Old, strong continental lithosphere with weak Archaean margin at ~1.8 Ga, Kaapvaal Craton, South Africa

Justine H. Tinker and Maarten J. de Wit
CIGCES, Geological Sciences, University of Cape Town, Rondebosch 7701, South Africa
Correspondence should be addressed to J.T.
(e-mail: Justine@cigces.uct.ac.za) or M.dW. (e-mail: Maarten@cigces.uct.ac.za)

Leigh H. Royden
EAPS, Massachusetts Institute of Technology, Cambridge, MA 02139-4307

ABSTRACT

Low elastic strength of ancient lithosphere based on flexural analyses has been interpreted to reflect elevated regional geothermal gradients in response to higher global heat production in the past. Here we present a flexural analysis of Archean/Palaeoproterozoic sediment cover along the western margin of the Archaean Kaapvaal craton based on seismic stratigraphy. Our results show that between ~1.93 and ~1.75 Ga, the Archaean margin of the craton had an effective elastic thickness of 7.5 to 10km compared to its present day value of 60 to 70km. Because the Kaapvaal craton had already stabilized by ~2.7 Ga and was underlain by 150 to 300km thick strong mantle lithosphere, it is unlikely that the relatively thin elastic thickness along this old margin reflects a change in secular cooling of the Earth. Instead, we interpret the low elastic strength to be a transient marginal tectonic effect similar to that recorded along modern continental margins.

Introduction

Archaean continental lithosphere is stronger to greater depth than that of younger continental lithosphere (Jordan, 1978; Shapiro *et al.*, 1999). It is not known, however, whether this is a function of its age or of the well-known chemical difference between old and young continental lithosphere. Understanding of how the flexural strength of present-day continental lithosphere, expressed as its effective elastic thickness, has varied over time is hampered by a lack of Archaean/Palaeoproterozoic estimates of lithospheric strength. Although present-day lithospheric elastic thickness variation calculated at different neo-tectonic environments of the world is well known (*e.g.* Doucouré *et al.*, 1996), only one similar calculation has been made for very old palaeo-tectonic environments (Grotzinger and Royden, 1990), because such measurements can only be made by proxy methods, using for example, stratigraphic analysis of ancient sedimentary basins.

Here we estimate the Palaeoproterozoic lithospheric elastic thickness of the Archaean Kaapvaal craton from analysis of the flexural shape of its Archaean/Palaeoproterozoic passive margin sequence in response to tectono-sedimentary loading of this margin at ~1.93 to ~1.75 Ga. We then compare this paleo-elastic thickness to the present day elastic thickness of the craton.

Regional Setting

The Kaapvaal craton comprises a complex mosaic of Archaean terranes that amalgamated episodically between about ~3.5 and ~2.8 Ga (de Wit *et al.*, 1992; de Wit, 1998; Schmitz *et al.*, 2004). Cratonic stability was attained in different areas at different times, but by ~2.7 Ga the entire Kaapvaal craton was part of a stable continent with a relatively cool, thick mantle of >150km (Boyd *et al.*, 1985; Richardson *et al.*, 2001; James *et al.*, 2001). Subsequent regional extension, peneplanation and deposition of a shallow marine sequence across the craton followed. This late Archaean history is recorded along the western margin of the Kaapvaal craton in the seismic profile KBF03A (located in Figure 1, interpreted in Figure 2). A two-stage (successor) tectono-stratigraphic evolution is evident from this profile (Tinker, 2001; Tinker *et al.*, 2002). The lower succession (Ventersdorp, Griqualand West and lower Olifantshoek units) is interpreted to have been deposited in a 'passive' continental margin environment during mechanical rifting between an unknown fragment and the Kaapvaal Craton in Ventersdorp times (~2.7 Ga), followed by continental separation (drifting) and regional thermal subsidence of the craton in Transvaal times (~2.6 to ~2.2 Ga). The 'passive' margin was subsequently transformed into an 'active' compressional margin during which stacked thrust-packages loaded the passive margin sequence mentioned above. The east-directed thrusting occurred between ~1929 and ~1750 Ma (age of regional Olifantshoek deformation; Cornell *et al.*, 1998), causing the foreland to be flexed downward to the west. This flexure allows determination of lithospheric effective elastic thickness of the Archaean lithosphere, thus its strength, at time of thrusting.

Data and Methods

The strength of the lithosphere can be expressed in terms of its rigidity (D) or related effective elastic thickness (Te). The method of determining Te is adapted from Royden's (1988) flexural equation that considers all

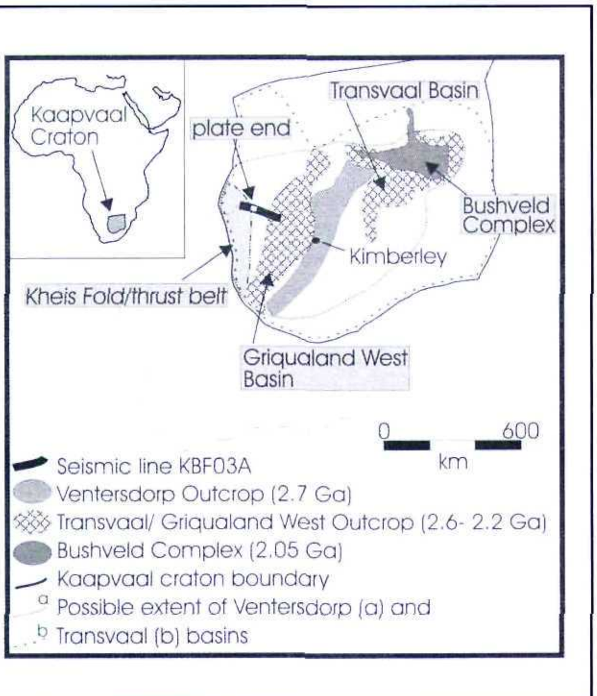

Figure 1. Location of the seismic reflection profile KBF03A across the western margin of the Kaapvaal craton. Also shown is the Kheis fold and thrust belt that comprises a tectono-stratigraphic sequence emplaced across the western edge of the craton between ~1.93 and ~1.75 Ga and the Bushveld Complex that introduced significant heat at lower to middle-crustal levels during its intrusion in ~2.05 Ga.

forces and torques acting on a flexed plate, and relates those to stress and strain changes coupled with deflection. The equation approximates the response of plates of variable elastic thickness under varying loads. Underlying the calculation is the assumption that the flexed lithosphere acts as an elastic plate overlying a fluid asthenosphere.

Estimation of lithospheric effective elastic thickness (Te) *involves the substitution of various estimates of* flexural wavelength of the lithosphere (related to Te) into the flexural equation given in Royden (1988). Theoretical curves generated by the solutions of the flexural equation for six different values of elastic thickness (5, 7.5, 10, 15, 20 and 30km) are then compared to flexure observed from the seismic profile, KBF03A. This profile was acquired by AngloGold using vibroseis methods across the western margin of the Kaapvaal Craton (Figures 1 and 2) and interpreted using Charisma software, Geoframe version 3.6, developed by Geoquest, Schlumberger (Tinker, 2001; Tinker *et al.*, 2002). The theoretical curve calculated from the flexural equation that best fits the observed data has the most realistic flexural wavelength and represents the most realistic Te (Figure 3).

Flexure produced by loading of sediments during the development of the passive margin imaged in profile KBF03A (~2.7 to ~2.2 Ga) must be separated from that produced by subsequent tectonic loading of these passive margin sediments (~1.93 to ~1.75 Ga). To *achieve this, a seismic reflector was chosen that is* assumed to have been sub-horizontal, prior to load emplacement. The base of the Campbellrand Subgroup is assumed originally horizontal for two reasons:

The Campbellrand Subgroup is a platform carbonate sequence, likely to have formed in shallow water depths during regional thermal subsidence.

The Campbellrand Subgroup does not thicken substantially to the west across the seismic profile, indicating that any passive margin subsidence was *similar across the margin.*

By observing deflection of this marker horizon, it is possible to isolate deflection due to the subsequent tectonic loading of the passive margin sediments, from flexure produced by preferential subsidence and sediment accumulation in the west during initial passive margin development.

For our calculations a 'plate end' (0km) was located at a point at 45km from the western end of line KBF03A (Figure 2). Flexure was thus estimated from the deflection of a marker horizon, the Campbellrand/ Schmidtsdrif contact (Figure 2), from plate end along the profile at 7.5km spaced intervals and plotted on Figure 3 (red squares). Two additional points were established from geological surface mapping at 180.5 and 202.5km from the plate end. Thus, an observation curve was generated and compared to the theoretical curves (Figure 3).

Results

Our results must be evaluated in light of a number of uncertainties. First, velocity/depth conversions on the seismic section are approximate. Second, there is no correction for sediment compaction due to the lack of lithological control from borehole data. Third, flexural observations made east of 52.5km are calculated by adding an average thickness for the Schmidtsdrif Subgroup to the granitic basement/Schmidtsdrif contact. The Schmidtsdrif Subgroup thins to the east, thus these observations may overestimate flexure. Fourth, there are no independent gravity data to offer an independent check of the results, as is the case in modern examples (Royden, 1988; Abers and Lyon-Caen, 1990; Stewart and Watts, 1997; Reemst and Cloetingh, 2000).

In general, curves representing lower Te offer a better fit to the observations (Figure 3). However, at Te = 5km, the curve is a poor fit. First, the curve does not match the observed deflection at plate end (0km). Second, at 120km the deflection is zero, yet geological surface mapping shows that the contact outcrops at 180.5km. Therefore, the calculated flexural curve results in a flexural bulge that is too narrow in width and that lies too far to the west. Clearly the elastic thickness at ~1.93 to ~1.75 Ga was greater than 5km.

Three flexural curves generated for Te = 15, 20 and 30km also show a poor fit to observations. Between 0 and 30km all three flexural curves underestimate the observed deflection, and between 30 and 90km the observed deflection is overestimated. In all three cases the flexural bulge occurs too far to the east and the curves differ by 150 to 300km from the two outcrop observations at 180.5 and 202.5km. Thus at time of load emplacement, elastic thickness was less than 15km.

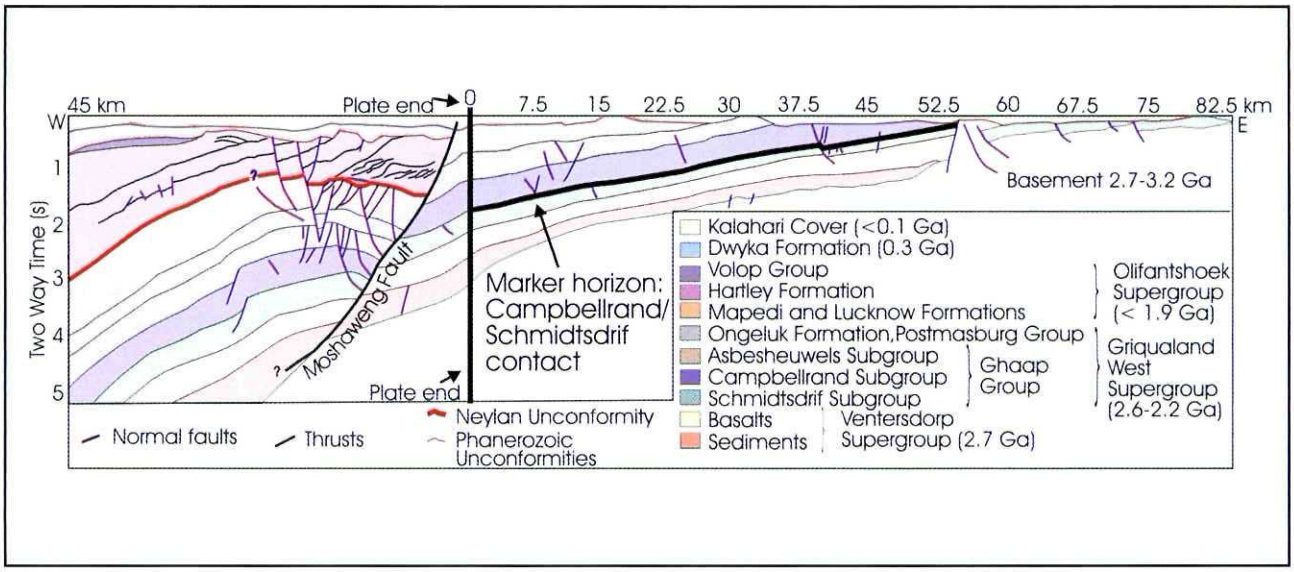

Figure 2. Stratigraphic and structural interpretation of seismic profile KBF03A. The detailed analysis of the seismic stratigraphy is given elsewhere (Tinker, 2001; Tinker *et al.*, 2002). The Campbellrand/Schmidtsdrif contact is assumed to have been horizontal prior to tectonic loading, and the deflection of this marker horizon defines differentiates the flexure developed due to tectonic loading at ~1.93 to ~1.75 Ga. The plate-end marks the western most extent of the measured flexure. Farther to the west, the marker horizon is displaced by faulting, and flexure estimates are unreliable.

Two curves with Te = 7.5 and 10km provide better fits. From 0 to 45km, both flexural curves closely fit the observed deflections. However, from 52.5 to 82.5km both curves overestimate the observed deflection. The curve of Te = 7.5km overestimates deflection to a lesser extent. At 180.5km, the flexural curve of Te = 10km differs from the observed curve by only ~ 7m. A least squares statistical technique is used to graphically confirm the best fit of curves for Te = 7.5 and 10km to the observed deflections (Figure 3, inset). Thus, the elastic thickness of the plate during time of flexure is best estimated to have been in the range of 7.5 to 10km, despite a number of important uncertainties (see Data and Methods above).

Discussion

Profile KBF03A lies within 250km of kimberlites that have yielded Paleoproterzoic-Archaean diamond xenocrysts derived from deep depleted mantle sources (Richardson *et al.*, 2001). Therefore, by ~1.8 Ga, the craton was already underlain by thick continental lithosphere. The present-day Te of this lithosphere has been calculated with a coherence technique using Bouguer gravity data and topographic information (Doucouré *et al.*, 1996). Their value of Te along line KBF03A ranges from ~ 60 to 70km, ~ 8 ± 2 times greater than that calculated by us at ~1.93 to ~1.75 Ga. This implies that there has been significant recovery of mechanical strength of the existing thick lithosphere.

A relatively thin palaeo-elastic thickness for old continental lithosphere has been reported once before. In a flexural study of the Kilohigok Basin in the Archean Slave Craton a palaeo-elastic thickness at 1.9 Ga of only 12 ± 4km was calculated. This contrasts with the present-day effective elastic thickness of 100 ± 25km for this area (Grotzinger and Royden, 1990). The authors concluded that at 1.9 Ga the Slave Craton must have lacked the several hundred kilometre thick mechanical mantle lithosphere layer that it has today, and contributed this significant thickening of the mantle lithosphere over the last ~1.9 Ga to related secular cooling of the Earth. More recently it has become apparent that the Slave Craton has an old (>3.0 Ga) thick, diamond-rich, Archaean mantle root (O'Reilly *et al.*, 2001), like that of the Kaapvaal Craton (Boyd *et al.*, 1995; Richardson *et al.*, 2001; James *et al.*, 2001). Therefore it appears that both these areas have a similar history of change in elastic thickness but the cause for this cannot be attributed to the absence in the Archaean of a thick relatively cool mantle lithosphere.

Several other possible explanations for a thin value for lithospheric Te at ~1.93 to ~1.75 Ga exist. High heat flow and/or fluid influx (hydration) have been inversely correlated to elastic strength (Zoetemeijer *et al.*, 1990; Hartley *et al.*, 1996; James and Sacks, 1999). Thus, thermal rejuvenation and/or hydration of the local crust, related to igneous activity at ~2.2 Ga and ~1.9 Ga (Ongeluk and Hartley lavas, respectively; Cornell *et al.*, 1996; Cornell *et al.*, 1998; Tinker, 2001; Tinker *et al.*, 2002), or the ~1.8 Ga tectonism may have reduced the mechanical strength of the underlying lithosphere. Associated lithospheric decoupling within a ductile lower crust (Abers and Lyon-Caen, 1990; Burov and Diament, 1995; 1996; Brown and Phillips, 2000; Doucouré and de Wit, 2002) may lower its elastic thickness further still. Although the link between magmatism and plate weakening is not fully understood, Doucouré and de Wit (2002) concluded that magmatic heat associated with the intrusion of the Bushveld complex (~2.05 Ga) induced regional mid-crustal decoupling and, in turn the low elastic thickness first calculated in Tinker (2001). Since the present studied

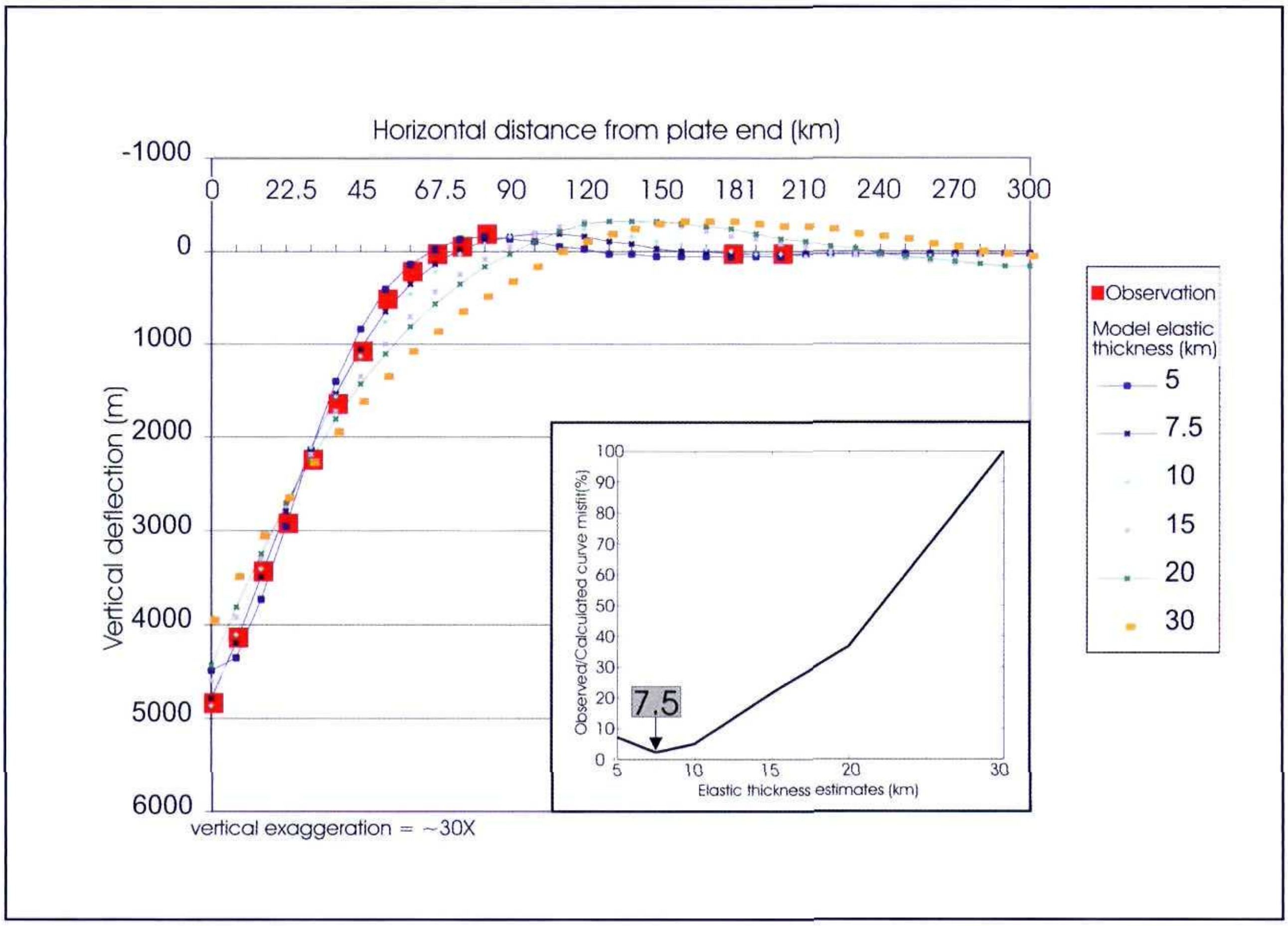

Figure 3. Theoretical curves generated from the flexural equation of Royden (1988). The best fit estimate of elastic thickness is evaluated against the flexure observed from the seismic profile shown in Figure 2. Low elastic thickness curves (7.5 to10km) closely resemble the observed flexural curve. Inset: Graph of results of a least squares comparison between the curves of various estimates of elastic thickness and the observed deflections. Difference between theoretical curves and observed data is represented as a % error using a least squares method. The curve for Te = 7.5km has the lowest % error and represents the best fit.

margin of the Kaapvaal Craton lies within a 1000km radius from the centre of the Bushveld intrusion; this is consistent with models of regional heat flow and magma activity channelled laterally over such distances away from a single hot-spot source such as the Cenozoic plume in northeast Africa (c.f. Ebinger and Sleep, 1998). There is, however, only limited isotopic evidence from lower crustal xenoliths near KBF03A for significant thermal rejuvenation in the lower crust during the 2.05 Ga Bushveld event (Schmitz, 2003).

Alternatively, low Te along the margin of the Kaapvaal craton may have been inherited from its tectonic history at a continental margin. Some of the lowest values for Te have been observed at present-day continental margins. High gradients of Te have been measured from thick and strong interior lithosphere to thin and weak lithosphere across the present-day continental margins of Scandinavia, South America, Australia and Antarctica (Stewart and Watts, 1997; Haddad and Watts, 1999; Reemst and Cloetingh, 2000) (Figure 4). The thin palaeo-Te calculated here thus may represent a weaker section along the palaeo-margin of the Kaapvaal craton with greater interior Te. Deposition of thick continental rift sequences (Waterberg) occurred from ~1.93 to ~1.75 Ga in fault-bounded rift basins across the Kaapvaal Craton nucleus. These brittle structures imply a stronger central cratonic interior at that time. This is consistent with the suggestion that the relatively low Palaeoproterozoic Te we have calculated along the western edge of the Kaapvaal craton represents a weak paleo-continental margin of a strong craton (Figure 4), a model that we prefer.

Conclusions

Our result confirms that since ~1.93 to ~1.75 Ga there has been significant lithospheric strength recovery along the margin of the Kaapvaal craton. Clearly, the low elastic strength of this Archaean lithosphere in the Palaeoproterozoic was not due to the lack of thick and mechanically strong mantle lithosphere. Along the margin of at least two Archaean cratons, it seems likely that mechanical weakening of their lithosphere was transient, and that initial lithospheric strength was recovered during younger lithospheric strengthening processes (Doucouré and de Wit, 2002). Although the origin for the low lithospheric strength of the craton margin at ~1.8 Ga is equivocal, the unusually low value for elastic thickness may reflect KBF03A's

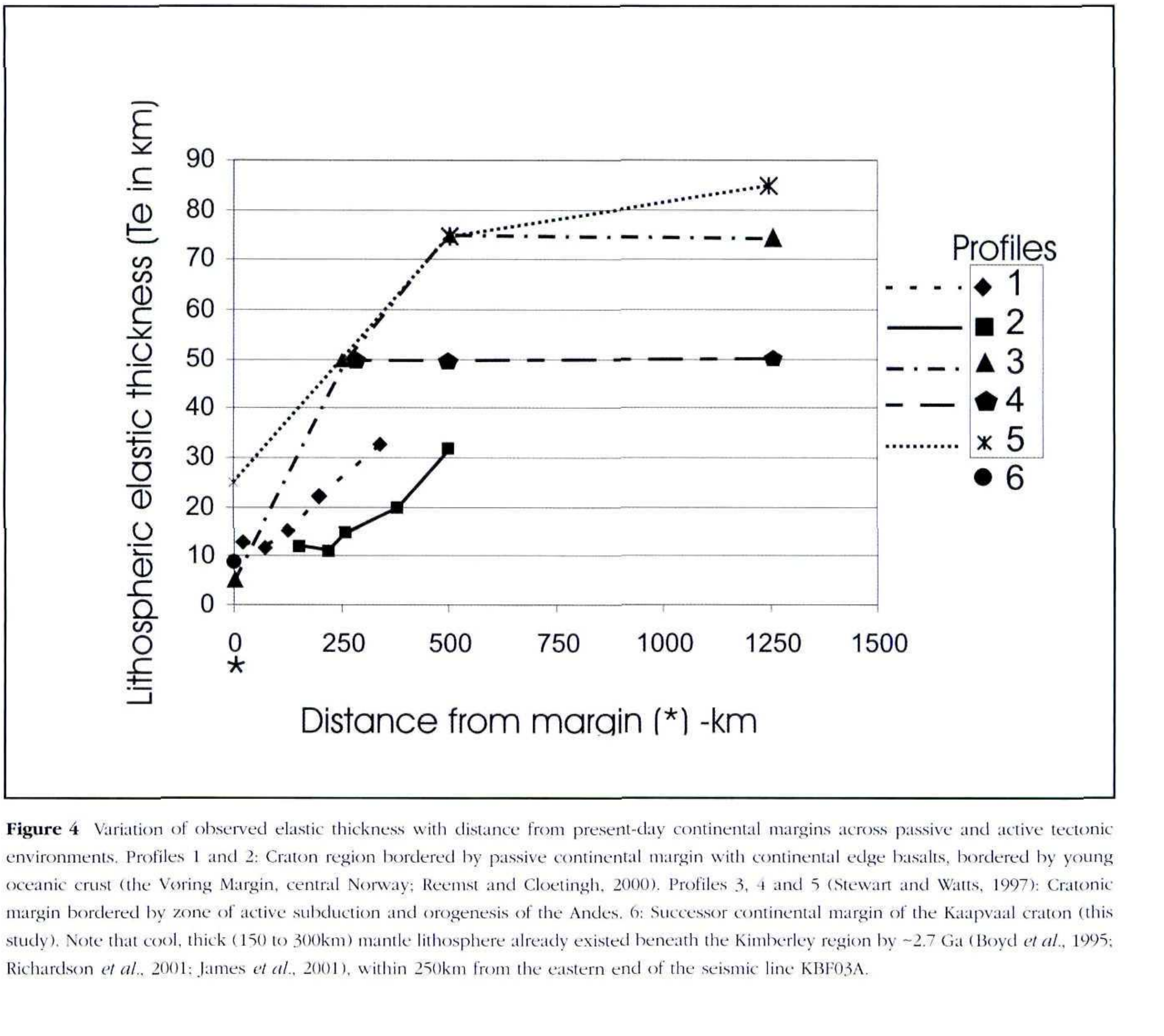

Figure 4 Variation of observed elastic thickness with distance from present-day continental margins across passive and active tectonic environments. Profiles 1 and 2: Craton region bordered by passive continental margin with continental edge basalts, bordered by young oceanic crust (the Vøring Margin, central Norway; Reemst and Cloetingh, 2000). Profiles 3, 4 and 5 (Stewart and Watts, 1997): Cratonic margin bordered by zone of active subduction and orogenesis of the Andes. 6: Successor continental margin of the Kaapvaal craton (this study). Note that cool, thick (150 to 300km) mantle lithosphere already existed beneath the Kimberley region by ~2.7 Ga (Boyd *et al.*, 1995; Richardson *et al.*, 2001; James *et al.*, 2001), within 250km from the eastern end of the seismic line KBF03A.

location near the craton margin, which acted as a passive extensional margin in the late Archaean to Paleoproterozoic. Recognition of Archaean cratonic lithosphere with low Te has numerous implications for the analysis of Archaean tectonics and geodynamic processes. For example, it supports models that propose that weak Archaean continental crustal sections were available for potential lithosphere recycling in Archaean subduction zones (*c.f.* Hildebrand and Bowring, 1999).

Acknowledgements

We thank J. Grotzinger for technical help and financial support for J.T. during two visits to MIT, and J. Stankiewicz for his help with the least squares statistical calculations. This work was supported by the South African National Research Foundation (NRF) and the Upstream Training Trust. We are particularly grateful to E. Kostlin (Anglo American Corp. Ltd.) for acting as a facilitator to acquire these data in 1996, 1997 and B. Steenkamp (AngloGold Ltd.) and M. Muller (Anglo American Corp. Ltd.) for access to their seismic reflection data. We thank our many Kaapvaal Craton Project colleagues for extended discussions over the last 6 years, and David James and Moctar Doucouré for their constructive reviews.

References

Abers, G.A. and Lyon-Caen, H. (1990). Regional gravity anomalies, depth of the foreland basin and isostatic compensation of the New Guinea Highlands. *Tectonics*, **9**, 1479-1493.

Boyd, F.R., Gurney, J.J. and Richardson, S.H. (1985). Evidence for a 150-200km thick Archean lithosphere from diamond inclusion thermobarometry. *Nature*, **315**, 387-389.

Brown, C.D. and Phillips, R. (2000). Crust-mantle decoupling by flexure of continental lithosphere. *Journal of Geophysical Research*, **105**, 13,221-13,237.

Burov, E.B. and Diament, M. (1995). The effective elastic thickness (Te) of continental lithosphere: What does it really mean? *Journal of Geophysical Research*, **100**, 3905-3927.

Burov, E.B. and Diament, M. (1996). Isostasy, equivalent elastic thickness and rheology of continents and oceans. *Geology*, **24**, 419-422.

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

De Wit, M.J. (1998). On Archaean granites, greenstones, cratons and tectonics: does the evidence demand a verdict? *Precambrian Research*, **91**, 181-226.

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

Doucouré, C.M. and de Wit, M.J. (2002). Temporal variation in rigidity and mechanical behaviour of old thick continental lithosphere. *South African Journal of Geology*, **105**, 39-50.

Doucouré, C.M., Mushayandebvu, M. F. and de Wit, M.J. (1996). Effective elastic thickness of the continental lithosphere in South Africa. *Journal of Geophysical Research*. **101** B5, 11,291-11,303.

Ebginger, C.J. and Sleep, N.H. (1998). Cenozoic magmatism throughout east Africa resulting from impact of a single plume. *Nature*, **395**, 788-791.

Grotzinger, J.P. and Royden, L. (1990). Elastic strength of the Slave craton at 1.9 Gyr and implications for the thermal evolution of the continents. *Nature*, **347**, 64-66.

Haddad, D. and Watts, A.B. (1999). Subsidence history, gravity anomalies, and flexure of the northeast Australian margin in Papua New Guinea. *Tectonics*, **18**, 827-842.

Hartley, R.W., Watts, A.B. and Fairhead, J.D. (1996). Isostasy of Africa. *Earth and Planetary Science Letters*, **137**, 1-18.

Hildebrand, R.S. and Bowring S.A. (1999). Crustal recycling by slab failure. *Geology*, **27**, 11-14.

James, D.E., Fouch, M.J., VanDecar, J.C., van der Lee, S. and Kaapvaal Seismic Group (2001). Tectonic structure beneath southern Africa. *Geophysical Research Letters*, **28**, 2485-2488.

James, D.E. and Sacks, S. (1999). Cenozoic Formation of the Central Andes: A Geophysical Perspective, 1-25. *In:* B. J. Skinner (Editor), Geology and Ore Deposits of the Central Andes. *Special Publication of the Society of Economic Geologists*, **7**, 1-25.

Jordan, T.H. (1978). Composition and development of the continental tectosphere. *Nature*, **274**, 544-548.

O'Reilly, S.Y., Griffin, W.L., Poudjom Djomani, Y.H. and Morgan, P. (2001). Are lithospheres forever? Tracking changes in subcontinental lithospheric mantle through time. *GSA Today*, **11**, 4-16.

Reemst, P. and Cloetingh, S. (2000). Polyphase rift evolution of the Voring margin (mid-Norway): Constraints from forward tectonostratigraphic modelling. *Tectonics*, **19**, 225-240.

Richardson, S.H., Shirey, S.B., Harris, J.W. and Carlson, R.W. (2001). Archaean subduction recorded by Re-Os isotopes in sulphide inclusions in diamonds. *Earth and Planetary Science Letters*, **191**, 257-266.

Royden, L. (1988). Flexural Behavior of the Continental Lithosphere in Italy: Constraints Imposed by Gravity and Deflection Data. *Journal of Geophysical Research*, **93** (B7), 7747-7766.

Schmitz MD and Bowring SA (2003) Constraints on the thermal evolution of continental lithosphere from U-Pb accessory mineral thermochronometry of lower crustal xenoliths, southern Africa. *Contributions To Mineralogy and Petrology*., **144**, 592-618.

Schmitz, M.D. Bowring, S.A., de Wit, M.J. and Gartz, V. (2004). Neoarchean continent collision in the western Kaapvaal Craton, southern Africa, and its implications for the stabilization of continental lithosphere *Earth and Planetary Science Letters*, (in Press)

Shapiro, S.S., Hager, B. and Jordan, T.H. (1999). Stability and dynamics of the continental tectosphere. *Lithos*, **48**, 115-133.

Stewart, J. and Watts, A.B. (1997). Gravity anomalies and spatial variations of flexural rigidity at mountain ranges. *Journal of Geophysical Research*, **102**, 5327-5352.

Tinker, J.H. (2001). Stratigraphic and structural interpretation of seismic reflection data across selected sections of the Kaapvaal Craton. *MSc Thesis (unpublished)*. University of Cape Town, South Africa. 184pp.

Tinker, J.H., de Wit, M.J. and Grotzinger, J. (2002). Seismic Stratigraphic Constraints on Neoarchean- Paleoproterozoic Evolution of the Western Margin of the Kaapvaal Craton, South Africa. *South African Journal of Geology*, **105**, 107-134.

Zoetemeijer, R., Desegaulx, P., Cloetingh, S., Roure, F. and Moretti, I. (1990). Lithospheric dynamics and tectonic-stratigraphic evolution of the Ebro Basin. *Journal of Geophysical Research*, **95**, 2701-2711.

Editorial handling: L.D. Ashwal