A PROPOSAL FOR

Determining Crustal and Upper Mantle Structure Beneath the Arabian Shield and Red Sea

Abstract

We propose to determine the seismic velocity structure of the crust and upper mantle beneath the Arabian Shield and Red Sea using a variety of analysis techniques on SGS broadband seismic waveform data. We will perform several analyses of broadband data. Teleseismic P- and S-wave travel time tomography will provide an image of upper mantle compressional and shear velocities related to thermal variations. Regional Pn tomography will map compressional velocity structure of the shallow mantle. Teleseismic P-wave receiver functions will be modeled to estimate crustal and upper mantle discontinuity structure. Finally, teleseismic shear-wave splitting will be measured to estimate upper mantle anisotropy. These analyses will provide estimates of the physical structure of the crust and upper mantle beneath the Arabian Shield and Red Sea. The results of this proposal will provide valuable new constraints on the processes at work during continental break-up. In particular we will have better models of upper mantle structure to determine the depth of the source of volcanism and uplift of the Arabian Shield.

Introduction

The Red Sea is a region of current tectonic activity where continental lithosphere is being rupture to form oceanic lithosphere. Opening of the Red Sea split the Arabian-Nubian Shield. While much work has been done to understand the uplift and volcanism of the Arabian Shield little is known about the structure of the underlying upper mantle. The Arabian Shield consists of at least five Precambrian terranes separated by suture zones (Schmidt et al., 1979). During the late Oligocene and early Miocene, the Arabian Shield was disrupted by the development of the Red Sea and Gulf of Aden rifts, and from the mid-Miocene to the present, the region experienced volcanism and uplift [Bohannon et al., 1989]. The uplift and volcanism are generally assumed to be the result of hot, buoyant material in the upper mantle that may have eroded the base of the lithosphere [Camp and Roobol, 1992]. However details about the nature of the upper mantle, such as its thermal and compositional state, are not known.

Previous Studies

The Saudi Arabian Broadband Deployment (SABD, Vernon et al., 1996) provided the first data set of broadband recordings of this region. This deployment consisted of 9 broadband three-component seismic stations along a similar transect an early seismic refraction study (Mooney et al., 1985; Gettings et al., 1986; Mechie et al., 1986). Data from the experiment resulted in several studies and models of the seismic structure of the Arabian Shield (Sandvol et al., 1998; Mellors et al., 1999; Rodgers et al., 1999; Benoit et al., 2002). These studies provided new constraints on crustal and upper mantle structure. Generally the Arabian Shield is estimated to have a crustal thickness of 35 km (Rodgers et al., 1999). Not surprising the crust thins nears the Red Sea (Mooney et al., 1985; Gettings et al., 1986; Mechie et al., 1986). High-frequency regional S-wave phases are quite different for paths sampling the Arabian Shield than those sampling the Arabian Platform (Mellors et al., 1999). In particular the mantle Sn phase is nearly absent for paths crossing parts of the Arabian Shield, while the crustal Lg phase is extremely large amplitude. This may result from an elastic propagation effect or extremely high mantle attenuation and low crustal attenuation occurring simultaneously, or a combination of both.

Previous reports of large scale seismic structure [e.g. Ritsema et al., 1999 and Debayle et al., 2001] suggest that a low velocity anomaly in the upper mantle extends laterally beneath the Arabian Shield from the Red Sea in the west to the shield – platform boundary in the east. Additionally, Debayle et al. [2001] observe a narrow region of low velocity beneath the Red Sea and western edge of the Arabian Shield, extending to 650 km depth. A recent tomographic velocity model and receiver function analysis by Benoit et al. (2002) suggests the upper mantle low velocity anomaly is smaller in extent, laterally and vertically, than imaged in previous studies.

Proposed Work

We propose to analyze a large data set of seismograms from the SGS to estimate detailed structure of the crust and upper mantle of the Arabian Shield and adjacent Red Sea. We expect to determine detailed models of compressional and shear velocities of the crust and upper mantle down to about 400 km using teleseismic receiver functions and P- and S-wave travel time tomography. The state of strain in the upper mantle will be determined from teleseismic shear wave splitting. Deep receiver functions will sample the upper mantle transition zone discontinuities at 410 and 660 km. The resulting model(s) will provide new constraints on tectonic models of the rupturing of continental lithosphere and the source of volcanism in the Arabian Shield.

Teleseismic Travel Time Tomography

To image upper mantle P wave velocity structure under the Arabian Shield, P wave travel time residuals will be determined from the KACST dataset following Benoit et al. (2002). This technique uses the multi-channel cross correlation [MCCC] method of VanDecar and Crossen [1990] and then modeled using the inversion method of VanDecar [1991]. The MCCC method of VanDecar and Crossen [1990], which makes use of the waveform coherency that is found across a regional network, involves three steps. First, the data is band-passed filtered between 0.5 and 5 Hz. A cross correlation is then computed for all possible pairs of stations to find the relative arrival times, and finally a least squares optimization scheme is applied to the arrival times to minimize inconsistencies in the data. The uncertainties in the relative P wave travel times are about 0.1 to 0.15 seconds. After computing the travel time residuals, we will independently invert for P wave slowness and earthquake relocations. The inversion searches for the smoothest model with the least amount of structure that will match the data. The earthquake relocations are used to stabilize the inversion. The inversion is linear and minimizes both spatial gradients and model roughness using a conjugate gradient scheme [VanDecar, 1991].

The P-wave velocity model of Benoit et al. (2002) is using the smaller 1995-7 Saudi Arabian Broadband Deployment data (SABD, Vernon et al., 1996). That model was comprised of 34 knots in depth, 51 knots in latitude, and 48 knots in longitude, and the grid extended from 0 to 1000 km depth, 10° to 34° latitude and 33° and 55° longitude. Between 0 and 700 km depth, the knot spacing was 25 km apart, and knot spacing was 50 km apart below 700 km. In the interior of our model, the horizontal knot spacing was 0.3°. Slower than average velocities are located in the southwestern most portion of the model near the Red Sea coast and extend to at least 500 km depth, while the fastest velocities are located in the northeastern portion of the model. Also, a small region with slower than average velocities (~1%) is centered at 23° N and 45.5° E at about 300 km depth.

Using the denser station spacing and larger event database of the SGS operated Saudi Arabian National Seismic Network (SANSN) we expect to get better resolution of the heterogeneity features of the upper mantle than that obtained by Benoit et al. (2002).

Receiver Functions

Receiver functions are now a wisely used technique to estimate the depth to discontinuities in the subsurface. The technique is generally applied to three-component broadband teleseismic P-waveforms. Using a deconvolution algorithm, the vertical component is deconvolved from the radial component leaving the P-to-S conversion response. This technique is very successful at estimating crustal thickness and the depths of the upper mantle transition zone discontinuities at 410 and 660 km. We propose to apply the receiver function technique to P-waves from large teleseismic earthquakes to determine both crustal structure and depths of the upper mantle transition zone discontinuities.

Following the work of Benoit et al. (2002) we will use a frequency domain deconvolution method with water level stabilization [Ammon, 1991] to obtain the P to S wave converted phases from the 410 km and 660 km discontinuities, and followed the stacking procedure used by Owens et al. [2000]. These discontinuities are generally regarded to be mineral

phase transformations [Bina and Helffrich, 1994], and the Clapeyron slopes of the equilibrium phase boundaries are such that in regions of higher than normal temperature, the depth of the 410 km discontinuity is depressed and the 660 km discontinuity is elevated, causing the transition zone to thin [Bina and Helffrich, 1994].
Generally, the Ps conversions produced by the 410 and 660 km discontinuities were strong and easily visible on the receiver function stacks . Both the 410 and 660 km discontinuities show long wavelength topography and are at their deepest positions beneath the slowest portion of the P wave velocity model recovered by our inversion .

Teleseismic Shear Wave Splitting

The most abundant and highly anisotropic upper mantle mineral, olivine, develops preferred lattice orientations when deformed in the dislocation creep regime (Karato, 1998). For large strains, the olivine a axes become parallel to the direction of shear. Therefore, measurements of seismic anisotropy can be used to investigate mantle deformation. While seismic anisotropy has been studied in several diverse tectonic settings, its interpretation in many cases is still enigmatic. No tectonic environment has been more difficult to understand than rift zones. Since Hess' (1964) pioneering study of anisotropy in ocean basins, it has been expected that extension should align fast directions of olivine parallel to the rifting direction through shear in the lithosphere or asthenosphere. However, recent studies of seismic anisotropy from SKS splitting in the Basin and Range (Savage et al., 1990), the Rio Grande Rift (Sandvol et al., 1992), the Baikal Rift (Gao et al., 1997) and an area adjacent to the Red Sea Rift Zone (Wolfe et al., 1999) have not found extension parallel fast directions. This suggests that flow in the asthenosphere is not completely driven by surface tectonics.

The anisotropic signature beneath continental rift zones can provide important constraints on the mechanism of extension. For example, a passive model of continental rifting, where the entire lithosphere is extended below the rift, would be expected to produce a lattice preferred orientation (LPO) of olivine aligned parallel to the direction of extension. Active rifting, involving thinning of the lithosphere through small-scale convection, might result in more complex flow and therefore more complicated LPO alignments, depending on the details of the small scale convection. In addition to LPO developed during mantle flow, alternative models for seismic anisotropy beneath rift zones include fossil LPO frozen into the lithosphere during a previous tectonic event and the alignment of magmatic cracks. These magma filled cracks are expected to align themselves perpendicular to the least compressive stress direction, resulting in rift parallel fast polarization directions. This mechanism is analogous to extensive dilatancy anisotropy, where parallel alignment of vertical, fluid-filled microcracks in the crust produces anisotropy. It has been suggested as the dominant cause of anisotropy beneath the Rio Grande and East African Rifts (Gao et al., 1997).

Results of previous research found a fast polarization direction parallel to the Red Sea Rift's spreading, by modeling far-regional surface waves (Schwartz et al., 2000). That study estimated crustal and upper mantle velocity structures for the Red Sea Rift Zone were derived by modeling regional and far-regional body and surface waveforms. The best-fit model had a 17 km thick crust with anomalously low upper mantle velocities (V_p = 7.7 km/s) underlain by a significant low velocity zone. Velocity models that fit the radial and vertical waveforms are unable to accurately predict the Love wave on the transverse component. Including 3-4% faster SH than SV velocities in the upper mantle replicates the Love wave and points to a fast anisotropic polarization axis parallel to the rift's spreading direction . These results are in direct contradiction to the SKS splitting results of Wolfe et al. (1999) and require further investigation of the anisotropic structure beneath the Red Sea Rift zone to understand its origin and relationship to the geodynamic processes involved in continental rifting.

Here we propose to use the SANSN data set to address this very important problem. Specifically, we propose to measure teleseismic shear wave splitting in S and SKS phases recorded by 26 broadband stations of the KACST network that border the Red Sea in Saudi Arabia. S and SKS splitting parameters will be analyzed for the possibility of lateral variations in anisotropic structure and dipping symmetry axes. Dipping symmetry axes were not considered in any of the previous studies of rift zone anisotropy, but may be able to reconcile the apparent difference in fast polarization directions obtained from body and surface waves for the Red Sea Rift Zone. Regional and far-regional surface waves from moderate sized events in the Red Sea region recorded by all available stations in the area will also be modeled to increase the surface wave observations and confirm or refute our previously obtained extension parallel fast propagation direction. The S, SKS and surface wave anisotropy results will be combined in an attempt to construct a consistent model for mantle flow beneath this rift zone.

The study of Wolfe et al. (1999) as well as most shear wave splitting studies concentrate on the SKS phase and average individual splitting measurements (fast polarization directions and delay times) made from events at various back-azimuths to obtain station averages. SKS is the favored phase because it passes through the liquid outer core and any effects of source-side splitting are obliterated due to its complete conversion to compressional motion in the outer core. This property of outer core traversing waves renders them very powerful to study receiver side anisotropy. The tendency to average individual splitting parameters is primarily due to the relatively small number of observations at each station (since SKS phases alone are favored) and large measurement errors. Averaging splitting parameters implicitly assumes that the anisotropy is adequately described by a single anisotropic region of hexagonal symmetry with the olivine a axes oriented horizontally, thus implying horizontal flow. This may not always be a valid assumption so rather than averaging individual splitting parameters obtained from different events to produce station averages, we strive to analyze the dependence of splitting parameters on arrival directions. This will allow us to determine: 1) if waves from different directions sample different anisotropic regions; and 2) if the anisotropic medium has a symmetry that is more general than hexagonal with a horizontal symmetry axis.

Although S phase splitting is more difficult to interpret than SKS, since its splitting could have occurred anywhere along its propagation path, the inclusion of S phases greatly increases the range of available incidence angles and back azimuths and allows interpretation of individual splitting measurements. We will incorporate S wave splitting in this study and remain aware of the possibility of source-side anisotropy for the S phases. We will however, preferably analyze S phases from deep focus events to minimize this effect.

We will use the horizontal velocity traces to obtain the splitting parameters. For SKS phases we will rotate and shift the two components to find those parameters (polarization direction, phi and delay time, dt) that minimize the energy on the transverse component and render the particle motion most linear, that is, we minimize the smallest eigenvalue of the covariance matrix. For S we will also use this covariance method. Measurement errors will be estimated by the commonly used F test method. Silver and Chan (1991) describe these methods in detail and we have applied them successfully to studies of mantle anisotropy in California (Hartog and Schwartz, 2000, 2001).

Regional and far-regional surface wave modeling

While knowledge of the velocity structure of northeastern Africa is important for understanding its tectonic development, progress has historically been hindered by both a lack of large African earthquakes and the sparseness of seismic stations at regional distance from seismic sources. Although large African earthquakes are still quite rare, station coverage in the area of the Red Sea Rift is now sufficient for regional waveform modeling of relatively pure paths traversing the Red Sea. We propose to test and refine our previously derived model of the crust and upper mantle structure beneath the Red Sea Rift zone through waveform modeling at regional and far-regional distances. Events with high signal to noise with known focal mechanisms will be culled to insure that the data possess distinct compressional, shear, and surface wave arrivals. Processing and modeling of the data will proceed following procedures used by Rodgers and Schwartz (1998) and Rodgers et al. (1999) and includes:

1) deconvolution of the station response to ground displacement;
2) initial bandpass filtering between 5-100 seconds;
3) rotation of horizontal components to the great-circle coordinates; and

4) application of a grid-search algorithm to determine crustal and mantle parameters that best-fit both the surface and body waves in the period ranges between 20-100 s.

Modeling surface and body waves together provides better constraints upon the crustal and upper mantle structure than modeling selected portions of the seismograms because it includes information about the surface wave group and phase velocities plus the body wave arrival times and their relative amplitude to the surface waves.

Using a range of velocity and layer thickness parameters, a suite of models is created and synthetic reflectivity seismograms (Randall, 1994) generated for each. The best parameters are chosen by calculating a normalized least-squares misfit between the data and synthetic components. Initial iterations focus on constraining the crustal velocities and thickness through fitting the absolute timing, amplitude, and dispersion of the Love and Rayleigh surface wave packets. Later iterations involve varying lid and upper mantle thickness and gradients, allowing shear velocity to increase independently of the P/SV velocity structure if necessary to fit the transverse and radial component surface waves and the P and S body wave arrivals and amplitudes.

Summary

We propose to apply several types of analysis to seismic data recorded by the Saudi Arabian National Seismic Network operated by the Saudi Geological Survey. These analyses will include:

1) teleseismic P- and S-wave travel time tomography;
2) teleseismic receiver functions for crustal structure;
3) teleseismic receiver functions for upper mantle discontinuity structure;
4) regional Pn tomography;
5) teleseismic shear-wave splitting; and
6) regional and far-regional surface waveform modeling.

This project will determine the seismic structure of the crust and upper mantle beneath the Arabian Shield and adjacent Red Sea with unprecedented resolution. This region of the earth is one of only a few places undergoing active continental rifting and formation of new oceanic lithosphere. Teleseismic tomography will provide an image of the seismic velocity and thermal variations in the upper mantle. Receiver functions will provide constraints on crustal thickness beneath each station of the SANSN. Upper mantle discontinuity structure will be determined from receiver function analysis. Shear-wave splitting will provide constraints on the state of strain in the upper mantle. Waveform modeling will provide additional constraints on velocity structure of the crust and upper mantle as well as upper mantle anisotropy.

Together these analyses will result in a unified model of the structure and physical state of the lithosphere beneath the Arabian Shield and Red Sea. The dense station spacing and excellent quality of the SANSN data will allow for very detailed resolution of structure. We expect to obtain the depth of the source of the volcanic activity in eastern Arabian (the Harrats).

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