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Lithospheric seismic velocity discontinuities beneath the Arabian Shield

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Abstract. We determined crustal and lithospheric mantle velocity structure beneath the Arabian Shield through the modeling of receiver function stacks obtained from teleseismic P waves recorded by the 9 station temporary broadband array in western Saudi Arabia. The receiver function deconvolution technique was used to isolate the receiver-side PS mode conversions. A grid search method, which should yield an unbiased global minimum, was used to solve for a shear wave velocity model that is optimal and has the minimum number of layers needed to fit the receiver function waveform. Results from this analysis show that the crustal thickness in the shield area varies from 35 to 40 km in the west, adjacent to the Red Sea, to 45 km in central Arabia. Stability tests of each solution indicate that the models are relatively well constrained. We have also observed evidence for a large positive velocity contrast at sub-Moho depths at four stations at depths of 80 to 100 km. This discontinuity may represent a change in rheology in the lower part of the lithosphere or remnant structure from the formation of the Arabian Shield.

Introduction

Western Saudi Arabia consists primarily of a continental shield bounded by young rifting and sea floor spreading to the west and the Zagros fold and thrust belt system to the east. The Arabian Shield is comprised of a series of accreted Proterozoic island arc terranes which were formed possibly during several subduction episodes [*Greenwood et al.*, 1980]. The eastern portion of the Arabian Shield is the Afif terrane which is composed of granites (640-580 Ma), volcanic rocks, and meta-sediments (660-600 Ma) which overlie a crystalline basement (Figure 1) [*Husseini*, 1988]. The volcanic fields in particular are very young; 21 eruptions are known to have occurred in the last 1500 years [*Stoeser and Camp*, 1985]. On the western margin of Saudi Arabia, geophysical studies indicate that the Red Sea is an active spreading center. To the east the shield is bounded by the Mesozoic sedimentary rocks of the Phanerozoic Arabian Platform which dip gently eastward and overlap the shield unconformably [*Powers et al.*, 1966].

There have been a number of geophysical studies of the crustal and upper mantle structure of the Arabian Shield [e.g., *Mooney et al.*, 1985; *Ghalib*, 1992; *Mokhtar*, 1995]. In particular, a large reversed refraction profile was shot in 1978 across the Saudi Arabian Shield [*Mooney et al.*, 1985]. The profile location is shown in Figure 1. Crustal thickness was found to increase gradually toward the center of the Arabian Platform and thin rapidly near the Red Sea coast [*Gettings et al.*, 1986]. Sub-Moho velocity discontinuities were also found beneath the Moho at approximately 60 to 70 km depth [*Mooney et al.*, 1985]. Studies of surface wave dispersion and attenuation beneath the Arabian Peninsula found an average crustal thickness of approximately 45 km in the eastern part of Arabia and high attenuation (Qs=60 to 150) beneath all of the Arabian Platform [*Seber and Mitchell*, 1992; *Mokhtar*, 1995]. *Badri and Sinno* [1991] found very high attenuation in the upper crust of the Arabian Platform (Qp=165) and very low in parts of the Arabian Shield upper crust (Qp=1560).

Data and Method

From November 1995 to March 1997, nine temporary broadband three-component stations were deployed across the Saudi Arabian Shield (Figure 1). These stations consisted of PASSCAL STS-2 seismometers and REFTEK data acquisition systems. All nine station sites proved to be exceptionally quiet

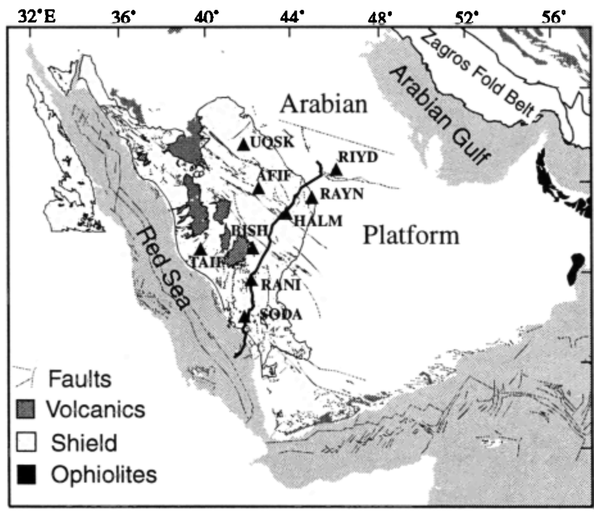

Figure 1. Simplified tectonic map of the Arabian peninsula. Also shown are all of the broadband stations (solid triangles) as well as the 1978 refraction profile line.

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Table 1. Best measurements of crustal thickness using the stacked receiver functions. Stations with fewer than 50 jackknife iterations are statistically undersampled; therefore those error estimates are not as reliable and are indicated by asterisks.

Station Name	Lat. (°)	Lon. (°)	Crustal Thickness (km)	# of events in stack	Jackknife Iterations
SODA	18.29	42.37	38.0 ± 1.0 12	67	
TAIF	21.28	40.34	40.5 ± 2.5*	6	20
RANI	21.31	42.77	35.0 ± 2.5*	7	35
HALM	22.84	44.31	40.0 ± 1.0 21	100	
AFIF	23.93	43.04	39.0 ± 1.0 18	90	
RAYN	23.52	45.50	44.0 ± 2.5*	6	20
RIYD	24.72	46.64	45.0 ± 2.0 10	50	
UQSK	25.79	42.36	37.0 ± 1.5 12	70	

and recorded very high quality data that we used to create receiver function stacks from a minimum of six receiver function waveforms (Table 1). Station BISH, however, recorded very little data before being damaged early in the experiment. We used the spectral deconvolution method to create the receiver function stacks. We applied a Gaussian low pass filter, with a corner frequency of 0.5 Hz, to our receiver functions. The majority of earthquakes that were used to create our receiver function stacks were located to the northeast of our stations. Therefore the teleseismic P waves are sampling crustal and upper mantle structure just to the northeast of each of the stations used in this study. The time domain receiver function method was used to test for waveform distortion from the spectral division technique. We found very little difference between the spectral division technique and the time domain deconvolution.

A grid search technique was used to model the radial receiver function stacks for the shear wave velocity stack. In order to model the observed receiver function stacks for the crustal shear wave velocity structure, we applied a two-iteration grid search method combined with a jackknife error estimation technique [*Sandvol et al.*, submitted 1998]. A reflectivity synthetic seismogram algorithm was used to create our synthetic receiver functions. To model the receiver function data we employed a grid search scheme using a maximum of six layers. It should be noted that the upper mantle velocities is constrained primarily by amplitudes of the PS_{Moho} and the subcrustal PS phases thereby making our upper mantle velocities more uncertain than the crustal velocities. We used results from surface wave studies [*Seber and Mitchell*, 1992; *Mokhtar*, 1995] to provide narrow constraints (± 0.2 km/s) on our upper mantle velocity grid searches beneath the Arabian Shield. The search interval was chosen to be 0.1 km/sec for the shear wave velocity and 2 km for layer thickness and in some cases 1 km for the first layer.

After obtaining the results from our grid search we qualitatively analyzed each layer as to whether or not it contributed a significant amount of energy to the synthetic. We performed this exercise for all 9 stations. The limited number of model parameters in the waveform inversion has allowed us to employ a jackknife resampling error estimation method.

A jackknife data resampling technique has the advantage of not requiring the estimation of a noise time series, and this technique has been proven to yield unbiased and robust error estimates for nonlinear inversions [*Tichelaar and Ruff*, 1989; Efron and Tibshirani, 1991]. Therefore, we have chosen this resampling method to estimate the stability of our shear wave velocity model solutions. The drawback of this technique is that it will not provide error estimates in our velocity models caused by systematic errors in the data. We have been able to test for effects of such systematic errors for stations where Moho depths have been measured using other geophysical studies.

This technique estimates the stability of each S wave velocity model as long as there is a sufficient number of receiver functions that can create a "large" (≥ 50) number of resampled stacks. In order to test the robustness of this error estimator we tried a number of different resampling schemes (i.e., delete-1, delete-2, etc.) and compared the resulting error estimates. We have found that our error estimates vary by no more than 20% depending upon which resampling method one uses. We use the largest error estimates from the different jackknife resampling schemes.

Results

We have found crustal thicknesses on the order of 40 km throughout the Arabian Shield. There are, however, some slight variations (±5 km). Near the southeastern Red Sea coast the crust appears thinner at stations SODA and RANI, where we have found good waveform matches for crustal thicknesses of 38

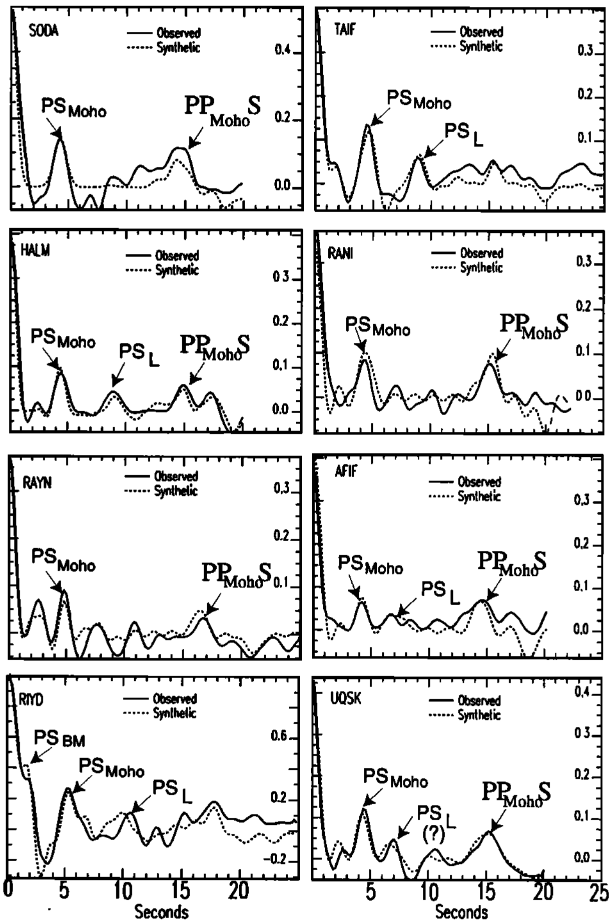

Figure 2. Stacked and optimal synthetic receiver function comparisons for all eight stations used in this study. We have obtained a reasonably good fit for all eight stations. At station RANI we allowed the Poisson's ratio to vary along with the shear velocity and layer thickness in order to obtain a good fit. Also identified are the P-to-S (PS) conversion at the basement (PS_{BM}), Moho (PS_{Moho}), and a mantle velocity discontinuity (PS_L) as well as crustal multiples such as $PP_{Moho}S$. We have also fit the amplitudes of the receiver functions, except for station RIYD. At station RIYD, due to an error with the gain of the vertical component, we have normalized the receiver function stack.

and 35 km, respectively (Figure 2). We found a crustal thickness of 40 km beneath station TAIF, within errors equivalent to station SODA (Figure 3). The 40 km Moho depth along the eastern Red Sea margin indicates that the transition from oceanic to continental crust is extremely abrupt which is consistent with the Mooney et al. [1985] interpretation of the 1978 Saudi Arabian refraction experiment. Beneath station RANI, the crust is relatively thin (35.0 ± 2.5 km). At this station it was necessary to vary the Vp-Vs ratio in order to fit both the P-to-S conversion as well as the crustal multiples. Using a Poisson's ratio of 0.24, we were able to fit the waveforms reasonably well (Figure 2). We found that a Poisson's ratio of 0.25 at the other stations fit the crustal multiple phases well.

At stations within the Arabian Shield the crust is consistently thicker than beneath coastal stations. We have found Moho depths of 39, 40, and 44 km at stations AFIF, HALM, and RAYN, respectively (Figure 3). Beneath the northernmost station, UQSK, the crust appears to thin to 37 km. At station RAYN we have also observed evidence of a boundary which separates the upper from the lower crust. This is the only station at which we required a major mid-crustal impedance contrast to fit the receiver function waveform. At station RIYD, located off the Arabian Shield, the crust is thicker than at the other stations, being about 45 km. This value is consistent with surface wave inversion studies that have also found a mean crustal thickness of 45 km beneath the eastern Arabian Platform [*Mokhtar*, 1995].

We found very fast mean crustal S wave velocities beneath all stations (except for station RANI). This result is consistent with the fast P wave velocities found by the 1978 refraction experiment [*Mooney et al.*, 1985] and the fast S wave velocities from surface wave studies [*Ghalib*, 1992]. These crustal velocities are consistent with crustal velocities in continental shields such as the Fennoscandia and Ukrainian shields [Mooney et al., 1985].

We found the depth to the basement-sedimentary cover contact to be 3 km beneath station RIYD. This depth is in good agreement with the depth to basement found from oil exploration wells in the region [*Peterson and Wilson*, 1986] which also found the basement to be 3 km beneath station RIYD. RIYD is

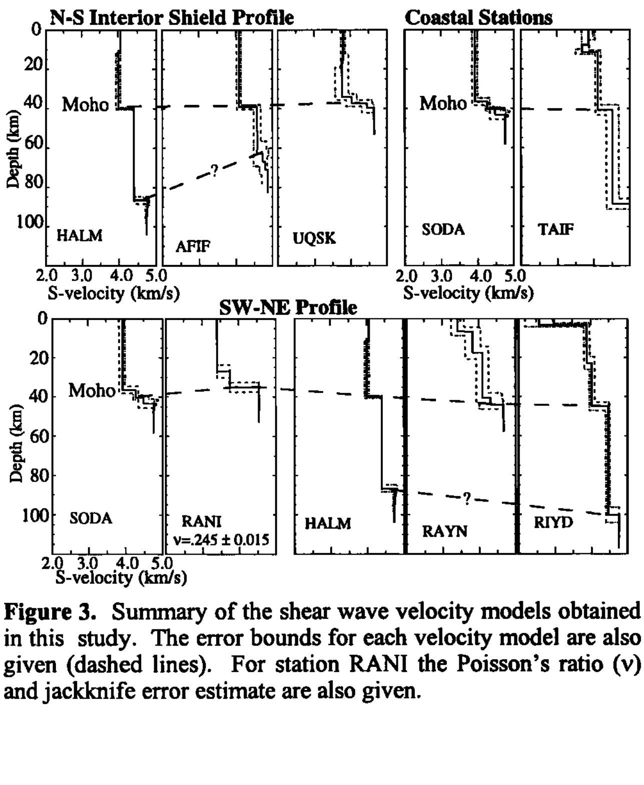

Figure 3. Summary of the shear wave velocity models obtained in this study. The error bounds for each velocity model are also given (dashed lines). For station RANI the Poisson's ratio (v) and jackknife error estimate are also given.

the only station where we have observed what can be reasonably interpreted as the basement-sedimentary cover contact.

We have also observed sub-Moho phases at several stations (Figure 2). These PS conversions provide strong evidence that the Arabian lithospheric mantle velocity structure cannot be described by a smooth velocity gradient. There appears to be at least one fairly discrete velocity boundary at a depth of about 90 km beneath four of the stations in the Arabian Shield. This boundary is not observed beneath stations SODA, RANI, and RAYN. Its absence beneath station RAYN may be due to destructive interference between the multiple reflections from a mid-crustal velocity discontinuity and the PS conversion at the mantle discontinuity (Figure 3); this is something we can rule out at the other stations since we observe no evidence for major mid-crustal velocity discontinuities. Given the large station spacing (~100 km), the sub-Moho velocity discontinuities could be isolated, small-scale features in the lithospheric mantle. The upper mantle velocities in our models agree with results from surface wave studies [Ghalib, 1992; Mokhtar, 1995].

We also observed evidence for a large positive velocity discontinuity at a depth of 90 km very clearly beneath station TAIF. This is an unexpected result since the lithosphere-asthenosphere boundary is thought to be at approximately 100 km depth along the Red Sea coast [*Ghalib*, 1992], with a negative velocity contrast. This may be an indication that the transition from oceanic lithosphere beneath the Red Sea to continental lithosphere beneath the Arabian Shield is very abrupt.

Interpretations and Conclusions

The 1978 refraction experiment [*Mooney et al.*, 1985] allows us an excellent opportunity to compare our velocity model results with an entirely independent data set (Figure 4). The refraction experiment measured compressional wave velocities, while receiver function inversions are sensitive to both S`111 wave and P wave velocity. The receiver function crustal thickness estimations are very similar to those obtained by *Mooney et al.* [1985]. Only at station RANI do we observe a significant (> 2 km) difference between the Moho depths of the two studies. However, we found little evidence for most of the mid-crustal velocity changes, probably because they are not large enough to produce significant S wave energy in the teleseismic P wave coda. At station RAYN, however, there are many similarities between the refraction and the receiver function models. Overall we can conclude that these two independent methods have given very similar results, lending validation to both methods.

Our estimates of crustal thickness and structure do not correlate well with the topography or the locations of major tectonic boundaries. We have observed a localized zone of relative crustal thinning at stations RANI as well as a small anomaly in the Poisson's ratio at station RANI. It is not clear what type of processes would lead to this localized crustal thinning; however, the amount of thinning is relatively small (< 5 km). There also is significant change in crustal structure between stations HALM and RAYN (Figure 4) which is very similar to that observed by *Mooney et al.* [1985]. This change in crustal velocities may be attributed to a change in the grade of metamorphism in the upper crust. Overall we observe crustal thickening towards the northeast and relatively little change in crustal thickness towards the north-northwest. This may be the result of the collision of Arabia with Eurasia along the Zagros fold and thrust belt.

The origin of the positive upper mantle S wave velocity discontinuity is not entirely clear. If these velocity contrasts are

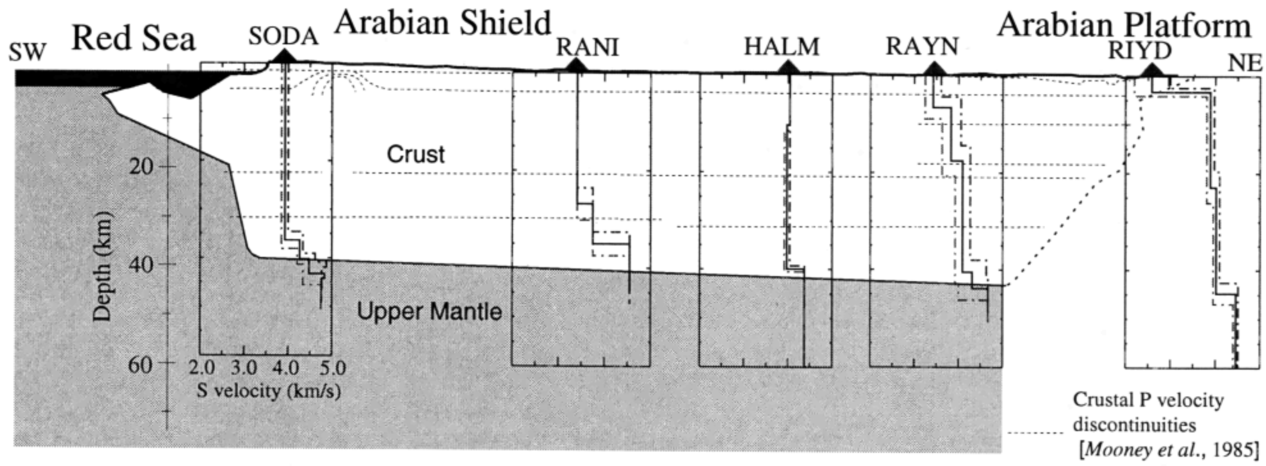

Figure 4. A comparison of our shear wave velocity models with the model of *Mooney et al.* [1985]. The shaded/white boundary marks the Moho boundary derived from the 1978 refraction experiment (Figure 1). Also shown are the major crustal P wave velocity anomalies (dashed lines). For the most part we observe no evidence of these boundaries; however, most of these are very subtle features (<0.15 km/s P wave velocity contrast). Only beneath station RAYN do we observe upper-crustal and mid-crustal velocity discontinuities. These features are also seen on the refraction model and correspond to substantial velocity contrast (~0.3 km/s).

representative of isolated upper mantle structure and not a continuos boundary underlying the entire Arabian Shield then they could be attributed to individual remnant structures from when the Arabian Shield was formed during the late Proterozoic orogenic events. Our observations bound a region where there is evidence for asthenospheric upwelling [*Camp and Roobol*, 1992]. However, the locations of our observations do not correlate well with either the paleo-subduction zones or the locations of surficial Neogene and Quaternary volcanics (Figure 4). Furthermore, our data indicate that there is a positive velocity contrast in the lithospheric mantle, not a negative one. A possible explanation would be that we are imaging the bottom portion of the lithosphere which has been altered through metasomatism. This alteration may have caused the seismic velocities to increase significantly. If these velocity discontinuities are at the base of the lithosphere, then it is interesting to note that the lithosphere does not appear to thin much eastward. Other than the lack of evidence for this anomaly at stations SODA, RANI, and UQSK this would seem to be the most likely explanation given what we know about the lithospheric thickness in this region.

The location of a positive velocity contrast at depths between 80 and 100 km beneath station TAIF is circumstantial evidence for a relatively thick lithosphere along the Red Sea coast. The existence of continental crust (with crustal thickness and S wave velocities that one would expect for a continental shield) along the eastern Red Sea margin, along with other key pieces of geologic evidence [e.g. McKenzie et al., 1970; Gettings et al., 1986], suggest that the Red Sea formed by continental splitting. Furthermore, the splitting would need to be fairly rapid in order that the continental lithosphere flanking the rift not be significantly thinned.

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