Imaging deep structures of Makran subduction zone by 3D joint inversion of gravity data and Rayleigh wave group velocities

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ABSTRACT

In this study, we developed a method to invert jointly gravity anomalies and Rayleigh wave group velocities for velocity and density structure of the crust and upper mantle. We applied the method to the Makran region, SE Iran. The reason for using different data sets is that each of these data sets is sensitive to different parameters. Surface wave group velocities are sensitive mainly to shear wave velocity distribution in depth but do not well resolve density variations. Therefore, joint inversion with gravity data increases the resolution of density distribution. Our approach differs from others mainly in the model parameterization: Instead of subdividing the model into a large number of thin layers, we invert for the properties of only four layers: thickness, P- and S-wave velocities and densities and their vertical gradients in sediments, upper-crust, lower-crust and upper mantle. The method is applied first to synthetic models in order to demonstrate its usefulness. We then applied the method to real data to investigate the lithosphere structure beneath the Makran. The resulting model shows that Moho depth increases from Oman Sea and Makran fore-arc to the volcanic-arc. The crustal density is high in the Oman Sea as should be expected for the oceanic crust.

Keywords: Rayleigh wave group velocity, Gravity, Joint inversion, Moho depth, Shear velocity

INTRODUCTION

In this study, we implemented an iterative, damped least squares inversion method to jointly invert surface wave group velocities and gravity anomaly data. Theoretically, the dispersion curve is a nonlinear function of shear and compressional wave velocity and density of the media. However, it has been proved that the sensitivity for the density and compressional wave velocity is smaller than the one for the shear velocity. Gravity data may supply additional constraints on the density variations. Thus, by combining Rayleigh wave group velocities and gravity observations into a single inversion, we expect to obtain well-resolved 1D shear and compressional wave velocities and 3D density distribution of the lithosphere. In contrast to earlier works, we chose not to model the lithosphere by a stack of many thin layers, but to subdivide it into its four principal layers, sediments, upper crust, lower crust and upper mantel and to invert for their thickness, P- and S-wave velocities and density as well as the vertical gradients of velocities and densities. This method is rapid and less time consuming than stochastic methods and it is able to provide results in relatively short time. First, we demonstrate its applicability using synthetic models. Then, we apply our method to data in Makran region (SE Iran) and surrounding areas.

GEOLOGICAL SETTING

Makran is one of the largest accretionary wedges on Earth (**Error! Reference source not found.**Figure. 1), located in SE Iran and South Pakistan and trending in E-W direction. The width of the wedge is 300-350 km from the offshore deformation front to the depressions of JazMurian in Iran and Hamun-Mashkel in Pakistan. More than half of the wedge is exposed onshore. The rest, the active frontal part, is below sea level. The Makran Accretionary Wedge is an excellent example to study the geology and structures of an active convergent plate boundary involving subduction of the oceanic lithosphere (Farhoudi & Karig, 1977; Burg et al, 2012).

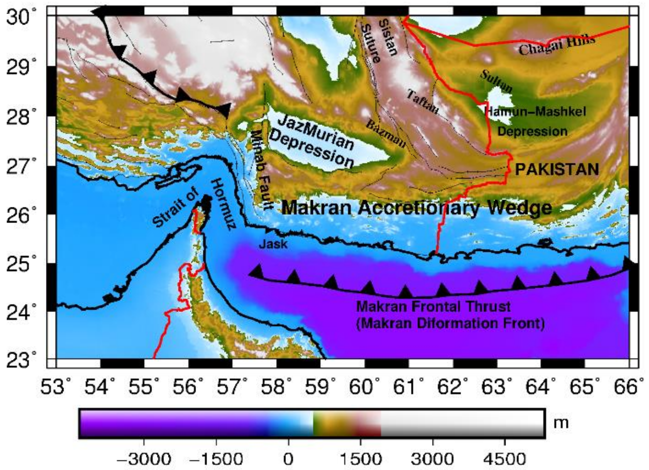

Figure 1. Location map of the principal structural units of the area (http://www.ngdc.noaa.gov/mgg/global/relief/ETOPO1).

Molinari & Morelli (2011) have found Moho depths of 20-25 km in the Oman Sea increasing northward and reaching 45 km in the Taftan-Bazman volcanic arc. The shear-wave velocity images of the upper-mantle across the Makran subduction zone depict a high-velocity anomaly under the Oman Sea which is continuing under the entire Makran belt. The crust under the fore-arc, volcanic-arc and back-arc in the area is characterized by relatively low velocities. Dehghani and Makris (1984), using gravity and seismic data, estimated the Bouguer anomaly for the whole Iranian plate and suggested a Moho depth of 30 km beneath the Makran region. Manaman et al., (2011) indicated a crustal thickness beneath the Oman Gulf and Makran complex of 25–30 km, increasing northwards up to the volcanic-arc, where Moho depth reaches 48–50 km.

DATA

The number of Rayleigh wave group velocities $N_U = N_{xU} \times N_{yU} \times 5 = (14 \times 8) \times 5 = 560$, where the distance between the data points of Rayleigh wave group velocity is equal to 1 degree and is measured at five periods of 16 s, 20 s, 24 s, 30 s and 40 s. Our dispersion velocity data set consists of fundamental mode Rayleigh wave group velocities that were taken from a surface wave tomographic study by Abdetedal et al. (2015). The gravity data used for inversion come from freely accessible global free air gravity data with a resolution of 2.5 arc-minute by 2.5 arc-minute grid (http://bgi.omp.obs-mip.fr/), which are extracted and then projected onto a rectangular grid in Cartesian coordinates with 0.2° by 0.2° grid spacing. The number of gravity data is thus equal to $N_g = N_{xg} \times N_{yg} = 70 \times 41 = 2870$. So, the total number of data is: $N_d = N_U + N_g = 2870 + 560 = 3430$.

METHOD AND APPLICATION TO SYNTHETIC AND REAL DATA

Our program minimises two terms, the relative importance of which may be controlled by the user. In fact, two difficulties have to be solved in the inversion process with these two terms: data adjustment and ill-posedness of the problem that minimizing the cost function ultimately takes the following form (Menke, 1984):

$$p^{k+1} = p^k + \left(A^T C_d^{-1} A + \lambda C_p^{-1}\right)^{-1} \left(A^T C_d^{-1} \Delta d\right) \qquad (1)$$

Here, Δd is the vector of difference between the measured data and those calculated with model parameters pk and Cd is the variance matrix of the data, containing on the diagonal the squared uncertainty of each data point. p is a vector with the model parameters, p0 is the vector of initial parameters and Cp the variance matrix of the parameters which has on its diagonal the uncertainties (variability) of the parameters. k is the number of iterations and G is the Fréchet derivative matrix. The damping factor λ controls the overall importance of data adjustment with respect to distance of calculated and initial model parameters. To test the ability of the method to determine the model parameters, several synthetic models with increasing complexity were constructed and inverted. In order to have a similar scale as in the real situation, the size of the area is in E–W (X): 53°E-66°E and in N–S (Y): 23°N-30°N.

The model consists of columns of 1° by 1° in size, converted for the gravity calculation into a cartesian coordinate system with blocks of 1° by 1°, giving 14 blocks in E–W and 8 blocks in N–S direction. In total we have thus $N_b = N_{xb} \times N_{yb} = 14 \times 8 = 112$ columns with 4 layers each and therefore the total number of parameters is $N_p = 20 \times 112 = 2240$ which is to be inverted, because there are 20 parameters are for each column of blocks.

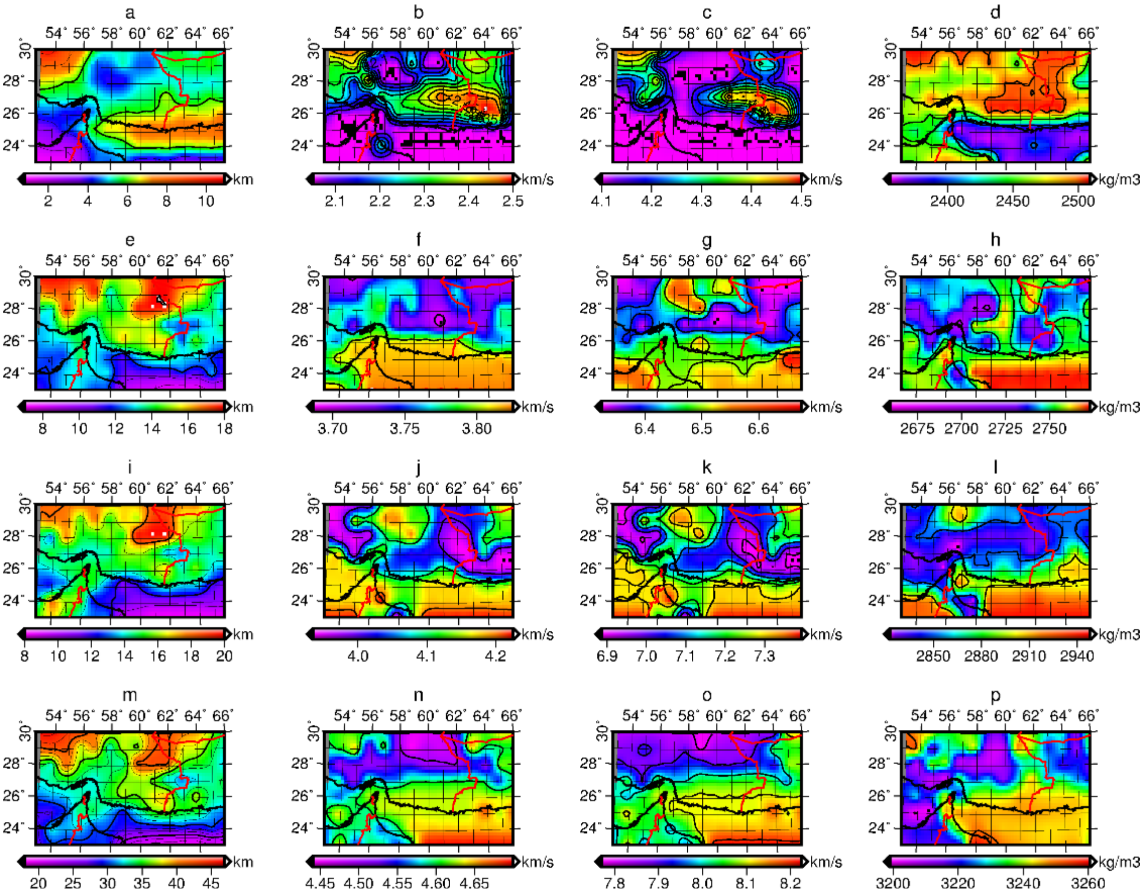

Figure 2. The final model based on joint inversion of real data. a) Thickness of sediments (km), b) Vs in the sediment layer (km/s), c) Vp in the sediment layer (km/s), d) Density of the sediments (kg/m3), e) Thickness of upper crust (km), f) Vs of upper crust (km/s), g) Vp of upper crust (km/s), h) Density of upper crust (kg/m3), i) Thickness of lower crust(km), j) Vs of lower crust (km/s), k) Vp of lower crust (km/s), l) Density of lower crust (kg/m3), m) Moho depth (km), n) Vs of mantle lithosphere (km/s), o) Vp of mantle lithosphere (km/s) and p) Density of mantle lithosphere (kg/m3).

Synthetic models were tested and showed the utility of these stabilizing procedures. We did different tests with the synthetic models using one single data set and two data sets together in order to investigate the importance of combing the data. Using Rayleigh wave group velocities alone, resulted in less well modeled densities. Using gravity alone doesn't give good results for layer thicknesses, whereas densities are better resolved, depending on the chosen initial model. Using gravity data and Rayleigh wave group velocities jointly gave good results with the synthetic model and led to better data fit.

For real data applications, the inversion process begins with a starting model which may result from application of simpler inversion methods (e.g. Abdollahi et al., 2018; Abdollahi et al., 2019). Also, many runs with different starting models and damping parameters have been done to estimate the uncertainties. In order to stabilize the inversion of the resulting matrix, we chose the following variability of model parameters p: 50 kg/m3 for density, 0.1 km/s for shear velocity and also for Vp/Vs ratio, 500 m for sediment thickness and 1000 m for both upper and lower crustal thickness. Figure. 2 shows the final model parameters after 40 iterations. We can see the thickness, the density, as well as shear and compressional wave velocities in the sediments, upper crust, lower crust and upper mantle. Finally, the Moho geometry, average crustal shear wave velocity and average crustal density for the Makran region are shown in Figure. 2a-p respectively. The data misfit between measured and calculated data are about 15 mGal for the gravity data and 0.1-0.3 km/s for the Rayleigh wave group velocity data.

CONCLUSIONS

In this study, we carried out a joint inversion of gravity and Rayleigh wave group velocities to find 3D shear and compressional wave velocities and a density model for sediments, upper crust, lower crust and upper mantel in Makran subduction zone. Figure. 2 shows the final results of joint inversion for model parameters. The main results of the obtained method are summarized as follows (Abdollahi et al., 2019):

- The Oman Gulf is characterized by a Moho depth are around 18 km that increases to 37 km below the JazMurian basin and 44–46 km beneath the Taftan-Bazman volcanic-arc further North.
- The average crustal density map shows the Gulf of Oman having a high density of about 2860 kg/m^3 as we expected for the oceanic crust and its value decreases to the North to 2760 kg/m^3 indecating a continental crust.
- The shear velocity images of the upper crust and lower crust display a high-velocity anomaly under the Gulf of Oman with an oceanic crust, decreasing northward towards the Makran region with a continental crust.

REFERENCES

Abdetedal, M., Shomali, Z.H., Gheitanchi, M.R., 2015. Ambient noise surface wave tomography of the Makran subduction zone, south-east Iran: Implications for crustal and uppermost mantle structures. Earthq. Sci. 28, 235–251.

Abdollahi, S., Ardestani, V.E., Zeyen, H., Shomali, Z.H., 2018. Crustal and upper mantle structures of Makran subduction zone, SE Iran by combined surface wave velocity analysis and gravity modeling. Tectonophysics 747–748, 191–210. https://doi.org/10.1016/j.tecto.2018.10.005

Abdollahi, S., Zeyen, H., Ardestani, V.E., Shomali, Z.H., 2019. 3D joint inversion of gravity data and Rayleigh wave group velocities to resolve shear-wave velocity and density structure in the Makran subduction zone, south-east Iran. J. Asian Earth Sci. 173, 275–290. https://doi.org/10.1016/j.jseaes.2019.01.029

Abdollahi, S., Ebrahimzadeh Ardestani, V., Zeyen, H., Shomali, Z.H., 2019. Imaging the crust and upper mantle structures in the Makran subduction zone in south-east of Iran. 3rd TRIGGER International Conference, Iran.

Burg, J. P. Bernoulli, D. Dolati, A. Muller, C. Smit, J. Spezzaferri, S., 2012. Stratigraphy and Structure of the Iranian Makran. p. AAPG International Conference and Exhibition, Mila.

Dehghani, G., Makris, J., 1984. The gravity field and crustal structure of Iran. Neues Jahrb. Geol. und Palaeontol. Abhandlungen 168,.

Farhoudi, G., Karig, D.E., 1977. Makran of Iran and Pakistan as an active arc system. Geology 5, 664.

Menke, W., 1984. Geophysical Data Analysis: Discrete Inverse Theory, in: Academic Press, London.

Molinari, I., Morelli, A., 2011. EPcrust: a reference crustal model for the European Plate. Geophys. J. Int. 185, 352–364.

Shad Manaman, N., Shomali, Z.H., Koyi, H., 2011. New constraints on upper-mantle S-velocity structure and crustal thickness of the Iranian plateau using partitioned waveform inversion. Geophys. J. Int. 184, 247–267.