Vaalbara, Earth's oldest assembled continent? A combined structural, geochronological, and palaeomagnetic test

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ABSTRACT

The only remaining areas of pristine 3.6–2.7 Ga crust on Earth are parts of the Kaapvaal and Pilbara cratons. General similarities of their rock records, especially of the overlying late Archean sequences, suggest that they were once part of a larger Vaalbara supercontinent. Here we show that the present geochronological, structural and palaeomagnetic data support such a Vaalbara model at least as far back as 3.1 Ga, and possibly further back to 3.6 Ga. Vaalbara fragmented prior to 2.1 Ga, and possibly as early as 2.7 Ga, suggesting supercontinent stability of at least 400 Myr, consistent with Neoproterozoic and Phanerozoic analogues.

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Introduction

The Archean Kaapvaal Craton of South Africa (KC) and Pilbara Craton of Australia (PC) are the only two sizable areas in the world (1.2×10^6 and 0.6×10^5 km^2, respectively) where granite–greenstone terrains ranging in age between 3.6 and 2.7 Gyr have been preserved in a relatively pristine state (Fig. 1). Late Archean to Palaeoproterozoic (2.7–2.1 Gyr old) volcanosedimentary sequences unconformably cover both cratons and indicate that the cratons were stable before 2.7 Ga (Barley *et al.*, 1997; Brandl and de Wit, 1997). These cover sequences show remarkable lithostratigraphic and chronostratigraphic similarities in the extent that individual formations have been correlated between the two cratons (Button, 1976; Cheney *et al.*, 1988; Grobler *et al.*, 1989; Nelson *et al.*, 1992; Martin *et al.*, 1998). Basal volcanic sequences of the Ventersdorp Group of the Transvaal Basin (KC) and the Fortescue Group of the Hamersley Basin (PC) have ages of 2714 ± 8 Myr and 2765 ± 8 Myr, respectively (Armstrong *et al.*, 1991; Arndt *et al.*, 1991). Based on sequence stratigraphy, Cheney (1996) suggested that between 2.7 and 2.1 Ga the Kaap**vaal** and Pil**bara** were part of one continent, which he called **Vaalbara**. An alternative interpretation is that global processes synchronized the same sequence in different parts of the Earth (Nelson *et al.*, 1992).

To test these alternatives further, a range of accurately dated geological events during the evolution of the two cratons is compared. Here, we first show that existing palaeomagnetic data from $\approx$ 2.87 Gyr old mafic complexes on both cratons supports the existence of a Vaalbara continent. Then we suggest that the Vaalbara continent may have been assembled in earlier Archean times because on a reconstructed palaeoposition at 2.87 Ga, the trends of major Archean tectonic lineaments on both cratons are subparallel. We test this hypothesis further by comparing the early Archean evolution of the two cratons, based on precise geochronology of magmatic and tectonic events.

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Archean tectonic architecture of the PC and KC

Tectonic lineaments/shear zones divide both cratons into distinct geophysical and tectonostratigraphic domains (Fig. 1; Krapez and Barley, 1987; de Wit *et al.*, 1992b). The domains have different age ranges and may represent distinct tectonostratigraphic terranes. The ENE trend, lineaments, shear zones and greenstone belts of the older eastern KC is truncated by the N–S tectonic grain of the younger western domain. The oldest domain in the east, the Ancient Gneiss Complex ($\approx$ 3.6 Gyr old) and adjacent Barberton Greenstone Belt, are flanked to the N and S by slightly younger domains of $\approx$ 3.2 and 3.4 Gyr old, respectively. Similar to the eastern KC, the PC is divided by NNE-to NE-trending lineaments/shear zones into domains with the oldest rocks ($\approx$ 3.6 Gyr old) restricted to the eastern Pilbara (Krapez and Barley, 1987).

In the eastern KC, the main episodes of tectonic activity on the ENE-trending lineaments were between 3.2 and 2.7 Ga (de Wit *et al.*, 1992a; Poujol *et al.*, 1996; Good and de Wit, 1997). The earliest tectonic (thrust) activity presently recognized along the Barberton–Wits Line (Fig. 1) is dated at 3.23 Ga. The earliest recorded tectonic (thrust) activity on the Thabazimbi-Murchison Line occurred at 2.96 Ga. Strike-slip movements on these two lineaments are dated at $\approx$ 3.1 and 2.7 Ga, respectively. The western part of the KC, with the N-trending $\approx$ 3.08 Gyr old greenstone belts (Robb *et al.*, 1991), is thought to have been accreted to the rest of the KC by $\approx$ 2.7 Ga (de la Winter, 1987; de Wit *et al.*, 1992a; Robb and Meyer, 1995). In the PC, sinistral strike slip activity on two of the NE trending lineaments has been dated at 2.93 Ga (Mulgandinnah Shear Zone, eastern Pilbara; Zegers *et al.*, 1998) and 2.96 Ga (Sholl Shear Zone, western Pilbara; Smith *et al.*, 1998), with earlier compressional activity on the Sholl Shear Zone between 3.15 and 3.05 Ga. The progression from early thrusting to later strike-slip tectonism, and the overlap in ages from both cratons, suggest that the pan-cratonic lineaments represent a common deformational history (prior to their shared late Archean evolution) and that the cratons are fragments of one larger continent.

We now test this reconstruction, based on palaeomagnetic poles dated at $\approx$ 2.87 Ga.

Palaeomagnetic poles at *c.* 2.87 Ga

The palaeomagnetic poles of two major igneous layered complexes, the Milli-

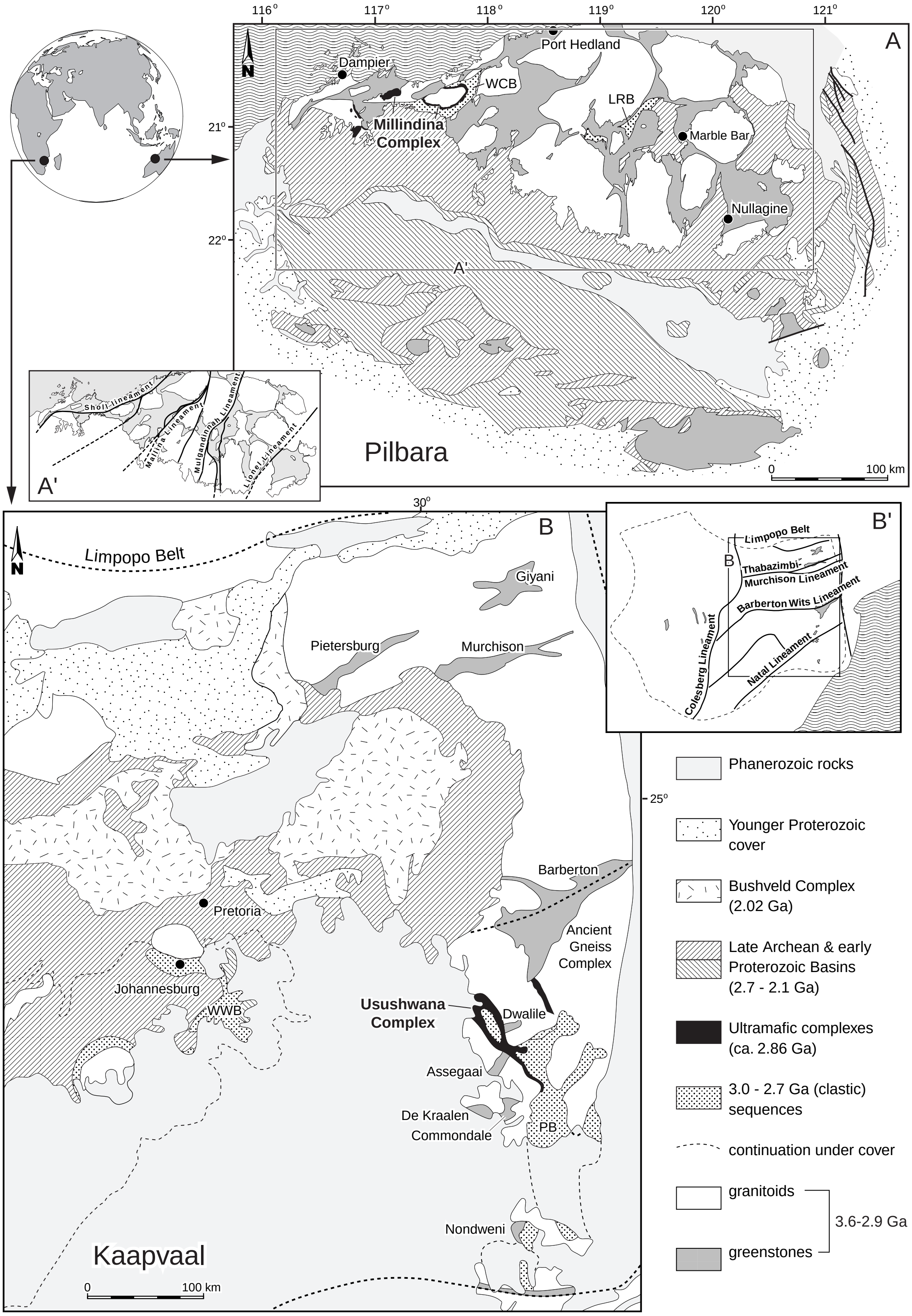

Fig. 1 Location and general geological maps of the Pilbara Craton and the eastern part of the Kaapvaal Craton. The insets show the late Archean lineaments which divide the cratons into domains. The eastern Pilbara Craton is defined as the part east of the Mallina Lineament, the western Kaapvaal Craton as the part west of the Colesberg Lineament. LRB, Lalla Rookh Basin; WCB, Whim Creek Basin; WWB, Witwatersrand Basin; PB, Pongola Basin. Note that the maps are on the same scale, but the insets with the lineaments are not. The lineament maps are shown on equal scale in Fig. 2.

ndina Complex (PC) and the Usushwana Complex (KC), have Sm–Nd ages that overlap within uncertainty of 2860 $\pm$ 20 Myr (Schmidt and Embelton, 1985) and 2871 $\pm$ 30 (Hegner *et al.*, 1984), respectively. The palaeomagnetic poles (Schmidt and Embelton, 1985; Layer *et al.*, 1988) have reliability indexes of 5 and 4 out of 7 (classification by van der Voo, 1993), the most reliable pre-2.7 Ga palaeomagnetic data available for the KC and PC. When the two virtual geomagnetic poles (VGP) are both placed on the present N-pole, the two cratons are brought into close proximity, consistent with Cheney's Vaalbara model (Fig. 2a). Since the palaeomagnetic data leave the longitude unconstrained, the cratons can be rotated with respect to each other. When the PC is rotated about 60° clockwise around the N-pole with respect to the KC, the two cratons are adjacent to each other with the Pilbara craton to the north-west of the Kaapvaal Craton, and the lineaments of the PC are subparallel to the lineaments of the eastern KC (Fig. 2b). In Fig. 2(c) the possible configuration is refined, taking into account the uncertainty in the determination of the VGP in the direction from the site to the VGP (∂p), the error in the determination of the palaeolatitude. When the PC is rotated to give the best proximity to the KC, i.e. the PC to the south-east of the eastern KC, the lineaments in the two cratons are subparallel. In our view this last fit is geologically the most robust, since lineaments with broadly similar ages and kinematics line up. This is not the case in Fig. 2(b), where the PC and the eastern KC are separated by the younger western KC. The reconstruction in Fig. 2(c) suggests that the lineaments may have been inherited from an earlier shared period of tectonism. We explore the correlations in the tectonostratigraphic histories of the cratons below.

Early Archean tectonostratigraphic histories

All geochronological data from the Pilbara and Kaapvaal Cratons are summarized in Fig. 3. With the aid of this figure, we outline the tectonostratigraphic histories of both cratons from the youngest period of intracratonic shear zones, granite intrusion, and basin sedimentation to the oldest period of formation and amalgamation of crustal blocks.[1]

3.1–2.9 Ga events: pan-cratonic shear zones (D_4SS), basins, and granites

On both cratons the late Archean basin sequences are related to tectonism and are deformed locally within the major pan-cratonic shear zones and intruded by crustally derived granites. The period terminates with the intrusion of the layered mafic complexes at $\approx$ 2.87 Ga. Strike-slip deformation in the shear zones is coincident with intrusion of late-to post-tectonic granites between 3075 and 2820 Ma (Poujol *et al.*, 1996; Zegers, 1996; Good and de Wit, 1997; Zegers *et al.*, 1998). The late granites are interpreted to represent melting of older crustal material (Bickle *et al.*, 1989; Robb *et al.*, 1992; Maphalala and Kröner, 1993). Remnants of clastic

a b c

Fig. 2 Palaeomagnetic reconstructions using the palaeomagnetic poles from the Millindinna (Pilbara, Schmidt and Embelton, 1985) and Ushushwana (Kaapvaal Craton, Layer *et al.*, 1988) ultramafic complexes at $\approx$ 2.87 Ga. The reconstructions were performed with the GMAP software package. The relative positions of the Kaapvaal and Pilbara Cratons in this reconstruction are different from the stratigraphically based reconstruction presented by Cheney (1996), where the Pilbara Craton is placed to the south of the Kaapvaal Craton in unrotated position. (a) The two VGP are placed on the present N-pole, resulting in the reconstructed positions of the Pilbara and Kaapvaal Cratons. (b) Similar to (a) but the Pilbara Craton is rotated with respect to the Kaapvaal Craton around the present pole (longitude is unconstrained by the palaeomagnetic data). Rotating the Pilbara to the north-west of the Kaapvaal Craton lines up the lineaments of the two cratons. In this position, the younger N–A striking western Kaapvaal lies between the old blocks of the craton. (c) Similar to (b) but the maximum δp (error is the latitude position of the site with respect to the VGP, 7.6 for KC and 6.8 for PC) is used for the reconstruction. In this reconstruction the Pilbara craton can be placed next to the Kaapvaal Craton in the south-eastern corner, lining up the major lineaments.

sedimentary basins ($\approx$ 3.0 Ga onward) are locally well preserved [Witwatersrand and Pongola basins (KC) and the Lalla Rookh and Whim Creek basins (PC)]. In the KC the ages of these basinal sequences are constrained by detrital zircons, zircons from volcanic horizons, and intrusive relations, to 2.95–2.70 Gyr (Armstrong *et al.*, 1991; de Wit *et al.*, 1992a; Robb and Meyer, 1995). In the upper parts of these upward coarsening sequences, coarse clastic units are variably deformed and separated by numerous internal unconformities and are interpreted to have been deposited in foreland basins with strike-slip activity (de la Winter, 1987; de Wit *et al.*, 1992a; Coward *et al.*, 1995). In the PC the Whim Creek and Lalla Rookh basins (PC) lack similar time constraints from detrital zircons but have been loosely constrained to 2950 Myr old, and have been described as pull-apart basins related to strike-slip movement on the ENE-trending shear zones which form the lineaments (Krapez and Barley, 1987).

3.2–3.1 Ga events: felsic volcanism, granites, and compression (D_3T)

In the western PC both felsic volcanism and granitoid intrusion occurred at 3.12 Ga, and compressional deformation occurred between 3.15 and 3.00 Ga (D_3(C) (Fig. 3; Smith *et al.*, 1998). At this time in the KC, felsic volcanics of the Dominion Group (3074 $\pm$ 6 Myr old; Armstrong *et al.*, 1991) erupted, and granodiorites, granites and syenogranites intruded the Barberton and Murchison area (e.g. Nelshoogte, Mpuluzi, Nelspruit; Maphalala and Kröner, 1993). A SE–NW-directed compressional deformation (D_3(C)), resulting in folding and thrusting is recorded to have occurred sometime between 3.23 and 3.09 Ga in the Barberton Belt (de Ronde and de Wit, 1994).

3.3–3.2 Ga events: felsic volcanism, syntectonic TTGs, and compression (D_2T)

In the Barberton Belt, SE–NW directed compressional deformation (D_2(C)) caused major thrusting and tight to isoclinal folding which accounts for the NE–SW map pattern of the Barberton Belt. Undeformed and deformed porphyries aged 3229 $\pm$ 5 and 3227 $\pm$ 3 Myr, respectively, locally constrain this deformation event to 3228 $\pm$ 5 Ma (de Ronde and de Wit, 1994). D_2 and D_3 in the KC may be part of long-lived period of progressive SE–NW-directed compression during deposition of the Moodies Group coarse clastic sediments in a foreland style basin (Lamb, 1986).

In the eastern PC, a similar age range of compressional structures has been recognized in various greenstone belts. These include isoclinal folding and bedding parallel shear zones with an E–W transport direction, which postdate the Wyman Formation at 3325 Ma and predate 3200 Ma, a $^{40}Ar/^{39}Ar$-age of postkinematic actinolites in one of those shear zones (Zegers *et al.* submitted). Compressional structures with similar time constraints and E–W shortening directions have been described in a large part of the eastern Pilbara (Boulter *et al.*, 1987; Nijman *et al.*, 1998; van Haaften and White, 1998). The compressional event coincides with the syntectonic deposition of the first major coarse clastic sequences of the upper Gorge Creek Group in the eastern Pilbara (Nijman *et al.*, 1998).

On both cratons these compressional structures are regionally associated with syntectonic TTG intrusions (de Ronde and de Wit, 1994; Kröner *et al.*, 1996; Zegers, 1996; van Haaften and White, 1998). The KC was intruded at $\approx$ 3.3 Ga (Ancient Gneiss Complex) and at $\approx$ 3.23 Ga (Barberton area). The Limpopo Belt shows similar protolith ages between 3.2 and 3.3 Gyr, but the Limpopo Belt may not have been part of the KC at that time (Jaeckel *et al.*, 1997) Similarly, the eastern PC was intruded at $\approx$ 3.3 Ga, and the west and central PC at $\approx$ 3.25 Ga (see Fig. 3).

3.4–3.5 Ga island arc and/or oceanic sequences and tectonism (D_1)

The oldest well-preserved supracrustal sequences on both cratons are the dominantly mafic to ultramafic Onverwacht (KC) and Warrawoona (PC) Groups, which have been variously interpreted as representing fragments of oceanic and/or island arc complexes (Barley, 1997; Brandl and de Wit, 1997; Barley *et al.*, 1998) or, in older literature, as rift sequences (Windley, 1977). Both sequences consist of a lower sequence of mafic and ultramafic rocks (Komati Formation and Talga Talga Subgroup, respectively). They are overlain by the Middle Marker clastic chert (KC) and Duffer Formation/North Pole Chert (PC), both dated at $\approx$ 3.47 Gyr age, providing a minimum age for the lower sequences. Both cherts have yielded the Earth's oldest microfossils (Schopf and Packer, 1987; Westall *et al.*, in press). In turn, these cherts are covered by tholeiitic pillow basalts with interbedded chert (Hooggenoeg Formation (KC) and Salgash Subgroup (PC)). The pillow basalts of the Hooggenoeg Formation are conformably to unconformably overlain and intruded by a 3.45 Gyr old felsic volcano-plutonic complex (de Wit *et al.*, 1987a). The Salgash Subgroup contains minor 3.45 Gyr old felsic units in the eastern PC (Thorpe *et al.*, 1992).

Despite extensive post-3.3 Ga deformation, there is good, but fragmented evidence for early, pre-3.45 Ga deformation in both cratons. In the Barberton area these include downward facing

[1]Although the U-Pb zircon dating method is undoubtedly the most reliable method to determine crystallization ages of magmatic rocks, different analytical techniques can produce distinct discrepancies in ages. For example, where similar rocks have been dated by SHRIMP, conventional and evaporation methods (see for example the Steynsdorp Pluton, SDP, Fig. 3), the SHRIMP age is often the oldest, generally followed by conventional, and evaporation ages, in that order. The difference between the SHRIMP, evaporation and conventional age may be as large as 20 Myr and in excess of the analytical error. This discrepancy is likely to be the result of nonuniform age distributions in groups of zircons and even within single zircons (Compston and Kröner, 1988; Pidgeon, 1992; Vavra *et al.*, 1996). It is now clear that metamorphic zircons and partly recrystallized areas within zircons, particularly at high metamorphic grade and in deformed rocks, are more common than previously suspected. Analysis of such composite zircon, will result in mixed, generally younger, ages which may not have geological meaning. Moreover, where a small number of zircons are used for analysis (3–4 zircons) the true variation of ages within a given sample may not be established. In our study, the SHRIMP ages are considered to be the most reliable, especially where the internal texture of the zircons has been analysed. Where only evaporation and/or conventional ages are available, the errors may be larger than the quoted errors.

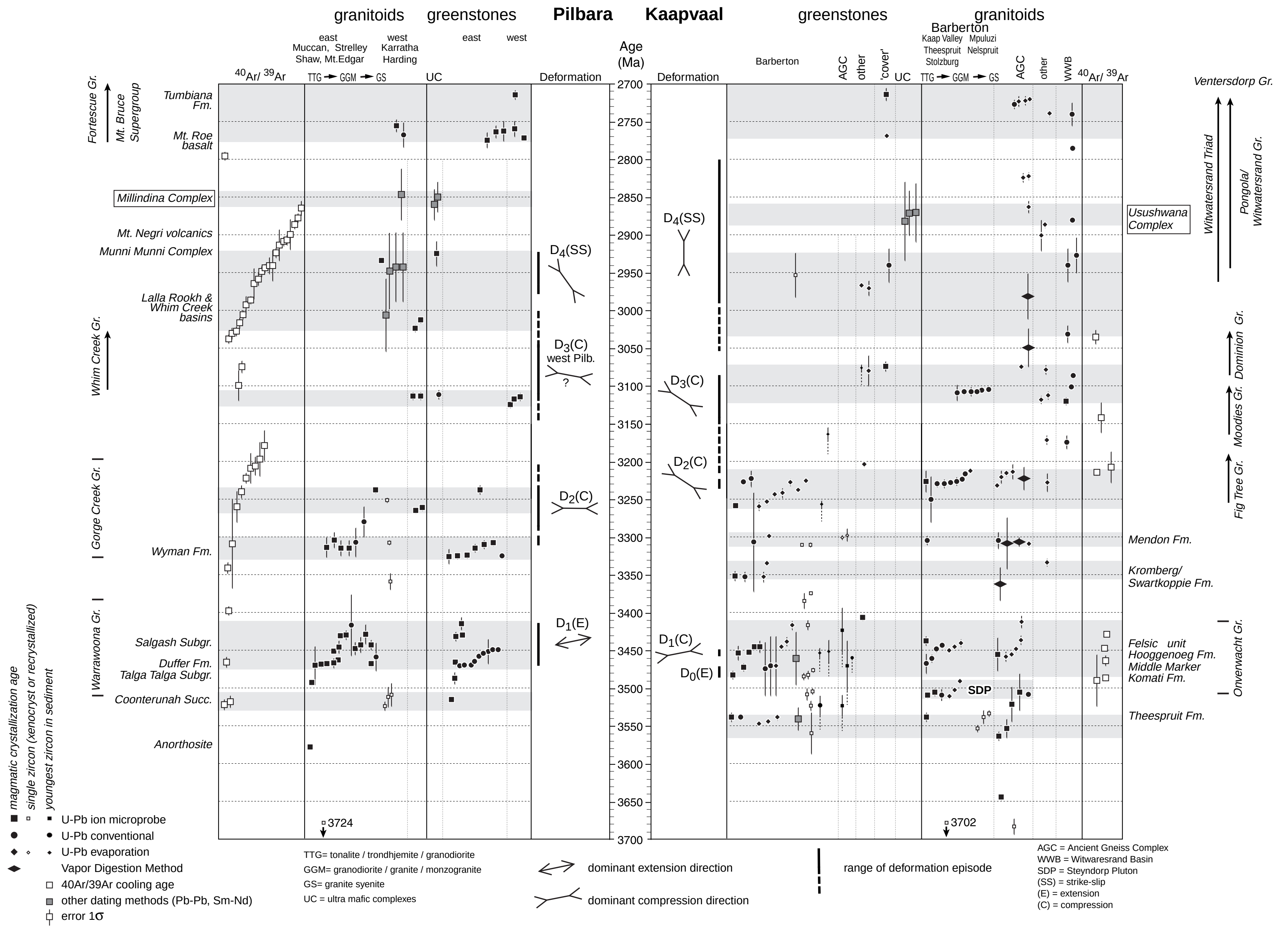
granitoids
greenstones
Pilbara
Kaapvaal
greenstones
granitoids
east
Muccan, Strelley
Shaw, Mt.Edgar
west
Karratha
Harding
east
west
Age
(Ma)
Barberton
Kaap Valley
Theespruit
Stolzburg
Mpuluzi
Nelspruit
40Ar/ 39Ar
TTG GGM GS
UC
Deformation
Deformation
AGC
other
'cover'
UC
TTG GGM GS
AGC
other
WWB
40Ar/ 39Ar
Fortescue Gr.
Mt. Bruce Supergroup
Tumbiana Fm.
Mt. Roe basalt
Millindina Complex
Mt. Negri volcanics
Munni Munni Complex
Lalla Rookh & Whim Creek basins
Whim Creek Gr.
Gorge Creek Gr.
Wyman Fm.
Warrawoona Gr.
Salgash Subgr.
Duffer Fm.
Talga Talga Subgr.
Coonterunah Succ.
Anorthosite
D4(SS)
D3(C)
west Pilb.
?
D2(C)
D1(E)
D4(SS)
D3(C)
D2(C)
D1(C)
D0(E)
SDP
3724
3702
Ventersdorp Gr.
Witwatersrand Triad
Pongola/ Witwatersrand Gr.
Usushwana Complex
Dominion Gr.
Moodies Gr.
Fig Tree Gr.
Mendon Fm.
Kromberg/ Swartkoppie Fm.
Felsic unit
Hooggenoeg Fm.
Middle Marker
Komati Fm.
Onverwacht Gr.
Theespruit Fm.
magmatic crystallization age
single zircon (xenocryst or recrystallized)
youngest zircon in sediment
U-Pb ion microprobe
U-Pb conventional
U-Pb evaporation
Vapor Digestion Method
40Ar/39Ar cooling age
other dating methods (Pb-Pb, Sm-Nd)
error 1σ
TTG= tonalite / trondhjemite / granodiorite
GGM= granodiorite / granite / monzogranite
GS= granite syenite
UC = ultra mafic complexes
dominant extension direction
dominant compression direction
range of deformation episode
AGC = Ancient Gneiss Complex
WWB = Witwatersrand Basin
SDP = Steyndorp Pluton
(SS) = strike-slip
(E) = extension
(C) = compression

Fig. 3 (Previous page) Table of geochronological data (U–Pb and $^{40}Ar/^{39}Ar$), structural events (extension or compression directions shown), and names of lithological units (where only lower age is constrained, shown with arrow). Supplementary data from areas other than the well studied eastern Pilbara and Barberton area (KC) are also shown where available and are lumped under west Pilbara and "other" for the Kaapvaal Craton. Note that different domains (east vs. west Pilbara and Barberton/Ancient Gneiss Complex vs. other) have different age ranges in both cratons. The grey bands represent the timespan of rockforming event as interpreted in this study, usually in both granitoids and greenstones. AGC, Ancient Gneiss Complex; WWR, Witwatersrand Basin; SDP, Steynsdorp Pluton. Data for the Kaapvaal Craton and the Pilbara Craton are from published literature (Davies *et al.*, 1970; Pidgeon, 1978a; Pidgeon, 1978b; Hamilton *et al.*, 1979; Williams *et al.*, 1983; Froude *et al.*, 1984; Hegner *et al.*, 1984; Pidgeon, 1984; Brévart *et al.*, 1986; Tegtmeyer and Kröner, 1987; Wijbrans and McDougall, 1987; Compston and Kröner, 1988; Kröner and Todt, 1988; McNaughton *et al.*, 1988; Armstrong, 1989; Bickle *et al.*, 1989; Kröner *et al.*, 1989; Layer *et al.*, 1989; York *et al.*, 1989; Armstrong *et al.*, 1990; Williams and Collins, 1990; Armstrong *et al.*, 1991; Arndt *et al.*, 1991; Kröner *et al.*, 1991; Robb *et al.*, 1991; Walraven *et al.*, 1991; Kamo, 1992; Layer *et al.*, 1992; Lopez-Martinez *et al.*, 1992; Robb *et al.*, 1992; Thorpe *et al.*, 1992; Bickle *et al.*, 1993; Brandl and Kröner, 1993; Horwitz and Pidgeon, 1993; Maphalala and Kröner, 1993; McNaughton *et al.*, 1993; Kamo and Davis, 1994; Kröner and Tegtmeyer, 1994; Walraven *et al.*, 1994; Robb and Meyer, 1995; Brandl *et al.*, 1996; Byerly *et al.*, 1996; Kröner *et al.*, 1996; Poujol *et al.*, 1996; Zegers, 1996; Davids *et al.*, 1997; Barley *et al.*, 1998; Smith *et al.*, 1998; Zegers *et al.* submitted).

sequences and recumbent nappes (de Wit *et al.*, 1983; de Wit *et al.*, 1987a). Transport directions of this folding phase (D_1(C)) have tentatively been interpreted as SSW–NNE, based on reconstructed orientation of fold-axes. Even earlier structures are zones of intense carbonate extension veining and shearing (tectonites), cross cutting bedding in the lower part (Komati Formation) and bedding parallel below chert bars in the Hooggenoeg Formation (de Wit *et al.*, 1982; de Wit, 1986; de Wit *et al.*, 1987b; Davies, 1997). These zones are distinguished from later faults by carbonate extension veins, intense alteration of mafic–ultramafic protoliths, and abundant fuchsite. Locally, abundant mafic dikes, cross-cutting these structures, are highly altered. Proof of their pre-3.45 Ga formation is based on: (i) fragments of the distinctive fuchsite–carbonate tectonite in a conglomerate at the base of the 3.45 Gyr old felsic unit unconformably covering the mafic-ultramafic sequence; (ii) the folded tectonites and chert bars are truncated by the $\approx$ 3.45 Gyr old felsic unit (de Wit *et al.*, 1987a). The relative timing of alteration, dike intrusion, and deformation, suggests that these zones were extensional structures (D_1(E)) active during the construction of the mafic–ultramafic sequence, $\approx$ 3.48–3.46 Ga.

The earliest recorded widespread structural event in the Pilbara is $\approx$ 3.47 Ga extension (Zegers *et al.*, 1996). Key structures are brittle extensional faults that cross-cut the stratigraphy and sole into highly altered bedding parallel ductile/brittle shear zones, preferentially located in ultramafic units. In the Shaw Batholith this extensional phase is represented by a ductile detachment, active during intrusion of the sheeted 3.47 Gyr old North Shaw granodiorite. The combined structures in the supracrustals and granitoids form a core-complex style geometry, with a WSW transport direction, active between 3470 and 3416 Ma (Zegers *et al.*, 1996). The Coonterunah Succession (see below) was folded and developed a foliation prior to deposition of the North Pole Chert, indicating that compressional deformation must have preceded the extension in the Pilbara.

Pre-3.5 Ga vestiges

In the KC, the southern margin of the Barberton Belt consists of the highly deformed Theespruit Formation, which is separated from the overlying Komati Formation by a major shear zone folded by D_2 deformation. The Theespruit Formation consists of an imbricate thrust stack of basaltic, ultramafic, felsic unit, and tonalite gneisses, which are metamorphosed and deformed into schists (de Wit *et al.*, 1983). One schistose tonalite unit was dated at 3538 Myr age (Armstrong *et al.*, 1990), whereas similar felsic schists contain units dated from 3547 Ma (Kröner *et al.*, 1996). The $\approx$ 3.51 Gyr old Steynsdorp TTG intrudes some of the schists of the Theespruit Fm. The Ancient Gneiss Complex includes the oldest TTG gneisses dated at 3644 $\pm$ 4 Myr (Compston and Kröner, 1988). In the PC, the oldest supracrustal sequence is the deformed Coonterunah Succession (> 3515 $\pm$ 3 Myr old, Buick *et al.*, 1995), which unconformably underlies cherts correlated with the North Pole Chert. The oldest rock in the PC is an anorthositic enclave in the Shaw Batholith dated at 3578 $\pm$ 4 Myr (McNaughton *et al.*, 1988). The oldest recorded xenocrystic zircons are 3702 $\pm$ 1 (KC) (Kröner *et al.*, 1996) and 3724 $\pm$ 1 Myr old (PC) (Thorpe *et al.*, 1992).

Discussion

The timing and tectonic evolution of the PC and KC are remarkably similar. Palaeomagnetic data from the two layered complexes at $\approx$ 2.87 Ga, together with structural data, validate Cheney's (1996) Vaalbara model and permit reconstructions of a Vaalbara continent in the Late Archean. Correlations suggested by Cheney (1996), however, appear to extend even further back in time. The parallel arrangement of lineaments on both cratons and the similar timing and association of pan-cratonic strike-slip faults, arenaceous basin sedimentation, and K-rich granite intrusion, suggests that the two cratons shared a period of stabilization at $\approx$ 3.1–2.7 Ga. However, in the KC a suite of I-type granites intrudes between 2780 and 2720 Ma which has as yet no equivalent in the PC. A significant proportion of coarse detritus in the auriferous portions of the Witswatersrand basin was derived from rocks formed between 3.1 and 2.9 Ga, lending support for the exhumation of granite-greenstone belts along the Thabizimbi–Murchison lineament and from the western KC greenstone belts (Vearncombe, 1992; Poujol *et al.*, 1996). The lack of major gold deposits within the Lalla Rookh basin remains an important difference. Part of the solution may lie hidden in divergent stratigraphic philosophies; in the PC, the $\approx$ 2.9 Gyr old coarse clastic sediments are included in the greenstone belt stratigraphy whereas in the KC the 2.9–2.7 Gyr old sediments are considered basinal cover, except in the Pietersburg greenstone belt, where they are more deformed.

Compressional deformation dominates the evolution of both cratons between 3.3 and 3.1 Ga and is intimately related to both the deposition of coarse clastic sequences and the intrusion of TTGs. Compression may have begun earlier in the PC than the KC (3.3 vs. 3.2 Ga), due either to diachronous events or as an artifact of incomplete age constrains on the compressional deformation. The compression was E–W directed in the PC and NW–SE directed in the KC in present geography, but if reconstructed as proposed in Fig. 2(c) the shortening directions are subparallel (Fig. 4) and may represent the final amalgamation of the Vaalbara continent. The lithological correlations first noted by Anhaeusser *et al.* (1969) can now be interpreted with some confidence as being related to a common geological history. However, the most remarkable correlation is in the timing of pre-amalgamation felsic volcanism in the submarine sequences of both cratons (3.45 and 3.47 Ga), which predate the compressional phase. If the period of major compressional deformation represents amalgamation of Vaalbara and the onset of shared evolution, one might expect different preamalgamation histories for different crustal blocks. From the data presented here it seems unlikely that the two cratons formed in very similar ways at widely separated locations. Perhaps these submarine sequences formed along the margins of the same oceanic basin, pieces of which were accreted by a common attractor during the 3.3–3.1 Ga period of amalgamation. New data, specifically from age-integrated palaeomagnetic studies on both cratons, are now needed to resolve the pre-3.1 Ga kinematic history of crustal blocks.

An equally important question is the timing of break-up of Vaalbara. In the KC major regional metamorphic and fluid events associated with the intrusion of the Bushveld Complex at 2.045 Ga (Walraven *et al.*, 1990; Frimmel, 1997) and the Vredevort impact event at 2.025 Ga (Kamo *et al.*, 1995) have been recognized craton wide, as far south as the Barberton Belt (e.g. Weiss and Wasserberg, 1987). At the same time (*c.* 2027 Ma), a granulite facies event has been recognized in the Limpopo Belt (Jaeckel *et al.*, 1997). Events of that age and extent have not been recorded in the Pilbara Craton. Thus, the two cratons were separated before 2.05 Ga. The continental volcanics of the Ventersdorp (KC) and Mt Roe (PC) may mark the onset of the break-up of Vaalbara, ≈ 2.76–2.74 Ga (Blake and Groves, 1987; Barley *et al.*, 1997), in the same way as continental flood basalts are thought to precede the break-up of Phanerozoic supercontinents (Storey, 1995). Following rifting, the carbonate platforms of the Transvaal and Hamersley may represent thermal subsidence of passive margins formed on complimentary continental margins of diverging fragments of Vaalbara. Assuming final amalgamation at ≈ 3.1

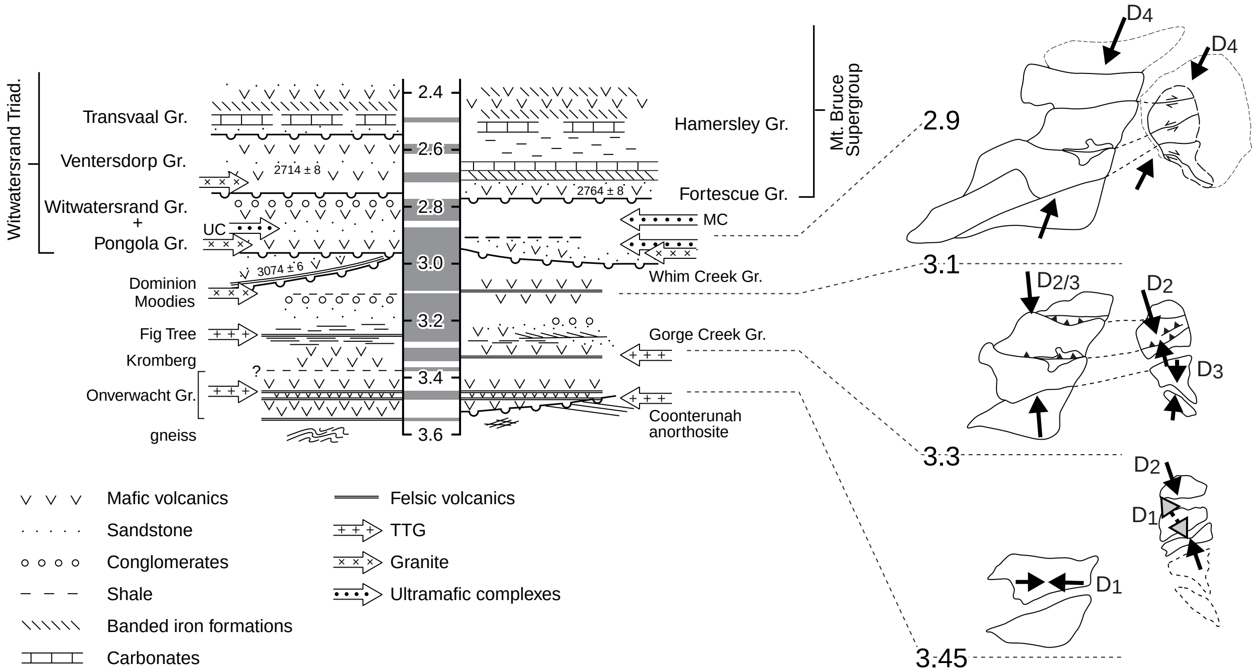

Fig. 4 Schematic accretion model of the tectonostratigraphic history of the Vaalbara continent as deduced from the data presented in this paper. The two cratons share an early period of accretion of oceanic terrains and then amalgamation into a continent during late 3.3–3.1 Ga compressive deformation. At ≈ 3.0 Ga pan-cratonic strike-slip zones formed, which apparently can be traced across the two cratons. These are associated with large volumes of granite intrusion. It remains uncertain at what stage the Limpopo Belt was accreted to the KC. Equally, the total extent of the PC remains uncertain, although granite -greenstone inliers of unknown age have been recognized in the southern PC. The subsequent break up of the Vaalbara continent may be signaled by the floodbasalts of the Ventersdorp and Fortescue Group starting at ≈ 2.75 Ga. The shading in the time bar schematically represents the amalgamated stage (grey bars) and subsequent breakup.

Ga and rifting between ≈ 2.7 and 2 Ga, Vaalbara was a stable continent for 1000–400 Myr. Thus, the life cycle of Vaalbara was similar to that of Earth's later supercontinents, such as Gondwana (600–180 Ma) and Rhodinia (1000–600 Ma) (Nance *et al.*, 1988).

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