard et al., 1982).

The Ventersdorp Supergroup rests conformably on Witwatersrand strata at such localities on the Rand as Benoni, Evander and in the Welkom Goldfields (DuToit, 1954, p. 93; S.A.C.S., 1980; Tankard et al., 1982). Elsewhere, for example along the northwestern margin of the Witwatersrand basin between Krugersdorp and Klerksdorp there is up to 5° of angular discordance between the two Supergroups, while in still other localities Ventersdorp strata onlap older units and in places rest on the



Archean granite–greenstone basement. The Ventersdorp Supergroup exhibits rapid lateral facies variations, volcanic rocks that are bimodal in silica content, irregular basement topography and linear faulted basin margins. For these reasons we suggest that the Supergroup may have been deposited in a continental rift environment, and we here attempt to characterize the nature of this Archean continental rifting event by a review of the Ventersdorp history.

STRATIGRAPHY

In an analysis of outcrop and borehole data Winter (1976) devised a regionally correlatable lithostratigraphic classification of the Ventersdorp Supergroup. This work eliminated much previous confusion about the complex Ventersdorp stratigraphy, usually attributable to lack of good exposure, interfingering of lithologies, pinching out of units and progressive onlap of the Ventersdorp strata. Winter (1976) divided the nearly 8 km thickness of the Ventersdorp Supergroup into the Klipriviersberg Group, the Platberg Group and the overlying Bothaville and Allanridge Formations (Pniel Series of DuToit, 1907, p. 93). (See Fig. 2.)

Klipriviersberg Group

Rocks of the Klipriviersberg Group form the lowest part of the Ventersdorp Supergroup. The Group is a maximum of 1830 m thick (S.A.C.S., 1980), and consists of a monotonous sequence of alkali-rich tholeiitic flood basalts (Tankard et al., 1982) (Table 1). This group is correlated with the lower volcanic stage of the Orange Free State Goldfield (Winter, 1976), and is also well developed in the Cape Province, Transvaal and southeastern Botswana. From base to top the Klipriviersberg Group consists of the following six formations (Winter, 1976):

- (1) Westonaria Formation, with the local development of the Meredale Member at its base.
- (2) Alberton Porphyry Formation.
- (3) Orkney Formation.
- (4) Jeannette Agglomerate Formation.
- (5) Lorainne Formation.
- (6) Edenville Formation.

Fig. 1. Location, outcrop distribution and inferred sub-surface distribution of the Ventersdorp Supergroup. Much of the area to the northeast of the Ventersdorp structure has been intruded by the Bushveld complex (not shown), or is obscured by younger rocks. The crescent shape of Ventersdorp outcrops southwest of Pretoria is related to overturning of strata associated with the Vredefort impact. The high-grade Limpopo Province is inferred to extend under younger cover along the "Limpopo Gravity High" (map based on S.A.C.S., 1980; Tankard et al., 1982 and Pretorius, 1976).

Meredale Member

The Meredale Member of the Klipriviersberg Group is composed of a sequence of mafic komatiitic high Mg basalt flows alternating with more normal basaltic horizons that also have high Mg contents. The Meredale Member is well developed at the base of the Ventersdorp Supergroup in the vicinity of Johannesburg, while in other areas “talcoose tuffs” thought to represent paleosols developed from mafic rocks (Westonaria Formation) may be lateral equivalents of the Meredale Member (Cawthorn et al., 1979). The mineralogy of the basalts (summarized from McIver et al., 1981), consists essentially of stubby tremolite–actinolite laths in a chloritic

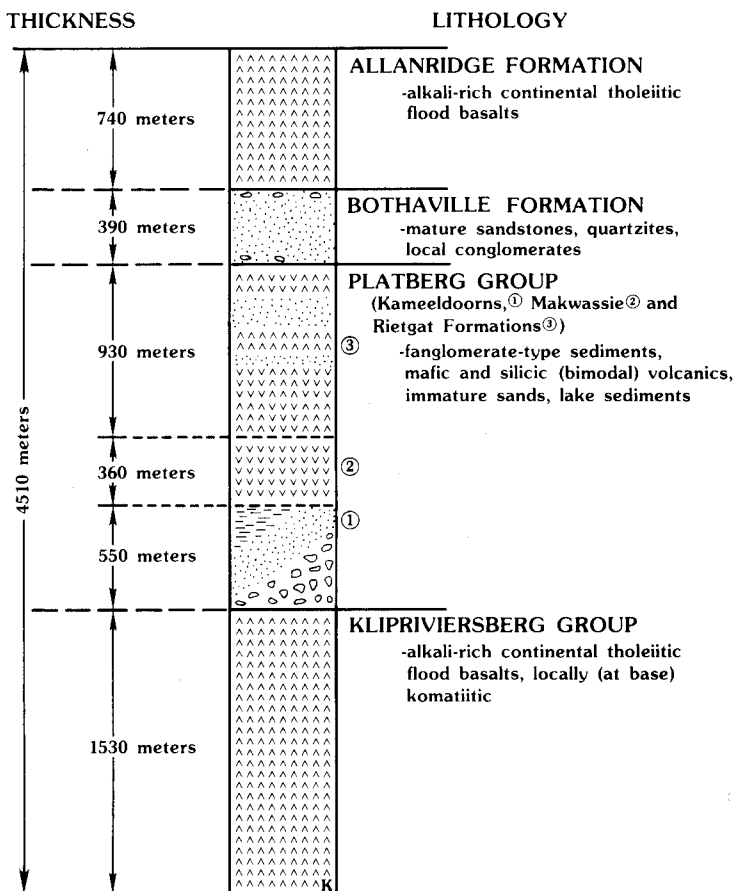


Fig. 2. Stratigraphic column of the Ventersdorp Supergroup from its type area near Bothaville showing many features which are typical of rift stratigraphy, including: immature basement derived sediments, rapid lateral facies variations and volcanic rocks that are bimodal in silica content (based on Winter, 1976 and S.A.C.S., 1980).

groundmass perhaps representing a devitrified glass. Accessory minerals include chlorite, clinozoisite, epidote and plagioclase microphenocrysts. Some acicular tremolite–actinolite needles in the groundmass have been suggested to have replaced original spinifex textured olivine or pyroxene needles, formed by the supercooling of komatiitic liquids (McIver et al., 1981; see their fig. 5.2).

Upper Klipriviersberg Group

Since the six formations that comprise the rest of the Klipriviersberg Group differ markedly only in their textures, lavas of the Westonaria, Alberton Porphyry, Orkney, Jeannette Agglomerate, Lorainne and Edenville Formations are here discussed together. These lava flows are commonly wedge shaped and of uneven thicknesses related to filling surface irregularities on underlying Witwatersrand strata. The Westonaria Formation is developed only in the deepest grabens, and overlying formations progressively onlap the rift margins. The remarkable chemical homogeneity (both lateral and vertical) of these basalts, coupled with the scarcity of

TABLE 1
Compositions of Ventersdorp Volcanic Rocks¹

Wt. %	Meredale Member					Klipriviersberg Group		Makwassie Formation		Allanridge Formation	
	1	2	3	4 ²	5 ³	6	7	8	9	10	11
SiO ₂	49.51	43.56	43.59	49.02	58.41	54.39	54.17	72.98	71.78	73.13	54.92
TiO ₂	1.03	1.00	1.02	1.04	0.93	1.07	0.81	0.43	0.46	0.46	1.22
Al ₂ O ₃	8.67	8.56	8.36	8.44	8.83	14.64	14.60	12.41	13.16	12.41	14.72
Fe ₂ O ₃	1.08	1.59	1.27	1.06	0.83	2.28	1.60	4.86	4.56	4.52	12.70
FeO	10.36	12.59	12.71	10.66	7.46	8.08	8.63	0.09	0.05	0.04	12.70
MnO	0.16	0.21	0.21	0.18	0.13	0.14	0.14	0.00	0.00	0.00	0.19
MgO	14.30	17.41	17.58	14.42	10.36	4.28	5.48	0.73	0.71	0.77	4.93
CaO	7.99	8.51	8.50	7.91	7.10	7.89	7.18	3.68	3.90	3.06	6.88
Na ₂ O	0.89	n.d.	n.d.	0.83	2.11	2.77	3.04	4.72	5.10	4.87	3.51
K ₂ O	0.31	0.01	0.04	0.18	0.11	1.83	1.47	0.10	0.11	0.20	0.68
P ₂ O ₅	0.21	0.22	0.21	0.21	0.18	0.18	0.19	0.37	0.45	0.16	0.27
H ₂ O ⁺	4.88	6.52	5.61	5.37	3.94	2.71	2.79	–	–	–	–
H ₂ O ⁻	0.11	0.14	0.18	0.11	0.06	0.05	0.04	0.37	0.45	0.16	–
Total	99.50	100.32	99.28	99.82	100.06	100.31	100.14	100.37	100.28	99.62	100.02
CaO:Al ₂ O ₃	0.92	0.99	1.02	0.93	0.80	0.54	0.49	–	–	–	0.47
Ppm											
Rb	3	n.d.	n.d.	1	2	67	50	–	–	–	12.4
Sr	67	34	33	90	103	466	274	–	–	–	311
Y	15	15	16	15	12	21	17	–	–	–	22.8
Zr	89	84	84	88	79	123	97	–	–	–	174
Nb	4	3	5	4	4	6.1	4.7	–	–	–	4.9
Cu	70	140	98	88	88	116	71	–	–	–	–
Ni	773	1301	1241	804	778	161	163	–	–	–	–
Zn	81	103	103	56	58	87	84	–	–	–	–
Cr	1876	1924	1982	1867	1674	157	1867	–	–	–	–
V	207	191	200	196	161	167	168	–	–	–	–
Ba	192	41	67	129	105	830	644	–	–	–	–

¹ Note that these rocks are bimodal in silica content, which is typical of volcanic rocks deposited in rifts. Analyses 1–7 from McIver et al. (1981), 4 = mean of eight analyses, 5 = mean of 3 analyses, 6 = mean of 12 analyses, 7 = mean of 14 analyses. Analyses 8, 9 and 10 from Tyler (1979) (his 92A, 93A and 94A). Analysis 11 from Tankard et al. (1982).

² Mean mafic.
³ Mean felsic.

interbedded sedimentary horizons suggests rapid effusion (Tyler, 1979). Faulting was contemporaneous with extrusion, as Tyler (1979) demonstrated in west central Transvaal for a thickened section of Klipriviersberg lavas interbedded with boulder conglomerate and basaltic breccia. Visser et al. (1976) describe angular granite pebble conglomerates and basement relief of up to 800 m from the lower Ventersdorp Supergroup (Fig. 3). In many areas of northern Cape Province the clastic wedges in these fault troughs were progressively rotated by up to 80° before deposition of the Bothaville Formation (Visser et al., 1976). Steepening of talus deposits next to basement horsts is consistent with the contention that fault activity

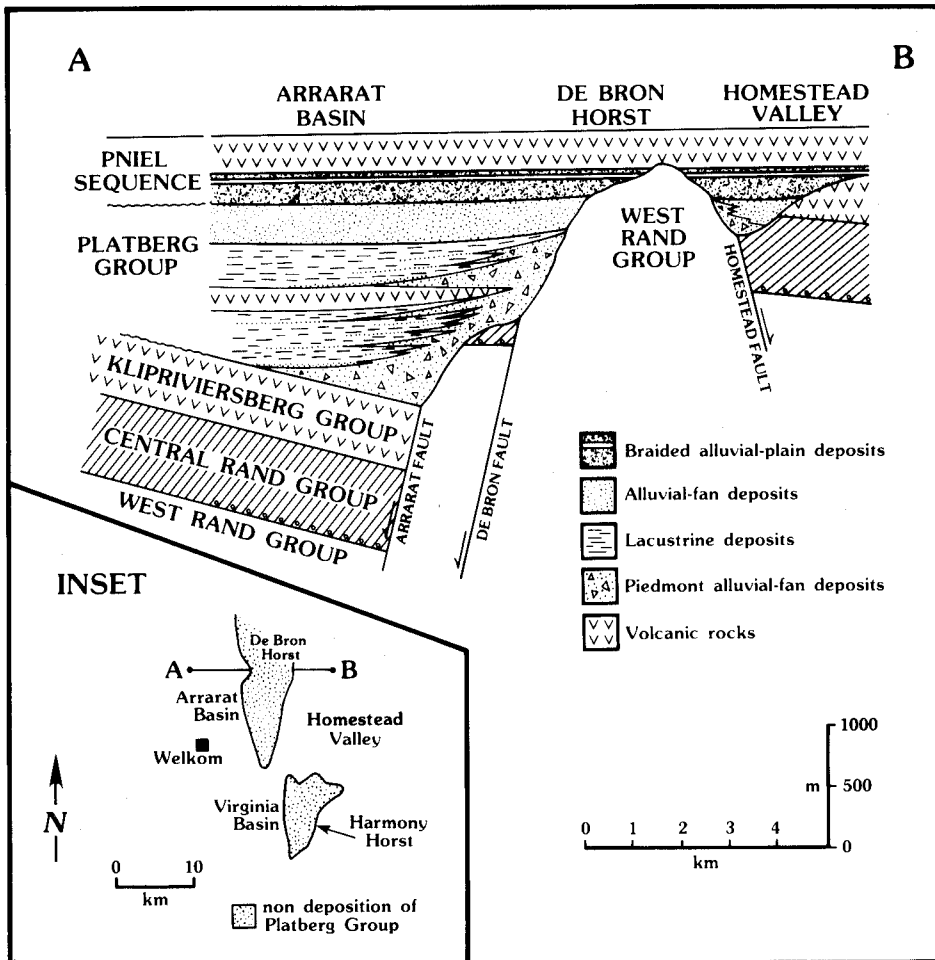


Fig. 3. Schematic cross-section of the Ventersdorp Supergroup across the De Bron Horst. Note the rapid lateral facies variations in the Platberg Group, the rotated attitude of the Klipriviersberg lavas with respect to overlying formations and the blanketing nature of the Pniel Sequence (Bothaville and Allanridge formations). After Buck (1980) and Tankard et al., (1982).

was contemporaneous with the deposition of the lower Ventersdorp Supergroup. The normal faults formed during this extensional episode may have served to localize eruptive centers of the Klipriviersberg lavas, as the flows are often thicker at, or confined to regions near these faults (Fig. 6). Crockett (1971b) has demonstrated that these flows were, at least locally, fed from gas blasted fissures.

Individual basalt flows within the Klipriviersberg Group may be porphyritic, amygdular (chert filled), or massive in texture although local agglomeratic horizons have been noted (S.A.C.S., 1980). Flow top breccias are commonly developed and volcaniclastic beds become increasingly more abundant towards the top of the group (Crockett, 1971). Mineralogically, the basalts are composed of a felted mass of calcic plagioclase microlites and subhedral clinopyroxene prisms, commonly altered to chlorite. Small magnetite grains are scattered throughout, and accessory minerals include quartz, chlorite, calcite and pyrite (Tyler, 1979). Some of the vugs in the basalt are filled with a mixture of quartz, calcite and radiating needles of fibrous pumpellyite, mantled by a cherty material containing chlorite and magnetite inclusions (Tyler, 1979).

The Klipriviersberg lavas show a remarkable chemical homogeneity both through their 2000 meter thickness and over a huge areal extent ($> 155,000 \text{ km}^2$). This, and the scarcity of explosive volcanics led Tyler (1979) to classify the Klipriviersberg lavas as flood basalts, an attribution which is supported by both chemical analyses (Table 1) and field relations. When compared to the "average" continental tholeiite, basalts of the Klipriviersberg Group appear to be enriched in K_2O and depleted in Al_2O_3 , although the K_2O enrichment may be attributed, at least in part, to later greenschist facies metamorphism. Wyatt (1976), noting the general low alumina, high total iron, intermediate Mg and low to intermediate silica content of the upper Klipriviersberg lavas described them as alkali-rich tholeiitic basalts.

Platberg Group

The Platberg Group represents an upward fining sequence of sediments and lavas, consisting of the Kameeldoorns, Makwassie and Rietgat Formations (Fig. 2). The Platberg Group rests conformably on the Klipriviersberg lavas in the central parts of the Ventersdorp Basin (Winter, 1976); elsewhere it lies on steeply dipping Witwatersrand strata or pre-Witwatersrand rocks.

The basal Kameeldoorns Formation (regarded as equivalent to the Klippan Formation of the Welkom Goldfield) was deposited mainly in fault troughs (S.A.C.S., 1980) and displays rapid lateral facies changes and complex interfingering of lithologies. The distribution and character of the Kameeldoorns sediments was determined by proximity to active (normal) fault scarps. Massive boulder conglomerates, talus breccias and debris flow deposits are concentrated near horst blocks, while lithologies typically grade laterally through arkoses and siltstones into lacustrine shales and carbonates, in some places less than 10 km away from the fault scarp (Winter, 1976). The boulder and cobble conglomerates range from chaotic

non-stratified clast supported wedges to matrix supported debris flow deposits containing subrounded to rounded clasts that frequently reach diameters of one meter. Clast and matrix lithologies strongly reflect the nature of the adjacent horst block; for example, in the New Kameeldoorns Graben conglomerates consist predominantly of fragments of Klipriviersberg volcanics clearly eroded from the adjacent horst (Winter, 1976). In areas where the adjacent horst block contains no earlier Ventersdorp strata the Kameeldoorns clast lithologies may also be correlated with the source area; for instance, near the Wesselbron "granitic arch" the conglomerates are arkosic, containing pebbles of mafic metavolcanics, graywacke and other pre-Ventersdorp metamorphic rock fragments (Hatch, 1903; Visser et al., 1976). In the vicinity of the Taljaardstam Fault conglomerates contain an increasing proportion of quartz arenite and shale pebbles towards the top of the formation, reflecting erosion through Ventersdorp lavas and into Witwatersrand strata in the adjacent horst block (Buck, 1980). All of these features are characteristic of modern day fanglomerate, talus scree and alluvial fan deposits, formed as wedges prograding into adjacent subsiding grabens.

Shales of the Kameeldoorns Formation are black, finely laminated and occur in siltstone–mudstone upward fining couplets generally less than 2 cm thick. They commonly display dessication cracks, ripple cross-laminations and shale intraclasts (Buck, 1980). Some of these lacustrine deposits contain laterally linked, low relief (< 5 cm) hemispheric stromatolites. Rare thick cross- and horizontally laminated oolite beds up to 2 m thick also occur in basin centers and on the sides of half grabens distal from fault scarps (Buck, 1980; and Fig. 4).

The Makwassie (Quartz Porphyry) Formation overlaps the Kameeldoorns Formation, progressively lapping onto the Klipriviersberg Group, Witwatersrand Supergroup and older Archean terranes. Although locally absent the formation has been described as over 2100 meters thick in the western Transvaal. However, the recognition of a thick pseudotachylite (?) zone separating similar lithologies (Winter, 1976, p. 42) suggests at least local repetition. Makwassie lithologies include abundant quartz porphyries, andesites, dacites, felsic ash flow tuffs, green-gray feldspar porphyritic lavas and non-porphyritic volcanics interbedded with sparse volcanoclastic conglomerates, coarse sands and flinty shales (Winter, 1976; Tankard et al., 1982), with the proportion of quartz porphyry to other lava types decreasing away from eruptive centers. Most of the eruptions that produced the Makwassie Formation were subaerial, as indicated by the numerous flow structures, agglomerates and graded tuffs, although some possible pillow lavas (Winter, 1976) suggest that subaqueous volcanism occurred as well. Massive to granular porphyritic and variolitic felsites of rhyolite composition occur interbedded with volcanoclastic sediments over a large area in the Transvaal (Tyler, 1979; Tankard et al., 1982). Sometimes these pyroclastic units that are correlated with the Makwassie Formation display an extensive layer with 15 cm lithic (porphyritic felsite) clasts, fragments of older lithic units and bands of bipolar fusiform lapilli (Tyler, 1979). Agglomerates of the

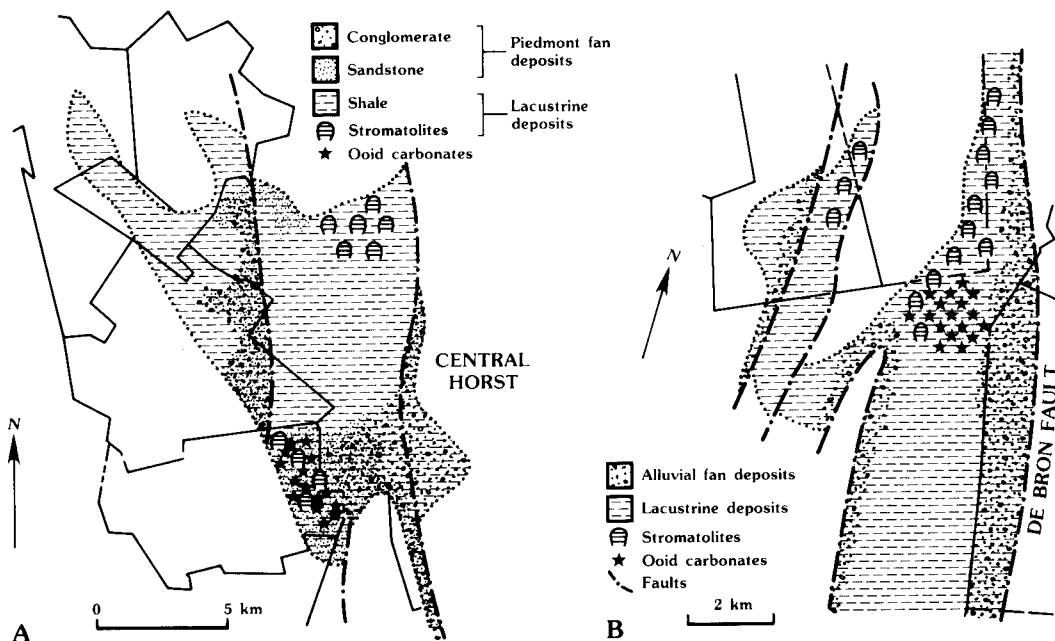


Fig. 4. Facies distribution for the lower Platberg Group in the vicinity of the De Bron Horst (from Buck, 1980). Note the fanglomerate deposits bounding major faults and the rapid transition into lacustrine deposits in basin centers. (A) is for the Arrarat Basin, and (B) is for the Virginia Basin. Inset in Fig. 3 for location.

Makwassie Formation are of two kinds; the first displays no stratification and consists essentially of ill-sorted angular blocks of siliceous volcanic material contained in a fine-grained matrix. This type is considered to have originated from an explosive vent (Tyler, 1979). The second type of agglomerate is composed of "chaotic, subrounded heterolithologic clasts in a schistose shaley matrix" (Tyler, 1979, p. 142), and may represent a laharc breccia. Crockett (1971) has noted that the explosive agglomerates were confined to volcanic vents (usually less than 10 m in diameter and cutting through older formations) during the early stages of Makwassie volcanism, and that the style of volcanic activity changed from these early vertical eruptions to horizontally directed eruptions in the later stages of Makwassie effusion, which spread agglomerates over larger areas. Geochemically, the Makwassie felsites roughly correspond to a rhyolitic composition (Table 1) except that they appear to be highly potassic and relatively deficient in Na_2O , MgO and CaO . The apparent Na_2O deficiency has been considered a result of alteration (Tyler, 1979).

Sedimentary rocks of the Makwassie Formation are typically very immature poorly sorted packages of arkosic or volcanoclastic debris. In the western Transvaal a 300 m thick lens of coarse, ill-sorted, poorly packed volcanoclastic conglomerates and sandstones accumulated as an upward fining series of channel-lag and point-bar deposits (Tyler, 1979).

The top of the Makwassie Formation grades into the basal (Garfield) member of the mixed volcanosedimentary Rietgat Formation, which may be up to 1300 m thick (S.A.C.S., 1980). Greenish-gray “andesitic” to dacitic lavas of the Rietgat Formation are usually porphyritic to extremely porphyritic, with short and lath-like feldspar phenocrysts (Winter, 1976). Many individual flows show flattened pumiceous lava tops and contain red chalcedony nodules. The proportion of sediments to lavas increases stratigraphically upward toward the overlying Bothaville Formation, which is entirely sedimentary. Sediments of the Rietgat Formation are similar to those in the Kameeldoorns and Makwassie Formations, except that the Rietgat Formation does not contain great thicknesses of coarse clastic debris (Winter, 1976). Thin breccia, talus scree and debris flow deposits commonly flank horst blocks and contain identifiable well rounded cobbles of Witwatersrand strata (Buck, 1980). Where the horsts are granitic the sediments are arkosic (Visser et al., 1976). These deposits grade laterally into graywackes, sandstones and impure lacustrine limestones that locally contain small stromatolites (Buck, 1980). Episodes of non-deposition, minor erosion and oxidation are recorded in a strong alteration of many lava flow tops, especially stratigraphically high in the formation (Winter, 1976).

In summary, sporadic ephemeral fluvial activity rapidly transported and deposited Rietgat sediments into coalescing alluvial fans that filled the basins and valleys developed by normal faulting of older strata. The formation progressively onlapped these horst blocks as they became deeply eroded (Buck, 1980), and the topographic difference between them and the grabens decreased (Fig. 5), implying the cessation or waning of fault activity during deposition of the Rietgat Formation.

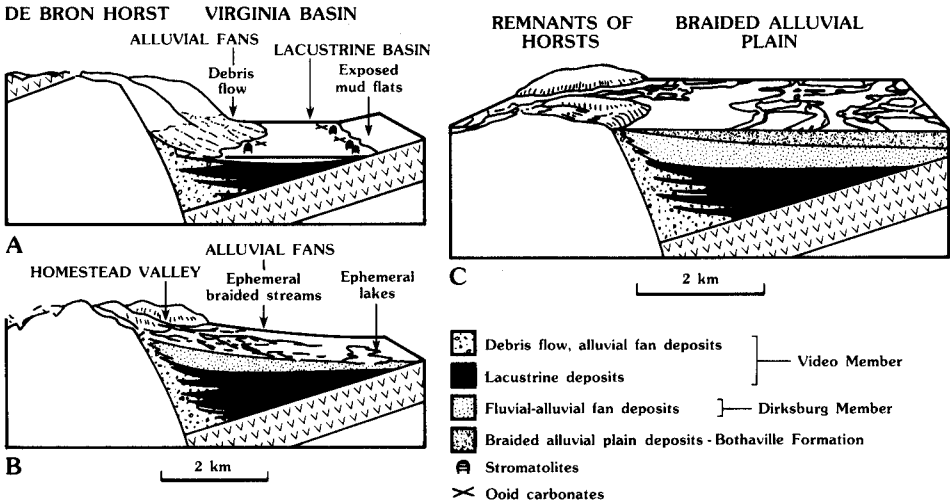


Fig. 5. Schematic paleoenvironmental reconstructions of the lower Platberg Group (A), upper Platberg Group (B), and Bothaville Formation (C). Note the gradual erosion of horst blocks and filling of grabens suggesting decreasing activity on faults during deposition of the upper Platberg Group. (From Buck, 1980.)

Bothaville Formation

The Bothaville Formation is approximately 430 m thick and rests conformably on the Rietgat Formation in its type area (Winter, 1976; S.A.C.S., 1980). However, in numerous other localities sediments of the Bothaville Formation unconformably onlap older Ventersdorp strata, Witwatersrand rocks or the Archean basement. The Bothaville Formation contains the most mature sediments of the Ventersdorp succession and differs markedly from rocks of the underlying formations as it is not characterized by the rapid facies changes typical of the Platberg Group and occurs in a fairly constant thickness over a relatively large area. It is interpreted as having been deposited on gently undulating plains.

A poorly sorted conglomerate containing well rounded pebbles of jasper, chert and (Makwassie) quartz porphyry lies at the base of the Bothaville Formation. The conglomerate is interbedded with quartzites, shales and stromatolitic limestone which give way to a upward fining sequence containing graded beds of siltstone, mudstone and sandstone of subarkose to subgraywacke composition (Winter, 1976). Sand bodies throughout the formation are lenticular in form, displaying shale drapes, shale intraclasts and low-angle cross-stratification indicating unimodal to trimodal current directions (Visser et al., 1976). The shales are usually planar bedded, often displaying dessication cracks and local stromatolites (Buck, 1980). This sequence contains another conglomeratic horizon near the top of the Formation.

The Bothaville Formation is interpreted to have been deposited by a southward flowing (present coordinates) braided and meandering stream network on an alluvial plain experiencing a marine transgression from the south and southeast (Visser et al., 1976; Tyler, 1979; Buck, 1980). The Bothaville sands appear to have been deposited and reworked in beach and shallow neritic environments, accumulating by the landward migration of sand bars. Variations in the amount and maturity of clastic debris shed into the Bothaville Basin could reflect shifting fan loci and variable river discharge related to climatic variation (Buck, 1980; Tankard et al., 1982).

Allanridge Formation

Extrusion of the Allanridge lavas abruptly terminated deposition of the Bothaville sediments. The Allanridge Formation which is up to 740 m thick (S.A.C.S., 1980) was laid down conformably on top of and overlaps the outcrop limits of the Bothaville Formation. It consists of a monotonous sequence of lavas ranging from tholeiitic flood basalts to andesitic flows (Table 1). The flows typically have a dark green-gray color, numerous amygdules, and are very fine grained. Porphyritic zones with acicular feldspar phenocrysts alternate with non-porphyritic zones (Winter, 1976) and the presence of pillow lavas in the lower part of the formation demonstrates the subaqueous nature of these flows (Visser et al., 1976). Although a few

early eruptions deposited relatively minor volcanic breccias and tuffs most of the volcanism was probably of a rapid and quiet effusive nature, as suggested by the lack of interbedded sedimentary horizons, the thickness (750 m) and uniformity of flows over large areas and the scarcity of pyroclastic deposits. The flows were most likely fissure fed (Visser et al., 1976) and are quite similar to the flood basalts of the Klipriviersberg Group.

TECTONIC SIGNIFICANCE OF VENTERSDORP VOLCANICS AND SEDIMENTS

Nature of the Klipriviersberg Group

Klipriviersberg lavas demonstrate remarkable chemical homogeneity, both laterally and vertically. Their substantial thickness (1830 m), wide distribution and bulk composition all strongly resemble more recent continental flood basalts. The Klipriviersberg lavas bear many similarities to alkalic magmas erupted in continental areas that have experienced lithospheric extension. Examples include the East African Rifts, Rhine Graben of western Germany, the Oslo Graben of Norway and the Cenozoic Basin and Range Province of the western United States (Basaltic Volcanism Study Project 1981). Continental basalts associated with rifting often have a quartz-tholeiite composition, which is consistent with the chemistry of the Klipriviersberg lavas (Table 1).

The komatiitic nature of the lower Meredale Member suggests that these lavas were derived directly from large amounts of partial melting in the mantle. The vast thickness and scarcity of sedimentary horizons in the Klipriviersberg Group is suggestive of considerable extension. Evidence was cited above demonstrating that extensional faulting did accompany extrusion of the Klipriviersberg flood basalts and it is therefore suggested that they represent a mantle-derived early rifting phase of volcanism in the Ventersdorp Province. The upper Klipriviersberg tholeiites could have formed by fractionation of liquids having a composition similar to the basal Meredale Member, as indicated by A-F-M plots of Ventersdorp volcanics and variation diagrams in McIver et al. (1981).

Nature of the Platberg Group

The Platberg Group consists essentially of silicic pyroclastic and volcanic rocks interdigitated with very immature locally derived sediments. These were rapidly deposited in linear fault troughs that evidently became active near the end of the extrusion of the Klipriviersberg flood basalts. Although some of these basin margin faults may have been active throughout the extrusion of the Klipriviersberg lavas, the enormous thickness and abundance of coarse talus deposits in the Platberg Group suggests increased faulting during this time. The faulting appears to have virtually ceased by the end of Platberg deposition, as the elevation of the horst

blocks was diminished by erosion, and the coarse locally derived sediments and pyroclastics of the Platberg Group gradually graded up into more mature recycled sediments, ultimately forming the entirely sedimentary Bothaville Formation. Sediments of the Platberg Group as a whole fine upward, also suggesting that most of the faulting activity occurred early. Sedimentary facies similar to those of the Platberg Group, typically grading from fanglomerates to fine lacustrine deposits over short distances, are characteristic of many rift valley provinces of today (Kinsman, 1975).

We suggest that the Platberg Group was deposited in grabens during the rapid initial subsidence phase of the Ventersdorp Rift System. The nature of volcanism in the Ventersdorp Rift Province changed from quartz-tholeiitic flood lava extrusion to silicic quartz porphyry and ignimbrite eruption (Makwassie Formation) at a time corresponding to an episode of increased faulting. A similar change in the style of volcanism with the onset of graben formation (tholeiitic basalt to quartz porphyry rhyolites) in the Oslo Graben of Norway was noted by Williams (1982).

Nature of the Bothaville Formation

In comparison with other formations of the Ventersdorp Supergroup, sediments of the Bothaville Formation are highly mature and were deposited over relatively subdued topography. The Bothaville Formation lacks volcanics, drapes over the outcrop limits of older formations and its deposition was not influenced by faulting. The geometry and nature of the Bothaville Formation therefore conforms to the upper part of the "Steer's Head Condition" (Burke, 1979) characteristic of the thermal phase of subsidence in rifts (Fig. 6). Sediments formed during this phase are a response to the recovery and sinking of mantle isotherms, with a concomitant conductive heat loss and increase in density of the lithosphere. Subsidence (and hence, deposition) during this phase is likely to be slower than during the rapid initial subsidence phase (McKenzie, 1978), favoring sediments reworking, and therefore, increased maturity compared to sediments deposited during the initial or stretching phase of subsidence. Sediments of the Rietgat Formation become interbedded with fewer volcanics and become more mature upward as they grade into the overlying Bothaville Formation, suggesting that the transition from initial to thermal subsidence was gradual. It also appears that the deposition of these thermal subsidence phase sediments was abruptly terminated by the extrusion of the Allanridge lavas.

Nature of the Allanridge Formation

Lavas of the Allanridge Formation were quietly extruded in both subaerial and subaquatic environments. Their chemistry, morphology and wide distribution suggest that they are continental flood lavas. There is a striking similarity between the

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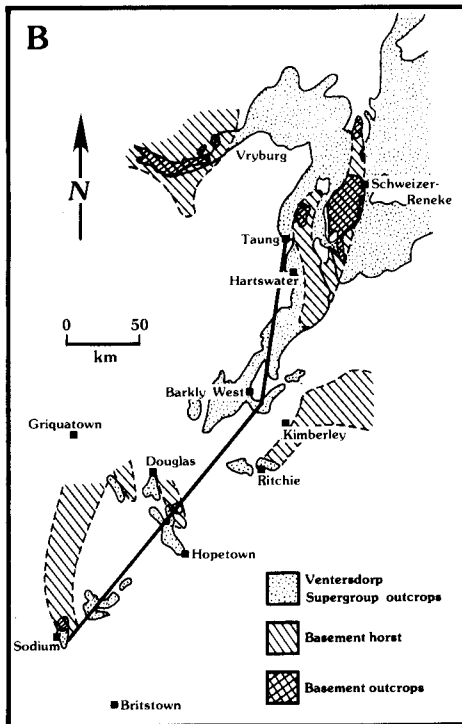
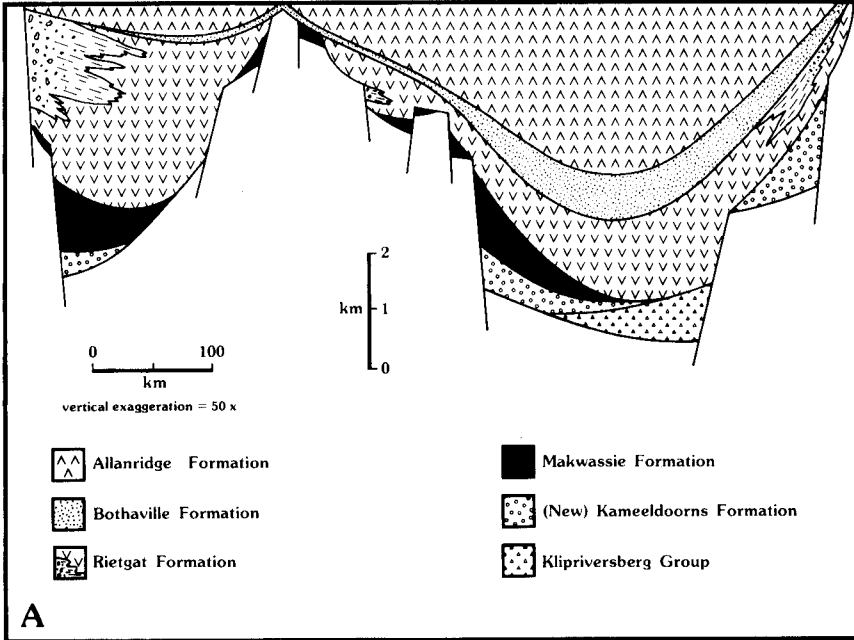


Fig. 6. A. Schematic cross section of the Ventersdorp structure between Sodium and Taung (from Visser et al., 1976). Note the draping of the Bothaville Formation, forming the "steer's head" geometry which is typical of the thermal subsidence phase of rift development (Burke, 1979). B. Location of the cross section, as well as basement horsts in the Ventersdorp Rift System.

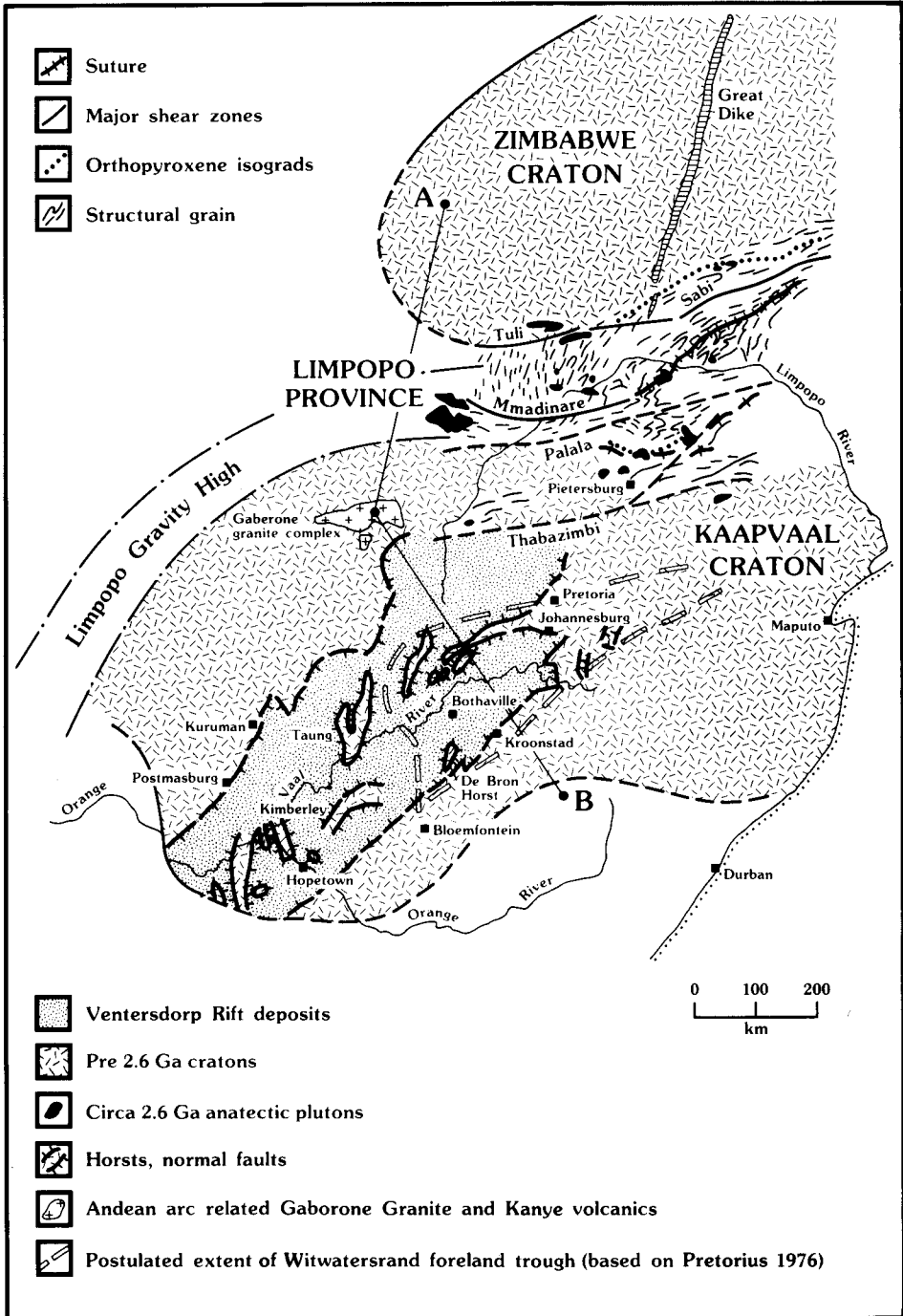
Klipriviersberg and Allanridge lavas, with the exception that the Allanridge basalts usually contain more feldspar phenocrysts of andesine composition (Visser et al., 1976; Winter, 1976). The Allanridge Formation appears to represent a renewed rifting event in the Ventersdorp Rift Province which disrupted the deposition of sediments of a wide spread thermal subsidence phase.

Age of the Ventersdorp Structure

Isotopic age determinations on rocks of the Ventersdorp Supergroup have yielded an array of ages ranging from 1920 ± 100 Ma (Rb–Sr whole rock; Cornell, 1978) to greater than 2.6 Ga, with most ages clustering around 2.3 and 2.6 Ga. This large spread of dates is attributed to the homogenization of the strontium isotopic system at 1970 ± 100 Ma (Cornell, 1978), which occurred during intense metasomatism related to a thermal pulse associated with the Bushveld intrusion and/or burial metamorphism under the thick Transvaal sequence (see below). Strontium isotope homogenization appears to have occurred on a scale of tens of meters (Cornell, 1978), rendering the interpretation of Rb–Sr age determinations difficult at best. However, a reliable age for the Ventersdorp Group has been obtained by Van Niekerk and Burger (1978), using the U–Pb isotopic system, the analytical techniques of Krogh (1973), and decay constants of Steiger and Jager (1977). These authors made measurements on zircon phenocrysts extracted from rocks of the Makwassie Formation at widely separated (330 km) sample localities. An age of 2643 ± 80 Ma (quoted 95% confidence level) is indicated by data that do not show recent bulk lead loss, although Van Niekerk and Burger's (1978) quoted uncertainty is certainly smaller than their data justifies. This age is indistinguishable from an earlier Rb–Sr whole rock date (recalculated) of 2638 ± 125 Ma reported by Crockett (1971b). A date of approximately 2.64 Ga is therefore accepted as the age of eruption and deposition of the Ventersdorp Supergroup.

Metamorphism

The Ventersdorp Supergroup has been metamorphosed to the lower greenschist facies although it lacks a penetrative deformation fabric (Tankard et al., 1982). The greenschist facies is characterized by the ubiquitous mineral assemblage albite–chlorite–actinolite–zoisite (Cornell, 1978; Winkler, 1979). In metabasites the mineral assemblage is commonly albite–epidote–quartz–chlorite–biotite–sphene–muscovite–actinolite, also characteristic of lower greenschist facies metamorphism. Based on oxygen isotope geothermometry Cornell (1978) estimated that the temperature of metamorphism was 200° – 400° C, and because of the lack of oriented fabrics and penetrative deformation he suggested the alteration was caused by burial metamorphism (cf. Miyashiro, 1973). The pressure required by the mineral parageneses suggest burial to a depth of six km (Cornell, 1978). The burial metamorphism was



associated with severe metasomatic alteration of the Ventersdorp rocks with a corresponding large scale (up to tens of meters) migration of the more mobile elements, and a complete resetting of the strontium isotopic system. A Rb–Sr whole rock isochron obtained from Ventersdorp rocks (Cornell, 1978) defines the time of this event as 1920 ± 100 Ma, roughly corresponding to the age of the Bushveld event, which occurred while the Ventersdorp rocks were buried under the thick Transvaal sequence. The metasomatic alteration is also suggested to have caused the anomalously low sodium content of some of the Ventersdorp rocks (Cornell, 1978).

KANYE VOLCANIC GROUP AND THE GABERONE GRANITE COMPLEX

The Gaberone Granite Complex and the Kanye Volcanic Group occur in the northern outcrop areas of the Ventersdorp Supergroup (Fig. 7), although the poor exposure has generally obscured their contact relationships with the Ventersdorp rocks. Tyler (1979) has suggested that the Ventersdorp rocks rest non-conformably on both the Kanye volcanics and the Gaberone Granite, while Key and Wright (1982) consider the Gaberone complex to be intrusive into the Ventersdorp rocks and possibly even the much younger (circa 2.3 Ga) Transvaal Supergroup.

The Kanye volcanics are calc-alkaline and consist of silicic agglomerates, massive red and blue felsites which contain occasional varioles, and are dacitic to rhyolitic in composition (Tyler, 1979). The wide range of reported Rb–Sr ages for the Kanye volcanics (1.8–3.4 Ga, Key, 1976; Tyler, 1979) emphasizes the confusion regarding their “true age”; however, a sericitic paleosol horizon occurs between rocks of the Kanye volcanic Group and the Ventersdorp Supergroup, suggesting subaerial weathering between eruption of the Kanye and Ventersdorp volcanics (Tyler, 1979).

The Gaberone Granite contains a core of rapikivi granite that is surrounded by leucocratic granite and porphyritic microgranite, and intrudes the Kanye Volcanic Group (Boocock, 1959; Crockett, 1971; Poldervaart, 1952; Key and Wright, 1982). It has yielded a Rb–Sr whole rock isochron of 2394 ± 26 Ma with an R_i of 0.74991 ± 0.00643 (Key and Wright, 1982), but dating of the Gaberone Granite Complex has proved enigmatic in the past, with reported Rb–Sr isochrons ranging from 2328 Ma (recalculated using decay constants of Harding et al., 1974; Steiger and Jager, 1977) to 2690 ± 75 Ma (Key, 1976).

Fig. 7. The Ventersdorp Rift System of the Kaapvaal Craton showing basement horsts, which along with the rift margins, strike at a high angle into the Limpopo continental collisional zone. Because the collision between the Kaapvaal and Zimbabwe Cratons and the formation of the Ventersdorp Rifts occurred synchronously (at approximately 2.64 Ga), we suggest that the Ventersdorp structures are impactogens. Numerous anatectic plutons of a similar age occur throughout the continental zone and are perhaps related to crustal thickening following collision. Limpopo style rocks do not outcrop along the northwestern part of the Kaapvaal Craton but are obscured by younger sequences. We interpret the Limpopo Gravity High (Pretorius, 1976), as indicating that they extend into this area. This map is based on data compiled from Tankard et al. (1982); Visser et al. (1976); DuToit et al. (1983); Pretorius (1976); Button (1981).

Following DuToit (1946) we suggest a possible relationship between the Dominion Reef volcanics and Kanye volcanism. We interpret both as products of Andean-type arc magmatism. Key and Wright (1982) and Tyler (1979) have identified the Kanye magmatism with that of the Gaborone Complex, and this seems compatible with our Andean interpretation. Rb/Sr whole rock ages were considered by Key and Wright to yield a younger age of about 2.4 Ga. If this result is confirmed by, for example, new zircon ages then our preferred hypothesis is invalid and the Gaborone Granite and Kanye volcanism are unrelated to the closure of the Limpopo Ocean (> 2.6 Ga and before the intrusion of the Great Dike).

THE LIMPOPO PROVINCE AS A CONTINENTAL COLLISION ZONE AND ITS RELATION TO VENTERSDORP RIFTING

The Limpopo Province contains some of the oldest rocks so far recognized on earth and has evidently experienced a complex and varied history prior to involvement in the suturing of the Kaapvaal and Zimbabwe Cratons. The collision appears to have been between an Atlantic-type margin developed on the southern (present coordinates) margin of the Zimbabwe Craton and an Andean-type margin developed on the Kaapvaal Craton side of the closing Limpopo Ocean. Following Dewey and Burke (1973) Light (1982) has identified the suture between the two cratons as a distinctive east-northeast trending line of sheared amphibolitic and peridotitic gneisses associated with schistose fuchsitic quartzites, aplitic riebeckite gneisses and granulites (Figs. 7 and 8). North of the line of the proposed suture is a belt of thrusts and nappes which emplaced greenstones of oceanic affinity over carbonate shelf facies rocks of the Beitbridge Group resting on the Craton (Fig. 8; Stowe, 1974; Light, 1982; Kidd, 1984; Eriksson and Kidd, in prep.). The Limpopo Province contains many major subvertical horizontally lineated shear zones, including the Tuli-Sabi, Mmadinare, Palala and Thabazimbi faults (Fig. 7) (Kidd, 1984). Collision related sinistral motion accommodating hundreds of kilometers of displacement has been suggested for some of these faults (Tankard et al., 1982). However, some possible dextral motion (Kidd, 1984) may involve an episode of strike-slip faulting different from that concurrent with the formation of the Ventersdorp rifts. The orientation of Ventersdorp rifts indicates sinistral motion on associated northeast trending shear zones (Fig. 7).

Metamorphic mineral assemblages from the central Limpopo Province indicated burial to greater than 30 km (Light, 1982), implying double crustal thickness at peak metamorphism (Kidd, 1984) consistent with the continental collision model set forth by Dewey and Burke (1973). The peak metamorphic/deformational event (2.7–2.6 Ga, Tankard et al., 1982) was associated with the intrusion of a large amount of syn-tectonic anatectic granites, including the Bulai Gneiss, Razi Granites, the Matok Pluton and numerous small bodies intruding the Baviaanskloof Gneiss (Robertson,

1973a, b; Light, 1982). DuToit et al. (1983) have shown that the Matok Pluton is cut by sinistral strike-slip faults.

Discussion

The Ventersdorp Supergroup was deposited in a complex rift system approximately 2.64 Ga ago. The development of this rift system closely resembled that of rifts which have formed more recently in the earth's history. Because rifts form in many tectonic environments in which the lithosphere is put into extension it is important to attempt to characterize the environment in which individual rifts form more fully. Collisional rifts are most numerous in the Phanerozoic and we here show that the Ventersdorp rifts were also associated with collision.

We have postulated elsewhere (Burke et al., in prep) that the Witwatersrand Supergroup was deposited in a foreland basin (c.f. Jordan, 1981) developed on the continental side of a complex Andean arc. This Andean margin of the Kaapvaal Craton collided with the Atlantic-type margin of the Zimbabwe Craton approximately 2.64 Ga ago, forming the Tibetan style Limpopo Province (Burke and Dewey, 1972; 1973; Dewey and Burke, 1973; Burke et al., 1976; Van Biljon, 1977; Light, 1982). The timing of the Kaapvaal–Zimbabwe continental collision is constrained between the age of the 2.7 Ga old “Bulawayan” greenstones and metasediments involved in the collision, and the 2.6 Ga old post-tectonic Chibi granite suite (Tankard et al., 1982). Barton et al., (1979) have reported ages of $2649 \pm 82\text{--}88$ Ma (Pb–Pb whole rock) and 2693 ± 45 Ma (Rb–Sr whole rock) from the syn-tectonic (their D2–D3) Bulai gneiss from the central zone of the Limpopo Province. Furthermore, the suturing occurred before 2.5 Ga, the age of the Great Dike of Zimbabwe (Nisbet, 1982), which intrudes the Limpopo Province (Fig. 7).

DuToit et al. (1983) and Tankard et al. (1982) have emphasized that the Limpopo zone is associated with a large amount of left lateral strike-slip faulting and anatectic granites (Fig. 7). We link these sideways motion on major strike-slip faults and anatexis related to crustal thickening following collision. The large amount of strike-slip faulting associated with this collision (Fig. 7) leads us to suggest that the contemporary Ventersdorp rifting occurred in a zone of “imperfect strike-slip faulting” associated with the collision, similar in a way to formation of the Basin and Range Province of the western United States (Şengör and Burke, 1978).

In summary

We suggest that the Ventersdorp Structure is impactogenal (cf. Şengör et al., 1978) because the Ventersdorp Rifts strike at a high angle into the Limpopo continental collision zone and because the age of the Ventersdorp rifting is indistinguishable from that of the suturing of the Kaapvaal and Zimbabwe Cratons. Analogous structures are forming at the present time in China and elsewhere in Asia

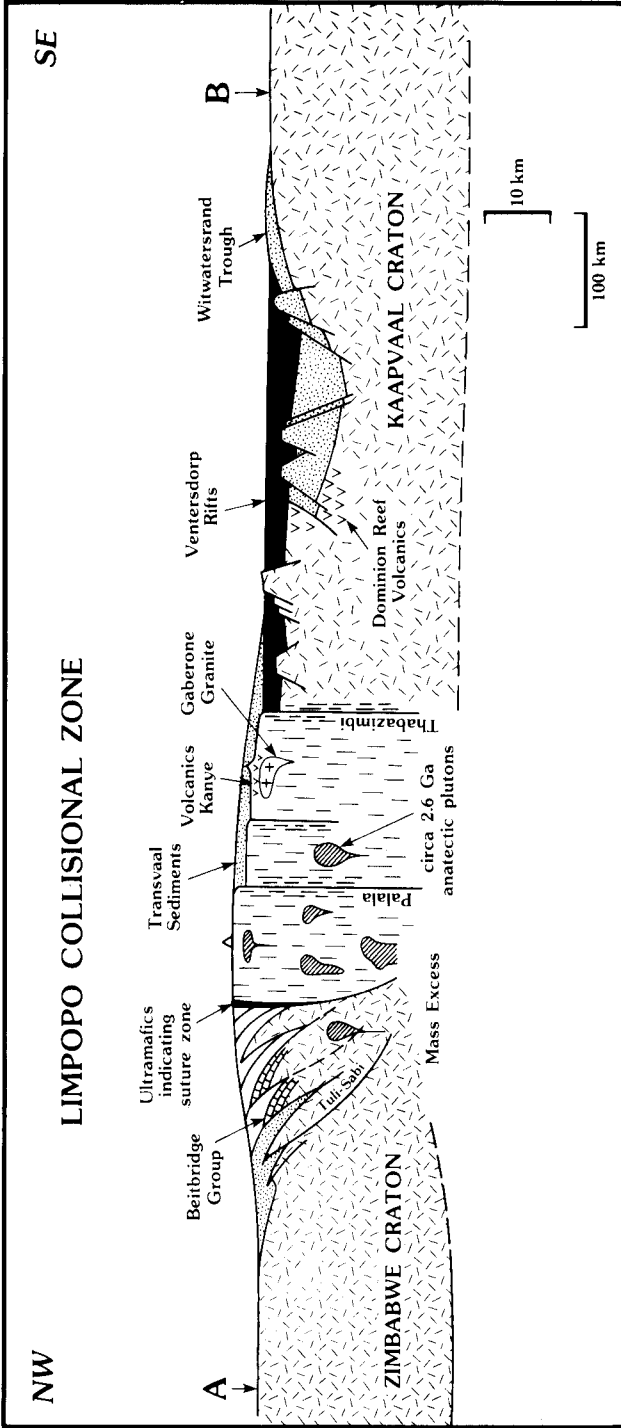


Fig. 8. Cross section (A–B) through the Zimbabwe and Kaapvaal Cratons across the Limpopo Province (Fig. 7), which is interpreted as the product of continental collision. The circa 2.64 Ga collision was between an Atlantic-type margin on the Rhodesian Craton (the Beitbridge Group represents the highly deformed remnants of the carbonate shelf; Kidd, 1984), and an Andean-type margin formed on the Kaapvaal Craton. The Witwatersrand Supergroup was deposited in a foreland trough behind this Andean arc, which is represented by the Kanye volcanics and the Gaborone Granite, as well as by the Dominion Reef lavas, which we correlate with the Kanye volcanics. The Ventersdorp Rifts strike at high angles into the Limpopo collisional zone (see Fig. 7), and are here interpreted as impactogens accommodating extension in a zone of imperfect left-lateral strike-slip faulting induced by the collision.

(for example; the Shansi Grabens and the Baikal Rift System) in response to the contemporary India–Asia continental collision (Molnar and Tapponnier, 1975). The deep erosional level (> 30 km) offered by the Limpopo collision zone could provide some useful insights about the processes currently occurring at inaccessible depths below the surface of Tibet and through much of Asia.

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