Deconstructing the Transvaal Supergroup, South Africa: implications for Palaeoproterozoic palaeoclimate models

John M. Moore, Harilaos Tsikos and Stefane Polteau

Geology Department, Rhodes University, Grahamstown 6140, South Africa

Department of Earth Sciences, University of Oxford, Parks Road, OX1 3PR, United Kingdom

Abstract

Current correlations between the Pretoria and Postmasburg Groups of the Transvaal Supergroup are shown to be invalid. The Postmasburg Group is also demonstrated to be broadly conformable with the underlying Ghaap Group and therefore considerably older (~2.4 Ga) than previously supposed. The new stratigraphy documents an extensive (100 Ma) and continuous cold-climate episode with a glacial maximum at the Makganyene Formation diamictite. Iron formations of the underlying Asbesheuwels and Koegas Subgroups and overlying Hotazel Formation have similar origins, related, respectively, to the onset and cessation of the glacial event. This interpretation of the Transvaal Supergroup stratigraphy has significant implications for various Palaeoproterozoic environmental models and for the timing of the development of an oxygenated atmosphere.

Keywords: Glacial palaeoclimate; stratigraphy; Neoarchaean-Palaeoproterozoic; Transvaal Supergroup; paleoatmosphere; paleoclimate; Proterozoic; stratigraphic correlation; South Africa

1. Introduction

The Transvaal Supergroup is an end-Archaean/earliest Proterozoic platform succession developed on the Kaapvaal Craton, spanning the approximate period of 2.65–2.05 Ga. It contains three unconformity-bounded sequences (Cheney, 1996) that are preserved and exposed in two geographically separate areas – the Transvaal basin, where it circumscribes the Bushveld Complex, and the Griqualand West basin at the western Kaapvaal margin, that extends into southern Botswana beneath Kalahari cover as the Kanye basin (Fig. 1). The two basins are separated by a broad basement high, referred to as the Vryburg arch.

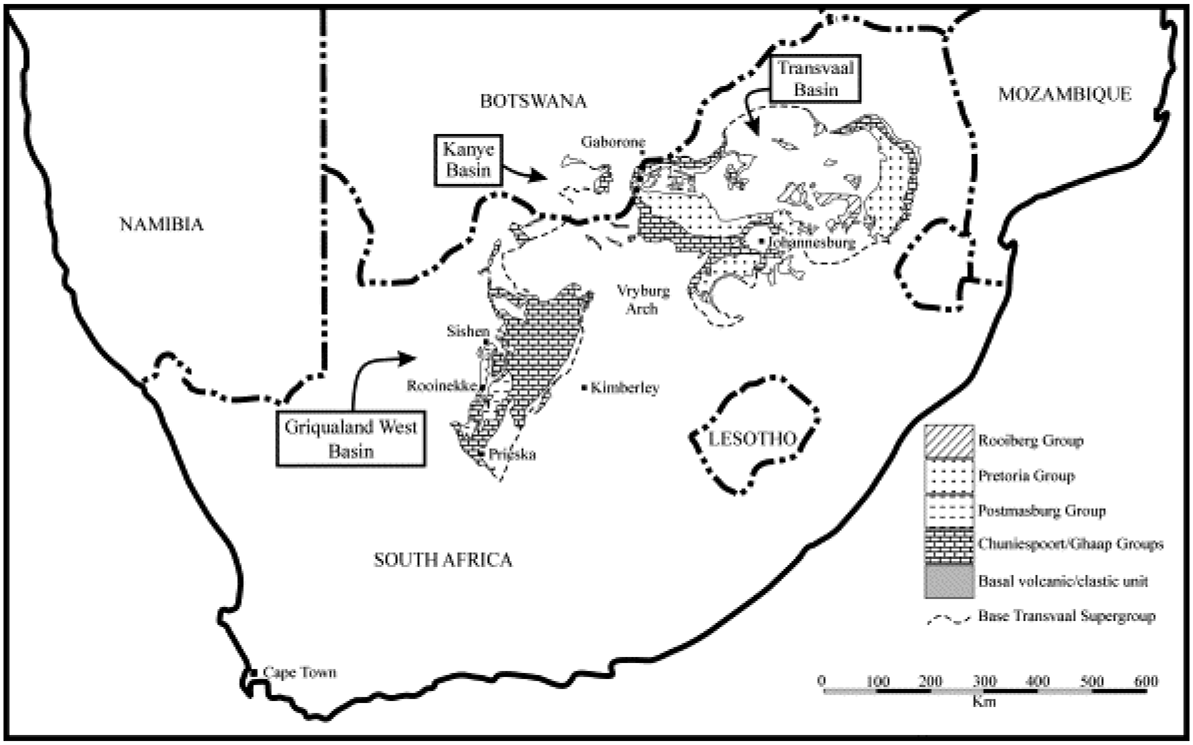

Fig. 1. Locality map, showing the distribution of the major subdivisions of the Transvaal Supergroup within the Transvaal, Griqualand West and Kanye basins in South Africa and southern Botswana.

In this threefold subdivision of the Transvaal Supergroup, the lowermost sequences (eastern Chuniespoort Group, western Ghaap Group), typified by basal quartz arenites, a thick succession of dolomites and upper iron formations, are most widespread and easily correlated across the two basins (Fig. 2). The middle sequence is represented in both the Transvaal (Pretoria Group) and Griqualand West (Postmasburg Group) basins, and the uppermost volcanic-dominated sequence (Rooiberg Group) is restricted to the Transvaal basin (Eriksson et al., 1993 and Eriksson et al., 1995). Whilst correlations within the lowermost and uppermost sequences are well constrained stratigraphically and geochronologically, those within the central sequence are not so, as the lithologies in the two basins are very different in nature. This paper provides a comparison between the Pretoria and Postmasburg Groups, and presents arguments that question the existence of a middle sequence in the main Griqualand West basin, restricting it, like its successor, the Rooiberg Group, to the Transvaal basin and southern Botswana.

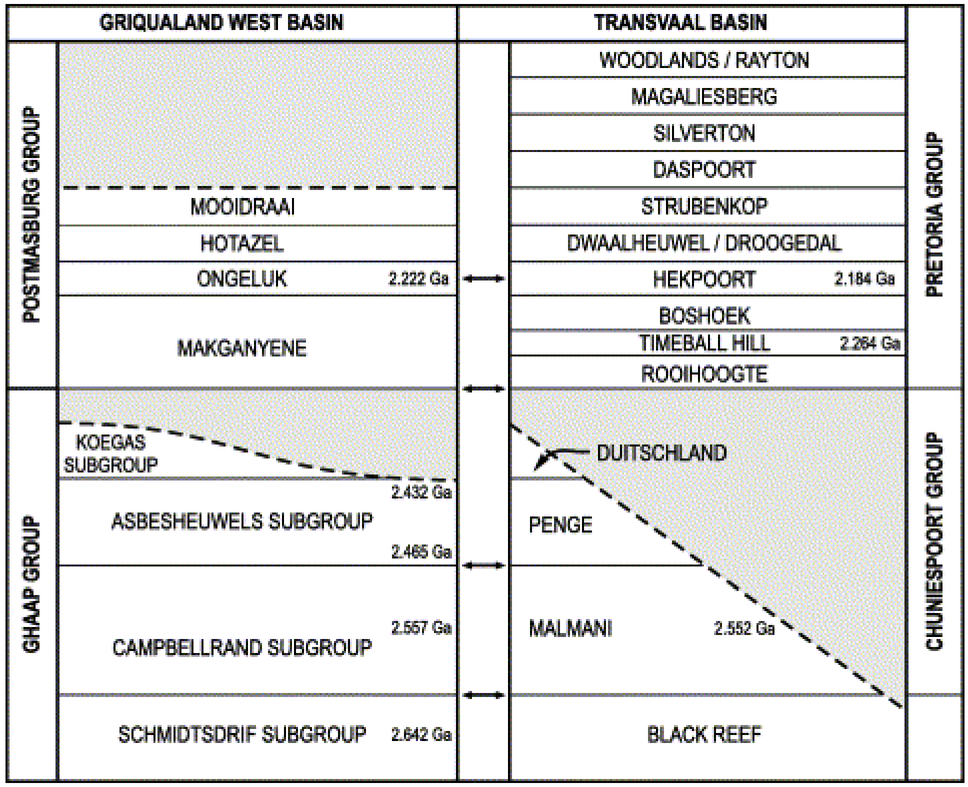

Fig. 2. Current correlations between subdivisions of the Transvaal Supergroup in the Griqualand West and Transvaal basins. Model ages are from Cornell et al. (1996); Sumner and Bowring (1996); and references therein. Shaded areas represent unconformities.

2. The mid-Transvaal unconformity

Throughout the eastern, Transvaal basin, the major unconformity that separates the underlying dolomite/iron formation sequence (Chuniespoort Group) and the overlying Pretoria Group sediments (Fig. 2) is characterised by a prominent chert breccia and chert-dominated conglomerates on a palaeokarst surface (Eriksson et al., 1993). The unconformity with the underlying sequence is distinctly angular and erosive, and the iron formations (Penge Formation) are only preserved in the northern parts of the basin (Eriksson and Reczko, 1995), with the Pretoria Group resting elsewhere directly on underlying dolomitic rocks with an irregular karstic contact. The unconformity progressively transgresses across the Chuniespoort Group from north (Potgietersrust) to south (Carolina) where, in places, the entire lower sequence has been eroded, a thickness of up to 3 km (Button, 1986; Eriksson and Reczko, 1995). A similar distinct unconformity is reported for the Kanye basin in southern Botswana where Pretoria Group equivalents (Segwagwa Group) overlie Ghaap Group equivalents (Taupone Group) (Eriksson et al., 1995). Here too, the banded iron formations are, in places, entirely eroded (Gould et al., 1987) and chert breccias are present.

The unconformity in the Griqualand West basin is characterised by an overlying glacial unit, the Makganyene Formation, that rests on iron formations of the Asbesheuwels and Koegas Subgroups (Fig. 2). Unconformable relationships with the underlying rocks are not observed on outcrop scale, but are assumed, due to the presence of chert, iron formation and carbonate fragments from the

Ghaap Group in the glacial diamictites. Across much of its present areal extent, however, the Makganyene Formation is essentially conformable, overlying a single 50-m thick member (Pietersberg) of the Asbesheuwels Subgroup (Beukes, 1980). It is only in the extreme south-west, where thrusting has complicated the stratigraphic interpretation, that it overlies the intervening Koegas Subgroup. The Makganyene Formation thickens progressively westwards, away from the Vryburg arch, from about 50 m to in excess of 200 m (Visser, 1999). The unconformity surfaces in the two basins are thus markedly different in character.

3. Pretoria–Postmasburg lithological comparisons

The Pretoria Group in the Transvaal basin is dominated by numerous alternating mudrock and sandstone units with lesser diamictite/conglomerate members and volcanic units that represent an alternation of alluvial sedimentation with epeiric marine sedimentation (Catuneanu and Eriksson, 1999). Lithological and thickness variations are common and the depositional setting has been described as falling within the continuum between intracratonic rift and sag basins (Eriksson and Reczko, 1995). The stratigraphy is truncated by several disconformities, some underlain by palaeosols (Button, 1986). Some 12–14 formations are recognised for the Pretoria Group, but only four in the Postmasburg Group (Fig. 2). In marked contrast, the Postmasburg Group in the Griqualand West basin consists of a conformable sheetlike sequence of diverse lithologies, commencing with a basal glacial diamictite, overlain by basaltic andesite lavas, iron formation and Mn-, Ca-, Mg-carbonates. In its chemical sedimentary nature, the succession is more comparable with the underlying Ghaap Group than the Pretoria Group (Tsikos and Moore, 1997).

3.1. Hekpoort–Ongeluk correlation

Correlation of the Pretoria and Postmasburg Groups has essentially hinged around similarities between thick basaltic andesite volcanic units in the two sequences (eastern Hekpoort Formation, western Ongeluk Formation; Fig. 2), in both composition and model age (Sharpe et al., 1983; Cornell et al., 1996). The Ongeluk volcanics contain pillow lavas and hyaloclastites, indicative of subaqueous conditions, and show extensive alteration that has been ascribed to sea-floor processes (Cornell et al., 1996), whereas the Hekpoort volcanics comprise subaerial coarse and fine graded volcaniclastics and associated amygdaloidal lavas, also showing intense alteration/metamorphism, probably related to the intrusion of the Bushveld Complex (Oberholzer and Eriksson, 2000). Myers et al. (1987) have demonstrated that a fundamentally uniform trace element pattern exists for 13 different basaltic volcanic sequences that have erupted onto the Kaapvaal Craton between 3.0 and 2.1 Ga, relating this to repeated melting of uniformly metasomatised subcontinental lithosphere. This, together with significant degrees of subsequent alteration, makes discrimination of individual basaltic andesite units in the Transvaal Supergroup difficult on geochemical grounds alone.

Rb–Sr and Pb–Pb whole-rock model ages obtained for both the Ongeluk Formation (2222 Ma, Pb–Pb isochron age) and Hekpoort Formation (2184 Ma Rb–Sr isochron age; Cornell et al., 1996) are thought to have been significantly influenced by subsequent metamorphic/metasomatic processes that also affected lavas of the older Ventersdorp Supergroup. The latter have yielded 2150 Ma Rb–Sr whole-rock, 2370 Ma Pb–Pb whole-rock and 2693 Ma U–Pb zircon ages (see Armstrong et al., 1991) (Table 1). Subsequent single-zircon dating of Ventersdorp basaltic andesite indicated a 2714 Ma crystallisation age, with a significant population of authigenic zircons giving ages between 2370 and 1765 Ma (Armstrong et al., 1991). Little credibility can therefore be attributed to correlations of the Ongeluk and Hekpoort Formations on the basis of available whole-rock model ages (see also Bau et al., 1999). There thus appear to be no compelling geological, geochemical or geochronological reasons to correlate these two volcanic formations.

Table 1. Radiometric ages (Ma) for the Hekpoort and Ongeluk Formations and Ventersdorp Supergroup

	Rb/Sr (whole rock)	Pb/Pb (whole rock)	U/Pb (zircon)
Hekpoort Formation	2224 ± 21		
	2184 ± 76	?	?
Ongeluk Formation	2023 ± 217	2236 ± 60	
		2222 ± 13	?
Ventersdorp Supergroup	c. 2150	2370 ± 70	2693 ± 60

Data from Armstrong et al. (1991) and Cornell et al. (1996) and references therein.

Correlations have been proposed between the Makganyene Formation and certain diamictites/matrix-supported conglomerates in the Timeball Hill and Boshoek Formations of the Pretoria Group (Eriksson et al., 1995) (Fig. 2). The glacial origin of the latter formations is, however, debatable. Schreiber et al. (1990) described dessication cracks in mudrocks and ascribed an alluvial origin to the Boshoek Formation. Whatever their origin, the Pretoria Group diamictites (generally <10 m thick and impersistent) nowhere match the thickness (60–200 m) and lateral extent of the Makganyene Formation.

Based on the Ongeluk–Hekpoort correlation, lithological differences between the Pretoria and Postmasburg Groups have been ascribed to facies changes from a proximal north-eastern coarse-clastic environment (Pretoria Group) to a distal chemical setting in the south-west (Postmasburg Group) (Button, 1986). Extensions of the Transvaal basin into southern Botswana, however, indicate no change in the subaerial volcaniclastic nature of the Hekpoort volcanics or in the coarse clastic nature of sediments immediately overlying the volcanic unit (Key, 1983). Possible extensions of the Postmasburg Group into southern Botswana are obscured by younger Kalahari cover, whereas undoubted Pretoria Group sediments occur in the Kanye and Molopo areas (Crockett, 1972), preserved as an erosional remnant surrounding the syn-Bushveld Molopo Farms igneous complex (Gould et al., 1987). This continuity of Pretoria Group clastic sediments into the Kanye basin, places it in close juxtaposition with, if not superposition on, the Postmasburg Group, contradicting the proposed broad facies model.

4. The Postmasburg Group

4.1. Makganyene Formation

Mixed sedimentation at the basal contact of the Makganyene Formation reveals intercalations between diamictite and lesser iron formation, shales, sandstones and conglomerates in the area between Sishen and Rooinekke (de Villiers and Visser, 1977; Polteau and Moore, 1999; Visser, 1999). The main diamictite is a massive rock with poorly sorted clasts, some of which are facetted and striated. Maximum clast size decreases progressively westwards across the Griqualand West basin (Visser, 1999). The basal intercalations with shale and sandstone include graded beds (diamictite-to-black shale) and occasional dropstones, indicating a transition to marine facies. Where the Koegas Subgroup underlies the Makganyene Formation, it consists of a similar diverse suite of rock types and the contact between the two units is of an intercalated nature. The iron formations interbedded with the Makganyene diamictites are compositionally and isotopically similar to those of the underlying Koegas and Asbesheuwels Subgroups (Polteau and Moore, 1999).

The Koegas Subgroup appears to represent a distal (marine) facies, in the west and at the base of the Makganyene massive diamictites. Previously, their interrelationship was regarded as unconformable, and represented by an invoked ‘Griquatown growth fault' (Beukes, 1980). This, taken with the observation that the Makganyene Formation rests on a single, 50 m thick member of the Asbesheuwels Subgroup over a 200 km strike distance between Hotazel and Griquatown (Beukes, 1980), indicates that no major discontinuity exists between the Ghaap and Postmasburg Groups. Within the Griqualand West basin, the Makganyene Formation apparently acted as a boundary surface, during a major base-level fall (regression), being conformably interbanded with Koegas-type sediments in the west, and transgressive across Asbesheuwels iron formations on the flanks of the Vryburg arch to the east. In sequence stratigraphic terms, the ‘Griquatown growth fault' represents the hinge-line between an eastern subaerial unconformity and its western correlative conformity.

4.2. Hotazel and Mooidraai Formations

Iron formations in the Hotazel Formation immediately overlying the Ongeluk lavas, are similar in major, trace and rare earth element composition and isotopic character to those of the Asbesheuwels and Koegas Subgroups beneath the Makganyene Formation (Tsikos and Moore, 1997; Tsikos, 1999). Taken as a single entity, the Ghaap–Postmasburg succession displays a symmetry: carbonate – iron formation – diamictite/lavas – iron formation – carbonate (Fig. 3). Carbonate O and C stable isotope profiles reveal a progressive excursion to lighter values from Campbellrand carbonates into Asbesheuwels iron formations (Beukes et al., 1990) that persists to the base of the Makganyene diamictite (Fig. 3). Above the Ongeluk lavas, a gradual return to heavier values is observed from the Hotazel iron formations to the overlying Mooidraai carbonates (Tsikos, 1999). The entire Ghaap–Postmasburg succession is interpreted as a single cold-climate excursion that reached a (glacial) maximum at the Makganyene diamictite (Tsikos and Moore, 1998).

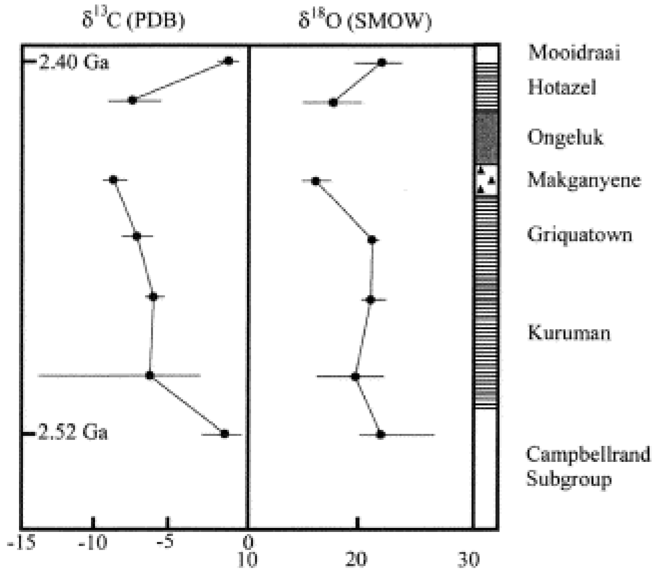

Fig. 3. Profiles showing variation (with error bars) of carbonate $\delta^{13}C$ and $\delta^{18}O$ through the upper part of the Ghaap and the Postmasburg Groups in the Northern Cape sub-basin. Data for Campbellrand Subgroup (*n*=14) and lower Kuruman iron formation, Asbesheuwels Subgroup (*n*=28) from Beukes et al. (1990); upper Kuruman iron formation (*n*=13) and Griquatown iron formation, Asbesheuwels Subgroup (*n*=8) from Beukes and Klein (1990); Makganyene Formation/Koegas Subgroup (*n*=5), this study; Hotazel Formation (*n*=9) and Mooidraai Formation (*n*=10) from Tsikos (1999).

Support for this interpretation is provided by a carbonate Pb–Pb isochron age of 2394±26 Ma, obtained for Mooidraai Formation carbonates at the top of the Postmasburg succession by Bau et al. (1999). This age is interpreted as a depositional/diagenetic (dolomitisation) age. Similar model ages (∼2.36 to ∼2.46 Ga) have been obtained from sulfide and carbonate Pb–Pb data from stratigraphically lower Campbellrand dolomites that are dated at 2521 Ma by zircon chronology (Sumner and Bowring, 1996). The carbonate Pb ages may thus relate to a post-depositional Zn–Pb mineralisation event associated with the formation of MVT-type sulfide deposits (Wheatley et al., 1986). Whatever the interpretation, the Mooidraai Formation Pb–Pb carbonate age indicates that the Postmasburg Group is probably significantly older than the 2.2 Ga model age provided by the Ongeluk lavas.

4.3. Duitschland Formation

There is a potential stratigraphic equivalent to the Postmasburg Group in the Transvaal basin, in the form of the Duitschland Formation (Fig. 2), which contains diamictite, intermediate volcanic rocks and carbonates, similar to the Postmasburg Group, and reaches a thickness of 1000 m (Martini, 1979). However, there is debate as to whether the Duitschland Formation occurs within the Chuniespoort Group (Button, 1986; Eriksson et al., 1993) or the Pretoria Group (Martini, 1979). Based on its marked unconformity with the underlying Penge Formation, the presence of several paleosol horizons, and the predominance of mudrocks in the sequence, the latter correlation may well be valid. The general absence of Postmasburg Group equivalents in the Transvaal basin may simply be related to the extensive pre-Pretoria Group erosion cycle.

5. Discussion

5.1. Regional correlations

Evidence presented demonstrates that the basal contact of the Makganyene Formation is broadly conformable with the underlying Koegas and Asbesheuwels Subgroups in the central part of the Griqualand West basin, and does not represent a major (200 Ma) hiatus or unconformity, as implied by geochronological studies on the overlying Ongeluk lavas (Fig. 4). Iron formations in the overlying Hotazel Formation are identical in their cyclicity, composition and genesis to those of the Koegas and Asbesheuwels Subgroups below the Makganyene and Ongeluk Formations. The Postmasburg Group is thus broadly conformable with the underlying Ghaap Group. Together with the Chuniespoort Group in the Transvaal basin, these two groups should be included in a single supergroup with an approximate age range 2650–2400 Ma.

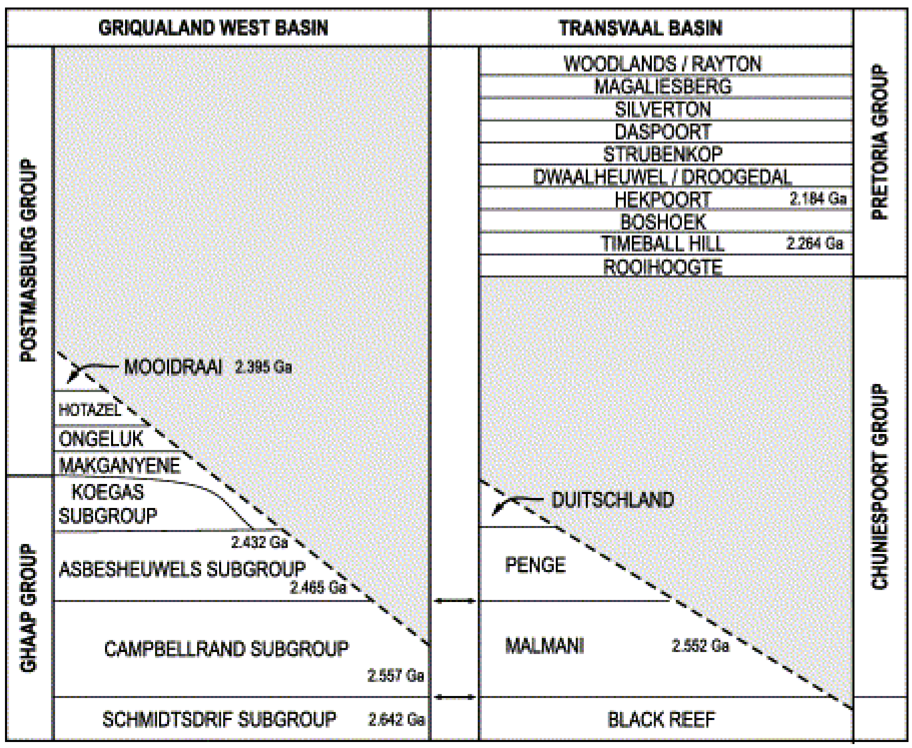

Fig. 4. Proposed new correlations between subdivisions of the Transvaal Supergroup in the Griqualand West and Transvaal basins. Model ages are from Cornell et al. (1996); Sumner and Bowring (1996); Bau et al. (1999); and references therein. Shaded areas represent unconformities.

There are no reliable lower age constraints on the Pretoria Group, given that the only direct ages are Rb–Sr whole-rock measurements from the Hekpoort lavas and ‘Pretoria shales' (2263 Ma, Hamilton, 1977). It is conceivable that the Pretoria Group is up to 150 Ma younger than the proposed supergroup above, and it has a far more restricted distribution, similar to that of the overlying Rooiberg Group (and the Bushveld/Molopo Farms igneous complexes) with which it might be combined in a second supergroup with an approximate age range 2250–2050 Ma. The Transvaal Supergroup has always appeared to be an anachronism, spanning 600 Ma and including a 100–150 Ma unconformity at its centre. Its deconstruction into two geographically, lithologically and temporally distinct entities is, therefore, warranted.

There are significant environmental differences between the two sequences. The older Chuniespoort/Ghaap/Postmasburg sequence formed predominantly in a widespread, starved intracratonic marine basin, typified by stable cratonic conditions (supercontinent?) and gradual thermal subsidence. In marked contrast, the upper Pretoria/Rooiberg sequence followed an extensive period of uplift and erosion, and is characterised by repetitive cycles of rifting and/or sag, represented by disconformities and paleosols (uplift), coarse-grained alluvial fans (syn-rifting) and mudrocks (post-rifting) (Eriksson et al., 1993 and Eriksson et al., 1995), in a more restricted basin. Increasing components of continental volcanism indicate progressive intracratonic instability (supercontinent breakup?).

5.2. Atmosphere–hydrosphere models

This interpretation of the Transvaal Supergroup will have significant implications for various global Palaeoproterozoic models concerning the evolution of the Earth's hydrosphere/atmosphere. The Transvaal Supergroup, providing one of the finest stratigraphic records that straddle the Archaean–Proterozoic boundary, has played a pivotal role in the development of several conflicting hypotheses regarding the timing of the oxygenation of the oceans and atmosphere (see Ohmoto, 1997; Holland, 1999). The two major models involve either an oxygenated atmosphere (within 50% of present atmospheric levels) throughout the geological record since ∼4 Ga (Dimroth and Kimberley, 1976; Ohmoto, 1997), or an anoxic, CO_2-rich atmosphere that became rapidly oxygenated in the period between 2.25 and 2.05 Ga (Cloud, 1973; Kasting, 1987; Holland and Beukes, 1990; Holland, 1999).

In the latter model, the Malmani and Campbellrand Subgroups are regarded as representing some of the earliest major platform carbonate successions (2.65–2.5 Ga) that acted as sinks for the CO_2 that dominated the Archaean atmosphere. The banded iron formations of the Asbesheuwels and Koegas Subgroups and Penge and Hotazel Formations are likewise interpreted as indicating a growth in the oxygen content of the upper/shallower parts of the oceans where Fe^{2+}, transported in seawater from deeper anoxic ocean basins, was oxidised and precipitated during photosynthesis (Cloud, 1973; Kasting, 1987) beneath a still mainly anoxic atmosphere. Based on the previous correlations and (Ongeluk) chronology, this period supposedly lasted from 2.5 to at least 2.2 Ga, and slightly younger in the case of the Hotazel Formation. Finally the hematitisation of iron formation on the unconformity between the Transvaal Supergroup and overlying 1.9 Ga Olifantshoek Supergroup has been interpreted as evidence of the relatively rapid development of an oxygenated atmosphere during the weathering cycle between 2.2 and 1.9 Ga (Holland and Beukes, 1990).

Using the new correlations and chronology (Bau et al., 1999), the period of iron formation deposition within the Ghaap and Postmasburg Groups is reduced to 100 Ma between 2.5 and 2.4 Ga, and the potential period for development of an oxygenated atmosphere extended to 500 Ma between 2.4 and 1.9 Ga. The major ‘Superior-type' iron formations of the late Archaean/early Proterozoic show considerable diachroneity, ranging from the Dhawar Group, India (c. 2.7 Ga) (Eriksson et al., 1999), through the Hamersley Group, Australia (2.63–2.44 Ga) (Nelson et al., 1999) and Transvaal Supergroup, South Africa (2.47–2.39 Ga), to the Penokean orogeny of the Lake Superior region, USA (2.20–1.85 Ga) (Morey and Southwick, 1995). It would thus appear more likely that they are the products of regional anoxic basins rather than of a global anoxic ocean.

5.3. Palaeoproterozoic glaciations

A glaciation-related origin is proposed for the iron formations of the Asbesheuwels and Koegas Subgroups and the Penge and Hotazel Formations (Tsikos and Moore, 1998), similar to the Neoproterozoic Rapitan-type iron formations, and by analogy (e.g. Cheney, 1996), a similar origin may be entertained for other major late Archaean/Palaeoproterozoic iron formations. Palaeomagnetic investigations of the Ongeluk lavas (Evans et al., 1997) indicate that the Makganyene glacial deposits were apparently deposited at low palaeolatitudes (6–16°). Explanations of near-equatorial glaciations during the Proterozoic generally involve an interplay between low solar luminosity (icehouse or snowball earth) and high concentrations of atmospheric CO_2 and other gases (greenhouse) (Kasting, 1987).

Applying this model to the Transvaal Supergroup, the following scenario can be constructed. Drawdown of CO_2 from the atmosphere during the deposition of the Campbellrand and Malmani platform carbonates may have initiated icehouse conditions. Asbesheuwels and Koegas iron formations were precipitated in stagnant, anoxic conditions developing beneath an advancing ice shelf. The Makganyene diamictites represent the products of a major glaciation-induced regression that partially exposed the continental shelf environment. The icehouse cycle was terminated by eruption of the Ongeluk lavas whose volatiles may have contributed to the re-establishment of a greenhouse cycle. The Hotazel iron formations and Mooidraai carbonates represent a return to greenhouse conditions.

Once again, however, the diachroneity of the major Palaeoproterozoic iron formations is of concern, as icehouse–greenhouse events would occur on a global scale. The mega-cycle represented by the Campbellrand carbonates – Asbesheuwels iron formations – Makganyene diamictite – Hotazel iron formations – Mooidraai carbonates took place over a period of about 150 Ma. In plate motion terms, this is an adequate timespan for the migration of a continental mass across a polar region. The eruption of the Ongeluk lavas may indicate a rifting event and a reversal/change in the direction of the wander path. The apparent low-latitude nature of the Makganyene glaciation would require explanation, possibly as the result of increased obliquity of the Earth's orbit (Williams, 1993). However, just as a re-setting of the Pb–Pb systematics of the Ongeluk lavas (Bau et al., 1999) has led to the current erroneous correlation of the Pretoria and Postmasburg Groups, so might the apparent palaeopoles of the same lavas represent a subsequent alteration event. Evans et al. (1997) provide no description of the mineralogy of the rocks used in their measurements, although Cornell et al. (1996) document the widespread presence of secondary Fe-bearing minerals such as epidote, actinolite and chlorite in the Ongeluk volcanics.

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References

Armstrong, R.A., Compston, W., Retief, E.A., Williams, I.S. and Welke, H.J., 1991. Zircon ion microprobe studies bearing on the age and evolution of the Witwatersrand triad. *Precambrian Research* **53**, pp. 243–266.

Bau, M., Romer, R.L., Lüders, V. and Beukes, N.J., 1999. Pb, O, and C isotopes in silicified Mooidraai dolomite (Transvaal Supergroup, South Africa): implications for the composition of Paleoproterozoic seawater and ‘dating' the increase of oxygen in the Precambrian atmosphere. *Earth Planetary Science Letters* **174**, pp. 43–57.

Beukes, N.J., 1980. Lithofacies and stratigraphy of the Kuruman and Griquatown iron-formations, northern Cape Province, South Africa. *Transactions Geological Society South Africa* **83**, pp. 69–86.

Beukes, N.J. and Klein, C., 1990. Geochemistry and sedimentology of a facies transition – from microbanded to granular iron-formation – in the early Proterozoic Transvaal Supergroup, South Africa. *Precambrian Research* **47**, pp. 99–139.

Beukes, N.J., Klein, C., Kaufman, A.J. and Hayes, J.M., 1990. Carbonate petrography, kerogen distribution, and carbon and oxygen isotope variations in an early Proterozoic transition from limestone to iron-formation deposition, Transvaal Supergroup, South Africa. *Economic Geology* **85**, pp. 663–689.

Button, A., 1986. The Transvaal sub-basin of the Transvaal Sequence. In: Anhaeusser, C.R. and Maske, S., Editors, 1986. *Mineral Deposits of Southern Africa*, Geological Society of South Africa, Johannesburg, pp. 811–817.

Catuneanu, O. and Eriksson, P.G., 1999. The sequence stratigraphic concept and the Precambrian rock record: an example from the 2.7–2.1 Ga Transvaal Supergroup, Kaapvaal craton. *Precambrian Research* **97**, pp. 215–251.

Cheney, E.S., 1996. Sequence stratigraphy and plate tectonic significance of the Transvaal succession of southern Africa and its equivalent in Westerrn Australia. *Precambrian Research* **79**, pp. 3–24.

Cloud, P., 1973. Paleoecological significance of the banded iron formation. *Economic Geology* **68**, pp. 1135–1143.

Cornell, D.H., Schutte, S.S. and Eglington, B.L., 1996. The Ongeluk basaltic andesite formation in Griqualand West, South Africa: submarine alteration in a 2222 Ma Proterozoic sea. *Precambrian Research* **79**, pp. 101–123.

Crockett, R.N., 1972. The Transvaal System in Botswana: its geotectonic and depositional environment and special problems. *Transactions Geological Society South Africa* **75**, pp. 275–292.

de Villiers, P.R. and Visser, J.H.J., 1977. The glacial beds of the Griqualand West Supergroup as revealed by four deep boreholes between Postmasburg and Sishen. *Transactions of the Geological Society of South Africa* **80**, pp. 1–8.

Dimroth, E. and Kimberley, M.M., 1976. Precambrian atmospheric oxygen: evidence in the sedimentary distributions of carbon, sulfur, uranium and iron. *Canadian Journal of Earth Science* **13**, pp. 1161–1185.

Eriksson, P.G. and Reczko, B.F.F., 1995. The sedimentary and tectonic setting of the Transvaal Supergroup floor rocks to the Bushveld Complex. *Journal of African Earth Sciences* **21**, pp. 487–504.

Eriksson, P.G., Schweitzer, J.K., Bosch, P.J.A., Schreiber, U.M., Van Deventer, J.L. and Hatton, C.J., 1993. The Transvaal Sequence: an overview. *Journal of African Earth Sciences* **16**, pp. 25–51.

Eriksson, P.G., Hattingh, P.J. and Altermann, W., 1995. An overview of the geology of the Transvaal Sequence and Bushveld Complex, South Africa. *Mineralium Deposita* **30**, pp. 98–111.

Eriksson, P.G., Mazumder, R., Sarkar, S., Bose, P.K., Altermann, W. and van der Merwe, R., 1999. The 2.7–2.0 Ga volcano-sedimentary record of Africa, India and Australia: evidence for global and local changes in sea level and continental freeboard. *Precambrian Research* **97**, pp. 269–302.

Evans, D.A., Beukes, N.J. and Kirschvink, J.L., 1997. Low-latitude glaciation in the Paleoproterozoic era. *Nature* **386**, pp. 262–266.

Gould, D., Rathbone, P.A. and Kimbell, G.S., 1987. The geology of the Molopo Farms Complex, southern Botswana. *Bulletin of the Geological Survey Botswana* **23** 178p .

Hamilton, J., 1977. Isotope and trace element studies of the Great Dyke and Bushveld mafic phase and their relation to Early Proterozoic magma genesis in southern Africa. *Journal of Petrology* **18**, pp. 24–52.

Holland, H.D., 1999. When did the Earth's atmosphere become oxic? A reply. *Geochemical News* **100**, pp. 20–22.

Holland, H.D. and Beukes, N.J., 1990. A paleoweathering profile from Griqualand West, south Africa: evidence for a dramatic rise in atmospheric oxygen between 2.2 and 1.9 BYB. *American Journal of Science* **290A**, pp. 1–34.

Kasting, J.F., 1987. Theoretical constraints on oxygen and carbon dioxide concentrations in the Precambrian atmosphere. *Precambrian Research* **34**, pp. 205–229.

Key, R.M., 1983. The geology of the area around Gaborone and Lobatse, Kweneng, Kgatleng, Southern and South East Districts. *District Memoir Geological Survey Botswana* **5** 230p .

Martini, J.E.J., 1979. A copper-bearing bed in the Pretoria Group in the northeastern Transvaal. *Special Publication Geological Society of South Africa* **6**, pp. 65–72.

Morey, G.b. and Southwick, D.L., 1995. Allostratigraphic relationships of early Proterozoic iron-formations in the Lake Superior region. *Economic Geology* **91**, pp. 1983–1993.

Myers, R.E., Cawthorn, R.G., McCarthy, T.S. and Anhaeusser, C.R., 1987. Fundamental uniformity in the trace element patterns of the volcanics of the Kaapvaal Craton from 3000 to 2100 Ma: evidence for the lithospheric origin of these continental tholeiites. *Special Publication Geological Society of South Africa* **33**, pp. 315–326.

Nelson, D.R., Trendall, A.F. and Altermann, W., 1999. Chronological correlations between the Pilbara and Kaapvaal Cratons. *Precambrian Research* **97**, pp. 165–189.

Oberholzer, J.D. and Eriksson, P.G., 2000. Subaerial volcanism in the Palaeoproterozoic Hekpoort Formation (Transvaal Supergroup), Kaapvaal craton. *Precambrian Research* **101**, pp. 193–210.

Ohmoto, H., 1997. When did the Earth's atmosphere become oxic?. *Geochemical News* **93**, pp. 12–27.

Polteau, S. and Moore, J.M., 1999. Stratigraphy and geochemistry of the Makganyene Formation, Transvaal Supergroup, South Africa. *Journal of African Earth Sciences* **28-4A**, p. 65.

Schreiber, U.M., Eriksson, P.G., Meyer, P.C. and Van der Neut, M., 1990. The sedimentology of the Boshoek Formation, Transvaal Sequence. *South African Journal of Geology* **93**, pp. 567–573.

Sharpe, M.R., Brits, R., Engelbrecht, J.P., 1983. Rare earth and trace element evidence pertaining to the petrogenesis of 2.3 Ga old continental andesites and other volcanic rocks from the Transvaal Sequence, South Africa. University of Pretoria Institute for Geological Research on the Bushveld Complex Research Report 40, 63 p

Sumner, D.Y. and Bowring, S.A., 1996. U–Pb geochronologic constraints on deposition of the Campbellrand Subgroup, Transvaal Supergroup, South Africa. *Precambrian Research* **79**, pp. 25–36.

Tsikos, H., 1999. Petrographic and geochemical constraints on the origin and post-depositional history of the Hotazel iron-manganese deposits, Kalahari Manganese Field. South Africa. Rhodes University PhD thesis. 217p

Tsikos, H. and Moore, J.M., 1997. Petrography and geochemistry of the Paleoproterozoic Hotazel iron-formation, Kalahari Manganese Field, South Africa: implications for Precambrian manganese metallogenesis. *Economic Geology* **92**, pp. 87–97.

Tsikos, H. and Moore, J.M., 1998. The Kalahari manganese field: an enigmatic association of iron and manganese. *South African Journal of Geology* **101**, pp. 287–290.

Visser, J.N.J., 1999. Lithostratigraphy of the Makganyene Formation (Postmasburg Group). *South African Committee for Stratigraphy, Lithostratigraphic Series* **34** 7p .

Wheatley, C.J.V., Whitfield, G.G., Kenny, K.J. and Birch, A., 1986. The Pering carbonate-hosted zinc–lead deposit, Griquatown West. In: Anhaeusser, C.R. and Maske, S., Editors, 1986. *Mineral Deposits of Southern Africa*, Geological Society of South Africa, Johannesburg, pp. 867–874.

Williams, G.E., 1993. History of Earth's obliquity. *Earth-Science Reviews* **34**, pp. 1–45.