Seismic Structure of the Arabian Shield Lithosphere and Red Sea Margin

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Introduction

In this MARGINS project we are using broadband seismic data from the Saudi Arabia National Digital Seismic Network (SANDSN) to investigate crust and upper mantle structure beneath the eastern margin of the Red Sea and the Arabian Shield. The SANDSN has been operated since 1998 by the King Abdulaziz City for Science and Technology (KACST), and consists of 38 stations mostly distributed across the Arabian Shield (Figure 1) [*Al-Amri and Al-Amri, 1999*]. Twenty-seven of the stations are equipped with broadband (Streckeisen STS-2) sensors. Five years of data (1999-2003) from the network have been made available for this project, and the data are being used to 1) map first-order structure surrounding the ruptured Red Sea lithosphere, 2) evaluate the heterogeneity of the continental lithosphere prior to rifting, and 3) constrain ambient stress fields and lithospheric rheology using local seismicity.

Here we report preliminary findings from a surface wave tomography study to map differences in upper mantle structure between the eastern margin of the Red Sea, the Arabian Shield, and the Arabian Platform (Figure 1). The basement of the study region consists of an amalgamation of Proterozoic terrains, and across the Arabian Shield these terrains have been subjected to Cenozoic uplift and volcanism. The locations of the volcanic regions are shown in Figure 1a. The oldest volcanic rocks on the Shield are contemporaneous with flood basalt volcanism in Yemen and Ethiopia and the initiation of rifting in the Red Sea c. 30 Ma [*Mohr, 1988*; *Camp et al., 1991*; *Coleman and McGuire, 1988*]. Younger volcanic rocks (c. 12 Ma to present; *Camp and Roobol, 1992*) are found in the central and northern part of the Shield (Figure 1a). The average elevation across the Shield is 1 km, but in some areas near the Red Sea elevations are as high as 3 km. The uplift of the Shield probably occurred between 20 and 13 Ma, post-dating the onset of rifting in the Red Sea by at least 10 Ma [*McGuire and Bohannon, 1989*; *Bohannon et al., 1989*].

Although a great deal of work has been done to understand the origin of Cenozoic uplift and volcanism in the Arabian Shield, the development of these features in relation to rifting in the Red Sea remains enigmatic and must be ascertained before the tectonic evolution of the Red Sea rift can be fully understood. The surface uplift and volcanism are generally assumed to be due to hot, buoyant material in the upper mantle that may have eroded the base of the lithosphere [*Camp and Roobol, 1992*]. However, the lateral and vertical extent of the thermal anomaly in the upper mantle under the Shield is uncertain, as is its relationship to rifting in the Red Sea.

Previous seismic work in the region has revealed low seismic velocities in the upper mantle beneath the Shield [e.g., *Sandvol et al., 1998*; *Mellors et al., 1999*; *Rodgers et al., 1999*; *Debayle et al., 2001*; *Julia et al., 2003*; *Benoit et al., 2003*], consistent with the presence of a mantle thermal anomaly. Global tomographic models suggest that the region of low seismic velocities could extend from shallow upper mantle depths across the transition zone into the lower mantle [e.g., *Ritsema et al., 1999*; *Debayle et al., 2001*; *Zhao, 2001*; *Grand, 2002*]. *Daradich et al.* [2003] have used these models to suggested that the uplift of the Shield is caused by thermally buoyant mantle rising from the core-mantle boundary all the way to the surface. Other studies, however, have found little evidence for thinning of the transition zone under the Shield, [e.g., *Kumar et al., 2002*; *Benoit et al, 2003*], suggesting that the low velocities, and hence thermal anomaly, do not extend as deep as the transition zone.

Hansen et al. [2006] recently published results from shear wave splitting analyses using data from the SANDSN stations. Their results show a N-S fast polarization direction across the Shield (Figure 1c), similar to the results from *Wolfe et al.* [1999] for the Saudi Arabian PASSCAL experiment stations [*Vernon et al., 1996*]. The N-S pattern of fast polarization directions is not easy to explain by flow in the mantle in the direction of plate motion or to fossil anisotropy in the Proterozoic lithosphere, and consequently *Hansen et al.* [2006] have attributed it to a combination of plate and density driven flow in the asthenosphere. The density driven flow is associated with warm material from the Afar hotspot moving to the northwest channeled by the thinner lithosphere under the Red Sea, implying the existence of a thermal anomaly within the upper part of the mantle beneath the Shield.

Surface Wave Tomography

To investigate further the depth and lateral extent of the low velocity region in the upper mantle beneath the eastern margin of the Red Sea and the Arabian Shield, we have conducted surface wave tomography using measurements of Rayleigh wave phase velocities. In addition to data from the SANDSN network, we have included data from two seismic experiments in Ethiopia (the Ethiopian Broadband Seismic Experiment, *Nyblade and Langston, 2002*; EAGLE, *Maguire et al., 2003*), the Saudi Arabia PASSCAL Experiment [*Vernon et al., 1996*], and several permanent seismic stations in the region (Figure 1a).

Interstation phase velocities were obtained using the method described by *Lawrence et al.* [2006], which is based

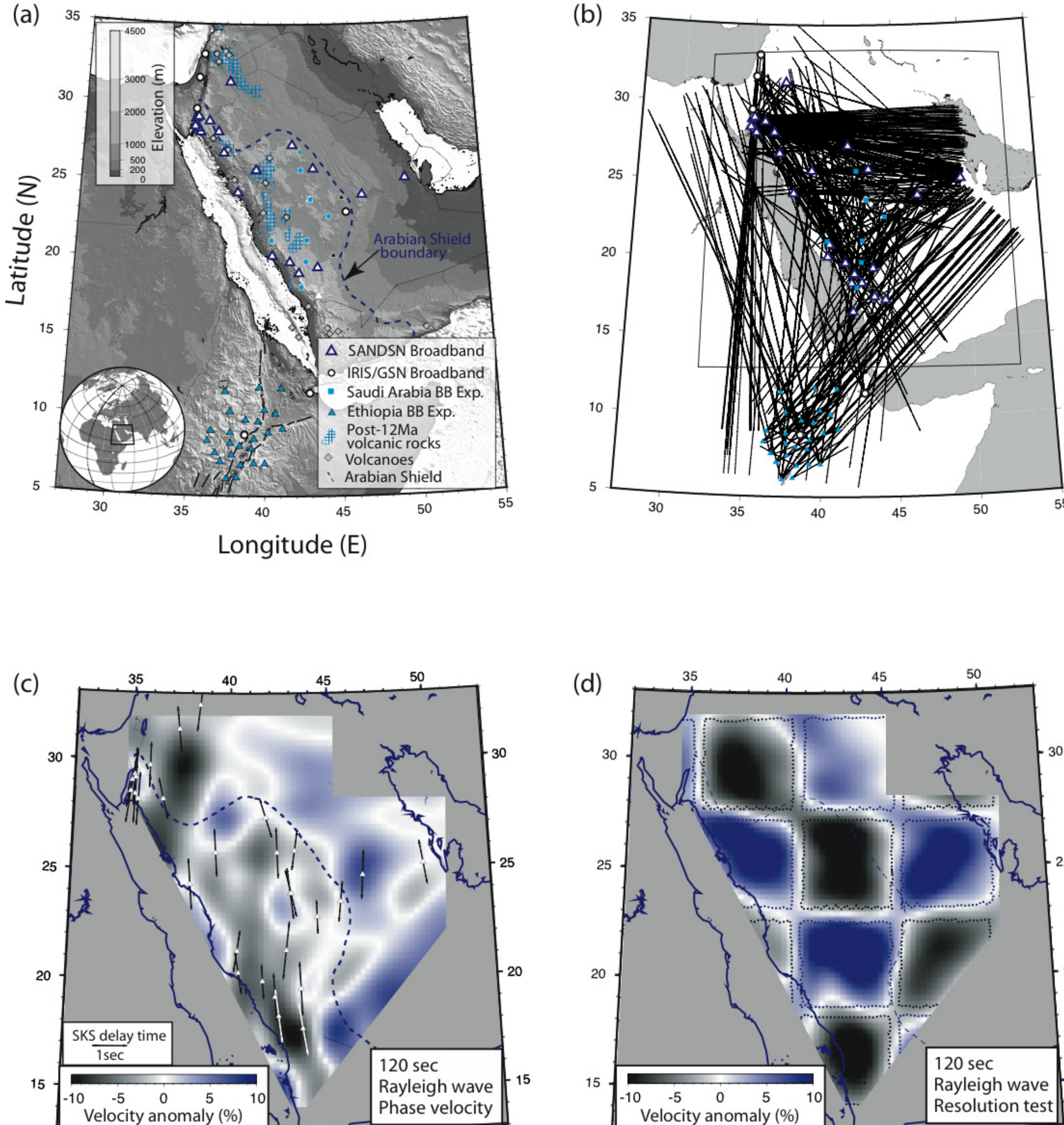

Figure 1. (a) Map of Arabian Peninsula and surrounding regions showing topography (grey scale), seismic station locations, Cenozoic volcanic fields, and the outline of the Arabian Shield. (b) Ray path coverage for 120 sec. period Rayleigh waves. (c) Phase velocity variations for 120 sec. period Rayleigh waves with shear-wave splitting results from Hansen et al. [2006] superimposed. (d) Checkerboard resolution test for Rayleigh wave phase velocity variations at 120 sec. period. The dotted lines show the +/- 9% contour interval for the input checkerboard anomalies. The blue and grey shaded regions show the recovered structure.

on an array analysis technique modified from *Menke and Levin* [2002], to solve for the variation in ray path from a great circle. When applied to the available data, we obtained 900 or more interstation phase velocity curves, each constructed from interstation phase velocities measured at up to 30 period bands from 16 to 180 s. The best ray coverage is obtained between periods of 60 and 120 s. Using the phase velocities measurements, we have preformed inversions using a least squares algorithm to construct phase velocity maps, and we have tested the resolution of the maps using standard checkerboard methods.

A preliminary result, using about 80% of the available data, is shown in Figures 1b, c and d. The ray coverage is best across the Shield and the northern and central parts of the Platform. The number of rays, as well as the density of crossing ray paths, degrades in the Red Sea and in the southern part of the Platform.

Because most of the teleseismic earthquakes come from the east or the west, there are relatively few ray paths oriented north-south. Inclusion of interstation measurements between the KACST and Ethiopian stations in the inversion was necessary to improve the density of crossing ray paths.

The phase velocity maps between periods of 65 and 120 s show similar velocity variations across the study region and have similar resolution. Because we are primarily interested in lithospheric mantle structure under the Shield, we show in Figure 1c the map for 120 s, which is broadly indicative of structure deeper than about 100-120 km. The map shows a simple pattern of lower-than-average phase velocities beneath the Shield, as well as to the north of the Shield near the Gulf of Aqaba. Faster-than-average velocities are found beneath the Platform surrounding the Shield.

Preliminary resolution tests indicate that anomalies on the order of a few hundred kilometers in wavelength can be resolved. Figure 1d shows the results from a 400x400 km checkerboard test; clearly anomalies of this size, which are somewhat smaller than the dimensions of the Shield, can be resolved.

Discussion

Our preliminary results suggest that the mantle lithosphere everywhere beneath the Shield to the east of the Red Sea rift has been modified thermally, and that there is a fairly abrupt change in lithospheric structure across the Shield-Platform boundary. The reduction in Rayleigh wave phase velocities at 120 s period under the Shield compared to the Platform is between 5 and 8%. Similar results have been reported recently by us [*Park et al., 2005*] from an S body wave tomography of the region using the SANDSN data, and preliminary results from S receiver function analysis of the SANDSN data also indicate the presence of thermally modified upper mantle beneath the eastern margin of the Red Sea and the Shield [*Hansen, personal communication*]. Previous tomographic images of the Arabian Peninsula using regional data sets indicate the presence of thermally perturbed mantle lithosphere under the Shield [*Benoit et al., 2003*; *Debayle et al, 2001*], but they do not show an abrupt change in lithospheric structure across the Shield-Platform boundary, as suggested by our preliminary results (Figure 1).

How do these results advance our general understanding of rift processes in continental settings? And more specifically, how do they help to achieve the science goals of the MARGINS Rupturing Continental Lithosphere initiative? Certainly, the rheology of the continental lithosphere on the eastern margin of the Red Sea has been thermally weakened, and thus the post-rift thermal evolution of the lithosphere has likely been affected. But beyond that, answers to these questions depend in large part on whether the thermal anomaly imaged in the upper mantle to the east of the Red Sea extends under the Red Sea. If the thermal anomaly under the shield developed about 10 Ma after the initiation of rifting, then it is not clear how this could have influenced strain partitioning at the time of rifting. However, if the anomalous mantle structure under the Shield extends beneath the Red Sea, then the tectonic development of the Red Sea and Shield would appear to be linked.

More detailed imaging of the upper mantle under the Red Sea and the Arabian Shield is clearly needed. Completion of the surface and body wave tomography studies underway at Penn State, King Saud University, and Lawrence Livermore National Lab using the SANDSN data should provide images with improved resolution of upper mantle structure across the region, letting us determine if the low velocity structure in the upper mantle under the Shield extends beneath the Red Sea.

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