DEEP CRUSTAL PROFILE ACROSS THE SOUTHERN KAROO BASIN AND BEATTIE MAGNETIC ANOMALY, SOUTH AFRICA: AN INTEGRATED INTERPRETATION WITH TECTONIC IMPLICATIONS

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ABSTRACT

Two geophysical onshore-offshore lines on the southern margin of Africa form the Agulhas-Karoo Geophysical Transect (AKGT) and cross prominent geological features such as the Karoo Basin, Cape Fold Belt (CFB) and the Beattie Magnetic Anomaly (BMA). Geophysical data acquired along this AKGTransect between 2004 and 2007 within the Inkaba yeAfrica (lyA) framework, provide the platform for constructing a deep crustal section (IyA-200501) for the centre 100 km of the western AKGT-transect in order to resolve these features at depth. We present a detailed deep crustal model constructed from the joint interpretation of:

i. archive data comprising surface geology, aeromagnetic data, nearby deep boreholes, teleseismic receiver functions and regional seismic reflection profiles, and
ii. line coincident newly acquired high-resolution geophysical data consisting of near vertical seismic reflection data, shallow P- and S-wave velocity data, wide-angle refraction data, high resolution magnetotelluric data and impedance spectroscopy measurements on borehole samples.

Our model differentiates four components in the up to 45 km thick crust:

1. a ~2 to 5 km thick folded Karoo Supergroup, disrupted by low-angle thrust faults rooted in a zone of local décollements in the lower Ecca Group and resting paraconformably on
2. a continuous undeformed sub-horizontal ~1.5 to 10 km thick wedge of the Cape Supergroup (CSG). This CSG wedge stretches from the Escarpment in the north to the tectonic front of the CFB in the south, and rests on an unconformity that dips about three degrees to the south. The angular unconformity is interpreted as an erosional peneplain that separates the CSG wedge from component
3. the ~13 to 21 km mid-crust basement below. The mid-crust contains a distinct north-dipping seismic fabric, here interpreted as ~1.4 to 1.0 Ga Mesoproterozoic Namaqua-Natal Metamorphic Belt (NNMB) crust. A south-dipping mid-crustal detachment, interpreted as a ductile thrust zone, separates the mid-crust from component
4. a highly reflective ~10 to 24 km thick lower crust. The latter is interpreted as an older Palaeoproterozoic section of the NNMB (or even Archean cratonic basement), and bounded by a ~2 to 5 km thick, highly reflective bottom layer below that lies sub-parallel to a clear Moho. This bottom layer is interpreted as a mafic underplate, metasomatic reaction zone, or lower-crust to mantle transition zone.

Collectively the seismic reflection and wide-angle refraction data support an interpretation that the NNMB mid-crustal layer contains the BMA source, possibly connected to two zones of strong reflectivity: a ~10 to 12 km wide northern zone and a ~5 to 7 km wide southern zone, both about 5 km thick and 7 to 8 km below surface. We interpret the BMA source to be at least in part, a Namaqua-like massive to disseminated, deformed/metamorphosed stratiform sulphide-magnetite ore body with metasomatic overprint.

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The seismic reflection and -refraction data support an interpretation that a Pan-African suture zone at the BMA is absent and that instead, the NNMB continues below the CFB tectonic front, probably up to the continental margin and the Agulhas Fracture Zone. The seismic reflection data also supports a thin-skinned tectonic thrust model for the evolution of the CFB without significant fore-deep stratigraphic thickening of the Karoo Basin strata. A compatible tectonic model implies a Palaeozoic collision orogen setting, coupled to a south verging subduction zone much farther south of the CFB. Similarly, the geophysical data support a south dipping subduction zone during the amalgamation of the NNMB in the Mesoproterozoic.

Current reconstructions of the Rodinia supercontinent link the NNMB and the Grenville Province of North America across the Grenville-Kibaran orogen. Our seismic section tests this reconstruction through a direct comparison with seismic profiles on the opposite flank of the orogen. Although the once adjacent continental blocks are now 1000s of kilometres apart, the seismic images show a good correlation and support the reconstruction.

Introduction

Southernmost Africa is dominated by the Palaeozoic-Mesozoic Cape Fold Belt (CFB) and its flanking Cape-Karoo Basin underlain by Precambrian basement, which includes the world's largest terrestrial magnetic anomaly, the Beattie Magnetic Anomaly (BMA) first detected over a century ago (Beattie, 1909). The deep crustal expressions of these surface features remain essentially unknown for lack of geophysical information. Under the auspices of the Inkaba yeAfrica research initiative (de Wit and Horsfield, 2006; www.inkaba.org) the Agulhas-Karoo Geophysical Transect (AKGT) was designed to investigate these, and other features through deep crustal geophysical data, with the aim of resolving the tectonic evolution of the southern continental margin of Africa further (e.g. Lindeque et al., 2006; 2007; Parsiegla et al., 2007; 2009; Stankiewicz et al., 2007; 2008; Weckmann et al., 2007a; 2007b).

The AKGT consists of two roughly parallel north-south, amphibian onshore/offshore lines (Figure 1). We focus on a ca. 100 km segment of the western AKGT line, which traverses the Karoo Basin from the southern escarpment of South Africa to the northern frontal ranges of the CFB, whilst crossing the ca. 1000 km long BMA close to the apparent bifurcation seen in the aeromagnetic data (Figure 1). Our work contributes the first high-resolution deep seismic reflection profile and deep crustal model through the Palaeozoic-Mesozoic sediments of the Cape-Karoo Basin and its underlying basement, both overprinted in the south by the mid-Phanerozoic Cape Fold Belt deformation (Figure 2). The regional geology of the southern Karoo Basin and CFB are well documented and not described in detail here (e.g. Hälbich 1983a, b, c; Söhnge and Hälbich, 1983; de Wit and Ransome, 1992; Hälbich, 1993; Thomas et al., 1993; Veevers et al., 1994; Johnson et al., 1996; 2006; Shone and Booth, 2005). Table 1 and Figure 2 summarise the stratigraphy compiled from the geological field maps (CGS, 2000) and nearby boreholes SA-1/66 and KW-1/67 (PASA, 1966; 1967b).

Our derived crustal model is based on the analyses of all the available datasets shown in Figure 2 and leads us to revise existing crustal models of the region (e.g. Hälbich, 1993). These datasets include: a near vertical deep seismic reflection profile hereafter referred to as IyA-200501 (Lindeque et al., 2007); a coincident shallow velocity Vs model (Bräuer et al., 2007); wide-angle refraction data and derived tomography models (Stankiewicz et al., 2007; 2008); archive seismic reflection lines in the Karoo Basin from the 1960's work of Soekor (now the Petroleum Agency of South Africa, (PASA), 1967a); teleseismic receiver function data (Harvey et al., 2001); high resolution magnetotelluric data and models (Weckmann et al., 2007a); regional aeromagnetic data (Council for Geoscience, (CGS), 2000); BMA models (e.g. Quesnel et al., 2009); existing geological data from surface mapping (CGS, 1979a; b; 1983; 1992) and borehole logs (PASA, 1966; 1967b).

Finally, we evaluate how each dataset and model provide information on the crustal location, depth, extent and possible source(s) of the BMA, and then present a simple model for the tectonic evolution of this southernmost sector of Africa – a prominent component in Gondwana and Rodinia supercontinent reconstructions.

Methodology

In deriving a deep crustal model, we combined diverse geological and geophysical local, as well as regional datasets (Figure 2) to ensure consistent conservative interpretations. For example, the near vertical seismic reflection technique records changes in velocity between geological layers and not necessarily the actual stratigraphic contact between units. Therefore if the seismic data are viewed in isolation, apparent correlations with surface geology or aeromagnetic data could be argued as a matter of coincidence, but if all datasets are viewed collectively, the interpretation becomes more robust. Our analyses are rooted in the IyA-200501 seismic image and a line interpretation thereof, shown in Figures 3 and 4a, respectively. Data acquisition, processing and interpretation procedures of IyA-200501 are described elsewhere (Lindeque et al., 2006; 2007).

To derive an integrated model for the upper-crust, we first considered surface geology. A geological cross section was constructed by hand exactly along the seismic profile IyA-200501, using information from the 1:250000 geological map sheets (CGS, 1979a, b; 1983; 1992, Figure 2 and the extract in Figure 4b). Surface structure and field observations of Stowe (1980; 1986), Albat (1984), Joubert (1971; 1986a, b), Macey (2000; 2001), and Macey et al. (2011) were incorporated. Particular attention was given to record the dip variation

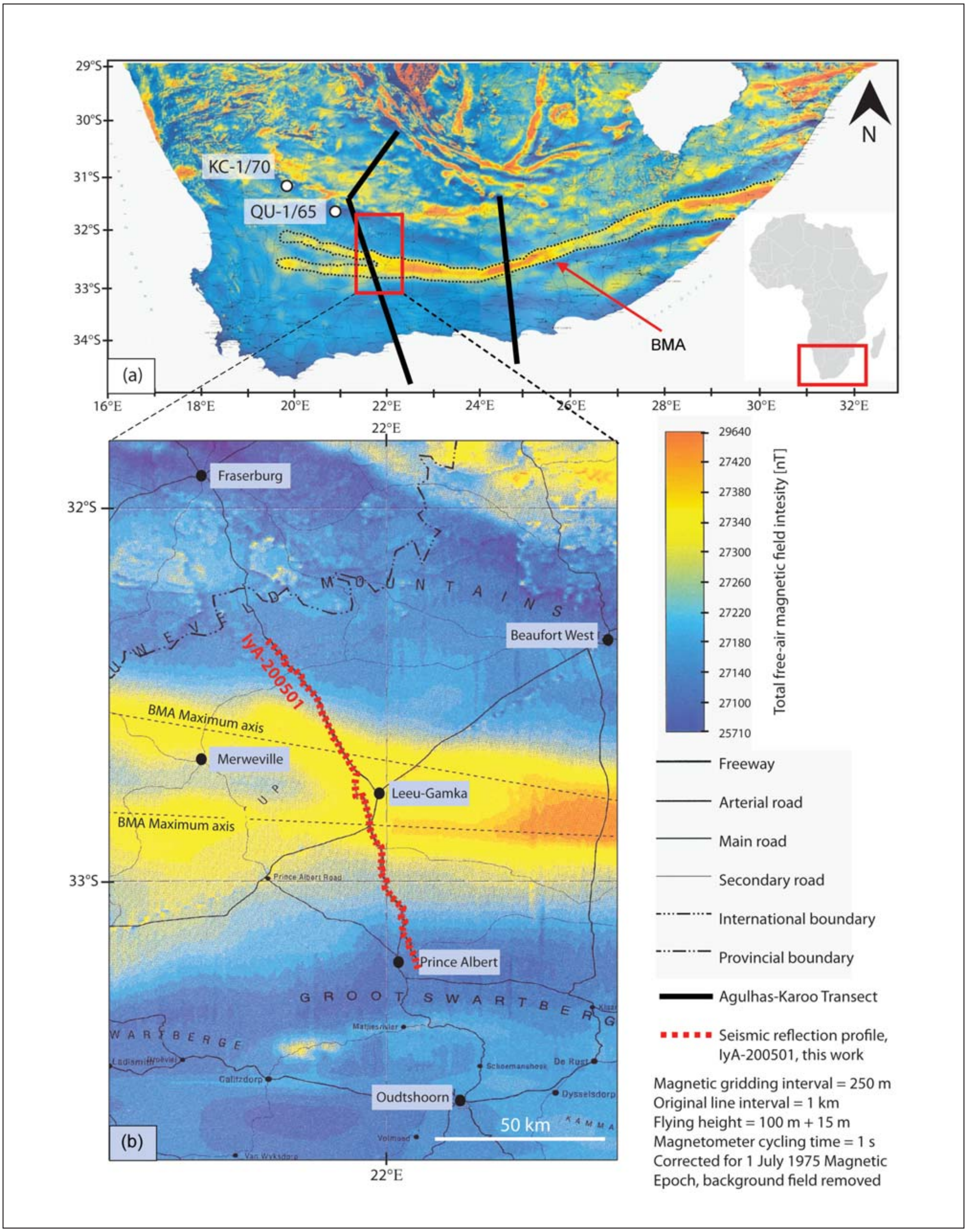


Figure 1. *(**a**) Total field free-air aeromagnetic map of southern Africa (CGS, 2000) showing the regional West-East striking Beattie Magnetic Anomaly (outlined and red arrow marked BMA), and the western and eastern lines comprising the Agulhas-Karoo Geophysical Transect (AKGT, black lines). This research focuses on the centre ~100 km segment of the western transect (left black line and red block) and refer to findings from boreholes QU-1/65 and KC-1/70 farther afield (white circles). (**b**) Close-up of the area of interest. Red dots = IyA-200501 seismic reflection profile of Lindeque et al. (2007) 50 m shot spacing; thin black dashed lines = BMA maximum axes; shades of yellow to red = ~30 km wide BMA extent. Note how the BMA bifurcates towards the West near Merweville, see text for discussion.*

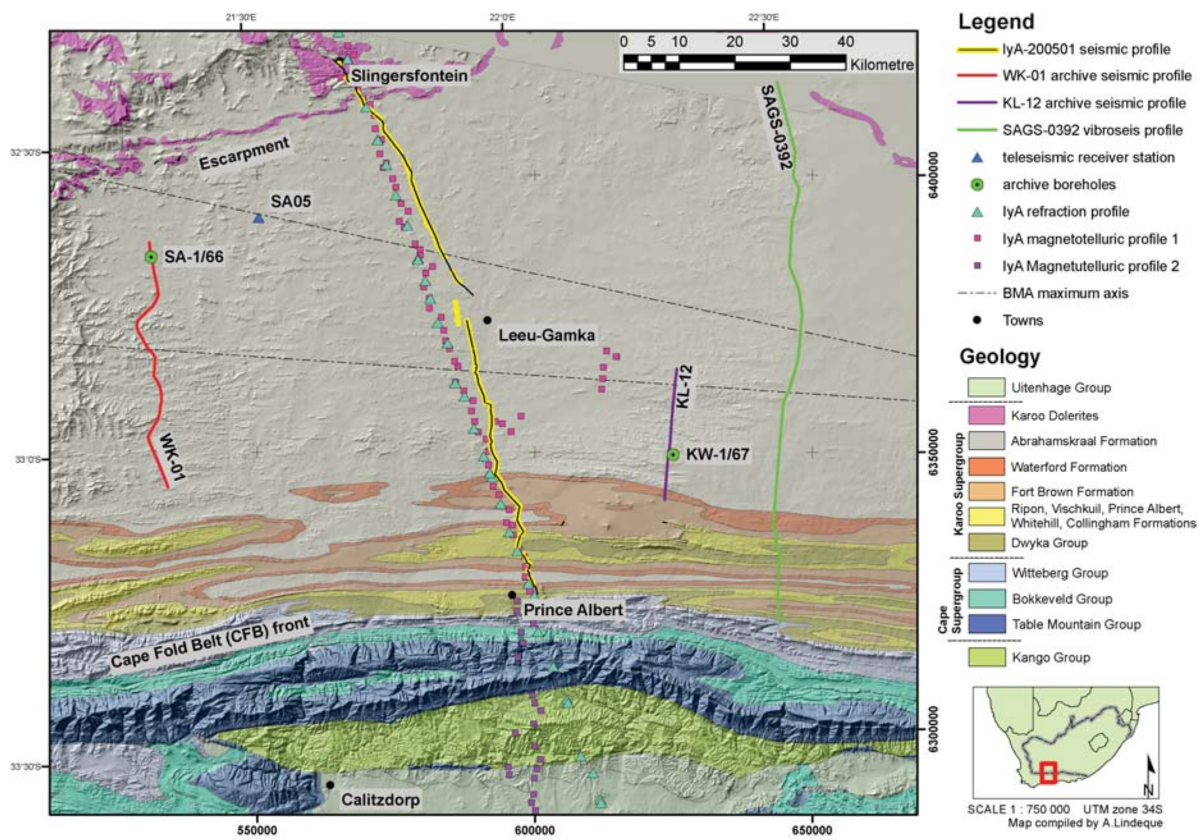


Figure 2. *Geological map of the study area shown in Figure 1b, overlain on the 20 m Digital Elevation Model (DEM); Seismic reflection profile IyA-200501 within the AKGtransect (yellow and black line, Lindeque et al., 2007). Faults and folds on the 1:250000 scale geological maps are not shown for the sake of clarity, but are meticulously annotated on the geological cross-section (Figure 8). Location of the BMA maximum axes are demarcated by the east-west trending black dashed lines. Other geophysical data used to construct the new crustal model include: triangles = wide-angle refraction experiment (Stankiewicz et al., 2007; 2008); squares = magnetotelluric measurements (Weckmann et al., 2007a, b); blue triangle = nearby receiver function station SA05 (Harvey et al., 2001); red line = archive seismic reflection profile WK-01 with coincident borehole SA-1/66, green circle; purple line = KL-12 and coincident borehole KW-1/67, green circle. IyA-200501 crosses the geological strike of the region at an angle of about 70°. Archive seismic profile SAGS-0392 (green line) and the position of the Cape Fold Belt Front at the Witteberg Group shown for reference.*

of fold limbs, location and orientation of fold axial planes, and fold axes. The resulting cross section is shown in Figure 4c and Figure 8, with 5x vertical exaggeration for clarity.

This geological cross section (Figure 4c), dovetails with the southernmost 50 km of the Vs shallow velocity image (Figure 4d; Bräuer et al., 2007). Specifically, high velocity regions in the Vs shallow velocity structure correlate to fold axes and folds in the cross-section, as well as with the reflectivity patterns in the upper 1 to 2 km of the seismic reflection data. These observations are useful to constrain the interpretation of the structures and lithologies in the upper 1 to 2 km of the IyA-200501 seismic profile, where much of the shallow sub-surface seismic data were lost due to noise from the blasts, and an instrument layout optimised to image the deeper crust.

Next, we considered stratigraphic control for the upper 1.5 km from boreholes SA-1/66 and KW-1/67 to the east and west of IyA-200501, respectively (Figure 2 and borehole logs in Table 1; PASA, 1966; 1967b; Winter and Venter, 1970; Rowsell and de Swart, 1976; Cole and McLachlan, 1994). Each borehole was projected into the seismic image along strike of the regional geology (Figures 5 and 6, overview maps). This technique ties surface geology to corresponding units in the borehole logs, and then to particular primary seismic reflectors which represent the boundary of a specific geological unit (Figures 5c and 6c).

Borehole SA-1/66 is coincident with archive Soekor seismic line WK-01 (PASA, 1967a) ~40 km to the west and parallel to seismic profile IyA-200501 (Figure 2). We compared an extract of the WK-01 seismic line paper record and coincident borehole log SA-1/66 (Figure 5a) to the paper-to-SEGY converted record (Figure 5b). Paper-to-SEGY describes a process to transform scanned raster images of paper seismic records to geo-referenced binary SEGY files, so one can view the data in standard seismic software and apply further data processing so as to enhance the seismic image (compare Figure 5a and b for example). We compared these archive records in Figure 5a and b, with the higher resolution seismic profile IyA-200501 (Figure 5c) to resolve the upper 1.5 km stratigraphy further. Similarly, borehole KW-1/67 is coincident with archive Soekor seismic line KL-12 (PASA, 1967a), ~30 km to the east and parallel to IyA-200501 (Figure 2). Again, we compared an extract of the seismic record, in this case KL-12 and borehole log KW-1/67 (Figure 6a), to the paper-to-SEGY converted record (Figure 6b), and the IyA-200501 extract (Figure 6c). Horizons were correlated with specific reflectors and traced along the profile, thereby refining the litho- and chrono-stratigraphy (Figure 6c). Additional magnetotelluric- and tomography data (Figure 7) were incorporated to test and constrain our final upper crust interpretation (Figure 8).

In order to determine what the mid-crust imaged in IyA-200501 may represent, we combined our observations in the seismic reflection data with an earlier interpretation (Lindeque et al., 2007), using far-field boreholes QU-1/65 and KC-1/70 (Figure 1, Eglington and Armstrong, 2003; Eglington, 2006), regional field observations from geological mapping (e.g. Joubert, 1971; 1986a, b; Albat, 1984; Macey 2000; 2001; Macey et al., 2011), the high resolution magnetotelluric model (Weckmann et al., 2007) and the tomography model derived from the wide-angle refraction data (Stankiewicz, et al., 2007; 2008), partly illustrated in Figures 7b–d.

To constrain the extent and depth of the contentious Beattie Magnetic Anomaly, the aeromagnetic data (CGS, 2000) were clipped to the same length and scale as the seismic profile (Figure 7a), and the location of the two axes with maximum magnetic signatures (~250 nT) within the BMA, projected into the IyA-200501 seismic image (Lindeque, et al., 2007; vertical black dashed lines in Figure 7b), as well as into the coincident high resolution magnetotelluric data (Weckmann, et al., 2007; Figure 7c), and the refraction tomography image (Stankiewicz et al., 2007; Figure 7d). We compared our BMA interpretation against previous models (Hälbich, 1993; Quesnel et al., 2009), an earlier interpretation (Lindeque et al., 2007) and regional geology (e.g. Naicker, 1993; Wilsher, 1995), to test our interpretation and postulate a possible BMA source.

Table 1. Simplified stratigraphy from bolehole data.

			depth to top of unit (m)		colour log	THICKNESS (m)		
	Group	**Formation**	**KW 1/67 log***	**SA 1/66 log***		**KW1/67**	**SA1/66**	**Seismic stratigraphy**
Karoo Supergroup	Beaufort	Abrahamskraal	2738	1267		2738	1267	Beaufort
	Upper Ecca	Waterford						Upper Ecca
		Fort Brown						
		Ripon	3049			311		
	Middle Ecca	Vischkuil						Middle
		Collingham	4361	2754		1312	1487	Ecca
	Lower Ecca	Whitehill	4404	2789		43	35	Whitehill
		Prince Albert	4558	2918		154	129	Prince Albert
	Dwyka		5556	3573		998+	655	Dwyka
Cape Supergroup	Witteberg		end of hole	pinched out		end of hole	0	Witteberg
	Bokkeveld			4105			532	Bokkeveld
	Table Mountain (TMS)	Nardouw		4170			65+	Nardouw
		Peninsula		end of hole			end of hole	

SA-1/66, location: 21.3292°E, -32.6694°S, completed: 12/09/1967, total depth: 13679 ft (4169.4 m).

KW-1/67, location: 22.3367°E, -32.9847°S, completed: 15/08/1968, total depth: 18224 ft (5554.7 m).

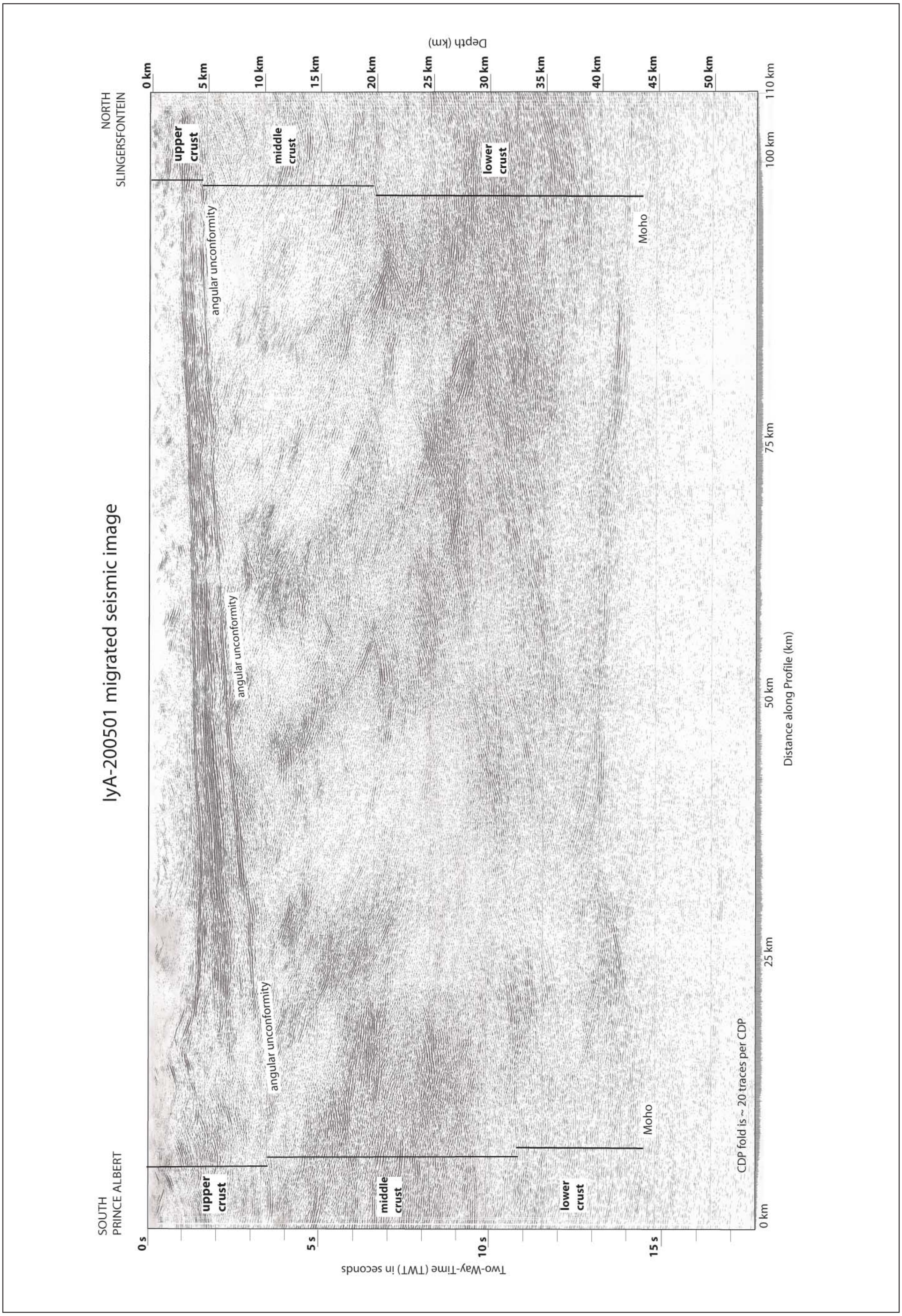
Logs compiled from PASA (1966, 1967b), Winter and Venter (1970), Rowsell and De Swart (1976), Cole and McLachlan (1994), Chevallier et al., (2004).

Discrepancies may exist with depths in the 1994 logs due to the removal of dolerite thickness.

** all depths are converted from feet to metres using a factor of 3.28 and measured to the base of the formation.*

Red dashed line = stratigraphic position of the local décollement between the Collingham and Whitehill Formations, see text for discussion.

Colours in the table correspond to the borehole logs for SA-1/66 and KW-1/67 illustrated in Figures 5 and 6, respectively.


IyA-200501 migrated seismic image
SOUTH
PRINCE ALBERT
NORTH
SLINGERSFONTEIN
upper crust
middle crust
lower crust
angular unconformity
angular unconformity
angular unconformity
Moho
Moho
CDP fold is ~ 20 traces per CDP
0 s
5 s
10 s
15 s
Two-Way-Time (TWT) in seconds
0 km
5 km
10 km
15 km
20 km
25 km
30 km
35 km
40 km
45 km
50 km
Depth (km)
0 km
25 km
50 km
75 km
100 km
110 km
Distance along Profile (km)

The lower-crust interpretation (Figure 9), was mostly determined from the seismic reflection data (Lindeque et al., 2007), knowledge of regional geological mapping (e.g. Joubert, 1986a, b; Thomas et al., 1993; 1994; 1996; Eglington, 2006) and seismic models of conterminous Grenville terranes on the conjugate Rodinia margin (e.g. Cook et al., 2004; 2005; Evenchick et al., 2005).

Lastly, we tested the depth of the major crustal divisions derived from the IyA-200501 seismic reflection data (i.e. upper-, middle-, lower crust and Moho depth) against crustal divisions recorded at the nearest teleseismic receiver function station (SA05 in Harvey et al., 2001, ~25 km east of IyA-200501, Figure 2), and in the large scale regional Agulhas-Karoo onshore-offshore refraction crustal model (Parsiegla et al., 2007; 2009; Stankiewicz et al., 2007; 2008).

We then compare and contrast our derived integrated crustal model (Figure 8, fold-out and Figure 9) to previous crustal models of southern South Africa (Figure 10; Hälbich, 1993, Chevallier et al., 2004; Lindeque et al., 2007; Figure 10). The collective analyses of all available data along the centre AKGT segment, allow us to:

i. propose new models for the tectonic evolution of southern Africa (Figures 11 and 12); and
ii. test existing Mesoproterozoic Rodinia models that link the Kibaran NNMB with the Grenville Mobile Belt of North America (e.g. Li et al., 2008), for the first time via direct comparison of corresponding seismic profiles and subsequent crustal models in the Canadian Lithoprobe Abitibi-Grenville Transect (Figures 13 and 14).

Results and interpretations

Sub-surface Geology (≤ 2 km)

The sub-surface continuation of folds interpreted in the upper 1 km shallow velocity structure (Bräuer et al., 2007) correlates well with the surface location of fold axes and faults in the Karoo Supergroup, determined from geological mapping and boreholes (Figures 4, 5 and 6). In the Vs model (Figure 4d) high velocities of 2.82 to 3.30 km/s correspond to anticlines, and lower velocities of 2.50 to 2.82 km/s to synclines. The Vs interpretation fits well with reflectors representing the Karoo Supergroup structure in the IyA-200501 seismic profile (compare Figure 4d with 4c and Figure 3). The integrated interpretation for the upper 2 km resolves the sub-surface structure of the Karoo Supergroup and in particular that of the Abrahamskraal Formation (yellow in Figures 5c, 6c; line drawing in Figure 4a). Four faults mapped at surface correlate to sub-surface low-angle listric faults in the seismic data (red dots, Figure 8) and several surface folds correlate to similar sub-surface structures in the seismic profile (Figure 8). Lateral variations of high- to low-velocities correspond to major listric faults in the IyA-200501 seismic data and to surface faults mapped in the Cape- and Karoo-Supergroups (compare Figure 4a, d and Figure 8).

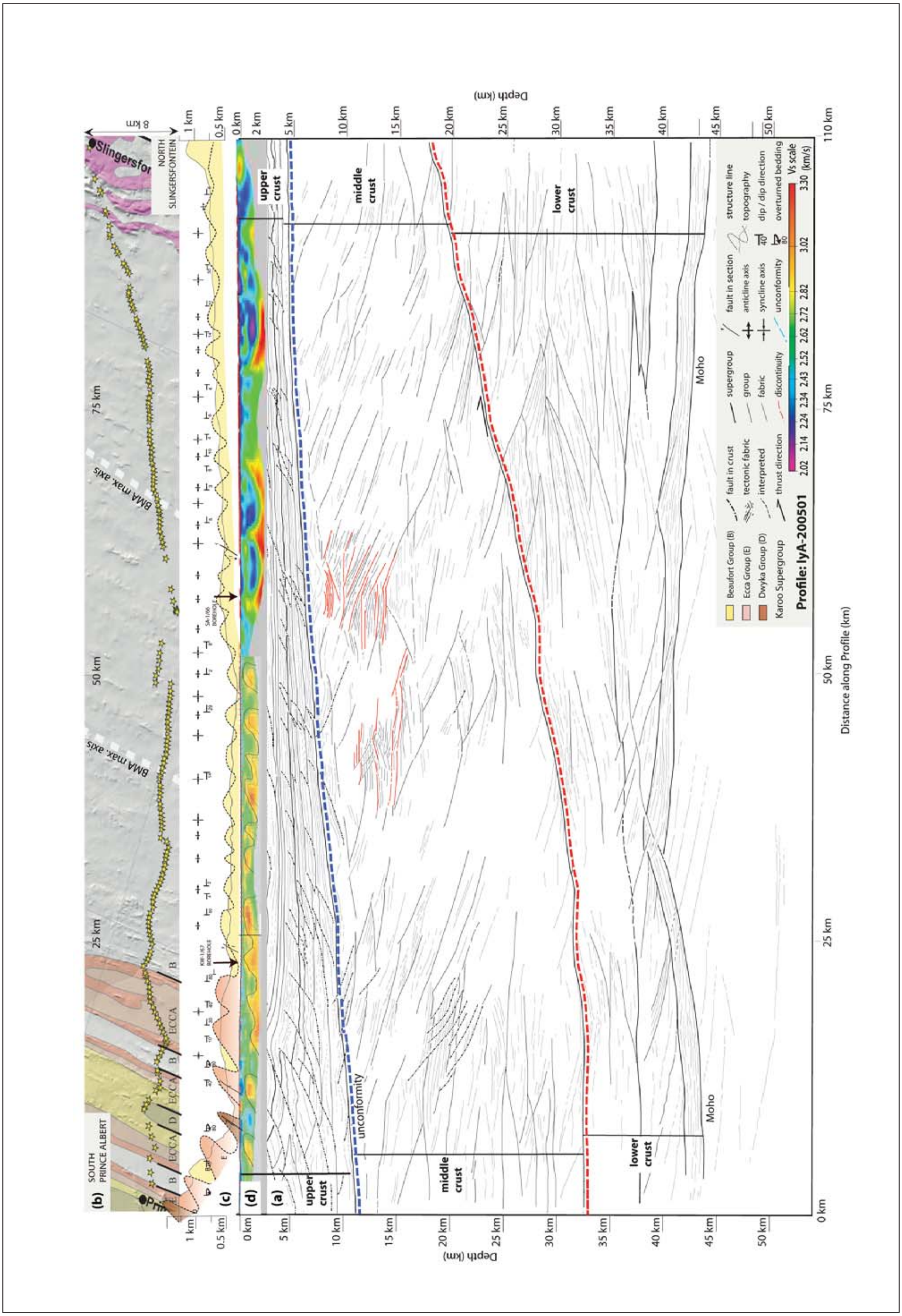
Upper crust (<10 km)

Borehole data and archive seismic profiles

The identification of lithologic contacts in the archive boreholes SA-1/66 and KW-1/67 hold inherent uncertainties. The first uncertainty is introduced when converting depth from Cape feet to metre. A Cape foot is a unit of length defined as 1.0330 English feet and equal to 0.314 metres. This uncertainty is compounded by poorly documented criteria used to define the stratigraphy at the time of logging the boreholes, especially the Dwyka−Ecca contact. In the 1960's when the boreholes were drilled, the Whitehill- and Prince Albert Formations were logged as part of the then "Upper Dwyka", and the transitional Dwyka−Ecca contact ill-defined. In 1980, the revised stratigraphy incorporated the "Upper Dwyka" (i.e. the Whitehill- and Prince Albert Formations) into the Ecca Supergroup (SACS, 1980). The lithostratigraphic contacts from the old well data therefore have limited reliability in a regional correlation.

The second uncertainty pertains to matching two-way-travel-time (TWT) in the archive seismic records to the borehole depths. A detailed velocity model is needed to convert TWT of reflectors in the archive paper records, to accurate depths and match it with the borehole logs. We used regional velocities from the tomography model (Stankiewicz et al., 2007) and constant velocity stacks from the IyA-200501 seismic reflection data processing (Lindeque et al., 2007) to convert TWT to depth. We illustrate this uncertainty in Figure 5a. Different interpretations of the Ecca−Dwyka contact are possible depending if interval velocities were used to convert the TWT of major reflectors to depth (Figure 5a, black lines), or if depths from the borehole logs were applied (Figure 5a, red lines). In the end, we collectively considered the borehole log depths, depths from the seismic velocity model (Lindeque et al., 2007), prominent reflectors in the archive paper records (Figure 5a) and paper-to-SEGY converted record (Figure 5b), as well as reflector positions in the 2007 seismic

Figure 3. *Migrated common mid-point (CMP) seismic profile IyA-200501 in depth domain, with coherency dip-scan filter applied before migration (Lindeque et al. 2007). A series of shallow, continuous, south dipping (~3 degrees) reflectors occur along most of the profile at approximately 1.5–3.5 s two-way-time (TWT) or 2 to10 km depth. The reflectivity of this package is notably different from the deeper reflections. A region of strong reflectivity outlines the expected region of the BMA at 5 s TWT (~10 to 15 km depth), and 55 to 65 km along the profile. The lower crust is highly reflective and imaged from 12–15 s TWT (20 to 40 km depths). The Moho appears at 42 to 45 km or ~15 s TWT. CMP interval is 50 m and the average fold 20. White gaps near surface depict data loss due to noise from the blast and constraints on borehole spacing.*


(b)
SOUTH PRINCE ALBERT
NORTH SLINGERSFONTEIN
Slingersfontein
8 km
25 km
50 km
75 km
BMA max. axis
B
ECCA
D
(c)
KW-1/67 BOREHOLE
SA 1/66 BOREHOLE
(d)
(a)
upper crust
middle crust
lower crust
unconformity
Moho
0 km
2 km
5 km
10 km
15 km
20 km
25 km
30 km
35 km
40 km
45 km
50 km
1 km
0.5 km
Depth (km)
0 km
25 km
50 km
75 km
110 km
Distance along Profile (km)
Beaufort Group (B)
Ecca Group (E)
Dwyka Group (D)
Karoo Supergroup
fault in crust
tectonic fabric
interpreted
thrust direction
supergroup
group
fabric
discontinuity
fault in section
anticline axis
syncline axis
unconformity
structure line
topography
dip / dip direction
overturned bedding
Profile: IyA-200501
Vs scale (km/s)
2.02 2.14 2.24 2.34 2.43 2.52 2.62 2.72 2.82 3.02 3.30

reflection data (Figure 5c) to determine a best fit for the stratigraphic contact. More weight was given to the prominent reflectors in the most recent seismic reflection data (Figure 5c) and the other records provided additional information. A similar approach was used in comparing the seismic profile KL-12 paper record, coincident borehole KW-1/67 (Figure 6a) and converted paper-to-SEGY record (Figure 6b), to the IyA-200501 extract (Figure 6c). Due to these depth-related uncertainties, the interpreted Dwyka contact and position of the Whitehill- and Prince Albert Formations in our model can differ up to 100 metres (e.g. two or three reflectors) from the borehole logs, archive paper and paper-to-SEGY records.

A third uncertainty relates to the distance of boreholes SA-1/66 and KW-1/67 respectively ~40 km to the west and 30 km to the east of lyA-200501 (Figure 2). When these boreholes are projected along strike into IyA-200501, regional variations in dip and thickness of the intervening strata make an accurate match unlikely, thus limiting the interpretation to a best fit solution.

Despite these uncertainties, SA-1/66 and KW-1/67 are the only boreholes near IyA-200501 therefore still duly considered for stratigraphic control. In both borehole logs, the base of the Beaufort- and Ecca Groups correlates well with the first group of broken reflectors at 1 to 2 km depth (Figures 5c and 6c). This is consistent with surface geology outcrop and shallow velocity sub-surface structure at 1.5 to 2 km depth (Figure 4). The Whitehill- and Prince Albert Formations (at 2754 m depth in SA-1/66, Figure 5c; and at 4361 m depth in KW-1/67, Figure 6c) correlate with our interpreted décollement surface in the IyA-200501 seismic image (Figures 8 and 9). In both archive seismic profiles (WK-01 in Figure 5a-b; KL-12 in Figure 6a–b) a series of strong, continuous, gently south-dipping reflectors can be traced. The paper-to-SEGY records (Figures 5b and 6b) suggest that the top of the Dwyka could be coincident with the first prominent reflector package (doublet, Figures 5c and 6c). However, the superimposed borehole logs show the top of the Dwyka to occur just above this doublet (thick arrow, Figures 5b and 6b). Contrary to the archive data, when the boreholes are projected into the IyA-200501 seismic section, the top of the Dwyka Group lies ~700 m above the doublet (SA-1/66, Figure 5c) or at the next reflector below the doublet (KW-1/67, Figure 6c). Since the Dwyka contact remains inconclusive in the archive seismic and borehole data, we look at field data to refine the interpretation. In the field, the transitional Dwyka-Ecca contact often occurs within shales. Such a transitional chronostratigraphic boundary within the same lithology (e.g. Ecca- and Dwyka shales) would not be recorded as a seismic reflector as there is no change in velocity across the contact. This makes it near impossible to pin down a precise contact in the seismic data without an IyA-200501 coincident borehole. It is therefore most likely that the first prominent reflector represents a transition from shale to the first massive tillite bed within the Dwyka Group. We incorporate knowledge from regional surface geology to further improve and test our Dwyka contact interpretation.

In the field, the IyA-200501 profile crosses Dwyka outcrops on surface twice, near the CFB front in the southern end of the seismic profile (Figures 2 and 4a, b). It is the only seismic line in the Karoo Basin to do so. Concentrating on this first 25 km of the profile and the regional geology (Figure 2) we can deduct the following: If we assume the first strong horizontal reflector represents some part of the Dwyka and incorporate surface geology, the Dwyka at 2 to 5 km depths must break through all continuous reflectors above, along a fault close to the tectonic front of the CFB to match the surface outcrops (Figures 4a–c). The IyA-200501 seismic data, archive seismic data profiles WK-01 and KL-12 and mapped surface geology allow the interpretation of a major thrust with duplexing, or a post-folding low-angle normal fault. Nearby field work recorded a strong décollement at the base of the Collingham Formation, or top of the Whitehill Formation (Figure 34, p.44 in Knütter, 1994). Thus the interpretation of a series of thrusts to bring the Dwyka to surface seems to work on all accounts. We therefore interpret the first prominent doublet reflector as the first massive tillite unit(s) in the Dwyka Group and draw the Dwyka−Ecca contact a few reflectors above the doublet (Figures 5c and 6c). Accordingly, the deeper packages of continuous, gently south-dipping reflectors between the doublet and the seismic discontinuity with the underlying basement are interpreted to represent lithologic units of the Cape Supergroup.

Figure 4. ***(a)*** *Line drawing interpretation of the migrated seismic reflection profile IyA-200501 in Figure 3. Note the difference in seismic fabric between the upper-, middle and lower crust: The upper crust fabric is mostly sub-horizontal with a series of low angle listric thrusts/faults. The mid-crust fabric dips dominantly north, whereas the lower crust fabric is more complex, dip to the north and south, and are bounded by a less reflective layer below. A highly reflective layer with dominantly horizontal fabric straddles the clearly defined Moho. Blue dashed line = the upper crust/mid-crust unconformity; red dashed line = the mid-crustal detachment interpreted as a thrust/shear plane.* ***(b)*** *Surface geology extract, legend same as in Figure 2: olive = Dwyka Group; yellow to orange = Ecca Group; grey = Beaufort Group; white dashed lines = BMA maximum axes; yellow stars = shot points of IyA-200501.* ***(c)*** *Geological cross-section with 5x vertical exaggeration. Brown = Dwyka Group; pale pink = Ecca Group; yellow = Beaufort Group.* ***(d)*** *Shallow velocity Vs-model for the upper ~1.5 km of the IyA-200501 line (Bräuer et al., 2007) and geological fold structures superimposed (dashed lines). High Vs velocities (reds and yellows) correspond to anticlines and low Vs velocities (greens) to synclines.*

Magnetotelluric data

A distinct band of high conductivity in the upper crust has previously been interpreted to image the Whitehill Formation (Weckmann et al., 2007a, b). Impedance spectroscopy measurements on samples from boreholes SA-1/66 and KW-1/67 showed that the high conductivity band also extends into the underlying Prince Albert Formation (Branch et al., 2007). To further interpret the lower Ecca sequences and particularly pinpoint the positions of the Whitehill- and Prince Albert Formations (Wh/PA), the magnetotelluric 2D conductivity model of Weckmann et al. (2007a) is superimposed on seismic line IyA-200501 and the high conductivity band annotated (red dotted line above the horizontal reflectors in Figure 7c). The high conductivity band matches our Wh/PA Formations interpretation in the borehole and seismic data (Figures 5c and 6c) reasonably well. In combining the regional surface geology, borehole data, archive- and new seismic reflection data with the magnetotelluric data, we identified the depth of the Whitehill- and Prince Albert Formations in our IyA-200501 upper crust model with significant confidence (Figure 8).

Refraction data – Tomography model

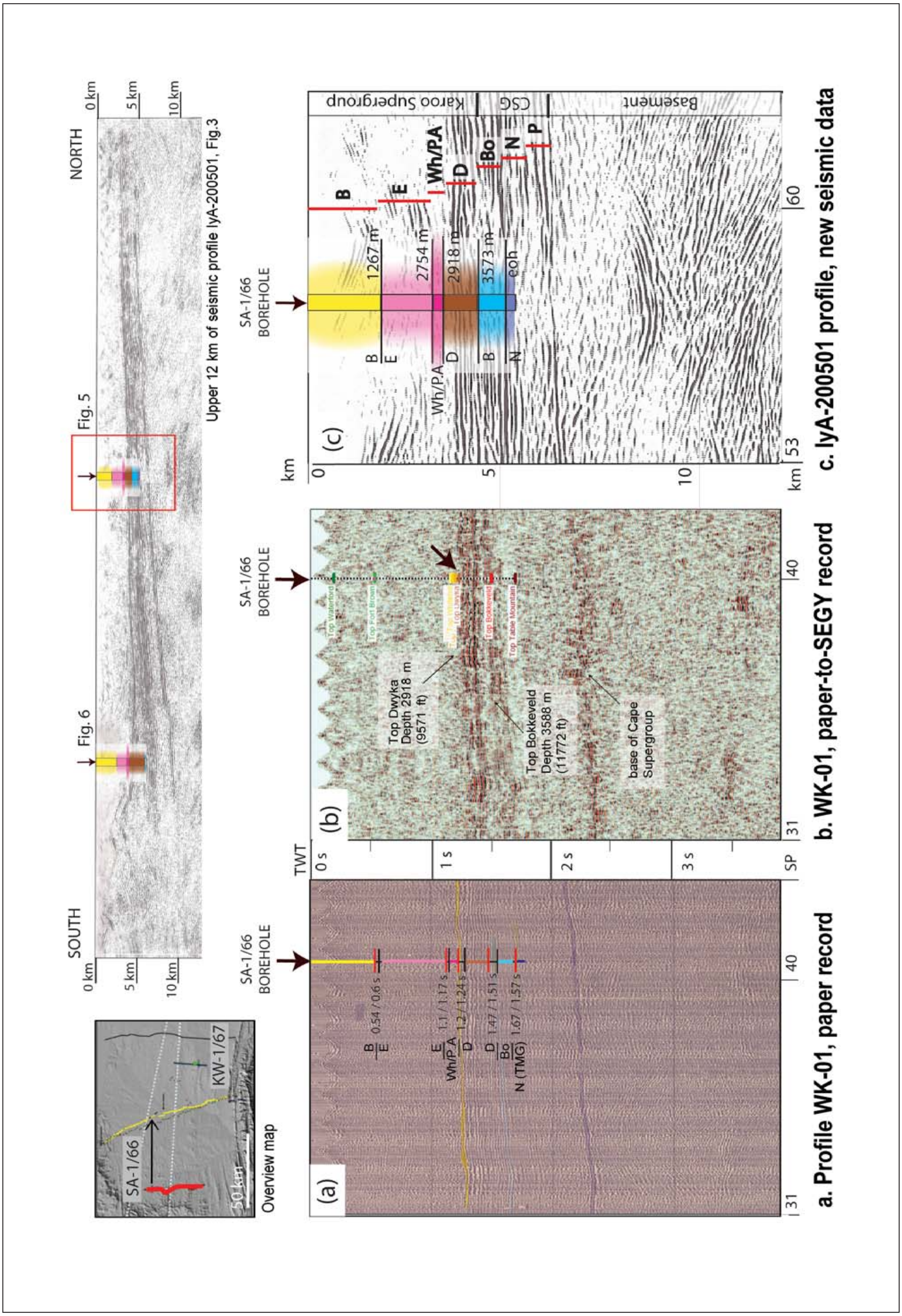
A tomography model derived from wide-angle seismic P-wave velocity experiments of Stankiewicz et al. (2007; 2008) is coincident to line IyA-200501 (Figure 2). When the tomography model is superimposed on the IyA-200501 seismic reflection image (Figure 7d), the low velocities (4.6 to 5.3 km/s) imaged in the tomography model occur in and above the package of sub-horizontal reflectors of the Cape Supergroup, whilst velocities increase rapidly below it (5.4 to 5.5 km/s). This downward increase in velocity occurs abruptly across the seismic discontinuity in IyA-200501, interpreted to define an apparent unconformity between the upper crust (Cape- and Karoo Supergroup) and the underlying mid-crust. An interpreted blind thrust fault in the tomography model (Stankiewicz et al., 2007) may be related to a series of low angle listric faults in the Cape- and Karoo Supergroup seen in the IyA-200501 seismic data (compare Figure 7d to Figures 3, 4 and 8). Although the blind thrust fault does not show up clearly in the seismic reflection image, the top of the thrust does coincide with the top of the interpreted Wh/PA Formations and the local décollement surface within the Ecca Group (red dashed line at the base of the Collingham Formation in Table 1; and Figure 8).

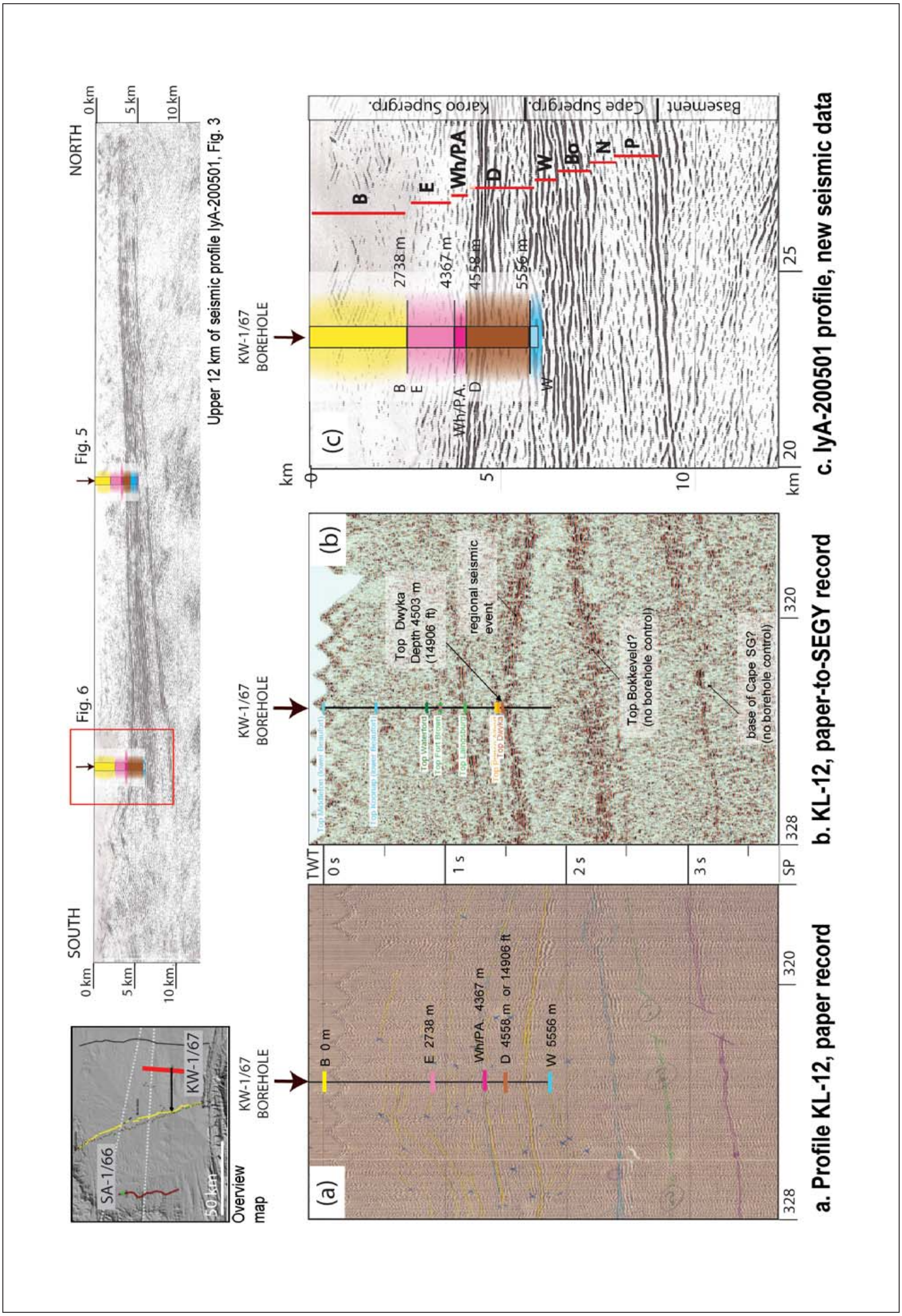
In summary, the seismic data, borehole information and magnetotelluric data collectively resolve the depths of individual formations in the Cape- and Karoo-Supergroups along the entire profile length, thereby concluding our interpretation of the upper-crust (Figure 8). The base of the Cape Supergroup is well constrained in all available datasets and marked by a flat truncating surface that dips slightly (at ~3 degrees) to the south. This erosional surface is labelled as an angular unconformity at the CSG base in Figures 3, 8 and 9 and is consistent with field observations throughout western South Africa (e.g. Johnson et al., 2006). More accurate regional chronostratigraphy to test our upper-crust interpretation against, can be only be obtained through re-logging boreholes SA-1/66 and KW-1/67, and/or by drilling new boreholes on line IyA-200501 with down-hole geophysical logging.

Mid-crust (~10 to 30 km)

Along the entire length of IyA-200501, the seismic data imaged reflectors in the mid-crust dipping north at approximately 20 degrees (Figures 3 and 4). This is interpreted as a tectonic fabric truncated abruptly by the strong, slightly south-dipping reflectors of the Cape Supergroup above (Lindeque et al., 2007; Figures 4, 8 and 9). The upper-crust/mid-crust interface is therefore represented by the sharp and near sub-horizontal unconformity. Boreholes farther afield ended in the Namaqua-Natal Metamorphic Belt (NNMB) gneisses below the Cape Supergroup (e.g. QU-1/65 and KC-1/70, Figure 1; Eglington and Armstrong, 2003; Eglington,

Figure 5. *Borehole log compared to seismic data. Top left: overview map of borehole SA-1/66, thick red line = seismic line WK-01; arrow = borehole projection along strike; yellow line= seismic profile IyA-200501; background image = 20 m DEM in Figure 2; white dashed lines = BMA maximum axes. Top right: Migrated image of the upper 12 km of seismic reflection profile IyA-200501 and boreholes. Red block = area shown in Figures 5a-c below.* ***(a)*** *Paper record extract of archive seismic line WK-01 and line coincident borehole SA-1/66 superimposed. From the compiled borehole log in Table 1: top of the Ecca Group (E) lie at ~0.5 s TWT; top of the Whitehill- and Prince Albert Formations (Wh/PA) at ~1.1 s TWT; top of the Dwyka Group (D) just above the first reflector at ~1.2 s TWT; top of the Bokkeveld Group (Bo) at ~1.47 s TWT; and top of the Nardouw Formation (N), in the Table Mountain Group (TMG) at ~1.67 s TWT. Black and red horizontal lines mark the top of each group or formation, based on either using interval velocities to convert TWT to depth, or the depths in the borehole logs.* ***(b)*** *Paper record in (a) converted to SEGY data and same horizons marked. Thick black arrow marks the interpreted top of the Dwyka Group above the first horizontal reflector* ***(c)*** *IyA-200501 seismic data and projected borehole log SA-1/66 superimposed. Red vertical lines match stratigraphic units in the seismic image to the corresponding borehole units. The Karoo Supergroup: B = Beaufort Group; E = Ecca Group; Wh/PA = Whitehill- and Prince Albert Formations forming the base of the Ecca Group; D = Dwyka Group. The Cape Supergroup (CSG): Witteberg Group absent and pinched out to the left of the borehole; Bo = Bokkeveld Group; N = Nardouw Formation and P = Peninsula Formation forming part of the Table Mountain Group. Compare (a) and (b), to (c): pale pink = top of the Ecca Group; darker pink = Whitehill- and Prince Albert Formations; brown = top of the Dwyka Group above the first prominent reflector. See text for discussion of the Dwyka contact.*


Overview map
SA-1/66
KW-1/67
50 km
SOUTH
NORTH
Fig. 6
Fig. 5
0 km
5 km
10 km
Upper 12 km of seismic profile IyA-200501, Fig.3
SA-1/66 BOREHOLE
(a)
(b)
(c)
TWT
SP
km
Top Dwyka Depth 2918 m (9571 ft)
Top Bokkeveld Depth 3588 m (11772 ft)
base of Cape Supergroup
1267 m
2754 m
2918 m
3573 m
eoh
Karoo Supergroup
CSG
Basement
a. Profile WK-01, paper record
b. WK-01, paper-to-SEGY record
c. IyA-200501 profile, new seismic data



Overview map
SA-1/66
KW-1/67
50 km
SOUTH
NORTH
0 km
5 km
10 km
Fig. 6
Fig. 5
Upper 12 km of seismic profile IyA-200501, Fig. 3
KW-1/67 BOREHOLE
(a)
B 0 m
E 2738 m
Wh/PA 4367 m
D 4558 m or 14906 ft
W 5556 m
328
320
TWT
0 s
1 s
2 s
3 s
SP
a. Profile KL-12, paper record
(b)
Top Dwyka Depth 4503 m (14906 ft)
regional seismic event
Top Bokkeveld? (no borehole control)
base of Cape SG? (no borehole control)
b. KL-12, paper-to-SEGY record
(c)
km
2738 m
4367 m
4558 m
5556 m
Wh/P.A.
B
E
D
W
Wh/PA
Bo
N
P
Karoo Supergrp.
Cape Supergrp.
Basement
20
25
c. IyA-200501 profile, new seismic data

***Figure 6**. Borehole log compared to seismic data. Top left: overview map of borehole KW-1/67, thick red line = seismic line KL-12; arrow = borehole projection; yellow line = seismic profile IyA-200501; background image = 20 m DEM in Figure 2; white dashed lines = BMA maximum axes. (**a**) Extract from archive seismic line KL-12 paper record and line coincident borehole KW-1/67. From the compiled borehole log in Table 1: top of the Ecca Group (E) lie at ~0.7 s TWT; top of the Whitehill- and Prince Albert Formations (Wh/PA) at ~1.25 s TWT; top of the Dwyka Group (D) just at the first reflector (~1.5 s TWT in (a) and 4502 m depth in (**b**)); top of the Bokkeveld Group (Bo) at ~2.5 s TWT; base of the Cape Supergroup (CSG) at 3.25 s TWT. Compare with the same horizons marked in the SEGY data (6b) derived from the same paper record shown in (a). (**c**) Seismic data of IyA-200501 and projected borehole log KW-1/67. Red vertical lines match stratigraphic units in seismic image to the corresponding borehole units. Compare (c) with the paper record (6a) and paper-to-SEGY record (6b) which suggests the top of the Dwyka occurs at the first prominent reflector and not below as is the case when the borehole is projected into the IyA-200501 seismic profile (6c). Borehole KW-1/67 ends in the Witteberg Group and a fault. The original log recorded that the Witteberg Group pinches out farther north (PASA, 1967b). In contrast to Figure 5c, borehole SA-1/66 on the IyA-200501 seismic image (Figure 6c), suggests the Prince Albert- and Whitehill Formations (purple) are represented by the first prominent reflector; the top of the Dwyka Formation lies just below. Lettering as for figure 5, and W = Witteberg Formation.*

2006). The basement beneath IyA-200501 is therefore also interpreted as NNMB crystalline basement and most likely, as stacked wedges of 1.0 to 1.4 Ga granitic gneisses of the Bushmanland terrane (Lindeque et al., 2007).

The north-dipping mid-crust fabric is concordant with the typical east-west trending and north-dipping D2 planar fabric (S2) of the NNMB gneisses, mapped in the field to the north of IyA-200501 (e.g. Joubert, 1971; 1986a, b; Albat, 1984; Macey 2000; 2001; Macey et al., 2011). These field observations document polyphase deformation events that resulted in complex, doubly-plunging basin-and-dome type interference structures, and refolded tight to isoclinal D2 folds with long limbs parallel to S2, generally represented by a strong gneissic banding with intense linear fabrics.

The magnetotelluric model cut at 30 km depth identified a number of high conductivity anomalies in the mid-crust (Weckmann et al., 2007). When superimposed on the IyA-200501 seismic profile, the seismic reflectors (black dashed lines, Figure 7c) appear to transect the boundaries of the high conductivity anomalies (red dashed lines in Figure 7c). The possible reason for this is discussed in the next section.

The tomography refraction model identified a high velocity > 6.5 km/s, ~20 km wide region near the centre of the mid-crust (Stankiewicz et al., 2007; 2008; oval in Figure 7d and insert). Although this high velocity region is 20 km north and 7 km deeper than regions of high reflectivity in IyA-200501, the latter identified as the Beattie Magnetic Anomaly (Lindeque et al., 2007), the southern part overlaps spatially with the seismic data and high conductivity zone seen in the MT data (Figure 7c and d). Regions of lower velocities ~6 to 6.5 km/s are coincident with the rest of the mid-crust sector of IyA-200501.

The Beattie Magnetic Anomaly

Two regions of high reflectivity in the IyA-200501 seismic image occur directly below the two diverging BMA axes of maximum aeromagnetic values (CGS, 2000; Figures 1, 3, 4 and 7). The seismic character of the two regions is complex and their internal reflectivity is stronger than that of the adjacent NNMB seismic fabric. The northern region is ~10 km wide, and the southern region 5 to 7 km wide, with an approximate gap of 6 km between them. Combined, the two regions appear as a ~24 km wide zone confined to the NNMB mid-crust at 7 to 12 km depth below surface, interpreted as the source of the BMA (Lindeque et al., 2006; 2007; Figures 7 and 9). The interpretation is consistent with the divergence of the BMA maximum axes seen in the aeromagnetic data (compare Figures 1 and 7). Another complex reflectivity cluster occurs 12 km farther south, and although spatially coincident with a similar high conductivity anomaly, it does not have a clear expression in the aeromagnetic data and falls outside the identified BMA region (dashed outlined region in Figure 1).

Apparent crossing reflectors in the mid-crust at 10 to 30 km depth and at ~40 km along the line may be interpreted as fold-like features resembling a flower structure, in which case strike-slip motion might explain the "duplication" of the anomaly. However, we find no further supporting evidence for this and since no flower structures were identified in the magnetotelluric data (Weckmann et al., in press), we discard this idea. The magnetotelluric data of Weckmann et al. (2007a) did image a "bean-shaped" conductivity anomaly (low resistivity of ca.1 ohm.m) in the mid-crust at kilometre 55 to 66 km along IyA-200501 (Figure 7c). It coincides with the northern maximum axis of the BMA, and the northern region of higher reflectivity in the seismic data (compare Figures 7a, b and c). Whilst the high conductivity anomaly is reasonably coincident with the complex reflectivity zone in the seismic data, it should be noted that the outlines of the conductivity anomalies apparently transgress the seismic reflectors (compare Figures 7b and c). We interpret this to indicate that the conductivity anomaly reflects, at least in part, a secondary metasomatic overprinting processes.

In summary, the southern part of the >20 km wide high reflectivity zone coincides with the BMA region identified in the magnetotelluric data, and the vertical downward projection of the northern BMA axis in aeromagnetic data. These observations are consistent with our interpretation that this region of complex

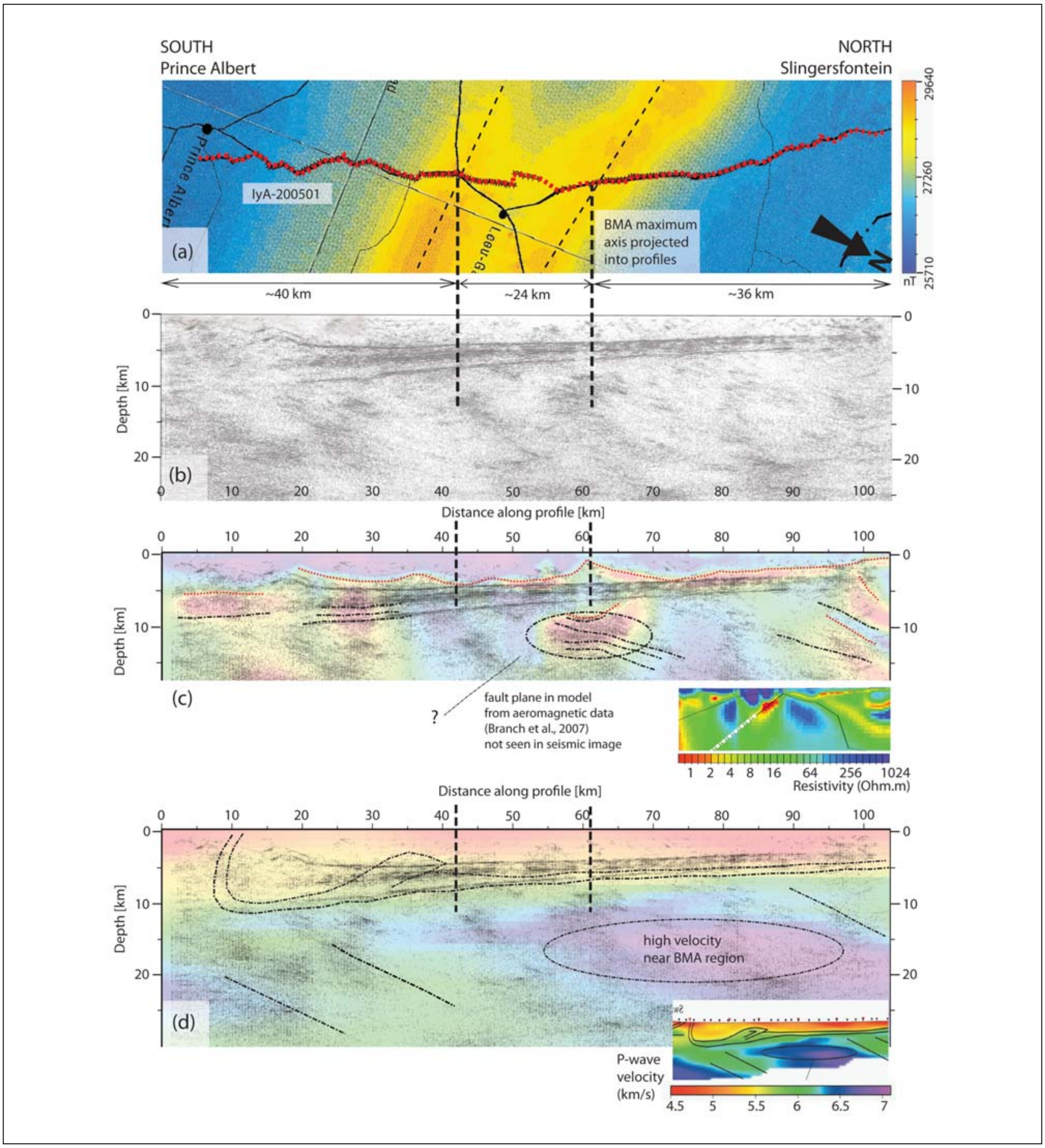


Figure 7. *Beattie Magnetic Anomaly (BMA) interpretation: (**a**) Total free air aeromagnetic data extracted from Figure 1 (CGS, 2000). Red dots = IyA-200501 seismic profile; thin black dashed lines = surface expression of the BMA maximum axes; black solid lines = main roads. Note the BMA divergence near the centre of the profile, 40 km from the south and 36 km from the north. Total estimated BMA width in the profile, measured from maximum to maximum = 24 km. (**b**) Extract of the upper ~20 km from the IyA-200501 seismic reflection profile. BMA maximum axes in (a) are projected into the seismic profile (b, thick black dashed lines) coinciding with two regions of greater reflective density near the centre of the profile at kilometres 40 to 60 and ~7 to15 km depth. (**c**) 2D conductivity model of Weckmann et al. (2007a) and migrated image of IyA-200501 superimposed for direct comparison. The northern BMA maximum axis aligns with a high conductivity anomaly (yellows to reds). Seismic reflectors in the mid-crust, cut across the margins of the high conductivity anomalies (black dot-dashed lines). The conductivity model best resolves the top of the conductors in the upper crust (red dotted lines). Insert: MT model and forward model of aeromagnetic data superimposed (Weckmann et al., 2007a, b). An inferred south dipping fault in the aeromagnetic data model (dashed white line) is not seen in the seismic data. (**d**) Tomography model and interpretation (thin black dot-dashed lines) from Stankiewicz et al. (2007), with seismic reflection data of profile IyA-200501 superimposed for direct comparison. Insert: complete tomography model of Stankiewicz et al. (2007).*

seismic reflectivity designates the two-part NNMB, BMA source. The presented interpretation agrees with previous work (Lindeque et al. 2007) and with the model of Quesnel et al. (2009) that recognizes two similar adjacent magnetized sheet-like prisms in the mid-crust at 9 to 12 km depth and 13 to 18 km depth, separated by a vertical offset of ~2 to 5 km.

The Lower crust (> 25 km) and Moho

The transition from mid- to lower crust is marked by a strong change in seismic reflectivity at ~32 km depth in the south and ~20 km depth in the north, interpreted as a tectonic break (e.g. a mid-crustal detachment; red line in Figure 4). Deflections of the north dipping seismic fabrics as it nears the detachment suggest it is a thrust zone, but parts of the deflections could also be interpreted to reflect normal shear displacements.

A previous interpretation of IyA-200501 indentified two components in the lower crust:

1. a wedge with north and south dipping fabric underlain and transposed by
2. a ~2 to 3 km thick layer near the 42 to 48 km deep Moho (Lindeque et al., 2007).

Detailed re-analysis of IyA-200501 reveals a more complex, possibly four-component lower crust model (Figures 3, 4 and 9). The four components are:

i. ii. Two interlocked wedges with a complicated north and south dipping fabric, interpreted as a series of interleaving slivers (greens, Figure 9). In a regional tectonic context, these wedges could be interpreted as an extension of the ~2.0 to 1.3 Ga juvenile crust NNMB basement in the Areachap Terrane, Richtersveld Terrane and Kheis Province in the Namaqua sector of the NNMB (Joubert, 1986a, b; Thomas et al., 1993; 1994; 1996; Eglington, 2006) or, as a continuation of the 1166 Ma Achab Gneiss basement below the Central Bushmanland Terrane (Cornell and Pettersson, 2007; Pettersson et al., 2007).

iii. A lower, ~10 km thick layer at 38 to 40 km depth and less reflective than the two wedges above (Figure 4; light grey in Figure 9). The dominant fabric dips north and penetrates the thin higher reflectivity layer below (dark grey layer in Figure 9), suggesting that the two lowermost layers may be related and older than the NNMB wedge above.

iv. A highly reflective thin (~2 to 5 km thick) layer at approximately 40 to 43 km depth lies parallel to the Moho (Figures 3 and 4; dark grey in Figure 9). This reflective layer may be interpreted as magmatic underplating, similar to that recorded in many other seismic sections globally and could be of metamorphic or metasomatic origin (e.g. Eaton, 2005). Alternatively, the strong reflective layer could be interpreted as a decoupling- or transition zone between the lower crust and uppermost mantle, with a vertical extent of a few kilometres (Oueity and Clowes, 2010). A few north dipping reflectors transect the underplated layer at two points, ~30 and 60 kilometres along IyA-200501. We interpret these as fault planes, but the cause for this Moho displacement is unclear. It could be argued that the two points are consistent with strike-slip motion normal to the plane of the seismic line and resemble a flower structure of lithospheric scale. However, similar to the mid-crust, we have no further substantial evidence for this idea and the interpretation is left as discussed. The Moho depths are in good agreement with receiver function analyses of Harvey et al. (2001; station SA05 in Figure 2), as well as results from the amphibian wide-angle refraction experiment along the entire western line of the AKGTransect (Figure 1; Parsiegla et al., 2007; 2009).

The reflectivity pattern seen in the lower crust is typical of interwedging terranes in continental collision zones (e.g. Wever and Sadowiak, 1991) and consistent with reflectivity patterns and interpretations from the Lithoprobe profiles across similar age Proterozoic terranes (e.g. Cook et al., 2004; 2005; Evenchick et al., 2005). The Abitibi-Grenville Transect (Winardi and Mereu, 1997; Ludden and Hynes, 2000; Mereu, 2000; White et al., 2000) is of particular interest for this comparisson and discussed later on.

Discussion

Our integrated crustal model in Figure 9 derived from the datasets discussed, contrasts distinctly with the previous model of Hälbich (1993) and subsequent models based thereon (e.g. Catuneanu et al., 1998; 2002; Chevallier et al., 2004; Johnson et al., 2006; Tankard et al., 2009). The most obvious differences with some of these models and their implications are briefly summarized, starting from the upper crust down to the Moho.

Karoo Basin

The Karoo Supergroup (yellow, pink and brown in Figures 8 and 9) retains a near constant thickness in the upper 2 to 3 km of IyA-200501, whereas the Cape Supergroup varies from 2.5 to 5 km thick. Previous models of Hälbich (1993), Chevallier et al. (2004) and Johnson et al. (2006) postulate a ~8 km thick Karoo Basin and significant stratigraphic fore-deep thickening at the Cape Fold Belt Front (Figure 10a–c). This is not seen in the seismic reflection data. The integrated crustal model presented here constrains a shallow Karoo Basin, with deformation of the Karoo Supergroup, at least locally, detached from the Cape Supergroup below. Low angle thrusts appear rooted in the Whitehill- and Prince Albert Formations of the Ecca Group, which acted as local décollement surfaces.

The Cape Supergroup

The Cape Supergroup continues all along IyA-200501 (blues and purples in Figures 8 and 9). The seismic data imaged the Cape Supergroup as a continuous undeformed sub-horizontal wedge, 1.5 km thick at the escarpment in the north and 10 km thick at the CFB front in the south. This wedge continues below the escarpment and does not pinch out as previous geological-based models suggest. However, the Witteberg Group still pinches out before borehole SA-1/66 (compare Figure 8 with Figure 10a–c). The base of the Cape Supergroup is defined by an angular unconformity dipping at ~3 degrees to the south. The crustal model presented here suggests the Cape Supergroup shortened via low-angle listric thrusting and thin-skinned tectonics beneath the Karoo Basin (Figure 8, fold-out). The northernmost limit of combined low angle thrusting and significant folding of the Cape Supergroup is restricted to the Cape Fold Belt front. The low angle faults do not appear to penetrate the basement as the Hälbich (1993) model implied (compare Figures 10a and 10d).

Extent of the NNMB mid-crust

In our model, the regional NNMB mid-crust fabric dips to the north at ~20 degrees (Figure 9). The mid-crust wedge thins to the north and consists of three units or blocks (shades of orange in Figure 9), each one made up of stacked smaller wedges and a strong north dipping fabric terminating against the NNMB mid-crust detachment and the older NNMB lower crust below (greens in Figure 9). The regional north-dipping fabric seen in the upper part of the mid-crust (orange in Figure 9) does not fit the major south dipping subduction zone model advocated by Hälbich (1993). In previous models, the southernmost boundary of the NNMB was defined by a deep BMA (serpentinised ophiolite wedge in Figure 10a) and the Southern Cape Conductive Belt, possibly abutting a Pan African (Neoproterozoic) suture zone beneath the Cape Supergroup (e.g. de Beer et al., 1982; de Beer and Meyer, 1983; 1984; Pitts et al., 1992; Eglington et al., 1993; Cornell et al., 2006; Eglington, 2006). The seismic data do not support these models:

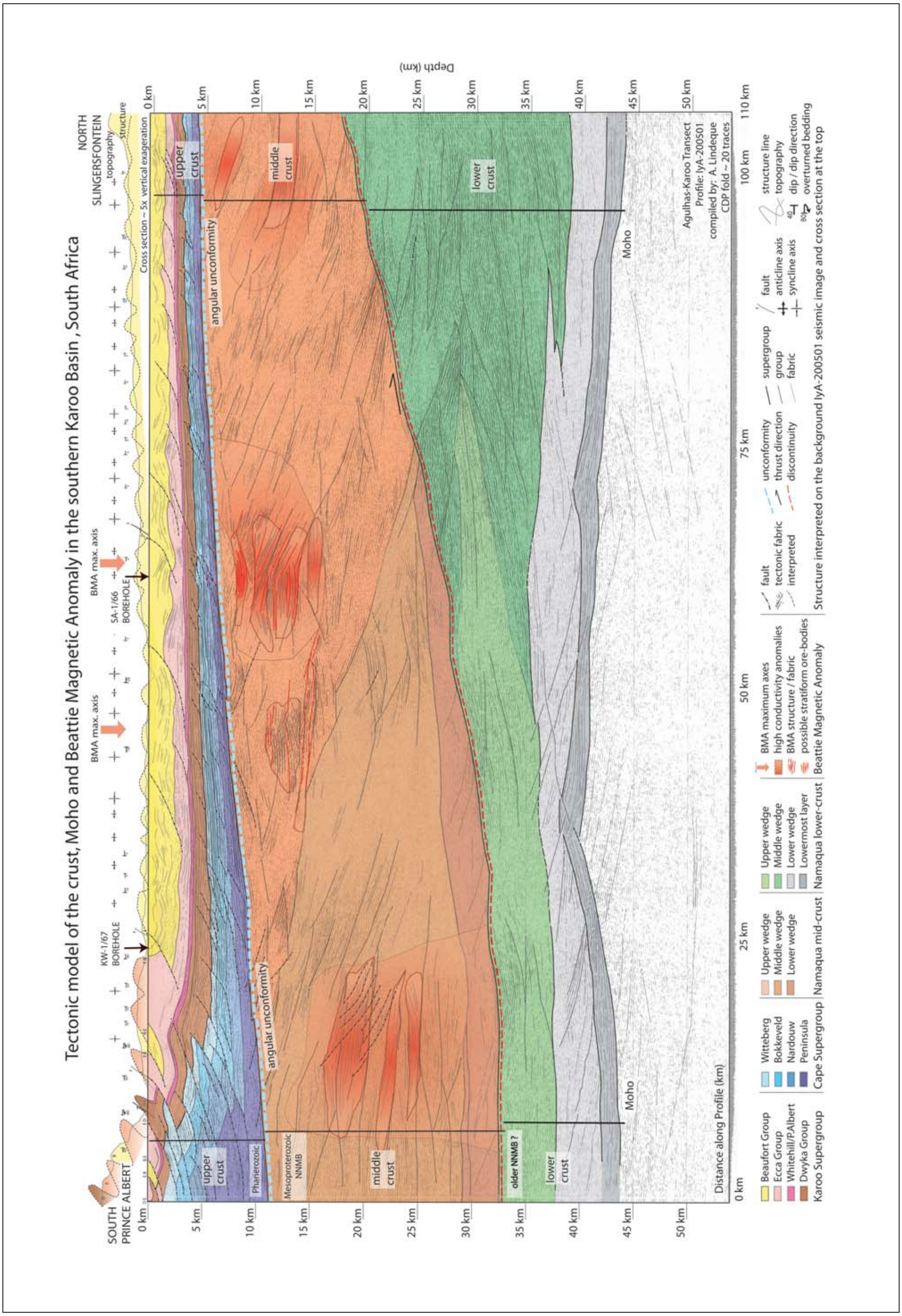
In our model, the top of the NNMB reflections (Figure 9) are truncated by a major angular unconformity at 5 km depth in the north, dipping to 12 km depth in the south and traceable along the full profile length. This unconformity, the flat CSG base and particular seismic characteristics of the mid-crust below, collectively suggest that the NNMB continues beneath the CFB and possibly farther south below the CFB up to the Agulhas Bank (Figure 11). Contradictory to all previous models, the seismic reflection image implies that Pan African Saldanian rocks are not present below the angular unconformity.

Our interpreted extension of the NNMB to the continental shelf and up to the Agulhas Falkland-Fracture Zone (AFZZ) as illustrated in Figure 11, is further supported by the seismic wide-angle refraction work and subsequent tomography crustal models of Parsiegla et al., (2007; 2009) and Stankiewicz et al. (2007; 2008). Their data indicate that the mid- and lower crust beneath the Cape-/Karoo Basin have similar seismic properties up to the continental boundary, thereby implying the nature of the crystalline basement beneath the CFB, and beyond, is likely Mesoproterozoic NNMB. In addition, magnetic crustal anomalies south of the BMA (Du Plessis and Thomas, 1991), borehole data (Eglington and Armstrong, 2003) and inherited ~2 Ga zircons from the ~550 Ma Cape Granite Suite plutons within the Cape Fold Belt (unpublished data, Eglington, 2006), are all consistent with an NNMB that extends much farther south, well beyond the BMA. Backeberg et al. (this volume) suggest that Mesoproterozoic crust, interpreted by them to be Bushmanland gneiss equivalents, is required to explain the crustal contamination of dolerite dykes intruding the Cape Peninsula.

The position and age of the Cape Meredith complex, provides additional evidence that the NNMB extends farther south below the CFB. Many Gondwana reconstructions place the Falkland Islands and surrounding plateau against the south coast of South Africa, conterminous with the Cape-Karoo basin (e.g. Grantham et al., 1997; Jacobs et al., 1997; Thomas et al., 1997; Storey et al., 1999; Figure 11). The basement to the Cape Supergroup equivalent rocks on the Falkland Islands are the ~1 Ga Mesoproterozoic amphibolite grade meta-volcanic and mafic sequences of the Cape Meredith Complex (Thistlewood et al., 1997; Thomas et al., 1997). In the Gondwana reconstruction, this Mesoproterozoic Eastern Falkland basement lies south of the CFB front and the West Falkland a bit further north (e.g. Figure 6 in Storey et al., 1999), supporting our interpretation that a Mesoproterozoic basement occurs well south of the BMA and CFB.

In short, the crustal model presented here reveals that the BMA is neither a southern boundary of the NNMB, nor a major Pan African suture, and calls for a significant adjustment of the crustal model of southern Africa as suggested in Figure 11.

Figure 9. *New crustal tectonic model derived from the integration of seismic reflection data; wide-angle refraction data; magnetotelluric measurements; aeromagnetic data; receiver function analyses and existing boreholes as discussed in the text. The upper crust comprises the Karoo Supergroup (yellow to brown) and Cape Supergroup (light blue to purple), separated from the basement by an angular unconformity (blue dashed line) and Namaqua-Natal Metamorphic Belt mid-crust (shades of orange). The interpreted two-part, stratiform sulphide-magnetite bearing Beattie Magnetic Anomaly (BMA) ore bodies (dark red polygons), at 7 to 15 km depth are coincident with MT conductivity anomalies (red dashed line polygons). The older NNMB or Palaeo-Proterozoic lower crust (shades of green) is bounded by a mid-crustal detachment above and older material below (light grey). See text for further explanation.*


Tectonic model of the crust, Moho and Beattie Magnetic Anomaly in the southern Karoo Basin, South Africa
SOUTH PRINCE ALBERT
NORTH SLINGERSFONTEIN
KW-1/67 BOREHOLE
SA-1/66 BOREHOLE
BMA max. axis
Cross section ~ 5x vertical exageration
topography
structure
upper crust
middle crust
lower crust
Phanerozoic
Mesoproterozoic NNMB
older NNMB ?
angular unconformity
Moho
Depth (km)
Distance along Profile (km)
Agulhas-Karoo Transect
Profile: IyA-200501
compiled by: A. Lindeque
CDP fold ~ 20 traces
Beaufort Group
Ecca Group
Whitehill/P.Albert
Dwyka Group
Karoo Supergroup
Witteberg
Bokkeveld
Nardouw
Peninsula
Cape Supergroup
Upper wedge
Middle wedge
Lower wedge
Namaqua mid-crust
Upper wedge
Middle wedge
Lower wedge
Lowermost layer
Namaqua lower-crust
BMA maximum axes
high conductivity anomalies
BMA structure / fabric
possible stratiform ore-bodies
Beattie Magnetic Anomaly
fault
tectonic fabric
interpreted
unconformity
thrust direction
discontinuity
supergroup
group
fabric
fault
anticline axis
syncline axis
structure line
topography
dip / dip direction
overturned bedding
Structure interpreted on the background IyA-200501 seismic image and cross section at the top

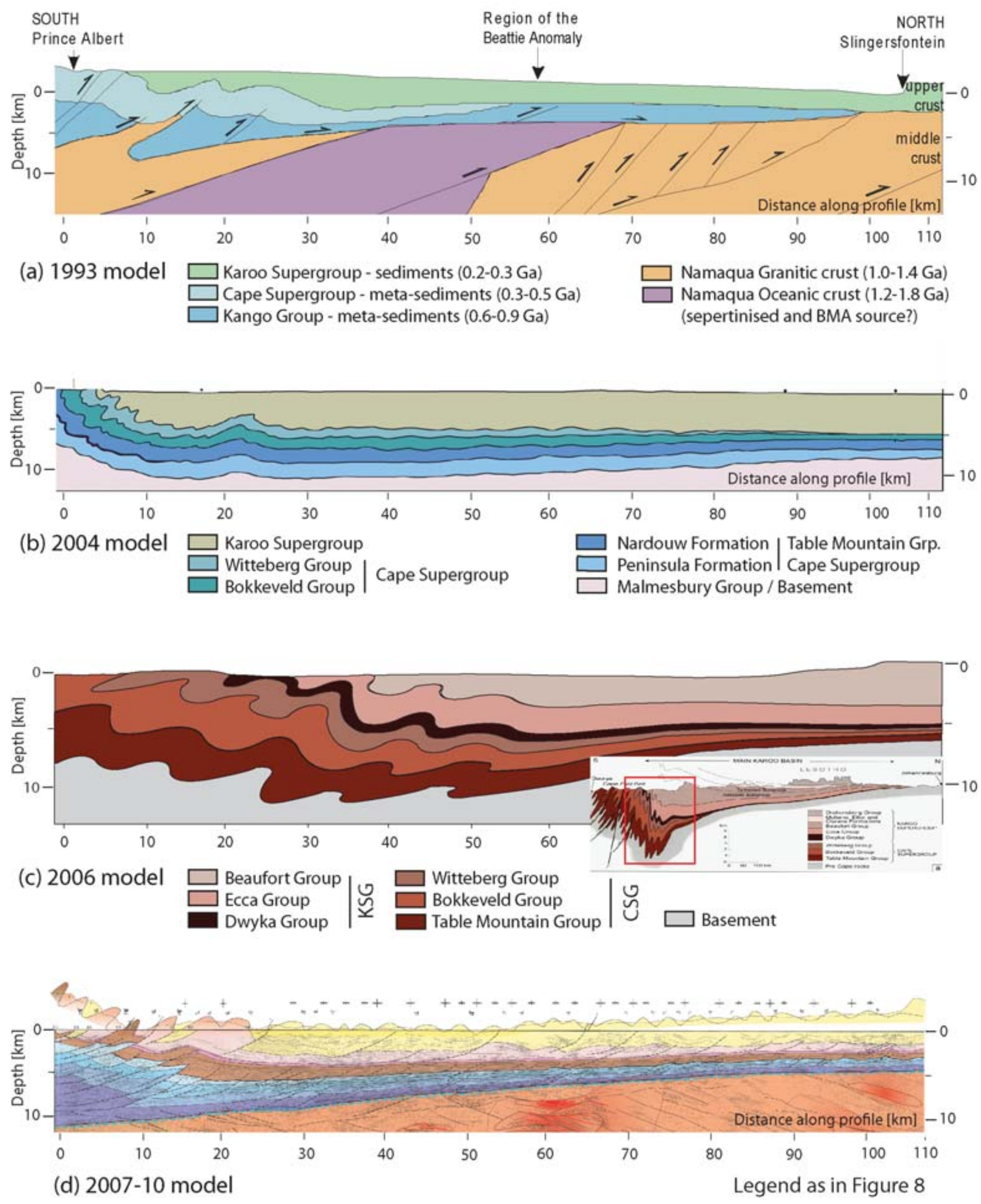


Figure 10. *Comparing models of the Cape- and Karoo Basins in the upper crust (< 15 km). (**a**) Hälbich et al. (1993) model: Purple = ophiolite wedge/serpentinised palaeoceanic crust, their interpreted BMA source. A series of southward dipping low-angle thrusts cut the upper and middle crustal regions. Thrust planes in the upper crust (e.g., Cape Fold Belt-Karoo Basin) have the same north-directed tectonic vergence as those in the underlying Natal-Namaqua crystalline basement (arrows). (**b**) Chevallier et al. (2004) model: Karoo Supergroup undifferentiated (light brown) and Cape Supergroup (in blues); (**c**) Johnson et al. (2006) model: Close-up from the regional model (insert), stretched to the same vertical and horizontal scale as the IyA-200501 line. Red square = profile extent. Note significant folding and deepening before the CFB compared to the new 2007–10 model. (**d**) 2007–10 model: legend same as in Figure 8 and 9: 2 to 5 km thick Karoo Supergroup: yellow = Beaufort Group; pale pink = Ecca Group; dark pink = Whitehill- and Prince Albert Formations forming the base of the Ecca Group; brown = Dwyka Group. Cape Supergroup below: light blue = Witteberg Group; blue = Bokkeveld Group; dark blue = Nardouw Formation; purple = Peninsula Formation. Dashed lines = listric faults; finer black lines = reflectors from the IyA-200501 seismic image interpreted as a litho-tectonic fabric. Non-folded ~1.5 to 10 km thick Cape Supergroup continues beneath the Karoo Basin along the entire length of the profile and rests unconformably on the Namaqua-Natal basement (orange) that hosts the two-part Beattie Magnetic Anomaly (highlighted in red). In contrast, the older 1993, 2004 and 2006 models in (a–c) show: (i) interconnected folding of both the Cape and Karoo Supergroups; (ii) significant thickening of the Karoo Supergroup before the Cape Fold Belt, interpreted as a fore-deep basin; and (iii), a root below the Cape Fold Belt. Such features are not observed in the 2007–10 model (Figure 10c). See text for further discussion.*

The Beattie Magnetic Anomaly and its possible source

From the geological and geophysical data presented, we described the apparent shape, depth and lateral extent of the two-part BMA hosted in mid-crustal rocks, interpreted as gneisses of the NNMB, at 7 to 15 km below surface. Along IyA-200501, the BMA is a 10 to 22 km wide zone, almost 6 km thick, with a distinct complex internal seismic character (Figures 7 and 9). The defined BMA region is coincident with the divergent maximum axes seen in aeromagnetic data, and in broad agreement with the magnetotelluric data, but the source of the BMA remains under debate.

Previous work based magnetic interpretations and vertical magnetic fields of a large magnetometer array, suggested the BMA source may be a steeply dipping slab of serpentinised oceanic lithosphere, representing a Neoproterozoic suture zone (e.g. de Beer et al., 1982; de Beer and Meyer, 1983; Hälbich, 1993; Figure 10a). In contrast, the new data show that the BMA appears to be confined to the gneisses of the NNMB mid-crust and can therefore not be a Neoproterozoic suture zone. Corner (1989) suggested magnetite enrichment of a granitic NNMB basement along low angle thrust faults, as a possible source for the BMA, but Weckmann et al. (2007a, b) concluded that unreasonably high magnetite contents would be needed to account for such a signature. They alternatively ascribed the anomalous high conductivity zone near the middle of IyA-200501 at 20 km depth to graphite mineralized shear zones (oval, Figure 7c). Forward modelling of the aeromagnetic data proposed a resistive but magnetized body, possibly intersected by a south-dipping fault plane (Weckmann et al., 2007b). Such a fault plane is not imaged in the IyA-200501 seismic data and mineralized shear zones in the NNMB fail to explain the extent or source of the BMA feature. We therefore propose an alternative explanation:

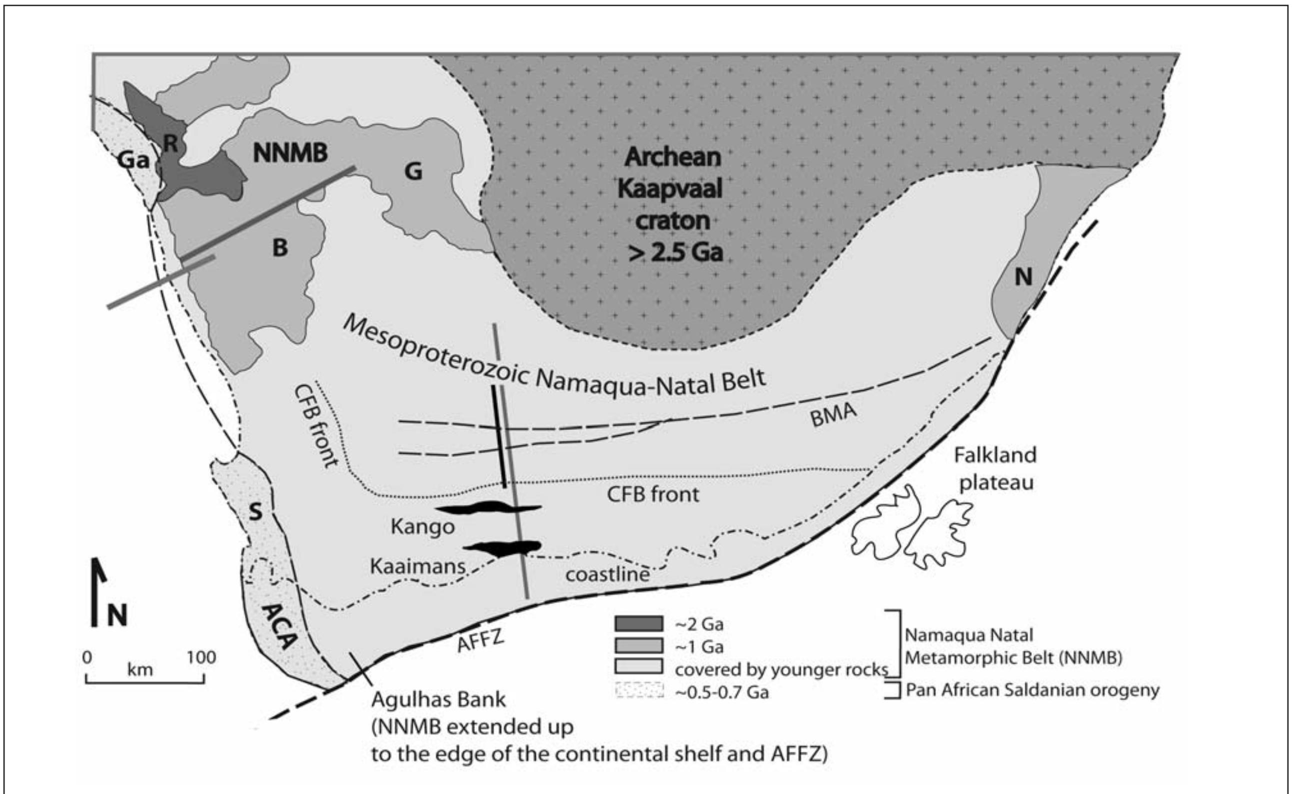


Figure 11. *Simplified geologic basement map of southern Africa (modified after Cornell et al. 2006, and references therein). Light grey = suggested revised extent of the Mesoproterozoic Namaqua-Natal Metamorphic Belt (NNMB) up to the Agulhas-Falkland Fracture Zone (AFFZ), based on the geophysical data presented and referenced in this paper. Dotted polygon = Pan-African Saldanian Orogenic Belt restricted to the west coast of southern Africa only and divided in the Gariep (Ga), Saldanian (S) and Agulhas-Columbine-Arch (ACA). The Falkland Islands are shown in their Gondwana position after Jacobs et al. (1997), Thomas et al. (1997) and Storey et al. (1999). Namaqua-Natal metamorphic terranes (NNMB): R = Richtersveld; G = Gordonia; B= Bushmanland of the Namaqua province; N = Natal province. Black = Kango and Kaaimans tectonic inliers generally linked to the Saldanian orogeny, but recently dated to be older (de Wit et al., unpublished data). Thick grey lines on the West coast = Seismic refraction and -reflection lines of Green and Durrheim (1990), Mahanyele et al. (2004), Hirsch et al. (2008); Lines on the South coast: light grey line = onland seismic refraction line of Stankiewicz et al. (2007; 2008) and the longer onshore-offshore seismic refraction line (Stankiewicz et al. 2008; Parsiegla et al. 2007; 2009); black line perpendicular to CFB front = IyA-200501 seismic reflection profile, this work and Lindeque et al. (2007). BMA = Beattie magnetic anomaly maximum axes.*

The regions with complex reflectivity patterns cross-cut by the high conductivity anomalies in the mid-crust (Figures 7 and 9) could also be interpreted as ore bodies, since ore minerals such as Pyrrhotite and other iron sulphides have a high conductivity. Impedance spectroscopy on samples from boreholes SA-1/66 and KW-1/67, proved high conductivity in the Wh/PA Formations, associated with pyrite and chalcopyrite (Branch et al., 2007). In the magnetotelluric model the high conductivity Wh/PA band show similar conductivity values as the identified BMA zone (Figure 7c). So it is plausible that part of the BMA source(s) can be both magnetic and conductive (i.e. the larger BMA polygon in Figure 9). Other anomalies imaged may be conductive, but without a corresponding high signature on the aeromagnetic data (i.e. high conductivity anomalies on the edges of the IyA-200501 profile, compare Figures 7 and 9) or vice versa (i.e. the smaller BMA polygon in the left centre, Figure 7b, c and Figure 9).

Considering all of the above, we postulate that the anomalous two BMA regions in the mid-crust could represent tectonically(?) disrupted stratabound ore deposits that may have been further remobilised through metasomatic processess of late stage hydrothermal fluids during NNMB orogenesis. We propose that the BMA may have originated as a stratabound massive sulphide-magnetite deposit(s), now flanked by smaller deposits with overlapping metasomatic aureoles.

Similar large ore bodies are common in the ~1.0 to 1.2 Ga Namaqua section of the NNMB, and have signatures in the aeromagnetic data similar to that of the BMA (Figure 1) for example: the world-class massive or laminated Pb-Zn-Cu-Ag sulphide-magnetite ore bodies of the Aggeneys, Broken Hill and Gamsberg ore deposits in the Bushmanland Ore District, located ~450 km to the northwest of the IyA-200501 seismic profile presented here. These deposits are typically hosted in intensely deformed gneisses and mafic to ultramafic supracrustal rocks, folded into nappes and isoclinal recumbent folds, subsequently refolded into late open synforms and antiforms (e.g. Ryan et al., 1986; Naicker, 1993; Reid et al., 1997; Colliston and Schoch, 2002; 2003; Bailie and Reid, 2005; Stalder and Rozendaal, 2005; Bailie et al., 2007) or, in plug- and sheet-like bodies e.g. the Koperberg Suite gneisses of the Okiep Copper District (e.g. Gibson et al., 1996).

Large scale stratiform mineralization in regional volcaniclastic basins in the Kibaran (Grenville-like) belts of Gondwana are common, and range from very high-grade to disseminated zones extending over 100s of kilometres, including some in the Natal-Namaqua Belt of South Africa (Naicker, 1993; Wilsher, 1995). The nature and geometry of these zones following intense deformation during the Kibaran Orogeny remains speculative, but the deformation is likely to have produced extensive stretching and redistribution of metallic elements. Whether the BMA and the SCCB may be geophysical manifestations of such metamorphosed and disseminated deposits, as we believe the case may be, remains to be tested by deep drilling.

Tectonic implications

The tectonic events that formed the complex crustal architecture of southernmost Africa described in this study are not fully understood, but some first order ideas are briefly explored:

Phanerozoic Tectonic Setting

The tectonic setting of the Karoo Basin is often modelled as a cordillera-type retro-arc foreland basin, on the continental side of a foreland fold-thrust belt (i.e. the ~250 Ma CFB) and adjacent to magmatic arcs (e.g. Hälbich 1983a, b, c; 1993; Thomas et al., 1993; Catuneanu et al., 1998; 2002; Johnson et al., 2006; Tankard et al., 2009). Some models argue that tectonics in the Cape Fold Belt are related to a strike-slip dominated environment (e.g. Tankard et al., 2009), but evidence to support strike-slip, such as persistent and penetrative horizontal lineations in the CFB, has not yet been reported.

The related subduction zone is often modelled dipping north with subduction of the Palaeo-Pacific oceanic crust south of the CFB (Figure 12a). This interpretation is however oversimplified (e.g. Milani and de Wit, 2008). The large distance between the CFB and the postulated subduction zone (> 1000 km) combined with the lack of ~300 Ma old granites and volcanism in South Africa, is problematic in such models. Frequently these issues are resolved by assuming flat plate subduction as originally suggested by Lock (1980). These northward subduction models do not fit the deep crustal seismic data presented here, because the latter do not image a deep suture zone beneath the CFB and/or the Karoo Basin.

Alternatively, if subduction to the south is postulated, Palaeozoic oceanic crust and arc systems should be present to the south of the CFB (Figure 12b; Burke et al., 1977; Winter, 1984) which they are in a Gondwana framework (e.g. de Wit et al., 1988). But this does not explain how the Karoo Basin and CFB could have formed relative to the long distance from the subduction zone. It has been repeatedly pointed out that the Karoo Basin does not have the lithostratigraphic attributes of a typical foreland basin (Cloetingh et al., 1992; Turner, 1999; Johnson et al., 2006; Milani and de Wit, 2008; Fildani et al., 2009). The IyA-200501 transect data confirm this. We therefore propose instead that the CFB-Karoo basin may represent a wide, upper crustal thin skinned Jura-type fold belt, formed in response to continent-continent-, arc collision, or suturing south of the CFB, with subduction to the south (Figure 12c). This seems perfectly feasible in a larger Gondwana framework (Milani and de Wit, 2008) and as was also suggested for the Sierra de la Ventana in Argentina (Ramos 1988, 2008).

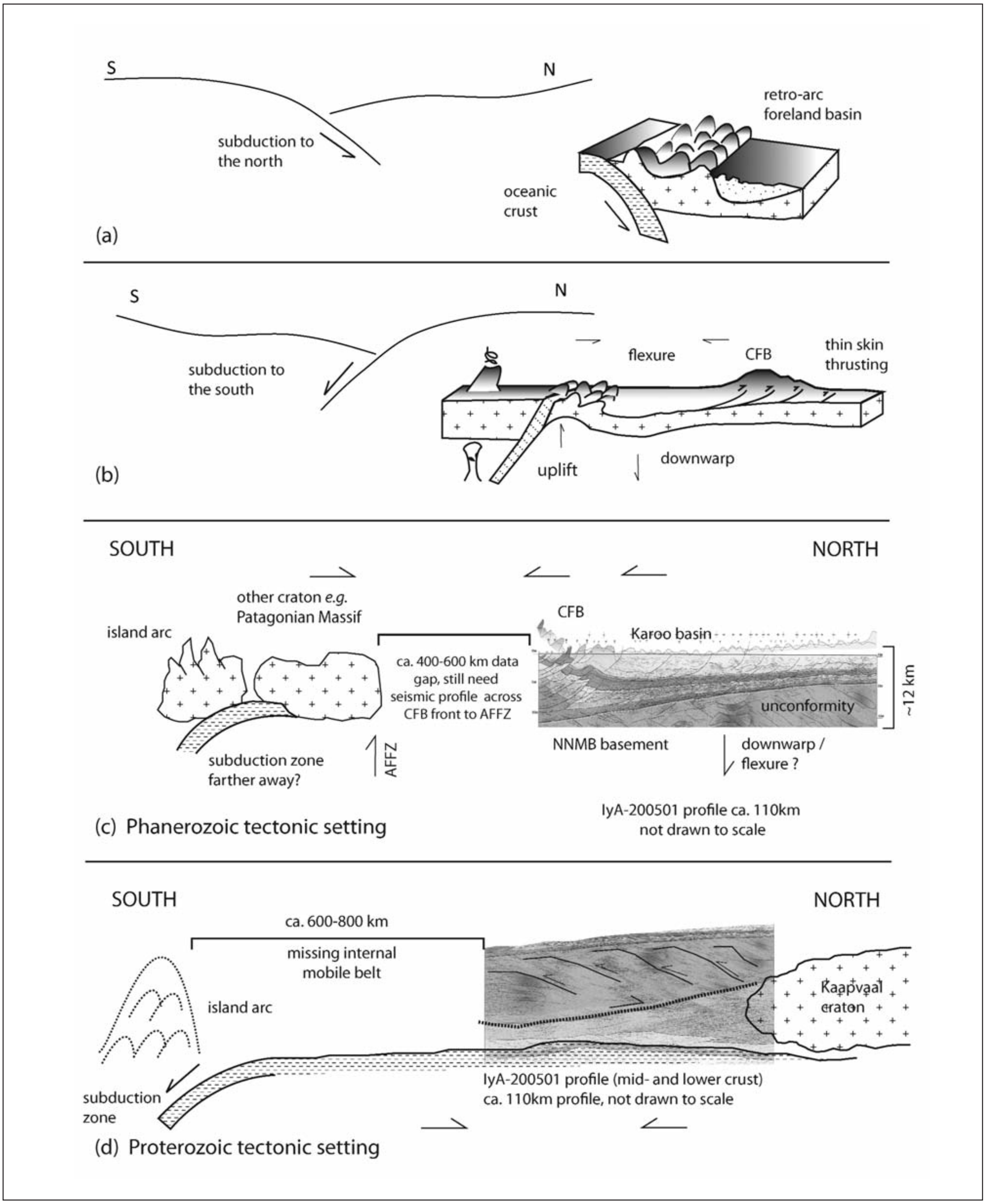


Figure 12. *Schematic models of various tectonic settings.* ***(a)*** *Phanerozoic origin of the Cape Fold Belt and Karoo Basin through the northward subduction of an oceanic plate below the continent.* ***(b)*** *Alternative continent-continent collision and subduction to the south model, accounting for the lack of 300 Ma granites in the Cape Fold Belt, and the absence of a suture zone and palaeoceanic crust below the Karoo Basin (e.g. Winter 1984).* ***(c)*** *Schematic model of the proposed Phanerozoic tectonic setting of the Cape- and Karoo Basins and the associated Cape Fold Belt: subduction to the south and collision(s) with a crustal block farther to the south (e.g. Patagonia), now embedded in South America (e.g. Ramos 1988; 2008).* ***(d)*** *Proposed Proterozoic tectonic setting of the Namaqua-Natal Metamorphic Belt: far-field flat plate subduction to the south. (c) and (d) are our preferred models and considered the most conservative for explaining the north dipping mid-crust tectonic fabric and thrust plane seen in IyA-200501. See text for further discussion.*

Palaeozoic

Traditionally, the Kaaimans and Kango inliers in the CFB have been linked to the Pan African-age Saldanian basement on the west coast of South Africa (e.g. Johnson et al., 2006; Figure 11). There is however, no substantial evidence for such a correlation. For example, the uppermost sequences of the Kango inlier have been dated and correlated with coarse clastic sequences that overlie the Saldanian rocks along the West coast (Barnett et al., 1997), whilst the lowermost sequences of the Kango inlier are much older than the Saldanian rocks, without evidence of any substantial Pan African tectonism (de Wit, unpublished).

Previous models presented a Pan African suture zone at the BMA to account for the occurrence of these inliers (i.e. the Kango inlier and the Kaaimans inlier intruded by the 538 Ma, George Granite). Instead, Pan African aged (520 to 650 Ma) outcrops are limited to the Gariep, Saldanian and the aligned Agulhas-Columbine Arch units on the West coast (Figure 11). On the South coast, the granite outcrops at George (latitude 34°S, longitude 22.5°E) might imply a Saldanian suture farther south, but not at the CFB front as the previous models assumed.

Mesoproterozoic Tectonic Setting

Many researchers suggested a Mesoproterozoic island arc tectonic setting and subduction-related arc volcanism for the formation of the NNMB juvenile crust, with subsequent amalgamation between these arcs and older crustal domains, followed by accretion against the Kaapvaal Craton and significant transpressional strike-slip deformation (e.g. Hartnady et al., 1985; Joubert, 1986a, b; Cornell et al., 1992; 2006; Gibson et al., 1996; Thomas et al., 1994; 1996; Basson and Watkeys, 2003; Colliston and Schoch, 2002; 2003; Eglington and Armstrong, 2003; Raith et al., 2003; Eglington, 2006; Bailie et al., 2007; Cornell and Pettersson, 2007 and references therein).

These accretion models usually explicitly depict the NNMB mid-crust with a tectonic fabric that dips south (e.g. Figures 4 and 6 in Thomas et al., 1994). However, the regional tectonic fabric imaged in profile IyA-200501 dips north and the shallow dipping décollement separating the mid- and lower crust is not a deep suture. To satisfy a northward subduction model at the southern margin of the Kaapvaal Craton (Figure 12a), a north dipping deep suture zone and thrusting to the south is required. Evidence for a northward subduction is not seen in the IyA-200501 seismic image (Figures 3, 4 and 9). Moreover, this geometry would predict that Mesoproterozoic granitoid intrusions should be present on the craton margin, which they are not.

Collectively, our observations rather suggest an NNMB accretion model with subduction to the south and thrusting of the mid-crust to the north (Figure 12b). Whilst a model with subduction to the south may explain the north-dipping tectonic fabric in the mid-crust, the disposition of the décollement boundary between the mid- and lower crust can only be explained if the subduction zone lay much further to the south, as it is not preserved in the IyA-200501 seismic image. In such a scenario, the NNMB island arc wedges would have accreted against each other and against the Kaapvaal Craton, along the mid-crust thrust plane without participation of the lower crust. If the mid-crustal detachment is a Mesoproterozoic thrust and related to the north dipping NNMB regional tectonic fabric above, we propose that a far-field southward subduction Mesoproterozoic tectonic model along an accreting continent margin, fit the IyA-200501 seismic data best (Figure 12d).

Rodinian connections

The IyA-200501 seismic reflection profile images part of a Proterozoic passive continental margin across which the Cape Supergroup was deposited. By implication, a conterminous and as yet unidentified continental block must have rifted-off and drifted away from the southern African Margin in Neoproterozoic times, perhaps during the continental break-up of the supercontinent Rodinia. If so, IyA-200501 can be used to identify the complementary block and reconstruct the larger continental fragment of which South Africa – and more specifically the Kalahari Craton – would have been a part. This can be achieved to a first degree with Rodinia models that place the NNMB terranes of the Kalahari Craton against the Grenville terranes of the Laurentian Craton (e.g. Li et al., 2008), and because similar geophysical transects are now completed along both these potentially conterminous margins or blocks (Figure 13 and 14).

The rocks of the NNMB and Grenville Province have a similar Mesoproterozoic age-range, crustal tectono-metamorphic evolution and metallogenesis (e.g. Moore et al., 1986; Sangster et al., 1992; Thomas et al., 1994; Robb et al., 1999). However, no geophysical comparisons have been made because until recently, no complementary seismic profiles have been available. With the completion of the Abitibi-Grenville (AG) transect during the Lithoprobe program (e.g. Clowes et al., 1996, Carr et al., 2000; Ludden and Hynes, 2000; Martignole et al., 2000; White et al., 2000), and now the AKGTransect completed during the Inkaba yeAfrica project, a direct comparison of the deep crustal structures of these two areas can be attempted. For the purpose of this brief analysis, AG lines 32 and 33 (Carr et al., 2000; Ludden and Hynes, 2000; White et al., 2000) are the most appropriate lines for direct comparison with the IyA-200501 seismic transect (Figures 13 and 14). Some similarities and differences are briefly noted:

The migrated image of AG 33–32 shows a highly reflective internal mid-crustal fabric with steeply dipping reflectors, similar to the mid-crust fabric seen in IyA-200501 (Figure 14). In both profiles, these reflectors taper towards an apparent internal seismic discontinuity, interpreted as mid-crustal detachment thrusts, separating the mid- and lower crust. These detachments display a

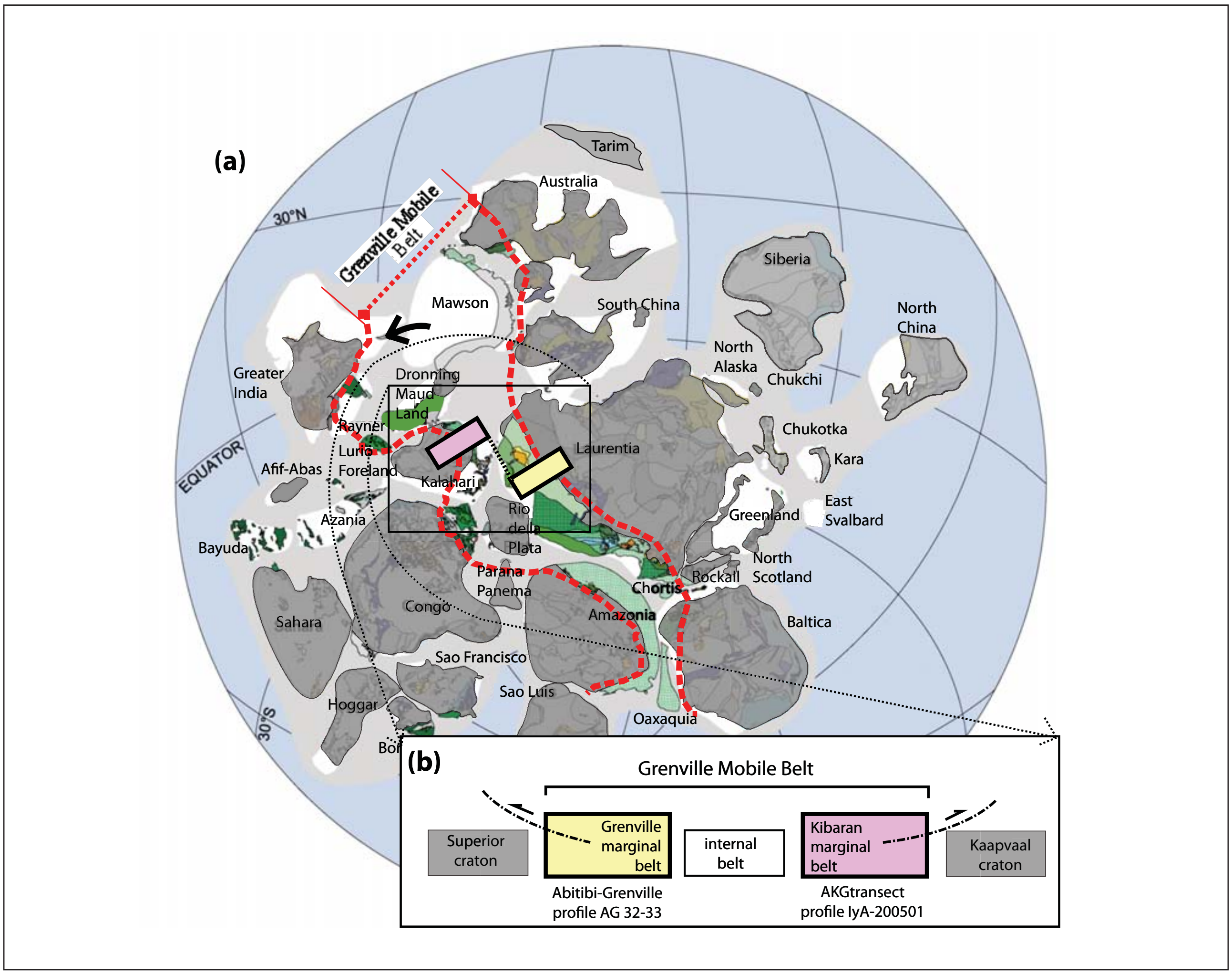


Figure 13. *(**a**) Rodinia model modified after Li et al. (2008). Shades of green = Grenville Mobile Belt (GMB) outcrops; red dashed lines = extent of the GMB; shades of grey = older cratons; black square = area of interest; pink block = IyA-200501 seismic reflection line and our derived crustal model; yellow block = approximate position of the Abitibi-Grenville seismic line AG 32–33. The two seismic lines are rotated 180 degrees to form a combined section (b), consistent with the present orientation of the Kalahari Craton (South Africa) and Laurentia (North America). (**b**) Simplified section as a block diagram: South African IyA-200501 seismic line (pink block on the right = pink block in a) and the comparative Abitibi-Grenville transect (yellow block on the left = yellow block in a). The seismic lines are projected into this diagram to form a composite section drawn within the context of the Grenville Mobile Belt, thrust directions and the respective cratons (Figure 14b).*

similar geometry in both profiles, and in both sections the mid-crustal reflectors end abruptly against the upper crust at an angular unconformity. The three-part crust in IyA-200501 (a highly reflective upper crust, a transparent intermediate crust and a more reflective lower crust underlain by a strong coherent lowermost reflector defining the Moho), is also present in AG 32–33, albeit not as clearly imaged (Figure 14). The Moho depth of ~42 to 45 km is similar and both profiles seismically track the transition of their respective high grade Mesoproterozoic gneisses across a thrust contact, to a low-grade Archean Craton (Figure 14b).

Some distinct differences occur between these two sections on either side of the Grenville-Kibaran Orogen, but none of these rule out their co-evolution. For example:

i. the continuous, horizontal package of reflectors that rests unconformably on the mid-crust in IyA-200501 is not present in AG 32–33, only because the AG transect does not cross the Palaeozoic platform sequences that overlie the Grenville elsewhere in the region.
ii. The lower-crust of IyA-200501 is more reflective and has a complex internal seismic fabric compared to the more transparent lower-crust imaged in AG 32–33. The lower crust of AG 32–33 cannot be subdivided into separate interleaving units as is the case in IyA-200501.
iii. The Moho in IyA-200501 is underlain by a thin (~2 to 5 km thick) lowermost highly reflective layer that is not seen in AG 32–33. The most striking difference however is.

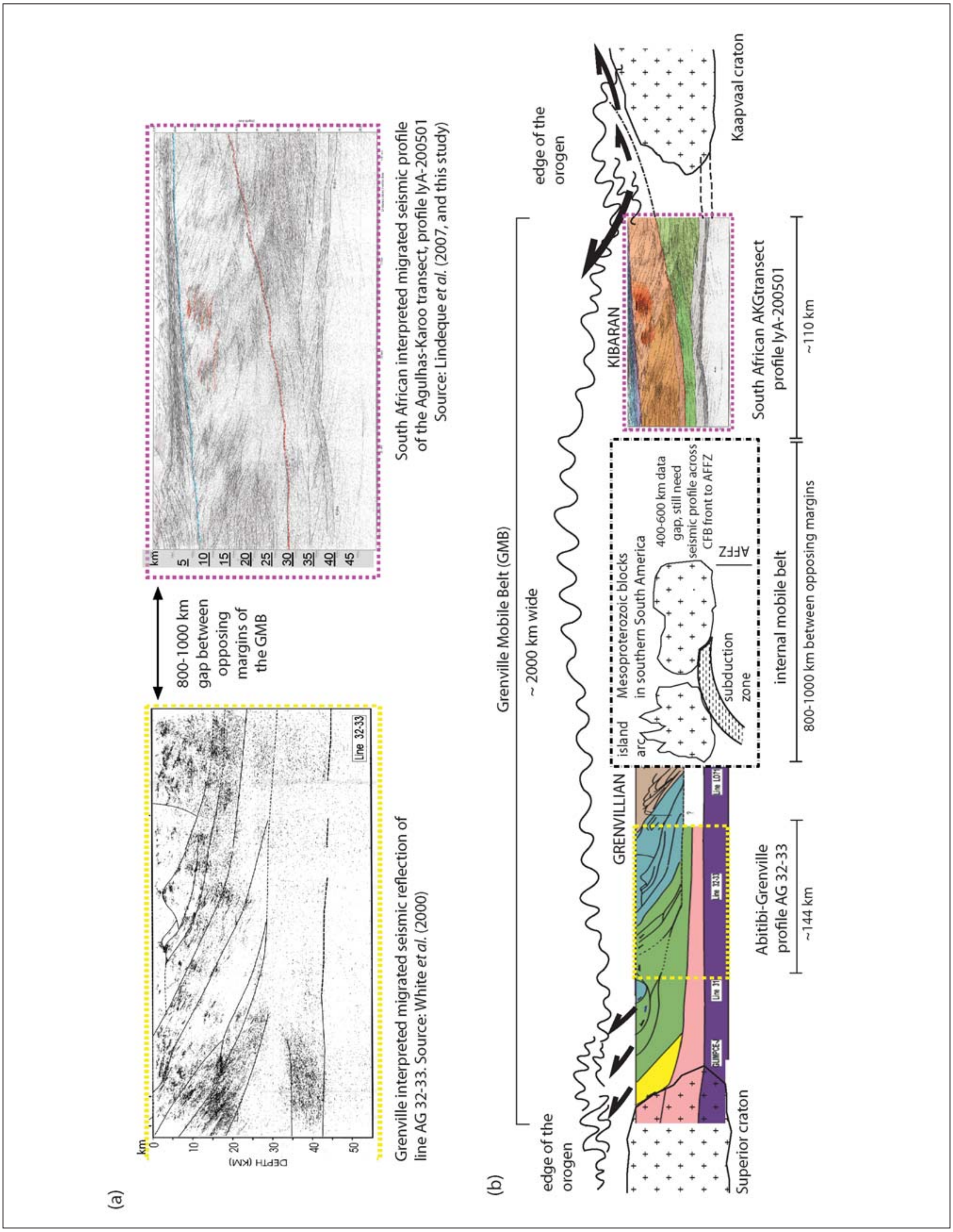


Figure14. ***(a)*** *LITHOPROBE Abitibi-Grenville transect line AG 32–33 migrated seismic reflection profiles (yellow block in Figure 13) and the South African IyA-200501 profile (pink block in Figure 13), see comparison in text.* ***(b)*** *Simplified composite section of the GRENVILLE line AG 32–33 tectonic model (Ludden and Hynes, 2000; White et al., 2000; yellow dashed box) and the SOUTH AFRICAN seismic profile IyA-200501 (pink dashed box). The angular unconformity with upper Phanerozoic sediments in AG 32–33 is not shown as it occurs farther north (yellows in Figure 13a, above the AG 32–33 block). Internal mobile belt in the middle of (b) interpreted. See text for explanation.*

iv. the mid-crustal tectonic fabric of the AG 32–33 profile dips away from the craton (green and blue, Figure 14b) whereas the mid-crust fabric in IyA-200501 dips towards the craton (orange, Figure 14b). The origin for this difference can only be speculated upon and will not be further pursued here.

Despite these differences, the seismic image and derived crustal model of both the IyA-200501 and AG 32–33 transects, generally fit the broader Rodinia reconstruction of Li et al. (2008). Both sections have similar deep crustal architecture, thrust across low grade craton margins and are severed from their outboard mobile belt sections (middle block in Figure 12d and 14b).

Summary and conclusions

Integration of archive borehole data, surface geology, and various geophysical datasets with the IyA-200501 seismic data, yields a complex tectonic model of the crust of southernmost Africa. Specific reflectivity regions and reflector packages have been linked to the geological formations of the Cape- and Karoo-Supergroups, sub-components of the NNMB mid-crust, and a possibly older lower crust. The integration of these datasets proved especially useful in resolving the upper 3 km. The seismic reflection data of IyA-200501 show the sub-horizontal Cape Supergroup resting unconformably on a flat and shallow south-dipping peneplain of NNMB basement for more than a 100 km, and likely much farther south.

The Phanerozoic-Mesozoic tectonic model presented here suggests:

1. Deformation along low angle listric faults rooted in apparent local décollement surfaces of the Whitehill- and Prince-Albert Formations in the lower Ecca. These two formations correspond to a thin (~100 m thick) continuous sub-horizontal high conductivity band imaged in the magnetotelluric data.
2. Absence of a notable fore-deep basin in the southern Karoo; and
3. shortening at the CFB tectonic-front through a series of low-angle listric thrusts and folds detached from the NNMB basement and the Karoo Supergroup.

For the Phanerozoic tectonic setting, the integrated data support a collisional tectonic setting and far-field subduction to the south, with the Karoo Basin developing ahead of a thin-skinned Jura-type fold belt, not as a retro-arc or orogenic foreland basin as it is generally modelled. The absence of a thick crustal root beneath the CFB front substantiates this interpretation further.

The Mesoproterozoic tectonic model presented suggests that NNMB formation is related to arc accretions at a subduction zone dipping to the south, followed by continental collision outboard of the present continental margin of southernmost Africa. This is supported by the general conclusion that the crust of the Namaqua-Natal Metamorphic Belt likely continues below the Cape Fold Belt front, probably extending as far south as the continental margin of Africa up to the Agulhas-Falkland Fracture Zone.

Two regions of complex reflectivity in the mid-crust, at 7 to 15 km depth, coincide with the maximum axes of the Beattie Magnetic Anomaly (BMA) seen in the aeromagnetic data. These two regions lie within the NMMB high grade gneisses of the mid-crust and are interpreted to represent the two-part BMA source. The high conductivity anomalies in the magnetotelluric data correspond spatially to the two zones of higher reflectivity identified in the IyA-200501 seismic data, but appear to transect seismic reflectors and may in part represent a late metasomatic overprint. It seems likely that the BMA source is related to conductive ore-bearing minerals. Such an interpretation would imply at least a 7 km thick by 10 km wide massive sulphide-magnetite ore deposit possibly with disseminated margins, below the maximum axes of the BMA imaged in the aeromagnetic data. This interpretation seems plausible, since the NNMB is known for extensive stratiform ore-bodies. It may also be that these complex seismic characteristics reflect duplication of the deposits through thrust stacking and subsequent metasomatic modification.

Direct comparison of seismic reflection profiles IyA-200501 and AG 32–33 across similar and coeval terranes of the NNMB- and Grenville Province respectively, is consistent with the most recent Rodinia reconstructions.

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