The crustal structure of Egypt and the northern Red Sea region

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Abstract

P-wave receiver functions from 26 stations in the Egyptian National Seismic Network (ENSN) have been modeled using the H-k stacking method and in a joint inversion method with Rayleigh wave group velocities to investigate crustal structure across Egypt and the northern Red Sea region. The new estimates of crustal structure, when combined with previous results, show that the rifted margins along the Red Sea, Gulf of Suez and Gulf of Aqaba crustal thickness ranges from 25-30 km, the average crustal Vp/Vs ratio is 1.77, and the average crustal shear-wave velocity is 3.6 km/s. Beneath northern and central Egypt, including the Sinai Peninsula, crustal thickness ranges from 32 to 38 km, the average crustal Vp/Vs ratio is 1.79, and the average crustal shear-wave velocity is 3.5 km/sec. Beneath southern Egypt, crustal thickness ranges from 35-40 km, the average crustal Vp/Vs ratio is 1.76, and the average crustal shear-wave velocity is 3.7 km/s. In southern Egypt, the crust is also characterized by a 10-20 km thick mafic lower crust. These findings indicate that crust along the rifted margins of the northern Red Sea, and Gulfs of Suez and Aqaba have been thinned by about 5 to 10 km. The thick mafic lower crust in southern Egypt can be attributed to suturing during the Neoproterozoic collision of east Gondwana against the Sahara metacraton. Overall, the structure of the crust in Egypt away from the northern Red Sea region is similar to the structure of Precambrian crust in many other parts of Africa.

Keywords

Egypt; Crustal structure; Velocity Model

1. Introduction

Compared to many parts of the African continent (i.e., eastern and southern Africa), little is known about crustal structure in the northeastern corner of the continent. In this paper, we address the lack of knowledge by modeling crustal structure beneath 26 stations in the Egyptian National Seismic Network (ENSN), and then combining our results with results from previous studies to characterize crustal structure across Egypt and the northern Red Sea region.

Over the past decade, many of the seismic stations in the ENSN have been upgraded with broadband sensors, while others are still equipped with three component short period seismometers. Here we use data from the broadband stations and the highest quality short-period stations to obtain 26 new point estimates of crustal thickness, V_p/V_s ratio, and crustal shear-wave velocity. These estimates are obtained by applying the H-k stacking method of Zhu and Kanamori (2000) to teleseismic P-wave receiver functions (PRFs), and by performing a joint inversion of the PRFs with Rayleigh wave group velocities (Juliá et al., 2000, 2003).

While much information on African crustal structure has been obtained from modeling PRFs in the past 20 years (e.g., see Kachingwe et al., 2015 and Tugume et al., 2013 for reviews), and the modeling of PRFs from a small number of broadband stations in the ENSN already has been done by Hosny and Nyblade, (2014), to date there has not been a comprehensive study of crustal structure in Egypt and the northern Red Sea region using seismic data from the ENSN. The results of this study elucidate the amount of crustal thinning beneath the rifted margins along the northern

Red Sea, and Gulfs of Suez and Aqaba, reveal a region of thick mafic lower crust in southern Egypt, and otherwise show that the Precambrian crust underlying much of Egypt is similar to Precambrian crust in many other parts of Africa. New information on crustal structure provided by this study is also important for seismic hazard studies, particularly for improving seismic event locations in regions of Egypt prone to large earthquakes.

2. Geologic Background

Figure 1 shows a simplified geologic map of Egypt. Precambrian basement rocks are exposed primarily in the southern and southeastern parts of the country and within the Sinai Peninsula. Most of the Precambrian basement is part of the northernmost section of the Neoproterozoic Mozambique mobile belt that formed the core of the East African Orogen, as well as the Nubian-Arabian Shield (e.g., Stern and Johnson, 2010 and references therein). However, in southern Egypt, a number of granitic outcrops have been interpreted to be part of the much older so-called Saharan metacraton. The suture between the Neoproterozoic terranes to the east and the metacraton to the west is marked by the Keraf shear zone, which can be traced from northeastern Sudan into southern Egypt (Abdelsalam and Stern, 1996a, b; Abdelsalam et al., 1998) (Figure 1). The Precambrian basement of the Nubian-Arabian Shield was disrupted along its eastern edge by the formation of the Red Sea in the Late Oligocene and the development of the Dead Sea/Gulf of Aqaba transform fault in the Middle Miocene.

Overlying the Precambrian basement across most of Egypt are Phanerozoic sedimentary rocks. Paleozoic sandstones and shales are found at the base of the sedimentary section, and in many places they are overlain by Mesozoic sandstones,

Paleogene and Neogene limestones, sandstones, and conglomerates, and unconsolidated Quaternary sediments.

Crustal structure beneath Egypt has been investigated previously in a number of studies. Using seismic refraction, gravity measurements, and tomography, crustal thickness estimates of 24-27 km have been reported along the margins of the northern Red Sea and the Gulf of Suez (Makris et al., 1988; Marzouk, 1988; Ginzberg et al., (1988), Gaulier et al., 1988; Rihm et al., 1991; Salah, 2011; and Abdelwahed et al., 2013). Also, Makris et al., (1988), Rihm et al. (1991), Makris et al. (1988), Guilier et al. (1988), and Abdelwahed et al. (2013) reported crustal thicknesses of 31-38 km inboard of the Red Sea and Gulf of Suez coastlines in northern and central Egypt, while Makris et al. (1988), Dorre et al. (1997) and Abdelwahed et al. (2013) reported crustal thicknesses of 34-40 km in southern Egypt.

Modeling PRFs from data recorded on seven of the ENSN stations, Hosny and Nyblade (2014) reported crustal thicknesses of 35–38 km around Lake Nasser in southern Egypt, and thinner crust (25–26 km) within 50 km of the Red Sea coast in southern and central Egypt. Additionally, for a single station in northeastern Egypt (station KEG), Salah (2011) modeled PRFs and obtained a crustal thickness of 33 km.

Estimates of crustal structure from gravity data have been reported by a number of investigators. Tugume et al. (2013) estimated crustal thickness across Africa and Arabia by inverting satellite gravity data. They reported an average crustal thickness of ~30-35 km for Egypt, with thinner crust (~25-30 km) near the coastlines. Mechie et al.(2013) also reported Moho depths beneath the Arabian plate and parts of Egypt from satellite gravity data modeling. Along the Red Sea coastline, their models show crustal thicknesses of ~25-30 km, similar to Tugume et al. (2013).

Estimates of crustal thickness for Egypt from terrestrial gravity data have been reported by Dorre et al. (1997), Saleh et al. (2006), and Tealeb (2003), showing an average crustal thickness beneath Egypt between 32 and 34 km.

3. Data and Methodology

3.1 Data collection

In 1997, the National Research Institute of Astronomy and Geophysics (NRIAG) established the ENSN. Today, the ENSN consists of 22 stations with broadband seismometers, 10 stations with 3-component short-period seismometers, and 47 stations with single component short-period seismometers. The broadband seismic stations are equipped with 240 s or 120 s Trillium sensor, a Trident digitizer, and a GPS (Global Positioning System) clock. Data are recorded at 100 or 200 samples per second. Data from 26 of the ENSN stations, including the 22 broadband stations and 4 of the highest quality three-component short-period stations (stations DK2, MRS, KAT, and BST; Figure 1) have been used in this study (Figure 1). To compute receiver functions, we used data for teleseismic events with magnitudes ≥ 5.5 within epicentral distances of 30° to 90° recorded between 2008 and 2013. Figure 2 shows the locations of the events used, and a list of the earthquakes is provided in the supplemental material.

3.2 Receiver Functions

Receiver functions are a time series that show the response of Earth's structure beneath a recording station and are commonly used to investigate crustal structure (Langston, 1979). The direct P wave, the P-to-S conversion from the Moho (Ps), and reverberations between the Moho and the free surface (PpPs and PsPs+PpSs) are the

main phases observed in the time series. The thickness of the crust and the Poisson's ratio can be determined using the arrival times of the direct and the converted phases (Langston, 1979; Ligorria and Ammon, 1999; Zandt and Ammon, 1995; Zhu and Kanamori, 2000).

To compute the receiver functions, each seismogram was de-trended and tapered, and a 0.05-8 Hz bandpass filter was applied to remove the low frequency noise. The waveforms were then decimated to 10 samples per second to avoid aliasing, and were cut 10s before and 80s after the first P-wave arrival. Next, the horizontal components were rotated to the great circle path to obtain radial and transverse components. The vertical component was then deconvolved from the radial and tangential components using the iterative time-domain deconvolution method (Ligorria and Ammon, 1999). A maximum of 500 iterations were used in the deconvolution method (Ligorria and Ammon, 1999).

Radial and tangential receiver functions were computed for each seismic event using Gaussian width factors of 1.0 (0.5 Hz) and 2.5 (1.25 Hz). The lower frequencies (0.5 Hz) result in longer wavelength receiver functions, which are best for observing longer period phases from the lower crust and mantle, while higher frequency receiver functions (1.25 Hz) can reveal detailed phases from shallow crustal structures (Owens and Zandt, 1985; Ligorria and Ammon, 1999; Julià et al., 2007).

To assess the quality of the receiver functions, a least squares minimization of the difference between the original radial component and the predicted radial component was applied. The predicted radial component was generated by convolving the original vertical component and the radial receiver function. A similarity of 85% or greater was used to select receiver functions for further analysis. In addition, events that resulted in transverse receiver functions with large amplitudes

were not considered for further processing, even if they passed the 85% criterion.

Figure 3 illustrates the quality of receiver functions for one station.

3.3 H-k stacking method

The H-k stacking method of Zhu and Kanamori (2000) was applied to the receiver functions to estimate the crustal thickness and the Vp/Vs ratio beneath each seismic station. This method reduces the ambiguity in Moho depth (H) and Vp/Vs (κ) estimates by incorporating the later multiple converted phases from the Moho (PpPs and PsPs+PpSs). In this method, the receiver functions are transformed from the time-amplitude domain into the stacking domain through

$$s(H, k) = \sum_{j=1}^N w_1 r_j(t_1) + w_2 r_j(t_2) - w_3 r_j(t_3) \quad (1)$$

where t_i are the travel times of the three main P-to-S converted phases from the Moho (Ps, PpPs, and PsPs+PpSs), w_i are weights assigned to each phase (sum of $w_i = 1$), r_j is the receiver function amplitude for the j -th receiver function, and N is the number of receiver functions. $S(H, \kappa)$ reaches its maximum when optimal values for H and κ are determined, satisfying a simple layer over a half-space model.

To apply the H- κ stacking method to the receiver functions, weights for the converted phases (Eq. 1) and an average crustal Vp must be selected. For each seismic station, an average crustal P-wave velocity of 6.3 and 6.5 km/s were used, which are typical values for Precambrian crust (e.g., Christensen and Mooney, 1995). The first two phases, Ps and PpPs, were more clearly seen in the receiver function waveforms for most stations, so we gave a weight to each of them of 0.4. The PsPs+PpSs

multiple was not as clear on many of the receiver functions and therefore we down-weighted it ($w_3=0.2$).

Results from the H- κ stacking method for crustal thickness and Vp/Vs ratio are tabulated in Table 1, examples for two stations are illustrated in Figures 4 and 5, and results for the other stations are provided in the supplemental material. The H- κ stacking method was performed on PRFs computed with both 1.0 and 2.5 Gaussian filters for all stations, and similar results were obtained using both filters.

For each seismic station, the formal uncertainties in both H and κ were estimated by bootstrapping the receiver function dataset (Julià and Mejía, 2004) using 200 replications (Efron and Tibshirani, 1991). The formal uncertainties for each station using a mean crustal Vp of 6.3 and 6.5 km/s for the H- κ stacking are given in Table 1. An overall uncertainty in H is obtained by combining the formal uncertainty with the range in H obtained using a crustal Vp of 6.3 and 6.5 km/s, and the overall uncertainty in κ is similarly obtained. The overall uncertainty in H, at each seismic station is thus $\sim\pm 2$ km, and the overall uncertainty in κ is $\sim\pm 0.08$.

Estimates of H and κ were obtained for all seismic stations except the ones without clear multiple converted phases. For the stations without clear Moho reverberations (stations TAMR, NBNS, SWA, MRS, DB2, BST, and FRF), the Moho depth has been computed using the Moho Ps arrival time, taken from a stack of the PRFs, and from the equation from Zandt et al. (1995) for H, an average crustal Vp of 6.5 km/s and a Vp/Vs ratio of 1.75.

3.4 Joint inversion of the receiver functions and Rayleigh wave group velocities

Using the method of Julià et al. (2000, 2003), the shear wave velocity structure of the crust beneath a seismic station can be obtained by jointly inverting receiver

functions and Rayleigh wave group velocity measurements. This method employs a linearized damped least-squares inversion that incorporates a priori smoothness and influence constraints. A combination of surface wave dispersion curves and receiver functions provides constraints on the shear wave velocity of the propagation medium ultimately improving those provided by either of the datasets modeled separately. This approach helps to prevent over-interpretation of single datasets (Ozalaybey et al., 1997; Juliá et al., 2000, 2003, 2005; Dugda et al., 2007).

For each dataset, the inversion was performed using receiver functions at low and high pass Gaussian filter bandwidths of 1.0 ($f \leq 0.5$ Hz) and of 2.5 ($f \leq 1.25$ Hz), respectively. For constraining the crust and uppermost mantle, fundamental-mode Rayleigh wave group velocities between periods of 10 and 100 s from Pasyanos and Nyblade (2007) are used. The starting model used in the inversion consists of a 38 km thick crust with a linear increase in S-wave velocity from 3.0 to 4.0 km/s, overlying a flattened PREM (Preliminary Reference Earth Model) model for the mantle (Dziewonski and Anderson, 1981). Following the approach of Juliá et al. (2008) for investigating the lateral variability of crustal structure around each seismic station, receiver functions were stacked into four groups by ray parameter, from 0.04 to 0.049 (with average value of 0.045); from 0.05 to 0.059 (with average value of 0.055); from 0.060 to 0.069 (with average value of 0.065); and from 0.070 to 0.079 (with average value of 0.075). For each seismic station, at least three receiver functions from each ray parameter group were used in the stacking.

The velocity model used in the inversion is parameterized with layers of constant velocity. Layer thicknesses are 1 and 2 km at the top of the model, 2.5 km thick between 5.5 and 53 km depth, 5 km thick between 53 and 260 km depth, and 10 km thick below a depth of 260 km. Velocities were fixed to PREM values below a

depth of 200 km. Poisson's ratio was fixed at 0.25 for crustal layers and at PREM values for mantle layers. During the inversion, an a priori smoothness factor of 0.1 was used for all stations and equal weight was given to the receiver functions and Rayleigh wave group velocities. The results for two stations are illustrated in Figure 6, and the Vs models for all the stations are shown in Figure 7. Results for the remaining stations are provided in the supplemental material.

4. Results

Shear wave velocities for typical lower crustal lithologies derived from experimentally determined Vp/Vs ratios have shown that the shear wave velocities in the lower crust do not likely exceed 4.3 km s^{-1} and that velocities greater than 4.3 km s^{-1} are typical for mantle lithologies (Christensen & Mooney 1995; Christensen 1996). Therefore, following the approach of Kachingwe et al. (2015) and Tugume et al. (2013), in the joint inversion models the Moho is defined as the depth at which the shear wave velocity exceeds 4.3 km s^{-1} (Figure 7). For most stations there is also a significant increase in velocity or a velocity discontinuity at the depth where the velocity exceeds 4.3 km s^{-1} . Additionally, from the models we obtain an average crustal shear wave velocity beneath each seismic station as well as the thickness of the mafic layering in the lower crust. Holbrook et al. (1992), Christensen and Mooney (1995), Rudnick and Fountain (1995), and Rudnick and Gao (2003) reported that common lower crustal mafic lithologies, such as amphibolites, garnet-bearing and garnet-free mafic granulite, and mafic gneiss, have high shear-wave velocities ($> 3.9 \text{ km/s}$) while intermediate-to-felsic lithologies have lower shear-wave velocities ($\leq 3.9 \text{ km/s}$). Therefore, we define the mafic lower crust as layers in the model with shear-wave velocities between 4.0 km/s and 4.3 km/s .

Results are summarized in Table 1. Based on the locations of the stations, we divided our study area into three geographic regions; (1) the rifted areas along the Red Sea, Gulf of Suez, and Gulf of Aqaba, (2) northern and central Egypt, and (3) southern Egypt. Moho depths beneath stations in region 1 (stations HRG, NADB, MRS, BST, and SHRM) are shallower, ranging from 26-30 km, with an average V_p/V_s ratio of 1.77. The mean crustal shear-wave velocity beneath this region is 3.6 km/s, and the average thickness of the mafic lower crust is 5 km.

Beneath stations in northern and central Egypt, including the Sinai Peninsula (stations NKL, KOT, NBNS, SLM, SIWA, FRF, TAMR, KAT, and DB2), the Moho depth ranges from 32-38 km, the average V_p/V_s is 1.79, the average crustal shear-wave velocity is 3.5 km/s and the average mafic lower crustal thickness is 3 km.

Beneath stations in southern Egypt (stations NAHD, NMAN, NNAL, MABD, NGRW, NGMR, NWAL, NWKL, DK2, NKUR, and NSKD), the Moho depth ranges from 35-40 km, the average V_p/V_s ratio is 1.76, the average crustal shear-wave velocity is 3.7 km/s, and the average mafic lower crust thickness is 15 km.

5. Discussion

No previous estimates of crustal structure from seismic data have been reported for several parts of Egypt, including the interior of the Sinai Peninsula, central Egypt, and northern Egypt along the Mediterranean coast. Results from this study thus provide new information about crustal structure for many parts of Egypt, and when combined with previously published results, can be used to more fully characterize crustal structure across Egypt and the northern Red Sea region. The ensemble of results of crustal structure across Egypt, the northern Red Sea and the

Gulfs of Suez and Aqaba, as well as beneath the northern Arabian Peninsula, is shown in Figure 8.

Where crustal structure beneath Egypt has been previously studied (see section 2.0), a comparison of published results with our findings shows good agreement. For example, along the rifted margins of the Red Sea and Gulf of Aqaba, estimates of crustal thickness in a number of studies (e.g. Makris et al., 1988; Marzouk, 1988; Ginzberg et al., 1988; Gaulier et al., 1988; Rihm et al., 1991; Hosny and Nyblade, 2014) range from ~25-30 km. Similarly, estimates of crustal thickness inboard from the coastlines in these studies indicate thicker crust, in the range of ~30-34 km, with the thickest crust found in south-central Egypt around Lake Nasser (~35-40 km) (Hosny and Nyblade, 2014). The V_p/V_s ratios obtained in this study for these regions are also similar to those reported by Hosny and Nyblade (2014), ranging between 1.7 and 1.8, on average.

Compared to crustal thickness estimates along the Arabian side of the Gulf of Aqaba and northern Red Sea, our results are similar to results obtained by Thalčić et al. (2006) and Al-Damegh et al. (2005). They report crustal thicknesses from 27 to 32 km beneath the Arabian rifted margins, and an average V_p/V_s ratio of 1.75. In comparison to crustal structure in the Arabian-Nubian Shield beneath Saudi Arabia, there is also good agreement. The average crustal thickness and V_p/V_s for the Arabian Shield in Saudi Arabia is 37 km and 1.76, respectively, similar to our results for southern, central and northern Egypt.

The compilation of results shown in Figure 8 indicates that there has been a ~ 5 to 10 km of crustal thinning along the rifted margins of the northern Red Sea, and Gulfs of Suez and Aqaba. Figure 8 shows a consistent crustal thickness of 25-30 km beneath all of the stations along the rifted margins in Egypt and Saudi Arabia. The

figure also shows crust that is 35-40 km thick away from the rifted margins beneath Egypt, the interior of the Sinai Peninsula, and the Arabian Shield of 35-40 km. Thus, the pre-rift crustal thickness beneath all of the rifted margins was likely in the 35-40 km range, and so ~5 to 10 km of crustal thinning must have occurred to create the 25-30 km thick crust found beneath the rifted margins.

Compared to crustal structure in similar tectonic settings elsewhere in Africa, our results also show good agreement. Crustal thickness beneath the Cenozoic East African Rift ranges from about 20-35 km (Fuchs et al., 1997 and references therein), overlapping with the range in crustal thickness we observe along the rifted margins of the Red Sea and the Gulf of Aqaba. Kachingwe et al. (2015) published a compilation of crustal structure for Precambrian terrains in the southern African subcontinent, expanding on the previous compilation of Tugume et al. (2013). Kachingwe et al. (2015) reported average crustal thicknesses of between 35 and 42 km, average V_p/V_s ratios of 1.7-1.8, and average crustal shear wave velocities of 3.6 to 3.8 km/s for five Neoproterozoic terrains. They also reported an average crustal thickness of 37 km, an average V_p/V_s ratio of 1.75, and an average crustal shear wave velocity of 3.6 km/s for the Mozambique Belt. As outlined previously, the Precambrian crust beneath most of Egypt is part of the Neoproterozoic Mozambique Belt. The crustal thickness beneath this area of Egypt ranges from 32-40 km, the V_p/V_s ratios range from 1.76 to 1.79, and the average crustal shear-wave velocities range from 3.6 to 3.7 km/s, in close agreement with the crustal parameters reported by Kachingwe et al. (2015) for the Mozambique Belt.

However, the V_s models for stations in southern Egypt reveal a significant difference in lower crustal structure compared to Mozambique Belt structure elsewhere in Africa. The lower crust beneath stations in the Lake Nasser region is

characterized by a thick layer of high velocity (> 3.9 km/s) rock, which we interpret as mafic lower crust. The average thickness of the mafic lower crust is 15 km (Table 1). In contrast, the thickness of the mafic lower crust in other parts of the Mozambique Belt is 2 km, and the mafic lower crust is no thicker than 7 km on average in many other Neoproterozoic terrain in Africa (Kachingwe et al., 2015).

The region in southern Egypt where we observe the thickened mafic lower crust (around Lake Nasser) is situated along a mapped Precambrian suture zone, the Keraf shear zone, which likely formed during the collision between east Gondwana and the Sahara metacraton during the final assembly of Gondwana in the Neoproterozoic, about 640-560 Ma (Johnson et al., 2011; Stern and Johnson, 2010; Bailo et al., 2003; Abdelsalam and Stern, 1996 a,b; Abdelsalam et al., 1998) (Figure 1). In Precambrian terrains of other ages in southern Africa where similarly thick, mafic lower crust is found, Kachingwe et al. (2015) attributed the mafic layering to suturing during continent-continent collision. Thick mafic crustal layers within Precambrian suture zones is also commonly observed in other continents (e.g., Thomas and Tanner, 1975; Kearey, 1976; Gibb and Thomas, 1976, 1977; Gibb et al., 1983; Mathur, 1974; Black et al., 1979). Consequently, we attribute the thick mafic lower crust in southern part of Egypt to modification of the crust during the collisional event that marked the final assembly of Gondwana in which east Gondwana collided with the Saharan metacraton.

The position of the Keraf suture zone in central and northern Egypt is uncertain, and so the lack of thick mafic crust beneath the stations to the north of the Lake Nasser region could simply result from a lack of station coverage. Or alternatively, the nature of the collisional event during the formation of Gondwana may have been different to the north of the Lake Nasser region.

As a final discussion point, we note that the velocity models obtained in this study also have value for hazard risk reduction for Egypt. Seismic hazards are significant within parts of Egypt (see Ambraseys, 2005 for reviews of seismicity in Egypt), and well constrained velocity models can be used to improve earthquake locations. To provide regional models useful for seismicity studies, we have averaged the velocity models from the stations in each of the three regions in Table 1. The average models are shown in Figure 7d and the velocity models are provided in the supplemental material.

6. Summary and Conclusions

To summarize, using seismic data from 26 station in the Egyptian National Seismic Network, estimates of crustal thickness, mean crustal shear-wave velocity, mean crustal V_p/V_s ratio, and the thickness of the mafic lower crust have been obtained.. No previous estimates of crustal structure from seismic data have been reported for several parts of Egypt, including the interior of the Sinai Peninsula, central Egypt, and northern Egypt along the Mediterranean coast. Results from this study thus provide new information about crustal structure for those parts of Egypt.

In areas of Egypt where crustal structure has been previously studied, a comparison of published findings with our results shows good agreement. Similarly, our results compare favorably with crustal thickness estimates along the Arabian side of the Gulf of Aqaba and northern Red Sea, and in the Arabian Shield. Compared to crustal structure in similar tectonic settings elsewhere in Africa, our results also show good agreement, except for in southern Egypt, where the thickness of the mafic lower crust is substantially greater than that beneath Neoproterozoic terrains in eastern, southern, and western Africa. We attribute the thickened mafic lower crust to

modification of the crust that occurred during the collision between east Gondwana and the Sahara metacraton along the Keraf suture zone during the final assembly of Gondwana in the Neoproterozoic.

When new results from this study are combined with results from previous studies, it is apparent that the crust is uniformly 35-40 km thick beneath regions of Egypt, the Sinai Peninsula, and the Arabian Shield away from the rifted margins of the northern Red Sea, and Gulfs of Suez and Aqaba. Thus, the pre-rift crustal thickness beneath the rifted margins was likely in the 35-40 km range, and so ~5 to 10 km of crustal thinning has probably occurred beneath the rifted margins to create the 25-30 km thick crust observed there.

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Figure captions:

Figure 1. Generalized geologic map of Egypt, redrawn after Egyptian Geological Survey and Mining Authority (1981). Black triangles show the locations the seismic stations used in this study. Stations DK2, MRS, KAT, and BST are short-period stations and the others are broadband stations.

Figure 2. Map showing the locations of the earthquakes (small solid circles) used in this study centered on the middle of the study region (star). The numbers on the circles give epicentral distance in degrees.

Figure 3. A plot of the radial (left) and tangential (right) receiver functions vs. ray backazimuth for station NAHD computed using a Gaussian filter of 1.0.

Figure 4. H-k stack results for station HRG with weights of $w_1=0.4$ $w_2=0.4$ $w_3=0.2$. On the right are the receiver functions labeled by event back azimuth (top number) and epicentral distance in degrees (bottom number). On the left is the H-k parameter space with the optimal results for H and k. The contours map out the percentage values of equation (1) given in the text. The optimal results for H and k found in the parameter space are summarized along the top with their formal uncertainties.

Figure 5. H-k stack results for station NAHD with weights of $w_1=0.4$ $w_2=0.4$ $w_3=0.2$. On the right are the receiver functions labeled by event back azimuth (top number) and epicentral distance in degrees (bottom number). On the left is the H-k parameter space with the optimal results for H and k. The contours map out the percentage values of equation (1) given in the text. The optimal results for H and k found in the parameter space are summarized along the top with their formal uncertainties.

Figure 6. Results from the joint inversion for stations HRG and NAHD. The three panels shown are a) receiver functions, b) Rayleigh wave group velocities, and c) the shear-wave velocity model.

Figure 7. Shear wave velocity models for each station obtained from the joint inversion of PRFs and Rayleigh wave group velocities. (a) Vs models for the stations located in the northern and central Egypt. (b) Vs model for stations located in southern Egypt. (c) Vs model for stations along the rifted margins of the Red Sea and Gulf of Aqaba. (d) The average velocity model for each geographic region; (1) northern and central Egypt, including the Sinai Peninsula, (2) southern Egypt, and (3)

for the rifted margins of the Red Sea and Gulf of Aqaba. The thin vertical line shows a V_s of 4.0 km/s and the vertical dashed line shows a V_s of 4.3 km/s.

Figure 8. (a) Moho depth in km and V_p/V_s (in small box) for seismic stations in Egypt and the northern Red Sea region. See text for references to stations not part of this study. A-A' and B-B' show the locations of the cross-sections in (b). (b) Cross section showing the crustal thickness variations west-east and southwest – northeast across Egypt, the northern Red Sea, the Gulfs of Suez and Aqaba, and northern Saudi Arabia. Moho depths beneath the Gulf of Suez and Gulf of Aqaba are taken from Gaulier et al. (1988). Cross section B-B' is modified from Hosny and Nyblade (2014). The unlabeled Moho depth estimates in B-B' (small solid squares) are reviewed in Hosny and Nyblade (2014).

Figure 1. Generalized geologic map of Egypt, redrawn after Egyptian Geological Survey and Mining Authority, EGSM, (1981), Black triangles show the locations the seismic stations used in this study, 24 BB stations and four are SP (DK2, MRS, KAT, and BST)

Figure 2. A map showing the locations of the earthquakes (small solid circles) used in this study centered on the middle of the study region (star). The numbers on the circles give epicentral distance in degrees

Figure 3. A plot of the radial and tangential receiver functions vs. ray parameter for station NAHD computed using a Gaussian filter of

$v_p = 6.5 \text{ km/s}$ $h = 26.6 \pm 1.1 \text{ km}$ $v_p/v_s = 1.72 \pm 0.06$ $\text{corr} = -83.1 \%$

Figure 4. H- k stack results for station HRG with weights of $w_1=0.4$ $w_2=0.4$ $w_3=0.2$. On the right are the receiver functions labeled by the event's back azimuth (top number) and epicentral distance in degrees (bottom number). On the left is the H- k parameter space with the optimal results for H and k. The contours map out the percentage values of the objective function given in the text. The optimal results for H and k found in the parameter space are summarized along the top with their formal uncertainties

$v_p = 6.5 \text{ km/s}$ $h = 39.2 \pm 1.0 \text{ km}$ $v_p/v_s = 1.71 \pm 0.05$ $\text{corr} = -96.1 \%$

Figure 5. H- k stack results for station NAHD with weights of $w_1=0.4$ $w_2=0.4$ $w_3=0.2$. On the right are the receiver functions labeled by the event's back azimuth (top number) and epicentral distance in degrees (bottom number). On the left is the H- k parameter space with the optimal results for H and k. The contours map out the percentage values of the objective function given in the text. The optimal results for H and k found in the parameter space are summarized along the top with their formal uncertainties

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Figure 8. (a) Moho depth beneath each seismic station used in the current study. Beneath each station, the values of the Moho depth and V_p/V_s ratio are written in the small boxes. A-A' and B-B' show the locations of the cross-sections in (b). (b) Cross section showing the crustal thickness variations west-east and southwest – northeast across Egypt, the northern Red Sea, the Gulfs of Suez and Aqaba, and northern Saudi Arabia. The Moho depth beneath the Gulf of Suez and Gulf of Aqaba is taken from the seismic profiling study of Gaulier et al., 1988. Cross section B-B' is modified from Hosny and Nyblade (2014), with unlabeled Moho depth estimates (small solid squares) are reviewed in that paper.

Table 1. Crustal structure results for the stations used in this study.

Geographic region	Station name	Lat (deg)	Lon (deg)	Elev. (m)	No of events	Depth (1) km	Depth (2) km	Depth (3) km	Depth (4) km	Ratio (1)	Ratio (2)	Mafic lower crust (km)	Avg Vs (km/s)
Rifted areas along the Red Sea and Aqaba Gulf	HRG	27.0517	33.6081	227	16	25.6±1.0	26.4±0.7	27.0	28.0	1.73±0.06	1.75±0.07	2.5	3.6
	NADB	25.3405	34.5021	298	23	25.4±0.8	26.3±0.9	29.0	28.0	1.88±0.05	1.87±0.05	0.0	3.6
	BRNS	23.8559	34.1143	332	13	27.2±1.7	28.1±1.5	28.0	28.0	1.72±0.05	1.72±0.05	7.5	3.7
	MRS*	25.0131	34.8386	215	15	----	-----	32.5	33.0	----	-----	5.0	3.6
	SHRM	27.8925	34.1322	100	8	26.3±2.2	27.3±2.2	27.0	28.0	1.77±0.05	1.77±0.05	7.5	3.6
	BST*	29.2166	34.7327	240	14	----	-----	33.5	33.0	----	-----	5.0	3.7
	Average					26.0±1.4+	27.0±1.3+	28.5	29.0	1.77	1.77	4.5	3.6
North and central Egypt and Sinai Peninsula	NKL	29.9293	33.9804	455	19	34.0±0.5	35.2±0.6	35.5	35.5	1.84±0.02	1.83±0.03	7.5	3.7
	KOT	29.9275	31.8291	507	14	33.6±0.9	34.8±0.9	35.0	35.5	1.79±0.04	1.78±0.04	2.5	3.3
	KAT*	28.5229	33.9927	1746	17	30.5±1.4	31.5±1.6	32.9	30.0	1.77±0.06	1.76±0.06	2.5	3.6
	NBNS	28.6226	31.2945	305	17	---	---	35.5	35.5	---	---	2.5	3.2
	DB2	31.0470	28.5038	25	20	----	---	33.0	33.0	----	----	0.0	3.4
	SLM	31.4916	25.2122	107	12	35.3±1.5	36.6±1.6	35.2	35.5	1.82±0.05	1.82±0.06	2.5	3.2
	SWA	29.2433	25.4556	65	13	---	---	37.0	35.5	---	---	0.0	3.5
	FRF	27.1484	28.3104	340	22	---	---	38.0	38.0	---	---	2.5	3.4
	TAMR	27.6821	30.9175	145	22	---	----	41.0	38.0	----	----	2.5	3.6
	Average					34.0±1.0+	34.5±1.2+	35.9	35.0	1.80	1.79	2.5	3.5

Table 1. Continue

Geographic region	Station name	Lat (deg)	Lon (deg)	Elev. (m)	No of event	Depth (1) km	Depth (2) km	Depth (3) km	Depth (4) km	Ratio (1)	Ratio (2)	Mafic lower crust (km)	Avg Vs (km/s)
Southern Egypt	NAHD	23.8022	32.7780	100	21	37.9±1.1	39.2 ±1.0	38.5	38.0	1.70±0.07	1.71±0.05	15.0	3.7
	NMAN	23.9169	33.0749	100	23	35.7±0.9	37.9 ±0.9	37.0	38.0	1.72±0.04	1.72±0.04	12.5	3.7
	NNAL	23.2931	32.6647	100	12	34.7±1.9	36.2 ±1.8	39.0	38.0	1.85±0.07	1.84±0.06	12.5	3.7
	MABD	22.9226	32.3258	280	12	35.7±0.8	37.0 ±0.7	40.0	40.5	1.85±0.04	1.82±0.03	12.5	3.7
	NWAL	23.3829	32.5779	224	15	38.3±1.2	39.7±1.2	41.8	40.5	1.76±0.05	1.75±0.05	12.5	3.7
	NWKL	23.4130	32.4488	232	15	38.0±0.7	39.4±0.9	41.6	40.5	1.80±0.03	1.79±0.03	17.0	3.8
	NGRW	23.6684	32.7911	194	29	38.3±0.5	39.7±0.6	39.6	40.5	1.73±0.03	1.73±0.03	17.0	3.7
	NGMR	23.5217	32.4074	237	22	36.9±0.8	38.1±0.9	39.6	40.5	1.79±0.04	1.78±0.05	20.0	3.8
	NSKD	28.9893	34.6397	090	17	38.4±2.5	39.7±2.5	40.8	40.5	1.79±0.07	1.78±0.07	20.0	3.7
	NKUR	24.0040	32.6510	198	24	37.6±0.7	39.0±0.7	37.5	38.0	1.74±0.04	1.74±0.04	15.0	3.7
	DK2*	24.3195	28.9546	380	13	34.1±2.1	35.3±2.3	36.0	35.5	1.75±0.06	1.74±0.06	10.0	3.7
	Average					36.9±1.1+	38.2±1.2+	39.2	39.1	1.77	1.76	14.9	3.7

Depth (1): Crustal thickness from H-k stacking using average $V_p=6.3$ km/sec

Depth (2): Crustal thickness from H-k stacking using average $V_p=6.5$ km/sec

Depth (3): Crustal thickness from moho P_s .

Depth (4): Crustal thickness from joint inversion of receiver functions and surface wave dispersion.

Ratio (1), (2): V_p/V_s ratio from H-k stacking using $V_p=6.3$ and $V_p=6.5$ km/sec, respectively.

+ uncertainty shown is the standard deviation of the mean

* denotes short-period stations