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Shallow seismic velocity structure of the Karoo Basin, South Africa

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ABSTRACT

A Near Vertical Reflection (NVR) Seismic profile from Prince Albert to Slingsfontein across the Karoo Basin of South Africa was generated using 182 controlled source shots at ~500 m spacing and receiver points at 100 m nominal spacing in an 18 km spread. Travel time data of seismic phases are used as input data to derive shallow velocity models of compressional waves (P) and shear waves (S). Using First Arrival Seismic Tomography (FAST) software, we derive shallow tomographic P- and S-velocity models for the upper 1 to 1.5 km. Checkerboard tests indicate good resolution down to 1 km depth. The models of P- and S-velocity and Vp/Vs ratio show an abrupt change at ~50 km, dividing the model into two regions. A southernmost region consists mainly of steeply dipping in-situ sedimentary bedrock with an east-west strike, approximately perpendicular to the profile. The northern 50 km region comprises predominantly unconsolidated sediment and/or highly weathered rock, yielding a high Vp/Vs ratio. The tomographic models compare well with corresponding lateral variation in the surface geology of the Permian Karoo Supergroup sedimentary rocks (Dwyka, Ecca and Beaufort Groups) deformed at the Cape Fold Belt front. The correlation between the velocity models and outcrops is stronger for the southernmost 25 km of the NVR seismic profile. Although the surface geology is more uniform from kilometre 25 to 50, the velocity models and Vp/Vs ratio suggest continued systematic lateral variation. Based on this, we infer a sub-surface continuation of tight folding not seen in outcrops. The S-velocity model supports this theory, as velocity variations correlate well with the location of major fold axes in the regional scale gentle tight folding of the Ecca Group (Abrahamskraal Formation). In the northern part of the model, from 50 to 100 km, minimal change in the velocity models indicate more uniform and undisturbed lithologies.

Introduction

A ~100 km Near Vertical Reflection (NVR) Seismic profile from Prince Albert to Slingsfontein (Lindeque *et al.* 2007), shown in Figure 1, forms part of a much longer onshore-offshore Inkaba yeAfrica Agulhas-Karoo Geoscience Transect (de Wit and Horsfield, 2006). Other datasets along this middle ~100 km segment comprise wide angle tomographic inversion of the crust to 30 km depth (Stankiewicz *et al.* 2007) and magnetotelluric data crossing the Beattie Magnetic Anomaly (Weckmann *et al.* 2007a; b). Here, we report on velocity tomography studies in the upper 1 km, derived from the NVR seismic data.

The data acquisition layout consisted of 180 receivers with ~100 m spacing distributed over a spread length of ~18 km and a total of 182 shots long the ~100 km profile. Each day 8 shots were completed every second kilometre, creating an asymmetric split-spread shooting geometry. On subsequent days, 36 receivers were moved from the tail-end to the front of the spread, in a roll-along procedure. An average shot spacing of 0.5 km and a maximum offset of 16 km were maintained.

We use a 2-D tomographic inversion code FAST (First Arrival Seismic Tomography, Zelt and Barton, 1998) to obtain a detailed tomographic image of the shallow

velocity structure under the Karoo Basin, using the travel times between the sources and receivers. We limit our focus to the upper 1 to 2 km of the Karoo Basin.

Geological Setting

The NVR seismic profile crosses the ~4 km thick siliciclastic Carboniferous to Jurassic shale, siltstone and sandstones strata of the Karoo Basin. The southern part was deformed at ~250 Ma during the Cape Fold Belt orogeny (Hälbich, 1993). Details of the Karoo Basin stratigraphy, sedimentology, structure and palaeoenvironments can be found elsewhere (Visser, 1987; Visser, 1992; Cole, 1992; Wickens, 1992; Johnson *et al.* 1997; Catuneanu *et al.* 1998). Surface lithologies encountered along the NVR profile are depicted in a simplified geology map (Figure 2) and Table 1. From oldest to youngest, the profile crosses the Dwyka Group, Ecca Group and the Abrahamskraal Formation of the Beaufort Group, ending in the Karoo Dolerites. Along the southern 30 km of the profile, the Karoo rocks are deformed into north-verging tight to isoclinal folds at the Cape Fold Belt front, and at surface, limbs are often steeply dipping and overturned. Northwards, these structures grade into gentler open folding and the

Figure 1. Location of the Near Vertical Reflection Seismic profile from Prince Albert to Slingsfontein, on a 90 m digital elevation topography model. Blue = national roads; black = receivers; red = sources. Insert shows regional setting of the profile (red box).

Table 1. Simplified stratigraphy along the NVR transect shown in the geological map (Figure 2), from the 1:1 000 000 geological map sheet series Council for Geoscience (Volquardsen *et al.*, 1984)

Age		Group	Formation	Key	Description
Jurassic	Karoo Supergroup (~4604 m)	Dolerites	Karoo Dolerites	Jd	Crystalline sills and dykes
Permian	Karoo Supergroup (~4604 m)	Beaufort	Abrahamskraal	Pa	Mudstone, sandstone and thin chert beds
	Karoo Supergroup (~4604 m)	Ecca	Waterford	Pw	Dark grey carbonaceous shale
			Fort Brown	Pf	Shale rythmite
			Ripon	Pr	Mottled grey sandstone and shale
			Vischkuil		Arenaceous shale and subordinate sandstone
			Collingham		Rhythmically bedded gray shale and thin tuff
			Whitehill		White weathering black shale with chert
			Prince Albert		Greenish gray shale
	Karoo Supergroup (~4604 m)	Dwyka		Pd	Glacial diamictite deposit – tillites and shales
Devonian	Cape Supergroup	Witteberg		Dw	Shale with sandstone and siltstone
					Quartzitic sandstone

Figure 2. Simplified geological map of the profile area. Red = Receiver line, black = national roads. The rectangles depict the areas shown in Figures 8 to 10. Geology taken from the Geological Map of South-West Africa (Volquardsen *et al.*, 1984). Explanation of the different lithological units is given in Table 1.

succession is near horizontal at the northern end of the profile.

Data Processing and Tomographic Inversion

In total, 26858 first P-wave arrivals and 12216 first S-wave arrivals were manually picked. The quality and the number of the S-wave travel time picks is lower than that for the P-waves. This may be because S-wave first arrivals are not easily recognized in the raw data due to interactions with the P-coda, the ground roll and converted phases (Figure 2).

Figure 3 illustrates a typical example of the raw data for one shot with first breaks of the P-waves (Figure 3a) and the S-waves (Figure 3b) clearly visible. The estimated picking error is ~5 ms for P-arrivals and ~20 ms for S-arrivals. Characteristic frequencies of the P-waves are about 25 Hz. With an average P-wave velocity of ~5 km/s (Figure 4) their wavelength is ~200 m. The average frequency of the S-waves is 10 to 12 Hz and the average S-wave velocity of 2.6 km/s results in wavelengths of ~200 m as well.

Given the profile length, source/receiver spacing and ray coverage, seismic velocities were sampled by shallow rays down to maximum depths of 1 to 1.5 km. This shallow penetration can be explained by high rock velocities at the surface (*e.g.*, 4.4 km/s for the P-waves) and a consequentially weak vertical velocity gradient.

The two-dimensional version of the inversion code FAST by Zelt (1998) and Zelt and Barton (1998), was

Figure 3. Raw data for shot point 141 with the P-wave and S-wave picks (red dots). (a) Shot-record highlighting the P-waves with reduction velocity of 5 km/s; (b) Shot-record highlighting the S-waves with reducing velocity 3 km/s. Reflections (R) and ground roll (GR) are annotated.

Figure 4. P-wave velocity model. (a) Section between 7 and 17 km with a vertical exaggeration of 1:1 and (b) Complete model for the P-waves with ten times vertical exaggeration. Red triangles are the shot points. Regions with hit counts below 30 have been blanked out.

Figure 5. S-wave velocity model (a) Section from kilometer 60 to 70; (b) Entire section (vertical exaggeration = 1:10). Red triangles represent the shot points. Regions with hit counts below 30 are blanked out.

Figure 6. The checkerboard tests results of the P- (a-d) and the S-waves (e-h) for various block-sizes: (a,e) 8 x 1 km (b,f) 4 x 0.4 km (c,g) 2 x 0.2 km (d,h) 1 x 0.1 km. Vertical exaggeration = 1:10.

used to derive a velocity model based on travel time data. For this, the shot and receiver locations were projected onto a straight line calculated by linear regression. The Vidale (1988; 1990) scheme was modified to handle large velocity contrasts according to the method of Hole and Zelt (1995; see Stankiewicz *et al.* 2007 for more details) and then used for the forward calculation of travel time and ray paths. The cross-section beneath the length of the profile was divided into rectangular blocks (*e.g.*, Ryberg *et al.* 2006) for calculation of the tomographic inversion model.

To derive a robust inversion model, we used an iterative approach of varying cell sizes as developed by Ryberg *et al.* (2007). The inversion starts with large block sizes (5 x 0.5 km) and the result of this first inversion is used as a starting model to invert for finer-scaled model (block size: 2.5 x 0.25 km). This procedure is repeated four times, yielding a final inversion block size of 0.25 x 0.05 km. The final P-wave-model is characterized by a root-mean-square (RMS) travel time misfit of ~5 ms for 26,858 travel time picks. This inversion technique, results in a very stable final model in which the appearance of tomographic artifacts are minimized.

An S-wave velocity model was obtained using the same procedure, with a final RMS misfit of ~23 ms for 12216 travel time picks. This is 4 - 5 times higher than the RMS misfit of the P-wave model.

Results and Reliability

The P-wave velocity model is shown in Figure 4. The overall velocities range between 4.40 and 5.44 km/s. In the southern part of the profile, the velocities are higher, varying between 5.0 to 5.44 km/s. The model changes abruptly at ~50 km and from there, the velocities are significantly slower (4.40 to 4.95 km/s) up to the end of the profile.

Figure 5 illustrates the S-wave velocity model. The result compares well with the P-wave model. Velocities in the southern 50 km of the S-wave model are high and range from 2.62 - 3.30 km/s. An abrupt change is observed also at ~50 km along the profile, after which the velocities are lower (2.02 to 2.72 km/s) along the northern section of the profile.

Checkerboard tests are used to evaluate the resolution of the two different velocity models (Figure 6). In these tests, a simple checkerboard

Figure 7. (a) P-wave model (b) S-wave model and (c) Vp/Vs ratio model along the ~100 km profile. Note the distinct change in the velocity structure at about 50 km along the profile. No vertical exaggeration.

synthetic velocity model with 5% velocity perturbations is overlain on a 1-D-background model. Synthetic travel times are calculated for the actual ray coverage provided by the P-wave (Figures 6a to d) and the S-wave (Figures 6e to h) models, and the inversion is then applied using different block sizes. This inversion result is compared to the initial checkerboard model. If the original blocks are recovered in the final model, it means that features of the checkerboard block size are resolvable and not a processing artifact. For example, the relatively high velocities observed between kilometer 60 and 90 at 0.5 km depth in the Vs model (Figure 5) should be regarded with caution since the checkerboard tests in Figure 6 indicate poorer resolution at this position and depth. In the P-wave velocity model, the checkerboard tests demonstrate that 8 km wide features are resolved to 1.5 km depth and 1 km wide features are resolved to a depth of ~500 m (Figure 6).

The ratio between the P- and S-wave velocities (V_p/V_s) is an important parameter for further interpretation as it gives insight into the physical properties of the rock strata. This ratio is illustrated in Figure 7. Higher V_p/V_s ratios of 1.9 to 2.5 occur mostly in the northern part of the profile, while lower values of 1.6 to 2.2 are observed in the southern part of the profile. The low V_p/V_s values of about 1.4 in the northern part at ~0.5 km depth are related to the extremely high Vs values at greater depth and are therefore uncertain. Again as seen in the Vp and Vs models, an abrupt change at ~50 km along the profile is evident. The change at the 50 km region thus appears confined to the upper 1 to 1.5 km of the crust.

Discussion

The velocity models and Vp/Vs ratio indicate that the profile, and by implication the uppermost zone of

Figure 8. Velocity model sections plotted against the geology map along the southernmost 25 km of the NVR seismic profile. Black line = receiver line; red dots = shot points. The geology colour codes are the same as in Figure 2: Pd = Dwyka Group, Pr = Prince Albert, Whitehill, Collingham, Vischkuil and Ripon Formations, Pf = Fort Brown Formation, Pw = Waterford Formation, Pa = Abrahamskraal Formation. The colour-coded velocity scales are the same as in Figure 7. Width of the geology strips ~2 km.

Figure 9. Comparison of the velocity models with the geology, from 25 - 50 km along the profile. Black line = receiver line; Red dots = shot points. The geology colour codes are the same as in Figure 2 and 8. Note the correspondence between synclinal fold axes and S-velocity lows (green-blue), and anticline axes to high S-velocities (yellow-red). Fold axes and dip information were independently mapped and taken from 1:250000 Geological map sheets 3220 Sutherland and 3322 Oudtshoorn published by the Council for Geoscience.

Figure 10. (a) 3-D Geological model derived from strike and dip information on geological maps (b) Vs model with superimposed interpretation of geological structures for the southernmost 50 km of the profile, in which high Vs correspond to anticlines and low Vs to synclines. Note the similarities and differences between a and b.

the southern Karoo Basin, can be divided in two parts. The southern part is characterized by high velocities in the P- and S-wave models and the velocity structure is heterogeneous. We interpret this to reflect a complex structural region with significant lateral lithology variation. In the northern part, a low and more homogeneous velocity structure is present, which we interpret to reflect a simple structural region of more uniform lithology.

The Vp/Vs ratio model can be subdivided in a similar way. In the south the ratio is below 2 (~1.7 on average), which is typical of unweathered bedrock. In contrast the northern section has ratios predominantly greater than or equal to two, except in the area of the anomalous high S-wave velocities at the lower edge of the model. Vp/Vs ratios greater than or equal to two are characteristic of unconsolidated sediments.

Because the tomography provides a well-resolved image of the first kilometer of crust, we look for correlations and/or discrepancies with the known surface geology in the areas depicted in the boxes in Figure 2, the southernmost 50 km of the profile.

Possible correlations between the velocity models and the geology are tested in Figures 8 and 9. We note a close correlation between the surface geology, velocity models and Vp/Vs ratio in the southernmost 25 km of the profile (Figure 8). Velocities of the Vp and Vs models vary systematically along the profile and appear to correspond with lateral changes in the lithologies of the Dwyka and Eccra Groups (Prince Albert, Whitehill, Collingham, Vischkuil, Ripon, Fort Brown, Waterford and Abrahamskraal Formations), repeated by folding. These systematic velocity variations may be due to different degrees of weathering or known lithological variations within the formations. Note that the glacial Dwyka Formation shows a distinctly higher velocity on the Vp model, probably because it has a denser matrix than that of the adjacent sedimentary rocks of the Eccra Group.

From kilometer 25 to 50, the surface lithology is dominated by the gentle folded Abrahamskraal Formation. Figure 9 is a plot of the location of major fold axes, the P- and S-velocity models and Vp/Vs ratio. We note a reasonable correlation between the geological structures and the seismic tomography. The velocity models, especially the S-wave model, suggest therefore that the fold structures seen in Figure 8 continue below surface up to kilometer 50. We illustrate this hypothesis in Figure 10. The geological model in Figure 10a is independently derived from existing geological maps. If we compare the Vs model and geologic interpretations in Figure 10b, the first 25 km changes in the surface geology correlates well with the velocity variations. Furthermore, we observe that the anticline fold axes mapped from surface geology corresponds reasonably well with high velocity zones in the Vs model and the synclines correspond with low S-velocities (b). We may therefore infer that complex tight folding continues after

kilometer 50, beneath the more gently folded shales and sandstones of the Abrahamskraal Formation.

Conclusions

The near-surface velocity structure down to depth of 1 to 1.5 km along a NVR seismic profile from Prince Albert to Slingersfontein across the Karoo Basin was determined from first arrivals of P- and S-waves. Four main conclusions are drawn from this:

- The profile is divided in two regions: the first 50 km comprises predominantly near surface bedrock and the second 50 km region comprises a predominantly thicker layer (> 1 km) of unconsolidated or highly weathered strata.
- The exact cause of the abrupt transitions in both the Vp and Vs models at 50 km is not clearly understood.
- The lateral variations in velocity models correlate well with folding of the rock strata seen in outcrop geology of the southernmost 25 km.
- The models suggest a sub-surface continuation of similar folds up to 50 km, where they are overlain by more gently folded to near horizontal strata of younger sequences.

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