Chapter 1

Introduction

1.1 Problem Statement

Recent SHRIMP analyses of a zircon grain revealed evidence for the presence of continental crust more than 4.3Ga ago (Wilde et al., 2001). Approximately 35 small fragments of continental crust, known as Archean cratons, developed prior to 2.5Ga, of which the Kaapvaal craton is one (Bleeker, 2003) (Fig 1.1).

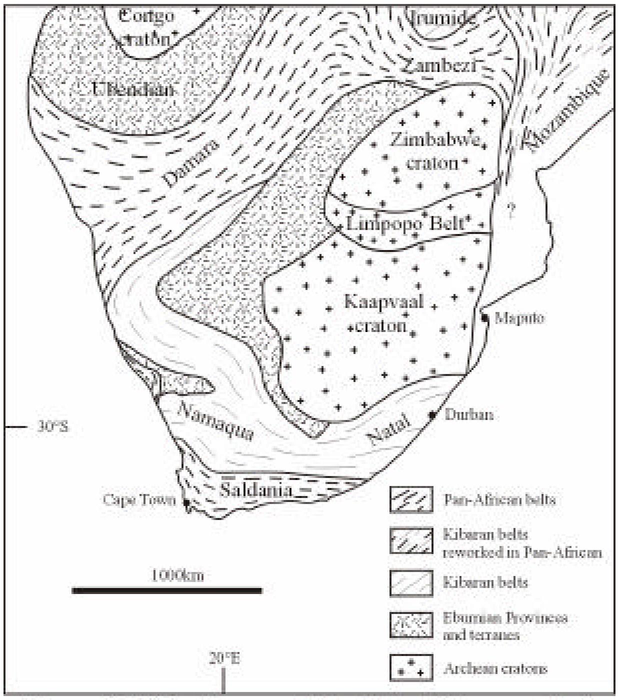

Figure 1.1 Sketch map of the tectonic framework of southern Africa (modified from Thomas et al., 1994)

The Kaapvaal craton is one of the best preserved Archean cratons known (De Wit et al., 1992). Cover sequences that include the Archean-late Paleoproterozoic Witwatersrand-Pongola Supergroup, the Ventersdorp Supergroup, the Transvaal Supergroup and several late Paleoproterozoic red bed sequences are well preserved on the craton (Figs 1.2 and 1.3). The almost continuous record of Archean-Paleoproterozoic sedimentation makes the Kaapvaal craton one of the best areas on the globe to study early Earth history.

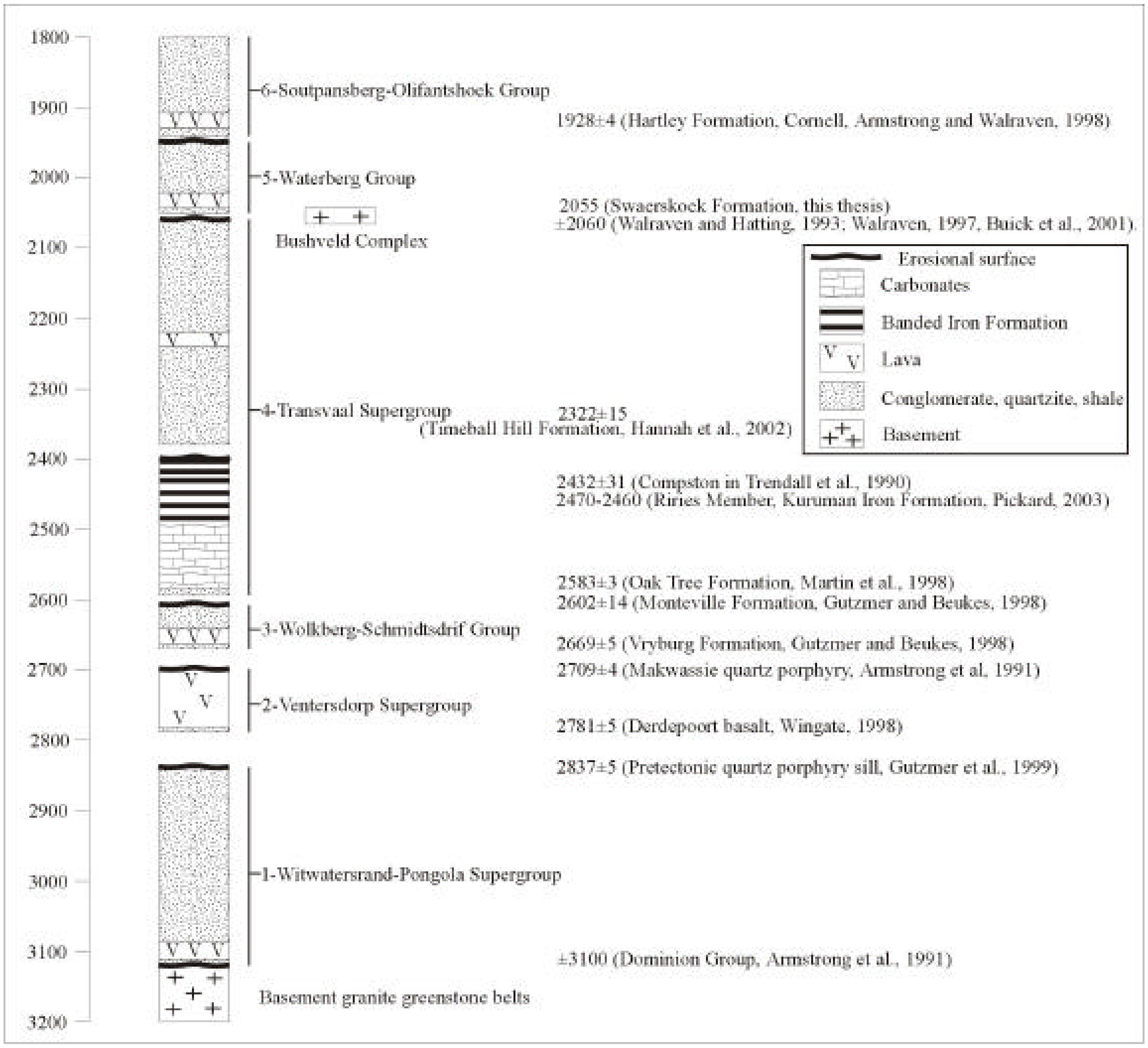

Figure 1.2 Archean to Paleoproterozoic sedimentary cover sequences on the Kaapvaal craton.

However, a number of striking uncertainties exist for the geology of the Kaapvaal craton, namely:

a) The paleogeographic relation of the Kaapvaal craton to other cratonic nuclei in the early Precambrian. Piper (1982) suggested, based on paleomagnetic data, the existence of a Paleoproterozoic supercontinent in which the Kaapvaal craton is placed next to South America, very distal to the Pilbara craton of Australia (Fig 1.4A). Rogers (1996) proposed a continent called Ur, which existed from the Neoarchean to the Paleoproterozoic (Fig 1.4B). Ur is proposed to consist of the Kaapvaal craton (De Wit et al., 1992), the Western Dharwar craton (Meen et al., 1992), the Bhandara craton (Sarkar et al., 1993), the Singhbhum craton (Sharma et al., 1994) and the Pilbara craton (Bickle et al., 1993; Blake, 1993)(Fig 1.4B). In addition to these five cratons, three small areas of Archean crust on the Indian Ocean coast of Antarctica show basement stabilization at ca. 3Ga, but no supracrustal cover suites of any age are preserved, namely western Dronning Maud Land (Groenewald et al., 1991), Vestfold Hills and the Napier Complex (Black et al., 1991)(Fig 1.4B). In the Ur configuration, Antarctica is situated between the Kaapvaal and Pilbara cratons, with the Zimbabwe craton situated to the immediate north of the Kaapvaal craton (Rogers, 1996). However, Rogers (1996) indicates that the Zimbabwe craton only became stable at ca. 2.5Ga. Cheney (1996) suggested that the Kaapvaal and Pilbara cratons were located adjacent to each other with the Pilbarra craton to the south of the Kaapvaal craton based on the striking resemblance between late Archean to early Paleoproterozoic sedimentary sequences on the two cratons (Fig 1.4C).

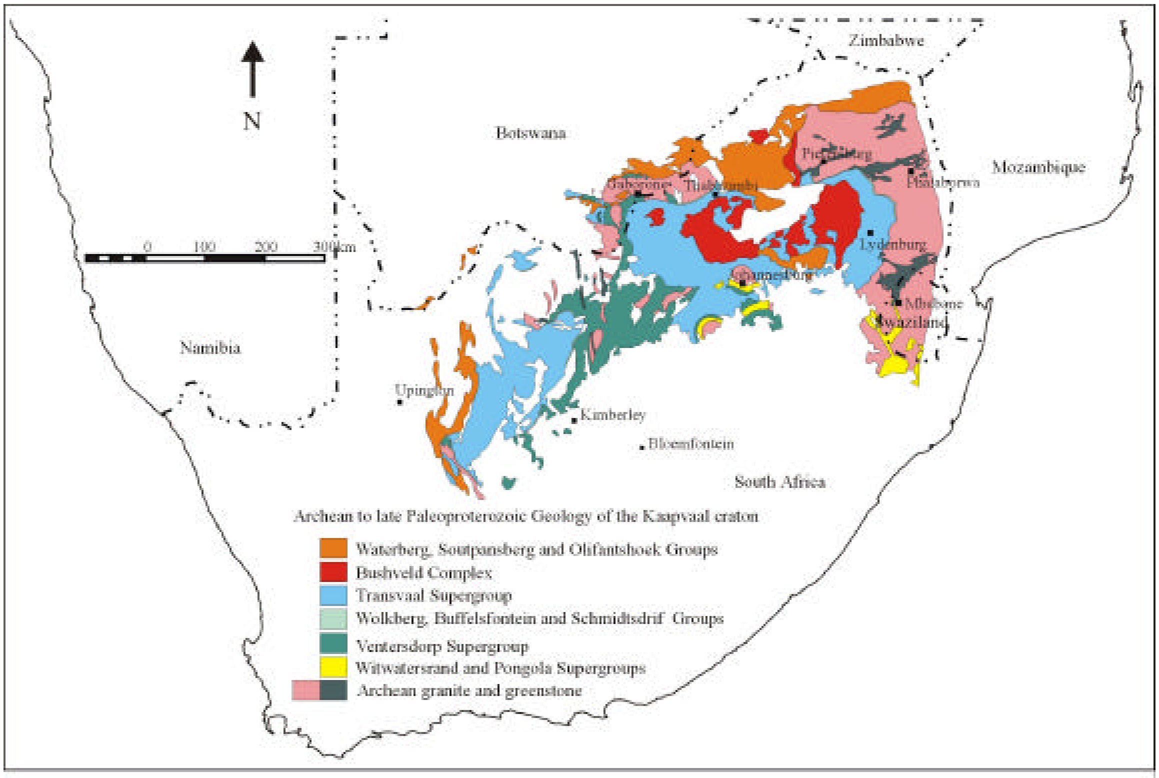

Figure 2.3 Archean to late Paleoproterozoic geology of the Kaapvaal craton. Modified from Cairncross (2004).

Zegers et al. (1998) placed the Pilbara craton immediately to the east of the Kaapvaal craton based on structural, geochronological and paleomagnetic data, but stated that it remains uncertain when the Limpopo Belt accreted to the Kaapvaal craton. It is important to note that in most reconstructions, the Zimbabwe and Kaapvaal cratons are placed next to each other since around 2.7Ga, the time of granulite facies metamorphism in the Limpopo metamorphic belt (Barton and Van Reenen, 1992). However, this model

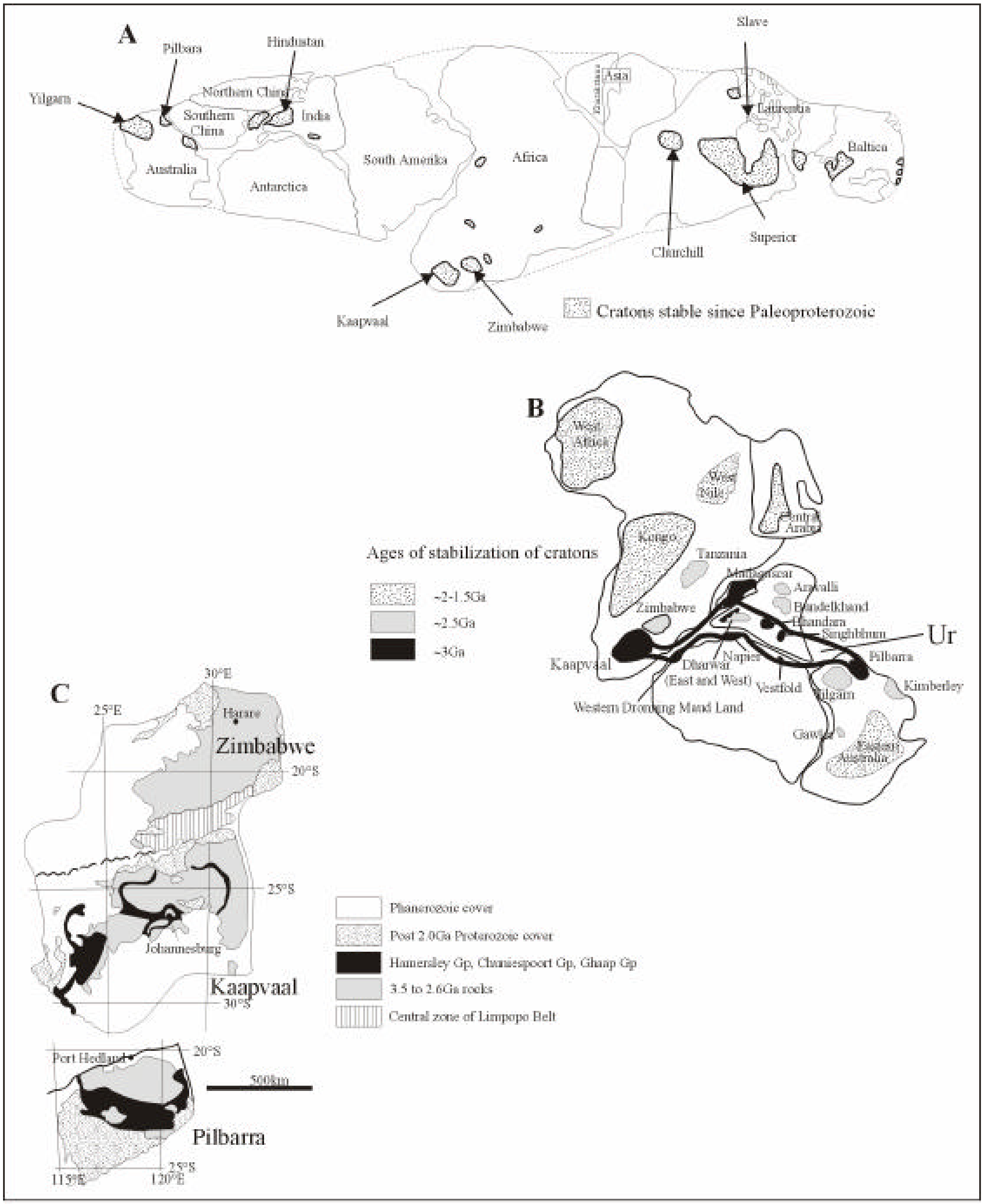

Figure 1. 4 **A**-Paleomagnetic reconstruction of continents between 2700 and 2200Ma after Piper (1982). **B**- Paleogeographical configuration of the Archean to Paleoproterozoic continent Ur after Rogers (1996). **C**- Proposed configuration of the Zimvaalbara continent after Cheney (1996).

is challenged since the identification of a 2000Ma old metamorphic event in the Limpopo metamorphic belt (Holzer et al., 1998).

b) The absence of radiometric ages for late Paleoproterozoic red bed successions such as the Waterberg and Soutpansberg Groups creates uncertainty in how the different red bed successions on the Kaapvaal craton correlate with one another.

c) Source areas and ages for detrital sedimentary sequences on the Kaapvaal craton are largely unknown.

These fundamental uncertainties surrounding the geology of the Kaapvaal craton may, at least in part, be resolved by radiometric SHRIMP dating of detrital zircons. Especially the identification of ages of source areas for detrital zircons could help unravel the paleogeographic setting of the Kaapvaal craton relative to other cratons in Archean-early Paleoproterozoic times.

1.2 Objectives of Study

Based on the above the objectives of this study were defined as follows:

a) To date magmatic zircons from certain lava units and granitic intrusions in order to constrain the ages of sedimentary basins. The lava units targeted were the Hekpoort and Ongeluk lavas of the Transvaal Supergroup, the Swaershoek and Rust de Winter lavas of the Waterberg Group, the Ngwanedsi lava of the Soutpansberg Group and the Selika lava of the Palapye Group (Fig 1.5). Furthermore, an accurate age was determined for the Entabeni granite.

b) To determine the ages of detrital zircon populations from several of the late Archean to early Paleoproterozoic successions on the Kaapvaal craton. Units targeted included the Transvaal Supergroup, Wolkberg, Waterberg, Soutpansberg and Palapye Groups and the Roodeberg Formation (Fig 1.5).

c) To attempt to construct a plate tectonic model for the Kaapvaal craton from late Archean to early Paleoproterozoic times, based on known tectono-sedimentary models for some of the cover sequences on the craton, combined with the ages of detrital zircon populations obtained during this study.

The three objectives outlined above forms the basis for the three major parts of this thesis.

1.2.1 Part 1: Constraining the Age of Paleoproterozoic Sedimentary Basins.

1.2.1.1 Transvaal Supergroup

The Transvaal Supergroup (Fig 1.2) is a remarkably well-preserved Paleoproterozoic sedimentary succession. The radiometric age of the basal portion of the Transvaal Supergroup has been well constrained between 2650-2400Ma by dating of zircons from various tuff layers (Altermann and Nelson, 1998; Martin et al., 1998; Sumner and Bowring, 1996, Gutzmer and Beukes, 1998). However, in the upper part of the Transvaal Supergroup, there are very few radiometric age constraints. A Re/Os age of 2320Ma has recently been obtained for pyrite of the lower Timeball Hill Formation (Hannah et al., 2002). The only geochronological data available from lava in the upper Transvaal Supergroup is whole rock Pb-Pb ages of 2222±12Ma and 2236±38Ma respectively for the Hekpoort and Ongeluk lavas (Cornell et al., 1996), which support the widely accepted suggestion that the Ongeluk and Hekpoort Formations are laterally correlative units. However, Bau et al (1999) obtained a secondary-lead age of 2394±26Ma for the Mooidraai dolomite that is stratigraphically above the Ongeluk Formation in Griqualand West (Beukes, 1986). This led to a proposed new correlation between the Transvaal Supergroup in the Griqualand West and Transvaal areas in which the Mooidraai Formation is correlated with the Duitschland Formation at the base of the Pretoria Group (Moore et al., 2001). Beukes et al. (2002) proposed that red beds of the Gamagara and Dwaal Heuvel Formations are in similar stratigraphic positions above the Gamagara-Dwaal Heuwel erosional surface. This stratigraphic correlation is further supported by distinct $\delta^{13}C$ excursions in carbonates that are in similar stratigraphic positions in the Lucknow and Silverton Formations (Swart, 1999, Buick et al., 1998). During this study, attempts were made to find suitable lithologies from which to isolate zircons and obtain radiometric ages using SHRIMP and TIMS for both the Hekpoort and Ongeluk Formations.

1.2.1.2 Waterberg and Soutpansberg-type Red Bed Sequences

Prior to this study, only one precise zircon U-Pb age existed for the Waterberg and Soutpansberg-type red bed sequences, (Fig 1.2), namely the age of 1928±4Ma (Cornell et al., 1998, Pb-Pb zircon age by Kober-technique) for the Hartley lava of the Olifanthoek Group. Stratigraphic relationships and relative ages of these red bed successions are thus not well understood and based on lithostratigraphic studies only (Jansen, 1976; Meinster, 1977; Bumby, 2000). These sedimentary successions include the Waterberg Group (Bumby, 2000; Callaghan et al., 1991; De Vries, 1969, Jansen, 1982), Soutpansberg Group (Barker, 1979; Barton and Pretorius, 1997; Cheney et al., 1990), Palapye Group (Ermanovics et al., 1978) and Roodeberg Formation (Gutzmer et al., 2002). These successions are preserved over more than 400 000km^2 on the Kaapvaal Craton (Fig 1.3), by volume the largest group of Precambrian siliciclastic successions on the Kaapvaal craton. Attempts were made in this study to obtain radiometric ages for several lava units from these successions in order to resolve some of the existing uncertainties.

1.2.1.3 The Age of the Entabeni Granite from the Limpopo Belt

The Entabeni granite is a post-tectonic granite that intrudes into the Limpopo belt (Barton et al., 1995). The age of this granite constrains the maximum age for the unconformably overlying Soutpansberg Group.

1.2.2 Part 2: Defining Detrital Zircon Populations within Late Archean to Late Paleoproterozoic Sedimentary Sequences

In an attempt to trace detrital zircon populations for the late Archean to Paleoproterozoic sedimentary sequences, representative samples of detrital zircons from several prominent quartzite successions (Fig 1.5) were analysed by SHRIMP, in order to obtain ^{207}Pb/^{206}Pb radiometric ages. As a method of defining the age of sedimentary provenance, detrital zircon are extremely useful, although subject to a number of potential biases. Firstly, the zircons will provide only the age of zircon-bearing lithologies in the source area, and, therefore, they certainly have a bias towards felsic rocks. Secondly, the necessity for producing near-concordant points in order to obtain reliable ages, requires that only

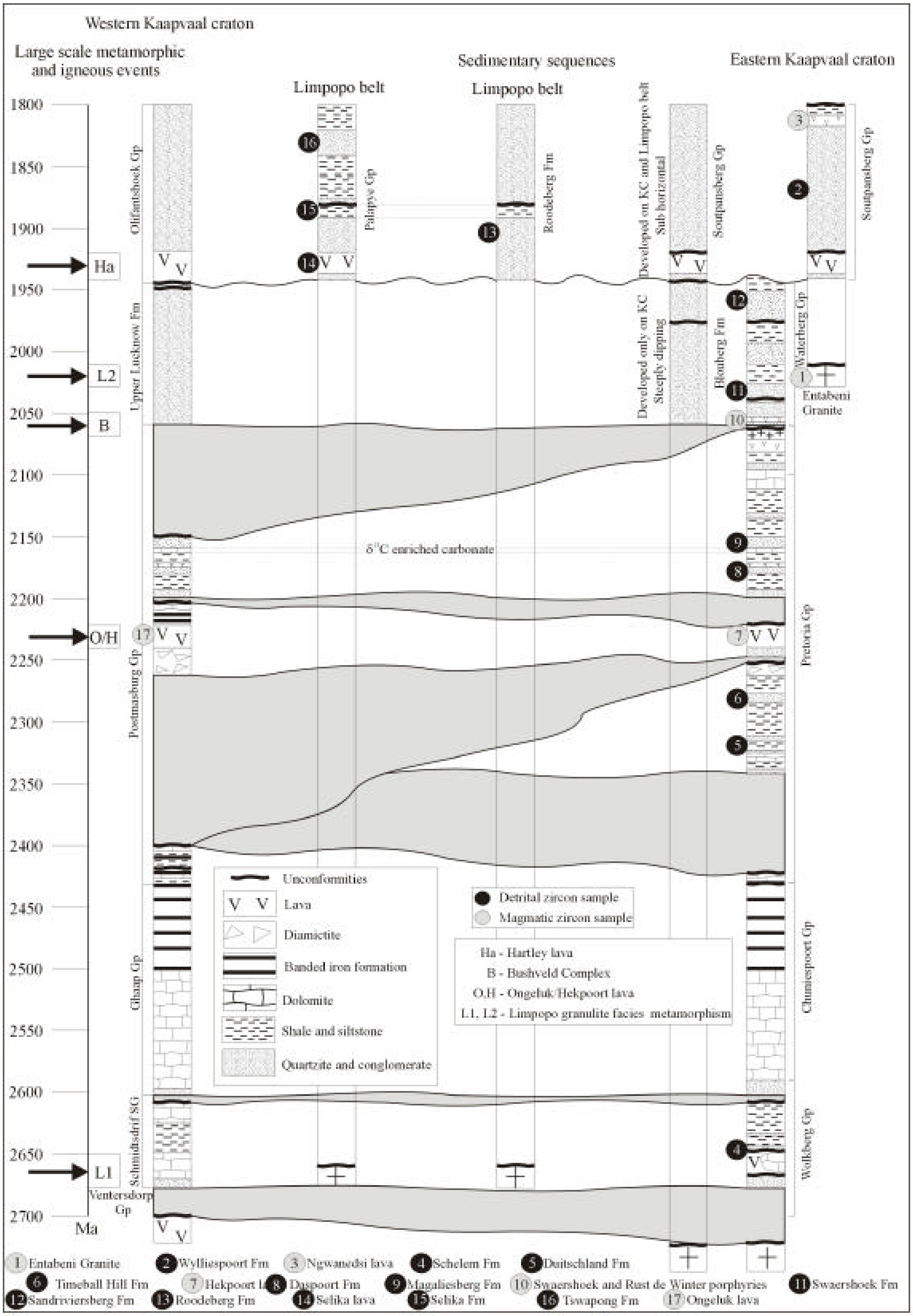

Figure 1.5 Tentative time-stratigraphic correlation of late Archean to Paleoproterozoic sedimentary successions on the Kaapvaal craton indicating units which have been sampled for SHRIMP dating of zircons during this study.

absolutely clear, crack-free grains with no evidence of alteration are chosen for analyses. These normally constitute only a small fraction of the total zircon population. Thirdly, Hartmann and Santos (2004), which studied the Brazilian Shield, found that ages obtained from detrital zircons in mature sandstones reflect magmatic sources, and not the full spectrum of orogenic events. They found that only less mature sedimentary rocks on the Brazilian Shield preserve a full record of orogenic rocks in the source (Hartmann and Santos, 2004). They suggest that high-U, metamorphic portions of zircon grains are more likely to undergo comminution by abrasian during weathering and transport, and they do not remain in the sand fraction (Hartmann and Santos, 2004). At this stage of it is not possible to tell what the implications of the findings by Hartmann and Santos (2004) may have for results presented here for the zircon provenance of sedimentary rocks of the Kaapvaal craton. Despite these limitations, detrital zircon SHRIMP analyses provide important constraints on the ages of source areas and the timing of sedimentation (Compston et al., 1984; Compston, 1996; Froude et al., 1983; Robb et al., 1990, Barton et al., 1989).

1.2.3 Part 3: Tectono sedimentary model

The focus of the third part of this thesis is to integrate radiometric ages that were obtained during this study with existing sedimentological data to reconstruct the plate tectonic history of the Kaapvaal craton during the late Archean to the early Paleoproterozoic.

1.3 Methods

In order to reach the outlined objective, detailed studies were undertaken on several late Archean to early Paleoproterozoic sedimentary sequences across the Kaapvaal craton and the southern marginal and central zones of the Limpopo Belt (Fig 1.5).

Suitable localities were selected and stratigraphic profiles measured in selected outcrop areas of the Wolkberg Group, Transvaal Supergroup, Waterberg Group, Soutpansberg Group, Palapye Group and Roodeberg Formations (Fig 1.5). Representative quartzite and specific lava samples were collected for several formations in these sequences from which zircons were then separated (Fig 1.5). Zircons were analysed by SHRIMP in order to obtain U-Pb and $^{207}Pb/^{206}Pb$ ages for the zircons from selected samples. All analytical methods used in this study are described in Appendix I. SHRIMP analyses were undertaken at Curtin University of Technology, Perth, Western Australia and the Australian National University in Canberra, Australian Capital Territory.

1.4 References

Altermann, W., Nelson, D.R. (1998). Sedimentation rates, basin analyses and regional correlations of three Neoarchean and Palaeoproterozoic sub basins of the Kaapvaal Craton as implied by precise SHRIMP U-Pb zircon ages from volcanic sediments. Journal of Sedimentary Geology, 120, 225-256.

Armstrong, R.A., Compston, W., Retief, E.A., Williams, I.S. and Welke, H.J. (1991). Single zircon ion microprobe studies bearing on the age and evolution of the Witwatersrand triad. Precambrian Research, 53, 243-266.

Barker, O.B. (1979). A contribution to the geology of the Soutpansberg Group Waterberg Supergroup, Northern Transvaal. M.Sc thesis (unpublished), University of the Witwatersrand, 116pp.

Barton, E.S., Compston, W., Williams, I.S., Bristow, J.W., Hallbauer, D.K. and Smith, C.B. (1989). Provenance ages for the Witwatersrand Supergroup and the Ventersdorp Contact Reef: Constraints from ion microprobe U-Pb ages of detrital zircons. Economic Geology, 84, 2012-2019.

Barton, J.M. and Van Reenen, D.D. (1992). When was the Limpopo orogeny? Precambrian Research, 55, 7-16.

Barton, J.M., Doig, R. and Smith C.B. (1995). Age, origin, and tectonic significance of the Entabeni granite, northern Transvaal, South Africa. South African Journal of Geology, 98(3), 326-330.

Barton, J.M. and Pretorius, W. (1997). The lower unconformity bounded sequence of the Soutpansberg Group and its correlatives- remnants of a Proterozoic large igneous province. South African Journal of Geology, 100(4), 335-339.

Bau, M., Romer, R.L., Luders, V., 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 and Planetary Science Letters, 174, 43-57.

Beukes, N.J. (1986). The Transvaal Sequence in Griqualand West, 819-828. In: Anhaeusser, C.R and Maske, S., (Editors), Mineral Deposits of Southern Africa, I. Geological Society of South Africa, 1020pp.

Beukes, N.J., Dorland, H.C., Gutzmer, J., Nedachi, M., and Ohmoto, H. (2002). Tropical laterites, life on land, and the history of atmospheric oxygen in the Paleoproterozoic. Geology, 30(6), 491-494.

Bickle, M.J., Bettenay, L.F., Chapman, H.J., Groves, D.I., McNaughton, N.J., Campbell, I.H., De Laeter, J.R. (1993). Origin of the 3500-3300Ma calcalkaline rocks in the Pilbara Archean: Isotopic and geochemical constraints from the Shaw batolith. In Blake, T.S. and Meakins, A (Editors), Archean and Early Proterozoic geology of the Pilbara region, Western Australia. Precambrian Research, 60, 117-149.

Black, L.P., Kinny, P.D., Sheraton, J.W., Delor, C.P. (1991). Rapid reproduction and evolution of late Archean felsic crust in the Vestfold Block of East Antarctica. Precambrian Research, 50, 283-310.

Blake, T.S. (1993). Late Archean crustal extension, sedimentary basin formation, flood basalt volcanism and continental rifting: The Nullagine and Mount Jope Supersequences, Western Australia. In Blake, T.S. and Meakins, A (Editors), Archean and Early

Proterozoic geology of the Pilbara region, Western Australia. Precambrian Research, 60, 185-241.

Bleeker, W. (2003). The late Archean record: a puzzle in ca. 35 pieces. Lithos, 71, 2-4, 99-134.

Buick, I.S., Maas, R. and Gibson, R. (2001). Precise U-Pb titanite age constraints on the emplacement of the Bushveld Complex, South Africa. Journal of the Geological Society, London, 158, 3-6.

Buick, I.S., Uken, R., Gibson, P.L. and Wallmach, T. (1998). High $\delta^{13}C$ Paleoproterozoic carbonates from the Transvaal Supergroup, South Africa. Geology, 26(10), 875-878.

Bumby, A.J. (2000). The geology of the Blouberg Formation, Waterberg and Soutpansberg Groups in the area of the Blouberg mountain, Northern Province, South Africa. PhD thesis (unpublished), University of Pretoria, 323pp.

Cairncross B (2004). A field guide to rocks and minerals of Southern Africa (in press).

Callaghan, C.A., Eriksson, P.G. and Snyman, C.P. (1991). The sedimentology of the Waterberg group in the Transvaal, South Africa: and overview. Journal of African Earth Science, 13, 121-139.

Cheney, E.S. (1996). Sequence stratigraphy and plate tectonic significance of the Transvaal succession of southern Africa and its equivalent in Western Australia. Precambrian Research, 79, 3-24.

Cheney, E.S., Barton, J.M., and Brandl, G., 1990. Extent and age of the Soutpansberg sequences of southern Africa. South African Journal of Geology, 93, 664-675.

Compston, W. (1996). Origins, impact and continuing evolution. Journal of the Royal Society of Western Australia, 79, 109-117.

Compston, W., Williams, I.S., and Meyer, C.J. (1984). U-Pb geochronology of zircons from lunar breccia 73217 using sensitive high mass-resolution ion microprobe: Journal of Geophysical. Research, 89, Supp., p.B525-B534.

Cornell, D.H., Armstrong, R.A. and Walraven, F. (1998). Geochronology of the Proterozoic Hartley Basalt Formation, South Africa: constraints on the Kheis tectogenesis and the Kaapvaal Craton's earliest Wilson cycle. Journal of African Earth Sciences, 26, 5-27.

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 2222Ma Proterozoic sea. Precambrian Research, 79, 101-123.

De Vries, W.C.P. (1969). Stratigraphy of the Waterberg system in the southern Waterberg area, north western Transvaal. Annals of the Geological Survey of South Africa, 7, 43-56.

De Wit, J. M., Roering, C., Hart, R. J., Armstrong, R.A., De Ronde, C.E.J., Green, R.W.E., Tredoux, M., Peberdy, E., Hart, R.A. (1992). Formation of an Archean continent. Nature, 357, 553-562.

Ermanovics, I., Key, R.M., Jones, M.T. (1978). The Palapye Group, central-eastern Botswana. Transactions of the Geological Society of South Africa, 81, 61-73.

Froude, D.O., Ireland, T.R., Kinny, P.D., Williams, I.S., Compston, W., Williams, I.R. and Meyers, J.S. (1983). Ion microprobe identification of 4100-4200 Myr-old terrestrial zircons. Nature, 303, 616-618.

Groenewald, P.B., Grantham, G.H., Watkeys, M.K. (1991). Geological evidence for a Proterozoic to Mesozoic link between southeastern Africa and Dronning Maud Land: Journal of the Geological Society, London, 148, 1115-1123.

Gutzmer, J. and Beukes, N.J. (1998). High grade manganese ores in the Kalahari manganese field: Characterisation and dating of ore forming events. Unpublished Report, Rand Afrikaans University, Johannesburg, 221p.

Gutzmer, J., Nhleko, N., Beukes, N.J., Pickard, A. and Barley, M.E. (1999). Geochemistry and ion microprobe (SHRIMP) age of a quartz porphyry sill in the Mozaan Group of the Pongola Supergroup: implications for the Pongola and Witwatersrand Supergroups. South African Journal of Geology, 102(2), 139-146.

Gutzmer, J., Schaefer, M.O., Beukes, N.J. (2002). Red bed-hosted oncolitic manganese ore of the Paleoproterozoic Soutpansberg Group, Bronkhorstfontein, South Africa. Economic Geology, 97, 6, 1151-1166.

Hannah, J.L., Stein, H.J., Bekker, A., Markey, R.J., Holland, H.D. (2002). Chondritic initial $^{187}Os/^{188}Os$ in Paleoproterozoic shale (seawater) and the onset of oxidative weathering. Geochimica and Cosmochimica Acta, 67, A-34.

Hartmann, L.A. and Santos, J.O.S. (2004). Predominance of high Th/U, magmatic zircon in Brazilian Shield sandstones. Geology, 32, 73-76.

Holzer, L., Frei, R., Barton, J.M., Kramers, J.D. (1998). Unravelling the record of successive high grade events in the Central zone of the Limpopo Belt using single phase dating of metamorphic minerals. Precambrian Research 87, 87-115.

Jansen, H. (1976). The Waterberg and Soutpansberg Groups in the Blouberg area, northern Transvaal. Transactions of the Geological Society of South Africa, 79, 281-291.

Jansen, H. (1982). The geology of the Waterberg Basins in the Transvaal, Republic of South Africa. Memoir of the Geological Survey of South Africa, 71, 98pp.

Martin, D.McB., Clendenin, C.W., Krapez, B., McNaughton, N.J. (1998). Tectonic and geochronological constraints on late Archean and Palaeoproterozoic stratigraphic correlations within and between the Kaapvaal and Pilbara Cratons. Journal of the Geological Society, London, 155, 311-322.

Meen, J.K., Rogers, J. J. W., Fullagar, P.D. (1992). Lead isotopic compositions of the Western Dharwar craton, southern India: Evidence for distinct Middle Archean terranesin a Late Archean craton. Geochimica and Cosmochimica Acta, 56, 2455-2470.

Meinster, B. (1977). Discussion on H. Jansen: The Waterberg and Soutpansberg Groups in the Blouberg area, northern Transvaal. Transactions of the Geological Society of South Africa, 80, 289-296.

Moore, J.M., Tsikos, H., Polteau, S. (2001). Deconstructing the Transvaal Supergroup, South Africa: implications for Palaeoproterozoic palaeoclimate models. Journal of African Earth Sciences, 33, 437-444.

Pickard, A.L. (2003). SHRIMP U-Pb zircon ages for the Paleoproterozoic Kuruman Iron Formation, Northern Cape Province, South Africa: evidence for simultaneous BIF deposition on Kaapvaal and Pilbara Cratons. Precambrian Research, 125, 275-315.

Piper, J.D.A. (1982). The Precambrian paleomagnetic record: The case for the Proterozoic supercontinent. Earth and Planetary Science Letters, 59, 61-89.

Robb, L.J., Davis, D.W., Kamo, S.L. (1990). U-Pb ages on single detrital zircon grains from the Witwatersrand Basin, South Africa: constraints on the age of sedimentation and on the evolution of granites adjacent to the basin. Journal of Geology, 98, 311-328.

Rogers, J.J.W. (1996). A history of continents in the past three billion years. Journal of Geology, 104, 91-107.

Sarkar, G., Corfu, F., Paul, D.K., McNaughton, N.J., Gupta, S.N., Bishui, P.K. (1993). Earth Archean crust in Bastar craton, central India-a geochemical and isotopic study. Precambrian Research, 62, 127-137.

Sharma, M., Basu, A.R., Ray, S.L. (1994). Sm-Nd isotopic and geochemical study of the Archean tonalite-amphibolite association from the eastern Indian craton. Contribution to Mineralogy and Petrology, 117, 43-55.

Sumner, D.Y., and Bowring, S. (1996). U-Pb geochronological constraints on deposition of the Campbellrand Subgroup, Transvaal Supergroup, South Africa. Precambrian Research, 79, 25-35.

Swart, Q.D. (1999). Carbonate rocks of the Paleoproterozoic Pretoria and Postmasburg Groups, Transvaal Supergroup. M.Sc thesis (unpublished), Rand Afrikaans University, Johannesburg, 126pp.

Thomas, R.J., Agenbacht, A.L.D, Cornell, D.H. and Moore, J.M. (1994). The Kibaran of southern Africa: Tectonic evolution and metallogeny. Ore Geology Reviews, 9, 131-160.

Trendall, A.F., Compston, W., Williams, I.S., Armstrong, R.A., Arndt, N.T., McNaughton, N.J., Nelson, D.R., Barley, M.E., Beukes, N.J., de Laeter, J.R., Retief, E.A., Thorne, A.M. (1990). Precise zircon U-Pb geochronological comparison of the volcano-sedimentary sequences of the Kaapvaal and Pilbara cratons between about 3.1 and 2.4Ga. Third International Archean Symposium, Perth, Extended Abstracts, 81-83.

Walraven, F. (1997). Geochronology of the Rooiberg Group, Transvaal Supergroup, South Africa. Economic Geology Research Unit Information Circular No. 316, 21pp University of the Witwatersrand, Johannesburg.

Walraven, F. and Hatting, E. (1993). Geochronology of the Nebo Granite, Bushveld Complex. South African Journal of Geology. 96, 31-41.

Wilde, SA, Valley, J.W, Peck, W.H., and Graham, C.M. (2001). Evidence from detrital zircons for the existence of continental crust and oceans on the Earth 4.4Gyr ago. Nature, 409, 175-178.

Wingate, M.T., (1998). A palaeomagnetic test of the Kaapvaal-Pilbara (Vaalbara) connection at 2.78Ga. South African Journal of Geology, 101, 257-274.

Zegers, T.E., M.J. de Wit, Dann, J., White, S.H. (1998). Vaalbarra, Earth's oldest assembled continent? A combined structural, geochronological, and palaeomagnetic test. Terra Nova, 10, 250-259.