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Application of Tesseral 2D to resolving the nature and origin of seismic horizons in the sub-crustal mantle lithosphere

Marcus V.A.G. De Lima, Universidade Federal do Pampa, Caçapava do Sul/RS, Brazil
Randell Stephenson, School of Geosciences, University of Aberdeen, Scotland
Ivan Iantsevitch, Tesseral Ai, Calgary

Project background and target

In the realm of controlled-source seismic exploration of the Earth's crust and sub-crustal mantle the main focus until the 1990s was on wide-angle and refraction (WARR) phases that could illuminate the Moho (crust-mantle boundary) but not deeper and, accordingly, the maximum offset of such WARR profiles rarely exceeded about 300 km. Nevertheless, there were some longer profiles, mainly in Europe, including on the East European Craton in what was then the Soviet Union, that recorded long-offset high velocity (8.4-8.6 km/s) seismic phases that were interpreted to be caused by over critical reflections from a series of high velocity layers in the sub-crustal lithosphere (e.g. Fuchs et al., 1986).

Starting in the late 1980s, deep seismic reflection (DSR) profiling, with profiles hundreds of kilometres long, replaced WARR profiling as the primary focus for studies of the continental crust as a whole as well as its underlying lithosphere mantle (e.g. Clowes et al., 1999). Upper mantle reflecting horizons were regularly observed by DSR surveys but they are predominantly dipping and have almost always been interpreted in terms of collisional or contractional tectonics involving large-scale thrusting or as the fossil legacies of subduction related sutures. The geometry of these DSR features contrasted with those inferred by the long offset WARR profiles, which had been attributed to near horizontal layering although not with rigorous testing by modelling capabilities available at the time. Although upper mantle phases continued to be reported in some WARR profiles carried out in the 1990s and 2000s, little attention was paid to them other than noting their important role as an obvious record of some degree of mantle lithosphere heterogeneity (e.g. Thybo, 2006). Nothing has been done towards integrated study of the WARR features with the DSR ones (or lack of), partly because of a lack of imaging on near coincident WARR and DSR surveys, both of high quality and very long.

This changed in the mid-2010s with PBAP (the Parnaíba Basin Analysis Program). PBAP was a multidisciplinary, multinational activity aimed at learning about the processes involved in forming intracontinental basins using the Parnaíba Basin as a case study. Its primary funding was from BP (cf. Daly et al., 2014) and involved numerous academic institutions in Brazil and the United Kingdom. It is an intracontinental Palaeozoic sag basin, roughly circular in shape, occupying a 660,000 km^2 area of northern Brazil. The geophysical component of PBAP included wide-angle reflection-refraction (WARR) data acquisition as well as near-vertical, deep seismic reflection (DSR) profiling and complementary passive seismological studies. The WARR line is an E-W, 1,200 km long profile crossing the basin and its western and eastern limits, approximately coincident with the PABIP DSR profile, with its main results to date published by Soares et al. (2018), de Lima et al. (2019) and Schiffer et al. (2021).

This report describes an ongoing project undertaken in collaboration with Tesseral AI that revisits the puzzle of strong seismic horizons imaged in the upper mantle segment of continental lithosphere and which are ubiquitously observed along the 1200 km long PBAP WARR profile. The focus at this stage of the project is using the full wave equation synthetic modelling capabilities afforded by Tesseral 2D for eventual interpretation in the context of the other controlled source (DSR) and passive seismological data.

Method

Tesseral 2D allows modelling the propagation of seismic waves in a heterogeneous medium for the scalar, acoustic, elastic and elastic anisotropic wave equations, assigning different seismic acquisition geometries. The embedded algorithms use a fast and accurate computational scheme based on the finite difference method, which allows effective modelling of an arbitrarily complex geological medium, including the combination of solid and liquid state bodies. The computed wave fields can be processed, directly within the software, to obtain seismic images with the help of different modifications of the time and depth migration, facilitating an interactive analysis and examination of depth-velocity models.

Observations and provisional results

Synthetic seismic data have been generated using Tesseral 2D seismic full wavefield modelling in order to simulate phases observed in the PBAP seismograms mainly between 300 and 700 km. An interface at a depth of 60 km in the model of Soares et al. (2018) and simulated the shot gather to a source located at position 260 km along the profile (Figure 1).

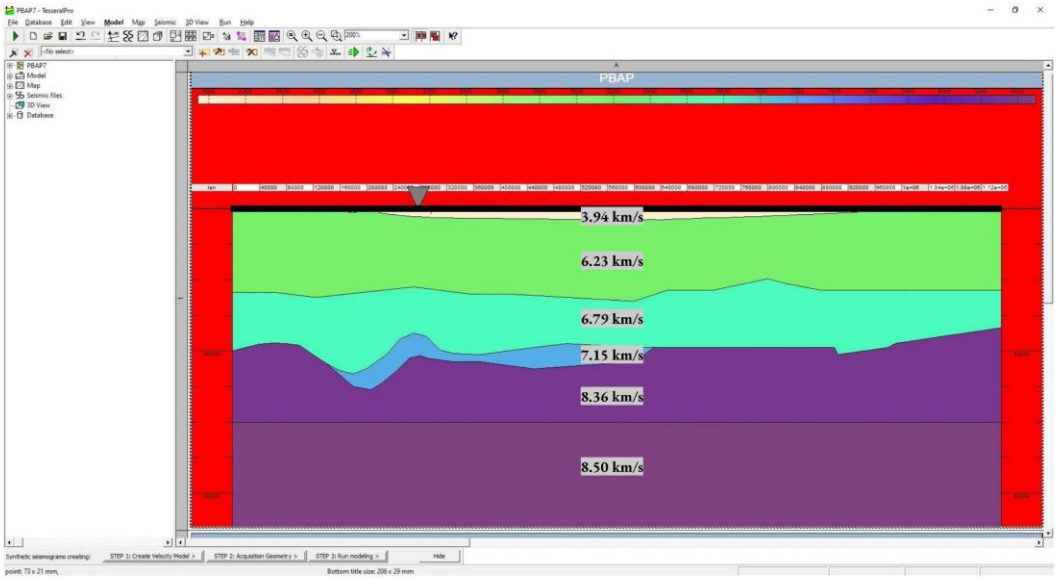


Figure 1 - Screenshot of the PBAP velocity model built in Tesseral software for testing a mantle model composed of a crust inferred from the results of Soares et al. (2018) and an upper mantle of two layers separated by a horizontal interface.

Tesseral 2D was able to reproduce the wave propagation of complex regional geological models, generating diffractions at sharp corners of the Moho, as well as multiple reverberations between the Moho and the base of the sedimentary basin resulting from the high impedance contrast between neighbouring layers and the continuation of refractions at the top of the upper mantle layer at large offsets (Figure 2). Furthermore, it is possible to see that the features observed in the synthetic data fit the real data satisfactorily well and overcome the inaccurate and biased interpretation obtained by travel times modelling based on ray tracing approach, which need to explicitly tell the algorithm to look for refractions, reflections or multiples.

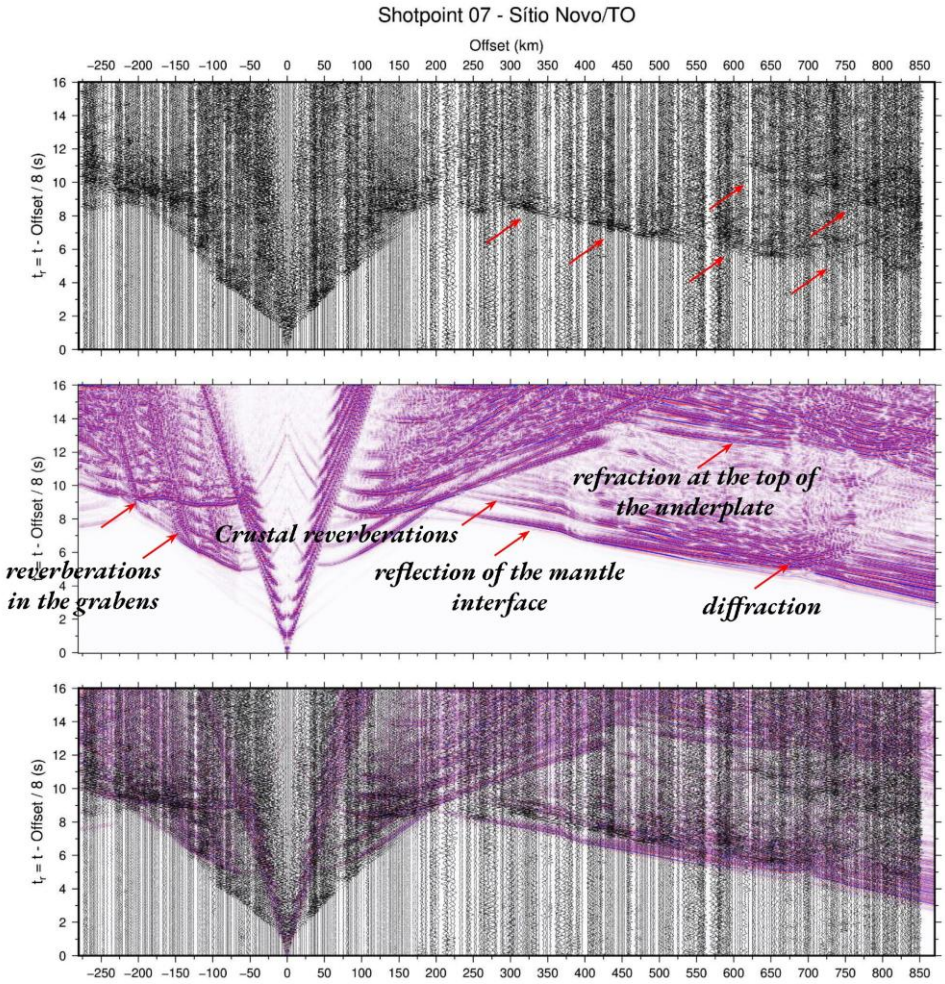


Figure 2 - (*Top*) Seismic section of Shotpoint 7 with seismic phases of interest highlighted by red arrows; (*Middle*) Synthetic seismograms showing the arrivals of primary and multiple reflections, diffractions and refractions at wide offsets; (Bottom) Overlay of real and synthetic data showing the comparison between observed and modelled features.

In contrast to traditional arrival time analysis, full waveform modelling made it possible to explore the amplitude and phase information contained in wiggle data. Variations in amplitude strength are associated with impedance and attenuation contrasts, which help identify compositional changes at the base of the crust and in the lithospheric mantle. Changes in the shape of the wave help pinpoint sharp boundaries rather than smooth gradients. These aspects have been crucial in establishing the interpretation of the origin and nature of seismic phases observed at large distances.

Provisional conclusion

This advancement allowing full waveform modelling of seismic horizons within the subcrustal mantle brings a new perspective to the interpretation of deep seismic data, including the potential integration of DSR and WARR seismic behaviours, promising new insights into the formation mechanisms of sedimentary basins, and therefore of interest to numerous academic and resource exploration objectives.

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References

Clowes, R., 1999. Canada's LITHOPROBE Project (Collaborative, multidisciplinary geoscience research leads to new understanding of continental evolution). Episodes, 22(1), 3-20.
De Lima, M.V.A.G.,Stephenson, R. et al., 2019. Characterisation of crustal structure by comparing reflectivity patterns of wide-angle and near vertical seismic data from the Parnaíba Basin, Brazil. Geophysical Journal International, 218, 1652-1664.
Daly, M.C., Andrade, V. et al., 2014. Brasiliano crustal structure and the tectonic setting of the Parnaíba basin of NE Brazil: results of a deep seismic reflection profile. Tectonics, 33, 1-19.
Fuchs, K., 1986. Reflections from the subcrustal lithosphere. AGU Geodynamics Series, 14, 67-76.
Soares, J.E.P, Stephenson, R. et al., 2018. Crust and upper mantle structure beneath the Parnaíba Basin, Brazil, from wide angle reflection-refraction data. Geological Society, London, Special Publications, 472, 67-82.
Schiffer, C., de Lima, M.V.A.G., et al. 2021. Vp/Vs ratios in the Parnaíba Basin from joint active-passive seismic analysis – Implications for continental amalgamation and basin formation. Tectonophysics, 801, 228715.
Thybo, H., 2006. The heterogeneous mantle: preface. Tectonophysics, 416, 1-6.