Structural variations of the crust in the Southwestern Cape, deduced from seismic receiver functions

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ABSTRACT

Receiver functions were generated from seismic traces recorded by seismographs in the southwestern Cape to estimate the crustal thickness and other crustal features in this area. The Moho here is found at variable depths. Crustal thicknesses below the Karoo basin gradually increases from ~46km in the north, near Kenhard, to ~50km, 300km farther south near the northern margin of the Southern Cape Conductive Belt that is buried beneath the southern Karoo basin. From there southward for about 150km beneath the frontal sector of the eastern branch of the Cape Fold Belt (as far as the Kango Fault), the crust thins to less than 40km. Farther southward still, for ~ 50km beneath the central sector of the eastern branch of the Cape Fold Belt to the extension of the Worcester Fault, the crust thickens to about 45km. Then towards the south-coast, beneath the southernmost sector of the eastern branch of the Cape Fold Belt, the crust thins rapidly to less than 30km. This thinning is likely associated with Jurassic-Cretaceous crustal stretching recorded in the stratigraphy of extensional basins of South Africa and its continental margin. Small scale variations in crustal thicknesses of ~4km around each recording station reflect variability of the Moho on a small scale which, beneath the Namaqua-Natal Mobile Belt is possibly related to the tectonic accretion history of this Kibaran-age belt; and beneath the Cape Fold Belt due to differential crustal extension and thinning in the Mesozoic.

Beneath the frontal sector of the Cape Fold Belt, sharp crustal discontinuities at ~8 and ~18km depth are detected at four seismic stations. These stations are all located above the Southern Cape Conductive Belt (SCCB) and its associated regional east-west trending positive magnetic anomaly (the Beattie Anomaly; the largest of its kind in Africa) that can be traced for almost 1000km across southern South Africa. The intracrustal discontinuities are interpreted as the upper and lower bounds of a ~10km thick block of altered Mesoproterozoic (Kibaran) mafic-ultramafic rocks that are assumed to be the source for the Beattie Anomaly and the electrically conductive SCCB. Towards the west, the upper contact of the source of the Beattie Anomaly/SCCB deepens from ~8km to ~11km before the magnetic signature disappears beneath the western branch of the Cape Fold Belt.

Introduction

The Kaapvaal Seismic Experiment was initiated in April 1997 as part of a multinational, multidisciplinary project to study the Kaapvaal Craton and its surrounds (Carlson *et al.*, 1996; James *et al.*, 2001; http://www.uct.ac.za/depts/cigces/visual.htm). Fifty-five broad-band seismometers were deployed at 82 seismic stations across southern Africa over a two year period (Figure 1a). During this time over 1500 teleseismic earthquakes generated by natural events were recorded, traversing the structure of the crust and lithosphere from Cape Town in the south to Masvingo, Zimbabwe in the north, crossing parts of Cape Fold Belt, the Namaqua-Natal Mobile Belt, the Kaapvaal Craton, the Limpopo Belt and the southern portion of the Zimbabwe Craton. For this study, twelve stations in the southwestern Cape were selected (Figure 1, Table 1) to determine aspects such as crustal thickness and its azimuthal variation beneath the late Paleozoic-early Mesozoic Cape Fold Belt. Another target of this study was to identify the depth and thickness of the crustal source responsible for the large (~500nT) regional positive Beattie Magnetic Anomaly, a well known magnetic feature of southern Africa that is coincident with a 100-200km wide electrically conductive zone in the crust, known as the Southern Cape Conductive Belt (SCCB, Figure 1).

Tectonic framework of the area

The Kaapvaal Craton forms the nucleus of the lithosphere of southern Africa. Since its stabilization about 2.7 Ga ago (de Wit *et al.*, 1992), crustal blocks have accreted to and surrounded it during successive tectonic events (Figure 1). Along the southern and southwestern boundary of the craton, the Namaqua-Natal Mobile Belt formed in Mesoproterozoic during such tectonic events between about 1.0-1.3 Ga (Tankard *et al.,* 1982; Thomas *et al.,* 1994; Eglington and Armstrong, 2001). During these events, Mesoproterozoic oceanic-like crust was obducted across the Kaapvaal Craton along its southeastern boundary in a series of nappe sheets (Matthews, 1990), and also along the inferred southernmost boundary of the Namaqua-Natal Mobile Belt (De Beer *et al.,* 1982; Hälbich 1993). Tectonism ceased by about 1.0 Ga when the Namaqua-Natal Mobile Belt finally stabilized against to the Kaapvaal Craton forming the "Kalahari Shield" (Thomas *et al.,* 1994; Eglington and Armstrong 2001). The southern extremity of the Namaqua-Natal lithosphere is buried beneath up to 5km of Late Paleozoic-Mesozoic sediments of the Karoo Basin (the Karoo Sequence). In turn, farther south still, up to 8km of early Paleozoic sediments of the Cape Basin (the Cape Supergroup) underlie the Karoo Sequence. Along the southernmost extremity of Africa, these sediments were extensively deformed about 250 myrs ago into a fold and thrust belt, known as the Cape Fold Belt. The origin of this belt is still subject to intense debate (Newton 1973; de Swardt, 1978; Hälbich, 1983; 1993; de Wit and Ransome 1992; Johnston 1998; 2000), in part because little is known about its structure at depth. Deformation was at low metamorphic grade. This, and associated structures suggest predominantly shallow and thin-skinned thrust tectonics (Booth and Shone, 1999; Booth 2001). The far-field stresses associated with this tectonics may have been located at a plate boundary more than a thousand kilometres to the south along the convergent margin of Gondwana (de Wit, 1977; Lock 1980; Trouw and de Wit 2001; Figure 1).

Crystalline basement to the Cape Fold Belt is not exposed in South Africa. In places deformed late Neoproterozoic to early Cambrian sediments, intruded by high-level Cambrian granites, are exposed below the Cape Basin sediments. These Eocambrian rocks are often referred to as Pan African, and locally known as Saldanian (Tankard *et al.,* 1982). These sediments/granites have been deformed with the Cape Supergroup during the late Paleozoic Orogeny and are also at low metamorphic grades. Thus the age and nature of mid-lower crustal basement to the Cape Fold Belt is not known. Detrital analyses and dating of zircons from the Eocambrian sediments, however, indicate a relatively proximal source of Namaqua-Natal crystalline rocks for the Cape Supergroup and the Saldanian sediments (Barnett *et al.,* 1998; Armstrong *et al.,* 1999).

Extensive uplift and volcanic activity followed during initial stages of Gondwana breakup and the formation of the Indian and South Atlantic oceans (~180 and ~130 Ma, respectively; Norton and Sclater, 1984; Brown *et al.,* 1995; Reeves and de Wit, 2000). Considerable crustal extension and the formation of continental margin sequences mark the present edge of the southern African continent (Brown, *et al.,* 1995; McMillan *et al.,* 1997). During this period of regional extension, a number of east-west trending asymmetric intramontaine Jurassic-Cretaceous basins formed throughout the eastern branch of the Cape Fold Belt, parallel to its east-west tectonic grain (Figure 2). These basins widen eastward into extensive offshore marine basins (Dingle *et al.,* 1993; Brown *et al.,* 1995). The basins are bound along their northern margins by extensive listric normal faults both within (Figure 2), and offshore to the east and south of the Cape Fold Belt (Viljoen, 1992; Brown *et al.,* 1995). The onshore faults (the largest being the Kango and Worcester faults, with displacement up to 6-10km, Dingle *et al.,* 1983) dip south beneath the asymmetric Cretaceous-Jurassic basins suggesting that significant north-south crustal extension has occurred. This has been verified by seismic reflection profiles and forward modelling across extensions of these basins where they are traced offshore (Viljoen, 1992; Cloeting *et al.,* 1992; Brown *et al.,* 1995; McMillan *et al.,* 1997). The region has further experienced extensive uplift and exhumation during the Tertiary (Partridge, 1998).

Table 1. Coordinates of the 12 seismic stations used in the study

Station	Lat. S	Lon. E	Height (m)
SA01	34.294	19.246	220
SA02	33.735	20.266	807
SA03	33.632	21.335	347
SA04	32.851	19.621	566
SA05	32.605	21.535	707
SA07	31.978	20.226	1280
SA08	31.91	22.073	1387
SA09	30.922	22.986	1231
SA10	30.972	23.914	1442
SA81	30.925	21.268	1267
SA82	30.977	22.247	1453
sur	32.38	20.812	1770

Early last century, Beattie (1909) first reported on the presence of a large and extensive positive static magnetic anomaly in the southern Cape (Figure 1). The Curie isotherm for the region was later calculated at 25-38km, thereby forcing a crustal source for the anomaly (De Beer and Gough, 1980). The Beattie Anomaly, as it is now known, extends from about 20°E for more than 1000 km to just beyond the east coast, where it is truncated by the Agulhas Fracture Zone. This suggests that it formed prior to the Jurassic strike-slip motion along this fracture zone (de Beer, 1983; Pitts *et al.,* 1992). In the west, the Beattie Anomaly staddles the surface expression of the frontal thrusts of the Cape Fold Belt that deform the southern margin of the Karoo Basin (Figure 1). Farther east the anomaly trends north-eastward away from the thrust front (Figure 1) suggesting a pre Cape Fold Belt origin for the source of the anomaly. In 1971, a magnetometer-array study in the southern Cape led to the discovery of a zone of electrically conductive material in the crust or upper

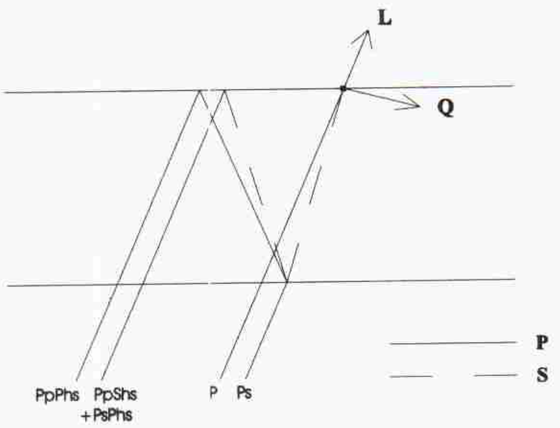


Figure 3a

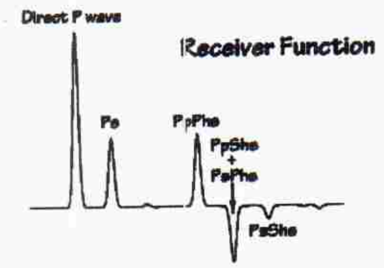


Figure 3a. Schematic figure depicting converted phases resulting from a seismic P-wave passing a discontinuity (modified from Ammon, 1991)

Figure 3b. Synthetic receiver function corresponding to raypaths shown in (a)

mantle (Gough *et al.*, 1973). This major east-west elongated intracontinental conductive structure, now known as the Southern Cape Conductive Belt (SCCB), is also located beneath the southern Karoo basin and frontal Cape Fold Belt. The central part of the SCCB coincides with the deepest part of the Karoo basin, but the Karoo sedimentary basin cannot be the source for the high electrical conductivity. A link between the SCCB and the Beattie Anomaly was later suggested (de Beer *et al.*, 1974; de Beer 1978). However, only later still were the margins of the SCCB mapped in detail during a follow-up induction study over the Beattie Anomaly (de Beer and Gough, 1980). This study showed that the Beattie Anomaly straddled the northern margin of the SCCB; and that the maximum depth of the conductive zone lies between 46 and 52km (de Beer and Gough 1980). Thus, like the similar trending Beattie anomaly, a crustal source for the conductive rocks is clear. De Beer and Gough (1980) and de Beer *et al.* (1974; 1982; 1992) interpreted this source to be an elongated body of relatively dense and electrically conductive crust, possibly a partially serpentinised (and thus rich in magnetite and hydrous minerals) slice of paleo-oceanic lithosphere which they suggested marked the southern edge of the Namaqua-Natal Mobile Belt. Further magnetic and gravity studies across the Beattie anomaly near 22°E, are consistent with such a source modelled as a body (density = 2.87 gcm^{-3}) about 30km wide and up to 20 thick, buried more than 7km below surface, and dipping shallowly south (Pitts *et al.*, 1992). The regional magnetic signature of the Beattie Anomaly indicates that the dip of the body changes from shallow dipping in the west to more steeply dipping towards the east coast (Figure 1b; J. de Beer, pers.comm. 2001). In addition the Beattie Anomaly becomes less distinctive westward of 20°E, before it is abruptly terminated (Figure 1b). In contrast, the associated SCCB continues beneath the north-south striking western branch of the Cape Fold Belt as far as the Atlantic coast (Figure 1a).

The receiver function method

When a longitudinal seismic P-wave passes through a physical or chemical discontinuity on its way up to the Earth's surface, it may be partially converted to a transverse S-wave. This simplest converted phase is known as the Ps phase. More complex phases occur when, for example, the P-wave passes the discontinuity, reflects at a point on the Earth's surface back to the discontinuity, from which it reflects back to the surface, converting partially to an S-wave at one of the reflections. These are labeled PpPhs and PpShs, depending on the number of P- and S-wave legs. The raypaths are illustrated in Figure 3a.

Knowing the velocity of each wave as well as the time difference between their arrivals and the angle of incidence of the incoming wave, it is possible to estimate the depth of the discontinuity concerned. A technique commonly used for that is that of receiver functions, developed by Langston (1979). Here the horizontal components from the 3-components seismogram are deconvolved from the vertical component to produce a trace dominated by arrivals P to S conversions and reverberating S-waves (*e.g.* Ammon, 1991). The trace does not contain signals with the energy in the P-direction, except for the direct P-wave arrival from the vertical component. Figure 3b shows a synthetic receiver function corresponding to the raypaths in Figure 3a.

It can be shown (e.g., Ammon, 1991; Gurrola *et al.*, 1994) that the depth of the discontinuity concerned can be estimated by

$$h = \frac{\Delta t}{\sqrt{v_s^2 - p^2} - \sqrt{v_p^2 - p^2}} \text{......... ....(1)}$$

where h is the depth of the discontinuity, Δt the time difference between the arrival of the converted Ps phase and the direct P-wave, v_s and v_p the mean seismic velocities of the S- and P-waves in the region, and p the ray parameter of the incident wave.

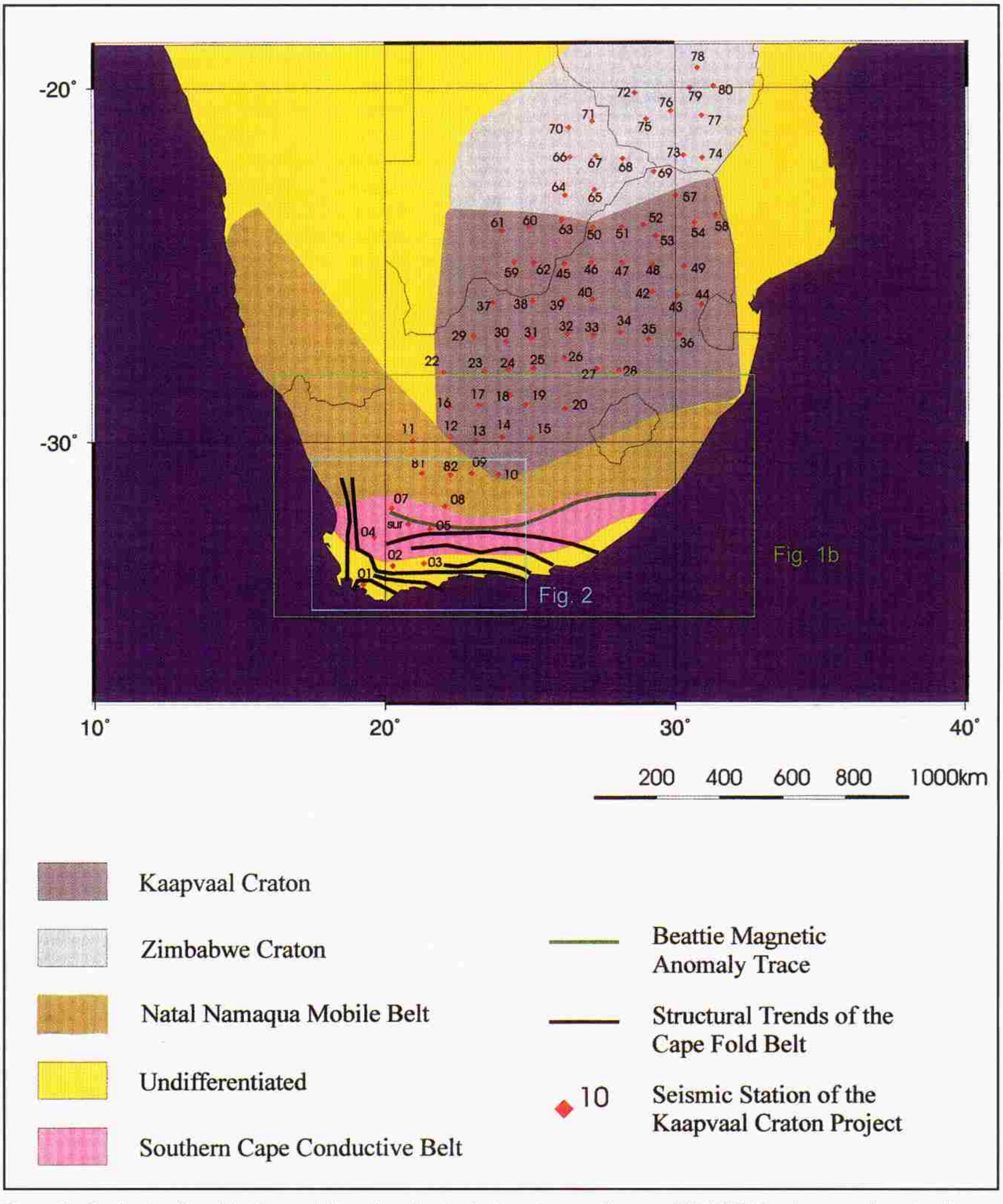


Figure 1a. Regional setting of the Kaapvaal Craton broadband seismic station array between 1997-1999. Also shown are the regional extent of the upper crustal geophysical anomalies (Beattie Magnetic Anomaly and the Southern Cape Conductive belt – SCCB). The two dominant structural surface trends of the Cape Fold Belt (N-S and E-W) represent the western branch and eastern branch of the Fold Belt, respectively.

It is important to stress the non-uniqueness of the receiver function method (e.g., Ammon *et al.,* 1990). To obtain an estimate for the depth to the discontinuity, it is necessary to assume values for the seismic velocities. As each area could have its own set of values for those velocities, it is important to obtain these values from a reliable source before performing the calculation. It is also important that these values are not obtained using receiver functions and assuming depths to particular discontinuities, as this would result in a circular argument.

In this study the seismic velocities given by the IASP91 model were used. This model, developed by Kennett (1991), gives global average values for a

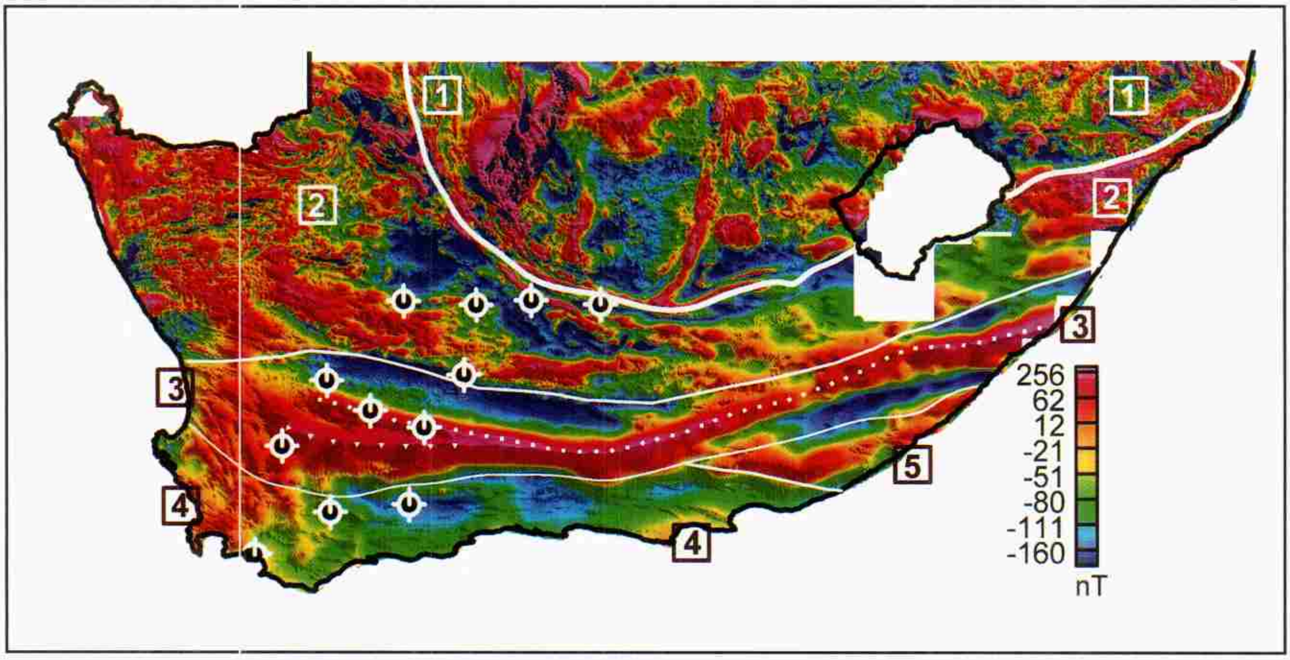
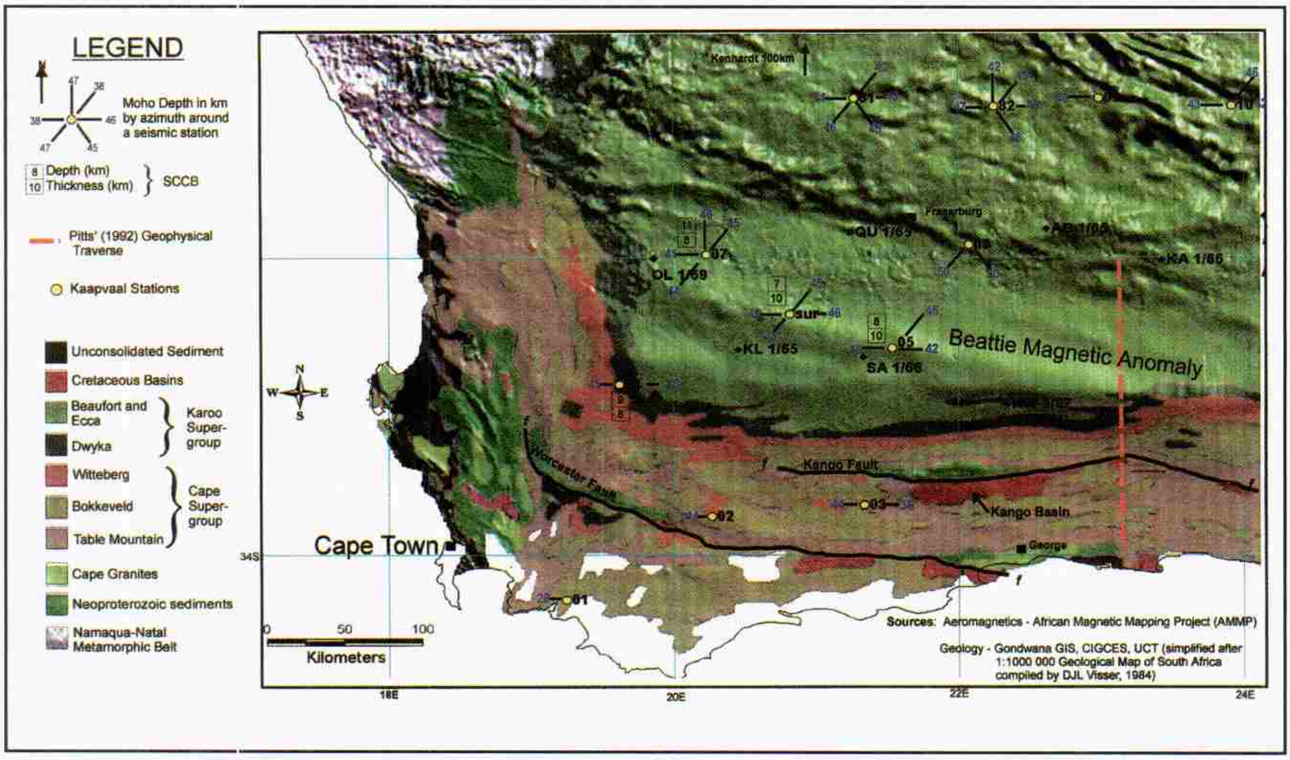


Figure 1b. Total magnetic anomaly map of southernmost South Africa. This map clearly outlines the large Beattie Magnetic Anomaly as defined by de Beer and Gough (1980) (white squares) and its southern branch in the west, nor previously outlined (white triangles). The map also clearly depicts the major tectonic subdivisions of southern Africa based on surface geology. 1= Kaapvaal Craton; 2= Natal Namaqua Mobile Belt; 3= Southern Cape Conductive Belt (SCCB); 4= undifferentiated Cape Fold Belt domain, with intramontaine Cretaceous extensional basins; 5= basement of unknown origin, but probably part of the Natal Namaqua Mobile Belt. Magnetic data from AMMP database (Barrett 1993); magnetic scale in nanotesla. Borehole symbols = position of seismic stations used in this study.



Sources: Aeromagnetics - African Magnetic Mapping Project (AMMP)
Geology - Gondwana GIS, CIGCES, UCT (simplified after 1:1000 000 Geological Map of South Africa compiled by DJL Visser, 1984)

Figure 2 The Kaapvaal Seismic Project array in the southwestern Cape showing the azimuthal variations in crustal thicknesses recorded at each seismic station, plotted on aeromagnetic data draped over the geological data (rasterised lithological polygons) as the height layer. The scale of the aeromagnetic layer is enhanced 2000 times for better 3D perception. Also shown are the depth of the upper crustal discontinuity (BU in Fig 5) of the SCCB and its total thickness inferred from the lower crustal discontinuity (BL in Figure 5) of the SCCB (see text for further explanation). SCCB = Southern Cape Conductive Belt. The location of the N-S magnetic and gravity profile of Pitts *et al.* (1992) is indicated by a brown broken line.

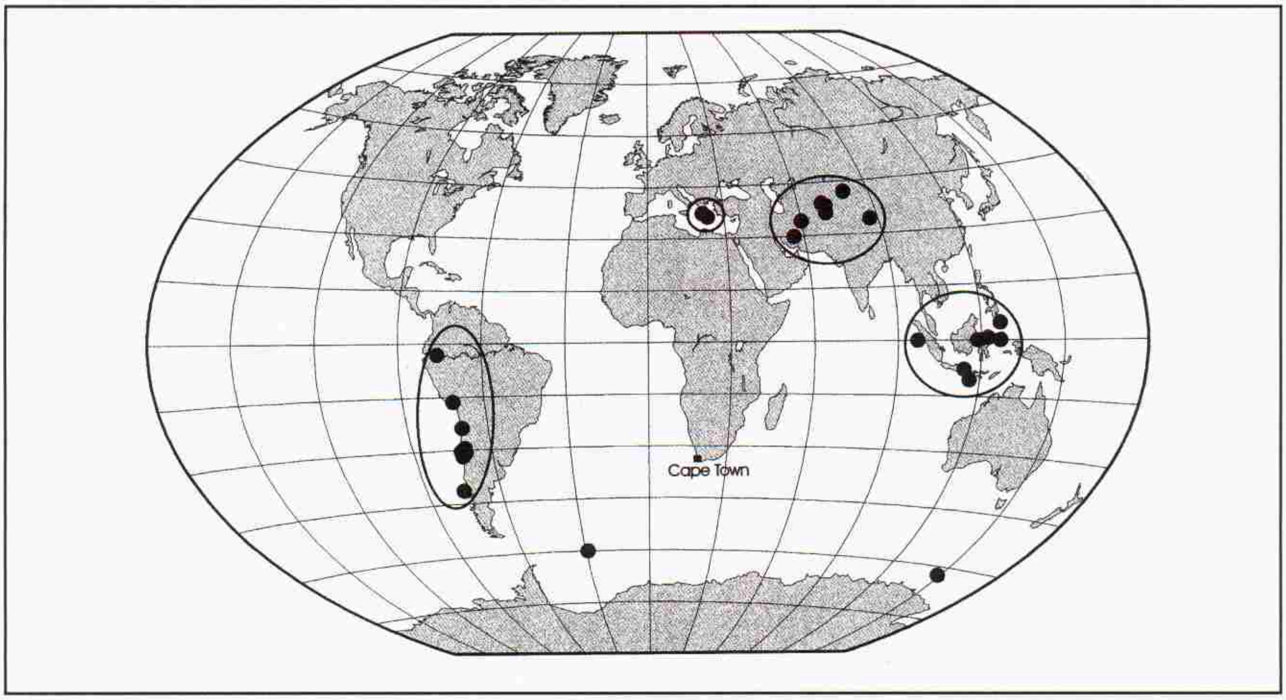


Figure 4. Location of epicenters of the 31 seismic events used in this study

number of parameters, including seismic velocities, for the Earth's crust and upper mantle. For the upper crust (down to a depth of 20km) it gives v_p = 5.8km/s and v_s = 3.36km/s, while for the lower crust (down to the Moho) v_p = 6.5km/s and v_s = 3.75km/s.

To improve the reliability of the data, receiver functions of events from similar areas are stacked together. In the process of stacking (*e.g.*, Schimmel and Paulssen, 1997) prominent features appearing in all individual traces will be clearly visible in the stack, while random seismic noise will be reduced, improving the signal-to-noise ratio.

All data in the present study were filtered using a Butterworth High Pass filter with a corner frequency of 0.03 Hz. The number of poles and the number of passes were both set to 2. The mean and the trend were both removed to correct for some signal noise.

Table 2a. Variations of crustal thickness observed

Station	Crustal thickness (km)	Results of Nguuri et al
SA01	26	30
SA02	44	36
SA03	36-44	48
SA04	36-45	45
SA05	40-45	44
SA07	41-46	47
SA08	50	50
SA09	46	48
SA10	42-46	45
SA81	42-46	47
SA82	42-48	50
sur	42-46	47

Results

Generally, seismic events within the Cape Fold Belt and Namaqua-Natal terrain are "noisy" compared with those on the Kaapvaal Craton (see also Stankiewicz, 2001; Nguuri *et al.,* 2001). Almost half of the receiver functions generated were difficult to interpret and were discarded. The remaining 31 events (Figure 4) had suitable signal to noise ratios and were deconvolved, grouped, then stacked and analyzed. The dominant Ps conversion observed on these records is produced by the Moho discontinuity at the base of the crust. Examples of representative receiver functions are shown in Figure 5; a complete set can be found in Harvey (1999). The results are plotted in Figure 2 and Table 2. The receiver function peaks are picked with an accuracy of 0.1 seconds, which gives an error for the Moho depth of approximately 1km, and approximately 300m in depth to upper crustal discontinuities.

In general, the variations in depth to the Moho are pronounced both below the Cape Fold Belt and the Namaqua Natal Mobile Belt domains (Figures 2 and 5, Table 2a). Three seismic stations of the Kaapvaal experiment were located within the Cape Fold Belt domain (SA01, SA02 and SA03). The quality of earthquake signatures received by these stations was poor, rendering the identification of the crust-mantle boundary difficult. Some receiver functions were, however, identified, but these results should be treated with caution. SA01, the southern most station, reveals a crustal thickness of 28 ± 1km. Farther north, beneath SA02 and SA03, the crust becomes thicker. At SA02, seismic rays sample the Moho at 44 ± 1km. At SA03 the depth varies from 36 to 44 ± 1km, depending on the direction of seismic sampling (azimuth; Figure 5a).

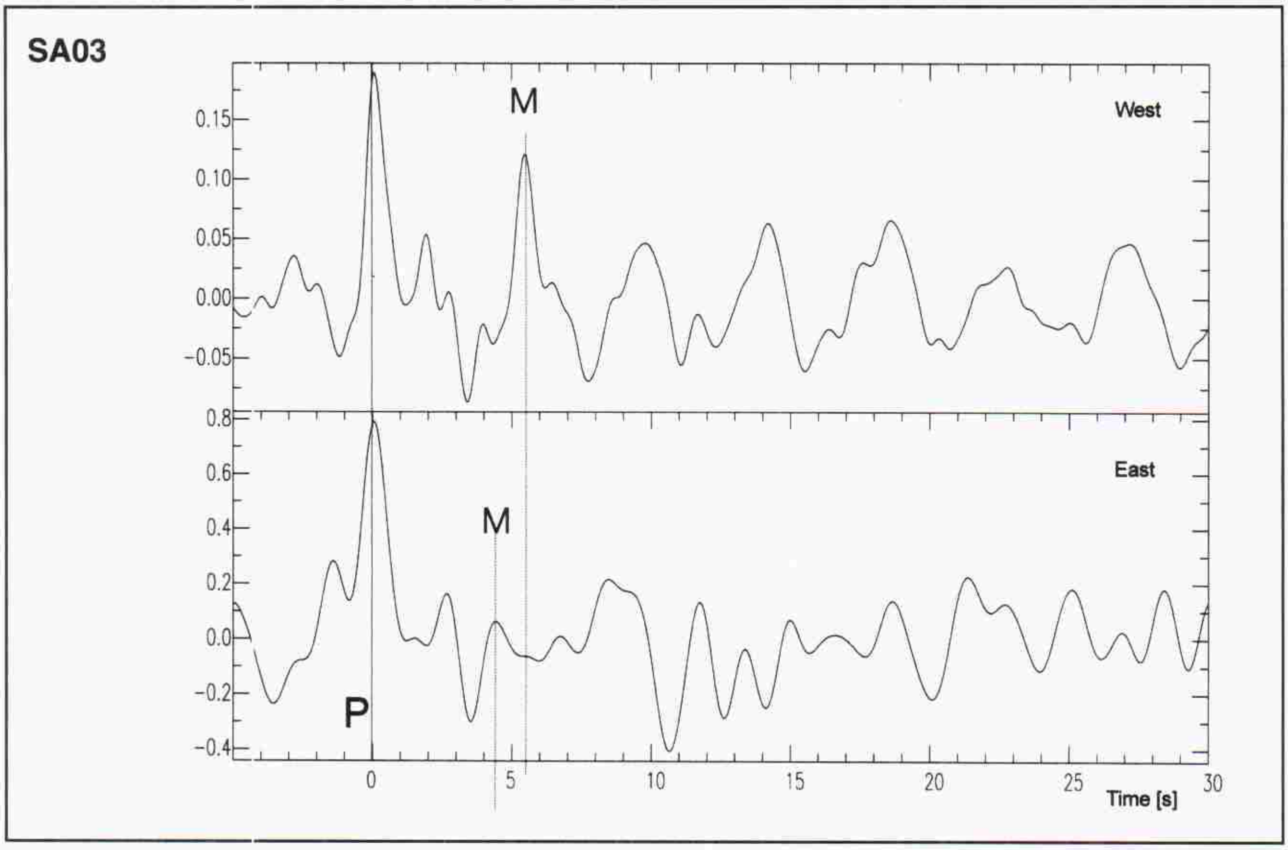


Figure 5. Examples of receiver functions computed in the study.

a Stacks for different azimuths recorded at station SA03 with Moho depth (M) at 44 and 35km for azimuths from the west and east, respectively.

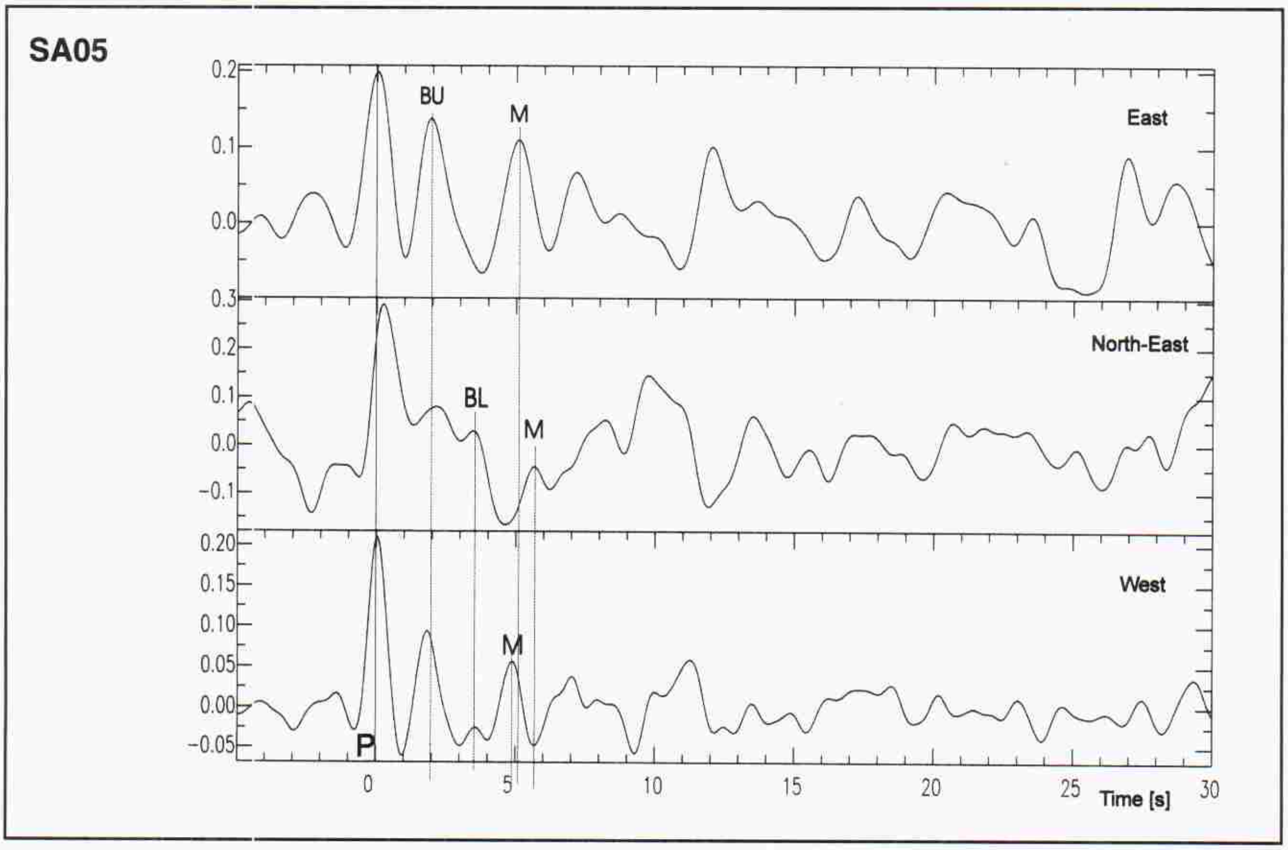


Figure 5b. Stacks of receiver functions of different azimuths (recorded at station SA05, with a range in depth to Moho (M) from 40km (west) to 45km (north east). Note the presence of distinct intracrustal discontinuities at 8km (BU) and 18km (BL).

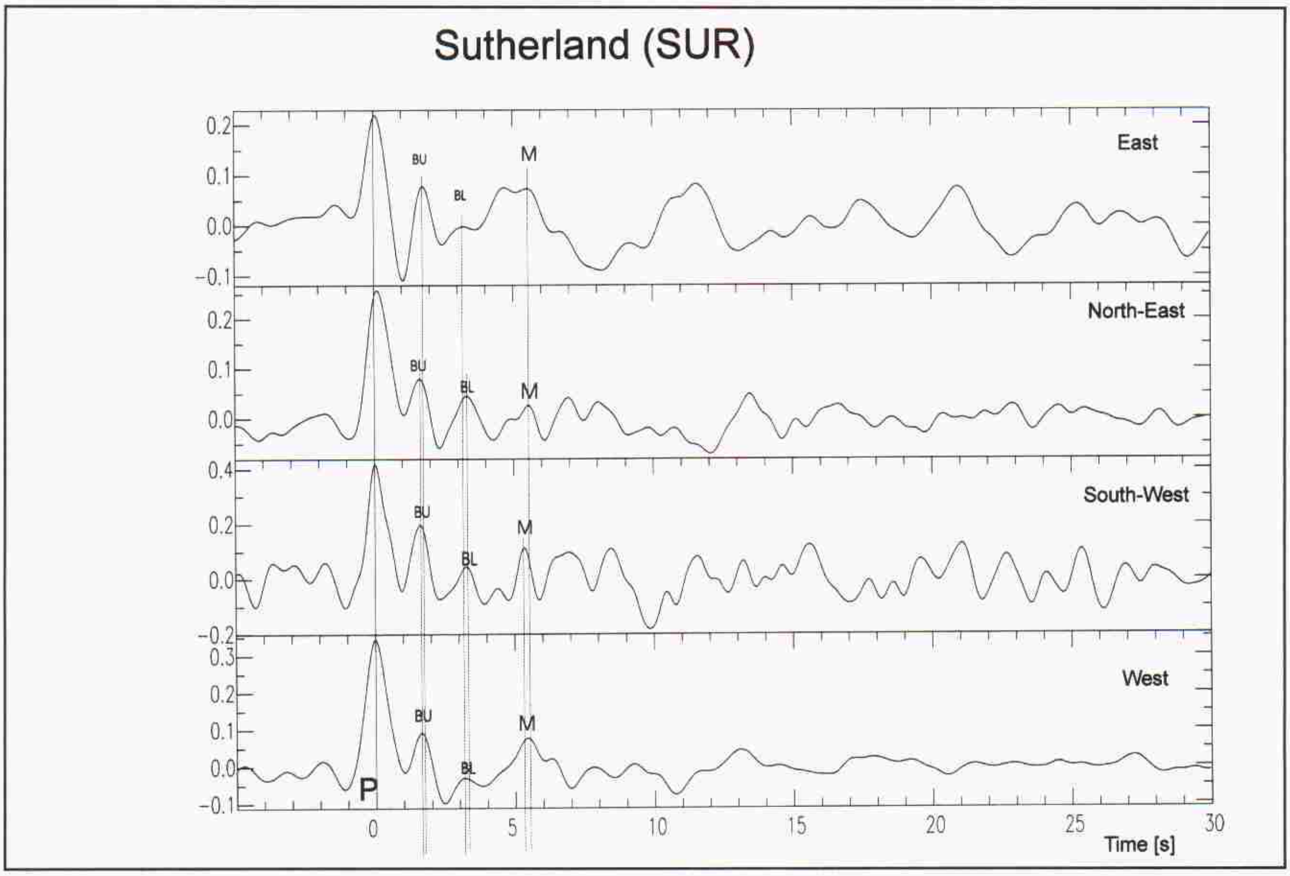


Figure 5c. Stacks of receiver function from events (grouped by azimuth) recorded at the SUR station. Moho depth (M) varies from 42km from the southwest to 46km from the east. Note the clear crustal discontinuities at 7km (BU) and ~17km (BL) depths.

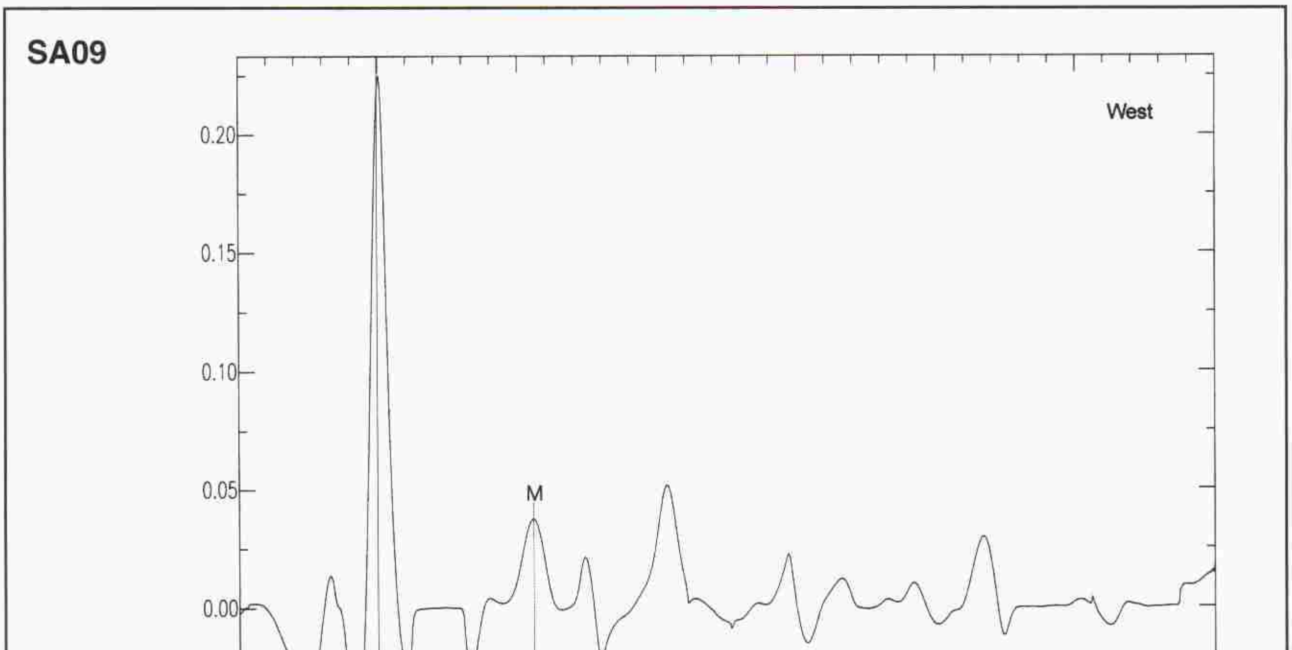


Figure 5d. Stacks of receiver functions recorded at station SA09 recorded from the west. Moho (M) depth is at 46km; note the absence of crustal discontinuities.

These results reflect the highly variable azimuthal thickness of the crust. The ~10km of lateral variation in crustal thickness is consistent with significant thinning of the crust along the southern margins of Southern Africa associated with the Jurassic-Cretaceous extensional basins. From the azimuthal variations beneath SA03, the crust appears to be thinner to the east of this station, towards the Kango basin in the Oudshoorn area, a Jurassic-Cretaceous fault-bounded extensional basin with large vertical displacements along its bounding, south-dipping listric fault (the Kango Fault, Figure 2; Dingle *et al.,* 1983; Viljoen, 1992; Brown *et al.,* 1995). The azimuthal difference in crustal thicknesses around SA03 is similar to the known minimum throw of ~9km along the Kango Fault (Dingle *et al.,* 1983).

To the north of the Cape Fold Belt, stations SA-80, -81,-09 and -10 (Figure 2) are situated in that part of the Karoo Basin that is known to be underlain by the Namaqua Natal Mobile Belt from drill core data (Eglington and Armstrong, 2001). Crustal thicknesses measured in this study range between 42 and 48km, with local variation of 3-6km at stations SA80/81 depending on the azimuth of the receiver function (Figure 2 Table 2a). These crustal thicknesses compare well with that of 42-46km determined by earlier seismic refraction studies across parts of the Namaqua-Natal Mobile Belt farther to the north still (Green and Durheim, 1990; Durheim and Green, 1992), and with those determined during a more regional study of data from all the Kaapvaal Craton Seismic Project stations (Nguuri *et al.,* 2001; Table 2a).

Comparing results from the northernmost stations within the study area to that farther south at station SA08, suggests a regional southward dip of the Moho

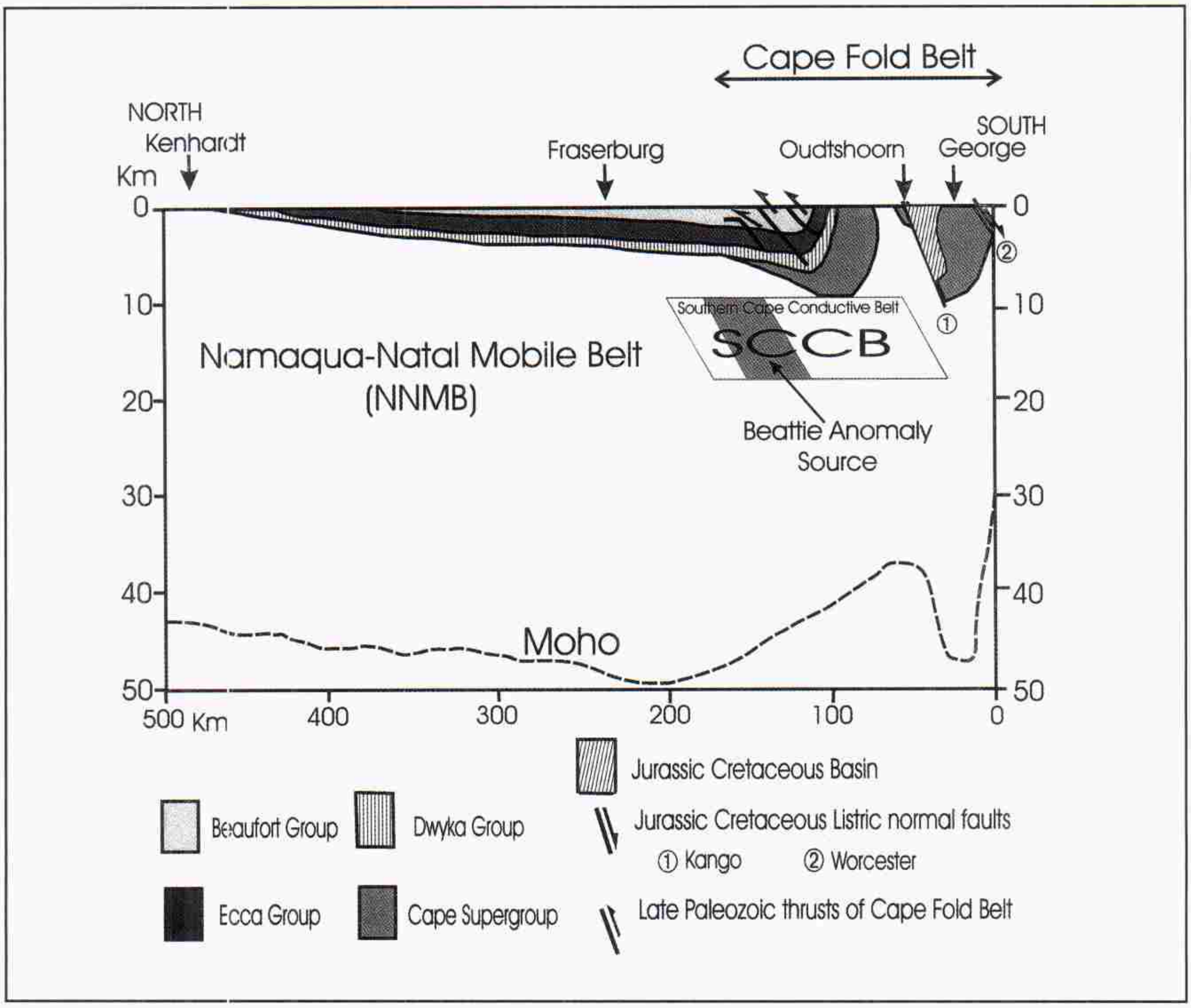


Figure 6. Schematic N-S cross section at about 21°E through the Karoo Basin (modified after Cole, 1992). The crust-mantle boundary obtained from the seismic data analysed in this study, is shown projected into this section from the different seismic stations. The positions of Kenhardt, Fraserburg and George are also projected into this section. The source of the Southern Cape Conductive Belt (SCCB) and the Beattie Anomaly are from De Beer (1983). The average depth extent of the SCCB are inferred from this study. The location of the frontal thrust of the Cape Fold Belt is not known precisely; the northernmost frontal thrust are almost certainly blind and buried beneath the Beaufort Group; the southernmost structures of the Cape Fold Belt are hidden offshore to the south. Location of the two regional Jurassic-Cretaceous listric extensional faults (the Kango and the Worcester faults) are also shown.

Table 2b. Depths to upper and lower intracrust boundaries.

Station	Upper	Lower
SA04	9km	17km
SA05	8km	18km
SA07	11km	19km
sur	7km	17km

under the Namaqua-Natal Mobile Belt, which mimics the dip of the base of the overlying Karoo basin (Figure 6). Over a distance of some 300km, from Kenhard southward, the Moho increases from about 45km to ~ 50km. This suggests that the crust was probably flexed during the formation of this foreland basin as a result of loading by the Cape Fold Belt thrusts (Cloeting *et al.*, 1992). Beneath the northern margin of the SCCB and the Beattie Anomaly, however, the Moho starts to dip to the north. Southward from there, for 150km beneath the frontal sector of the eastern branch of the Cape Fold Belt (north of the Kango Fault), the crust thins to less than 40km. Farther southward still, for ~ 50km beneath the central sector of the eastern branch of the Cape Fold Belt to the (extension of) the Worcester Fault, the crust thickens again to about 45km. South of the Worcester fault the crust thins again to less than 30km at the coast. The general thinning of the Moho beneath the Cape Fold Belt is counter-intuitive. This suggests that major extensional faults or décollements zones, associated with the regional Jurassic-Cretaceous extension, are rooted in the underlying crust, perhaps focussed along the south dipping contacts of the SCCB.

On a smaller scale, there are also noticeable changes in crustal thicknesses around the stations within the Namaqua Natal Mobile Belt (Figure 2, Table 2a). Crustal thickness varies by up to 3km around each station, depending on the azimuth. Based on field observations along the western extent of the Namaqua Natal Mobile Belt, Thomas (1989) and Thomas *et al.* (1994) identified a number of discreet east-west elongated terranes. They suggested that these elongated terranes were accreted and thrust across one another, and against the southern margin of the Kaapvaal Craton during the Mesoproterozoic. Tectonic episodes during which structural blocks of presumably different geometries are tectonically juxtaposed might result in an uneven crust-mantle boundary. These elongated terranes can be reasonably extrapolated to continue west beneath the sediments of the Karoo Basin, and so provide an explanation for the variations in the Moho depth determined by the seismic results in this study. This is consistent also with the rapid crustal thickness change of about 5-8km across the northern margin of the SCCB (Figure 2). Gravity, magnetic and electrical studies suggest that the SCCB represents a discrete crustal block (de Beer *et al.*, 1974; de Beer and Gough, 1980, Pitts *et al.*, 1992), that in turn may be a Mesoproterozoic allochthonous exotic terrane and/or paleo-suture zone (Hälbich 1993). Although Johnson (1998) has argued that the body represents a dyke-like mafic intrusion associated with the early stages of Gondwana extension, the above mentioned geophysical data render this unlikely.

Stations SA04, SA05, SA07 and SUR are positioned directly above the source of the SCCB. At all these stations, two distinct upper crustal discontinuities are observed in our seismic data (Figures 2 and 5 and Table 2b).

We interpret these discontinuities as the upper and lower contacts of the crustal block associated with the SCCB and the Beattie Anomaly. Depths to these contacts have been independently modelled at ~7-10km and 30km, respectively, using gravity and magnetic data (Pitts *et al.*, 1992). The seismic data shows that at SA05 and SUR (Figures 5b and c), the upper contact of the source of the SCCB lies 7 and 8km below the surface, respectively, and that the block is ~10km thick. The latter is about half as thick as the ~20km modelled by gravity and magnetic methods (Pitts *et al.*, 1992). Farther west at SA04 and SA07, the upper contact to the source lies deeper below the surface at 9 and 11km, and the lower contact at 17 and 19km, respectively. The block, therefore, appears to be thinner in the west by about 2km. The seismic evidence in this study supports the depths to upper surface of the block as modelled by Pitts *et al.* (1992), but differs in the estimation of its thickness. However, the profile of Pitts *et al.* (1992) lies some 150km east of SA05 (Figure 2). It is possible, therefore, that source block thins by as much as 12km towards the west where the associated Beattie Anomaly appears to split (Figure 1b) and then almost 200km father west of SA05, disappears. It is also possible, however, that the source block changes its southerly dip from shallow in the west to steep in the east, with a concomitant increase in apparent thickness. The general sharper focus of the Beattie magnetic Anomaly in the east is consistent with a more steeply dipping source (Figure 1b, J. de Beer, personal communication, 2001) The difference in the geometry of the model as determined by seismic methods and the gravity-magnetic modeling, could also be artefacts of the different methods used. This clearly requires further work. An alternative interpretation, that high magnetic content in thrust zones within the granitic basement is the source of the Beattie Anomaly (Corner, 1989) is unlikely in the light of our results that delineated distinct seismic discontinuities at similar depths beneath four different stations that are spread over distances of nearly 200km (east-west) and 100km (~north-south; Figure 2).

The source of the Beattie Anomaly becomes subdued west of stations SA07 and SA04, where our data indicates that it is more deeply buried. The Beattie Anomaly then disappears as it approaches the north-south trending Western Branch of the Cape Fold Belt (Figure 1). In contrast, the SCCB continues as far as the Atlantic coast (Figure 1), without being significantly affected by the north-south trending deformational fabrics of the Paleozoic and Saldanian structures. This suggest that the Mesoproterozoic basement of the Namaqua Natal

Mobile Belt continues below the Western branch of the Cape Fold Belt. The western limit of the Beattie Anomaly may therefore be a result of tectono-sedimentary burial by relatively shallow Saldanian- and Cape Basin-age sequences.

Summary and conclusions

Receiver functions in the southwestern Cape show that the crust is ~45km thick in the northern parts of the study area, and thickens up to ~50km near Fraserburg (SA08; Figures 2 and 6). The southward dip of the base of the Karoo basin in this area mimics the dip of the Moho and suggests that the entire crust was flexed during tectonic loading by structures of the Cape Fold Belt. From Fraserburg, the crust begins to thin southwards under the Southern Cape Conductive belt to ~28km at the coast (SA01). The general large scale thinning of the crust observed by seismic receiver functions is consistent with a Jurassic-Cretaceous extensional terrain that flanks the southern margin of Africa, and where stretching and thinning of the crust occurred during the formation of this "passive" continental margin and its associated listric-fault-bounded basins. This stretching is consistent with the absence of a thick crustal root beneath the Cape Fold Belt.

Small scale variations in crustal thicknesses are observed from seismic rays from different azimuths under each station. In the Namaqua-Natal Mobile Belt, this is related to east-west tectonic grain inherited from its Mesoproterozoic accretion history when a series of elongating east-west trending terranes with variable crustal structures were amalgamated. The distinct crustal features in the region of the Southern Cape Conductive Belt, with its distinct magnetic signature, is consistent with models that infer another accreted Mesoproterozoic allochthon of altered oceanic-like material, now buried beneath the southern Karoo and Cape basins and the northern sector of the eastern branch of the Cape Fold Belt.

Upper crustal velocity boundaries have identified the upper and lower limits of the Southern Cape Conductive Belt, the belt which is thought to host the source of the Beattie Magnetic Anomaly. The SCCB lies ~7 to ~8km below the surface, in agreement to previous geophysical models (*e.g.* Pitts *et al.*, 1993). However, the seismic results indicate a thickness of ~10km for this belt, in contrast to the 20km as reported by gravity-based models. This is either due to an artifact of the two different methods used in estimating the geometry of the body, or to the fact that it apparently thins by 10km from the geophysical section ~150km to the east of the seismic station (SA05) that has constrained the anomaly in this study. It is also possible that the apparent thickening of the SCCB to the east is due to a steepening of the source block.

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