Detailed velocity structure of salt domes in Pricaspian basin from refraction data

Valentina B. Piip, Nadezhda G. Zamozhnyaya, and Arsen K. Suleymanov demonstrate that seismic refraction data offers advantages in the imaging of salt domes.

We demonstrate a distinct methodology from the standard approach to interpretation of refraction data. First arrivals of refraction waves received from deep long offset CDP surveys in Pricaspian basin were inverted by a homogeneous function method. We not only received velocity images but the detailed inner structures of salt domes, including structures below the salt overhangs and against of flank of salt body, and also fault blocks. The conventional method using only reflected waves coincided with the more detailed image from refraction data.

Many discoveries of hydrocarbon locations in Russia's Pricaspian basin are associated with salt structures. The CDP reflection seismic survey method is usually the main method of investigating these structures. A 2D CDP survey formed part of a large research project in Russia to study deep structures of the crust down to the mantle. The 1-EV line passes through the European part of Russia from Murmansk in the north to the Caspian Sea in the south through Pricaspian basin. The seismic survey was carried out by Spetsgeofizika (Moscow). The 2D survey was acquired with long offsets (up to 10 km), 100-fold data, with 50 m receiver spacing and 100 m source spacing.

In the CDP survey a huge volume of first arrivals of refraction waves is usually obtained. However, these data are not processed or used in the full volume. The interpretation of refraction data encounters a number of difficulties. Tomography methods which can be used for such dense shotpoint-instrument coverage are usually characterized with a very smoothed resulting model without any velocity seismic discontinuities. In addition, these methods requires an initial model, which is usually derived by layer-based methods or by one-dimensional inversion, so the final section is too dependent on the initial model. Meanwhile other inversion methods are not automatic and cannot be used effectively.

In the Pricaspian basin we obtained from refraction data of the CDP survey the detailed velocity section. This imaged the location, shape, and velocity structure of salt domes, including the structure below overhangs and fault blocks. For the inversion of the refraction we used a homogeneous function method.

Geology

The 1-EV line southeast of Volgograd crosses the target area with salt structures with a wide variety of shapes and amplitudes joined into chains. The salt sequence is predominantly of Kungurian time. The salt overburden consists of terrigenous Upper Permian Triassic, Jurassic, Cretaceous, Paleogene, and Neogene sediments (Figure 1).

Data set

Processing of the CDP reflection data for the described interval of the 1-EV line was achieved using conventional methods. Velocity analysis included building of vertical and horizontal velocity spectra. The resulting depth cross section is shown in Figure 3d.

A very detailed dataset of first arrival traveltime curves was picked in the 1-140 km interval of the profile. We used the times for 0.1 km receiver spacing and 1 km source spacing for inversion by homogeneous function method. In Figure 2 we show traveltime curves used for the inversion at the interval 75-120 km of the profile.

Model and inversion method

The homogeneous function method (Piip, 1991, 2001) automatically inverts first arrival refractions to derive a 2D velocity distribution which involves seismic boundaries. This technique and the associated software package 'Godograf' which implements the technique were developed in Russia. There is considerable experience in using the technique for deep penetration surveys and in problems of shallow seismics (Piip and Efimova, 1996; Piip et al., 2006).

Geologic media are very complex. It follows that we must use suitable models to fit seismic media. One dominating feature in geologic sections consists in the similarity of geologic interfaces. To understand this, it is enough to recall synclines, anticlines, and other folds. Velocity isolines of homogeneous functions of two coordinates are curves that are similar to one another, while the shape of the curves may be arbitrary. Homogeneous functions of two coordinates involve no restrictions on the values of the vertical and horizontal components of the velocity gradient and can contain inclined straight velocity discontinuities. Homogeneous functions constitute a broad class of infinite-dimensional functions. In the polar coordinates these functions are product of two functions: power function of the radius and arbitrary function of the polar angle.

An important feature of solutions to direct and inverse 2D kinematic problems for homogeneuos velocity functions is the opportunity to transform them to solutions of these problems for 1D velocity functions.

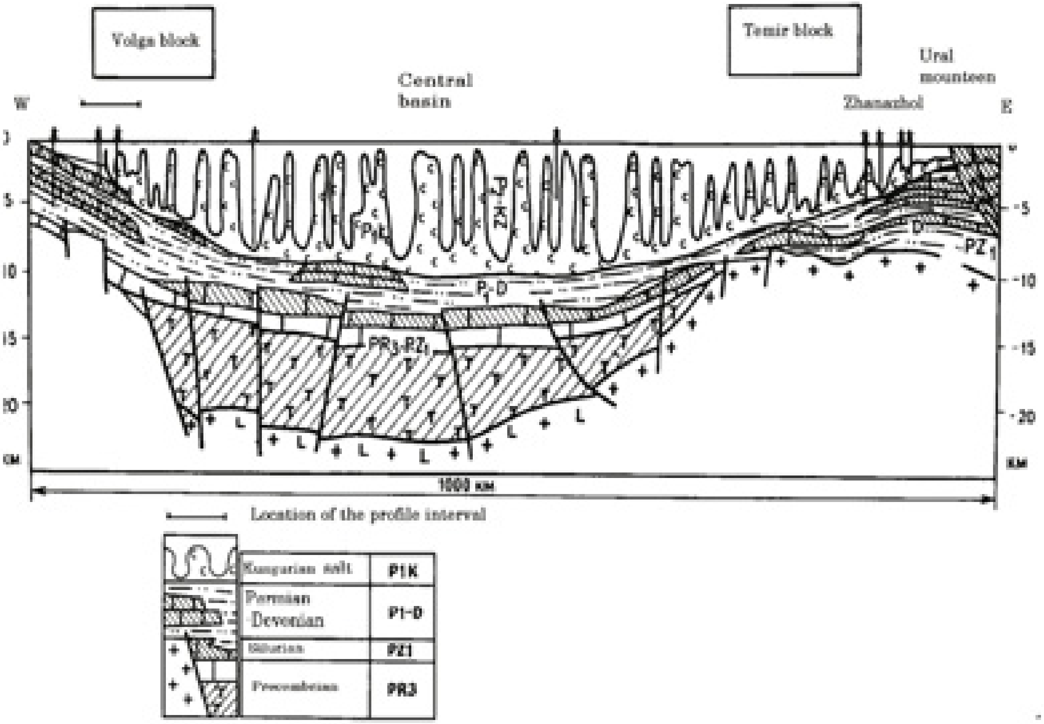

Figure 1 *Schematic geological section of the Pricaspian basin and profile location. (Modified from Perrodon, 1985).*

The Godograf program, designed for processing, interpretation, and construction of seismic sections from refracted wave data, locally fits the section applying 2D continuous homogeneous functions that are steadily increasing with the polar angle. The most detailed exposition of the relevant theory can be found in (Piip 2001).

If we have to deal with a complex set of observed traveltimes, we fit the homogeneous function to the actual velocity section for each pair of reversed traveltime curves selected from out the entire set of curves; the procedure for each pair is independent of that for any other. The result is a set of functions whose number equals the number of pairs of reversed traveltime curves. In this way we automatically set up a correspondence between the detail available in the velocity field and the shooting geometry. Consequently, we do not need any special tests to check this correspondence as is commonly done when using mathematical modelling methods.

Determination of the combined velocity field for a complex shooting geometry possesses the following features. The interpretation involves two main steps: a rigorous solution of the inverse problem, which is to determine an increasing homogeneous function from two reversed traveltime curves of first arrivals, and superposition of the velocity functions calculated for different pairs of traveltime curves. The result of this superposition leaves only the lower (those best determined) parts of the local velocity field in the overall velocity field, the upper parts being hidden by overlying velocity fields with shorter shotpoint distances. No initial model is required. We represent the final velocity section by velocity values computed at points of a rectangular grid (the grid representation). A section is thus represented as a grid at the final stage only for visualizing an available section. The time constant offset section is an image of the observed traveltimes in special coordinates.

The leading features of the actual depth section are reflected in the time constant offset section. This is shown by Piip (2001) using model computations and borehole data. A time constant

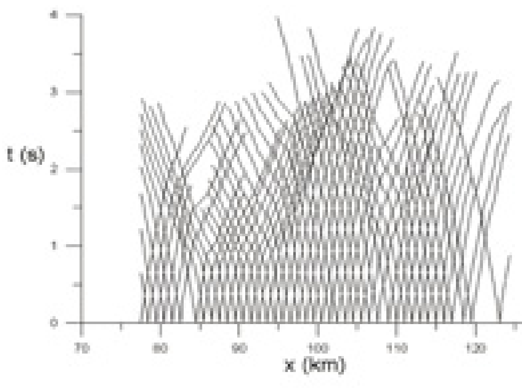

Figure 2 *Observed traveltime curves for 75-120 km of profile used for the inversion by the homogeneous function method.*

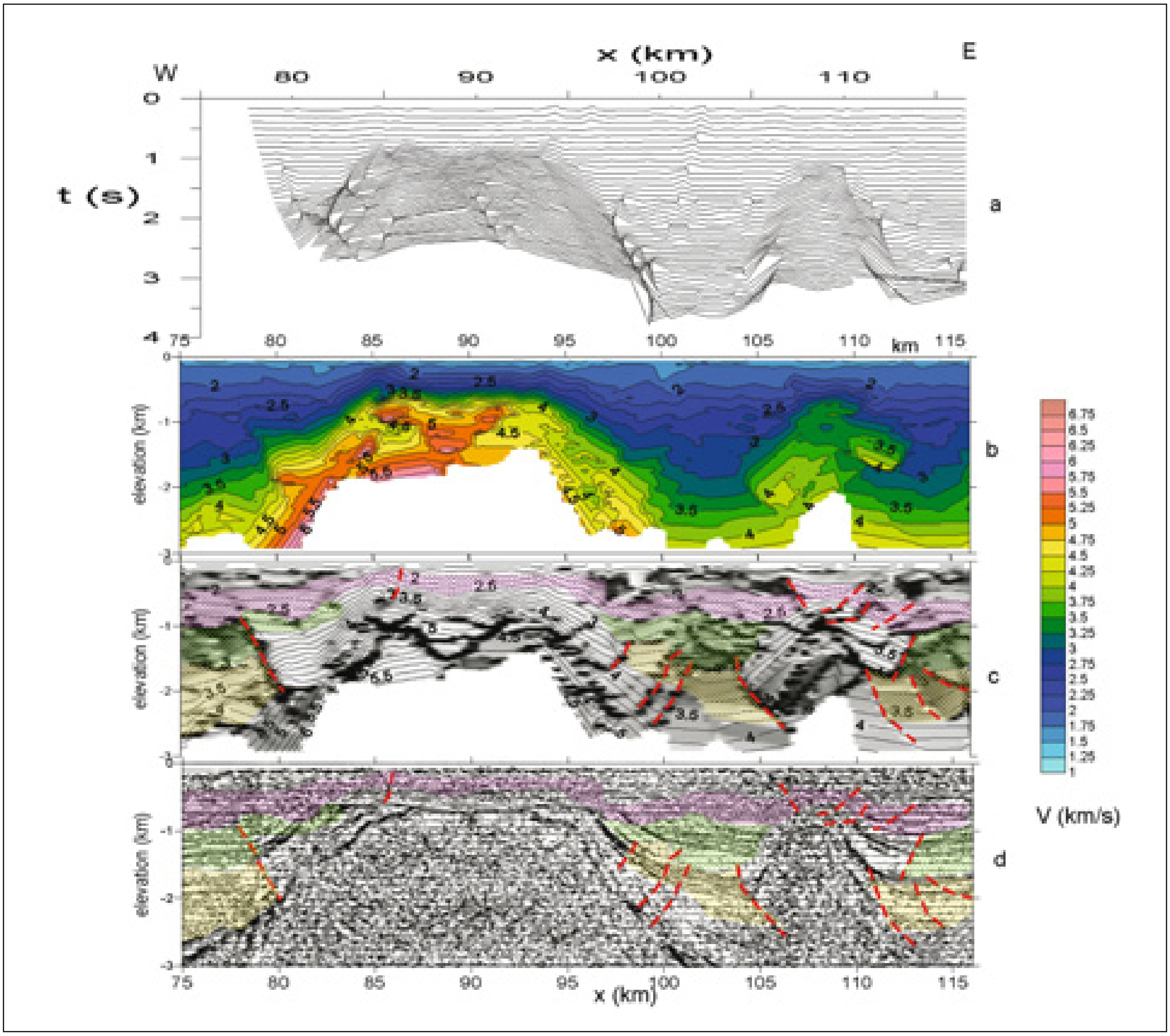

Figure 3 *Time offset (a), velocity (b), and structural (c) depth sections reconstructed on refraction data and depth section (d) on the CDP reflection data. The same areas and faults are shown by colour shading in the (c) and (d) sections.*

offset section enables us to see whether the leading features of the computed depth section have been reflected in the observed traveltime field.

Results

Figure 3a shows the observed time offset field of refracted waves for the 1-EV line in which salt domes are imaged. Offset contours are drawn with 0.2 km interval. The velocity field from refraction data was obtained by homogeneous function method. In Figure 3b velocity field is represented by colour. Simultaneously contours of velocity with a constant 0.25 km/s interval are shown. It allows visual estimation of the values of a gradient of velocity, because a gradient is inversely proportional to distance between contours. The salt domes are sharply allocated as the area with the increased values of velocity. Inside the east dome, the velocities do not exceed values 4 km/s, which means that the pure salt here is an insignificant amount.

The west dome is characterized by a complex internal structure. The velocities achieve values of more than 5.5 km/s. It is possible that a significant part of the filling of this dome is represented by anhydrite. The domes are surrounded with an aura of changed rocks. Salt overhangs are precisely displayed. The non-uniform depth of the section is caused by non-uniform penetration of seismic rays which are calculated during the solution of the inverse problem. The rays penetrate to a depth of 3 km between the salt domes and 1.5 km inside the domes. As the velocity is calculated in nodes of a rectangular grid, it is easy to calculate a field of gradient of velocity. The field of velocity in a

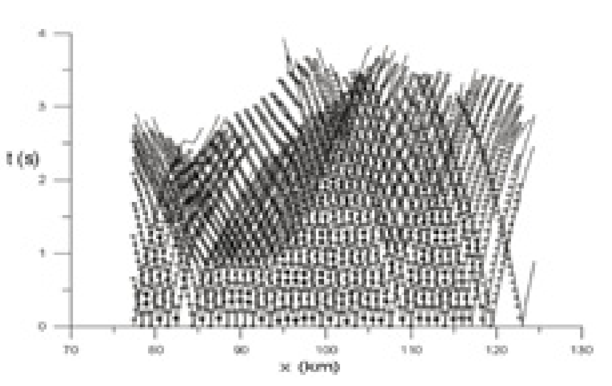

Figure 4 *Theoretical times (small squares) and observed traveltime curves (thin lines) for 75-120 km interval of the profile.*

mathematical sense is function of two coordinates. In Figure 3c the same velocity field is represented as a surface with the shaded relief. At this image the seismic boundaries and faults are allocated. In this figure also, velocity contours are inserted. It is a structural section. The greatest illumination (brighter lines) corresponds to transition zones where the velocity increases with depth and the lowest illumination (dark lines) corresponds to inversion discontinuities (tops of thin waveguides). The structural section (Figure 3c) allows a sight of blocks limited by faults.

The layers or strata are identified if extended boundaries exist, interval of changing of velocity from top to bottom of layer and values of a gradient of velocity are maintained along the layer. Using these criteria three strata were allocated in the enclosing rocks; they are designated with different colour shading in the structural section.

The upper layer is denoted by a pink colour. It is characterized by a constant velocity interval from 2 to 3 km/s, by gentle contours and relatively high velocity gradient.

The second layer is shown by a green colour. Velocities are changed from 2.5 to 3 km/s. Contours show significant disturbance of this layer. Velocity gradient is very low.

Third layer is painted by yellow colour. Velocity interval is from 2.5 to 4.5 km/c. contours are relatively gentle and gradient is characterised by low values.

Boundaries which divide these layers are inversion interfaces because seismic velocity in bottom of upper layer is higher then velocity in top of lower layer. To analyse the results from refraction and CDP reflection data we compared them at the same coordinates of the sections. The same spatial areas derived from the layers and faults in the refraction section are put on the CDP depth section. Figure 3d shows well how good correlation of these depth sections was calculated independently on the different data. The same depths and thicknesses of allocated layers confirm the coincidence of these sections in the whole. To confirm reality of the velocity section the theoretical times of refraction were calculated with the software program Firstomo. This program is part of the tomography software package (Ditmar and Yu, Roslov, 1993). We obtained 0.07 s for RMS deviation of observed picks from calculated ones (Figure 4). Rays (Figure 5) corresponded to these times densely are filling space of the section and penetrate to correct depths as figure 5 shows.

Conclusion

We used a homogeneous function method for automatic inversion of the super detailed refraction data received from a CDP survey in Pricaspian basin. We received detailed velocity sections which allowed estimation of the location, shape, velocities, structure and contents of salt domes, fault blocks and also the structure of below salt overhangs. Independently received refraction and reflection CDP sections show very good coincidence, although the refraction section is more detailed.

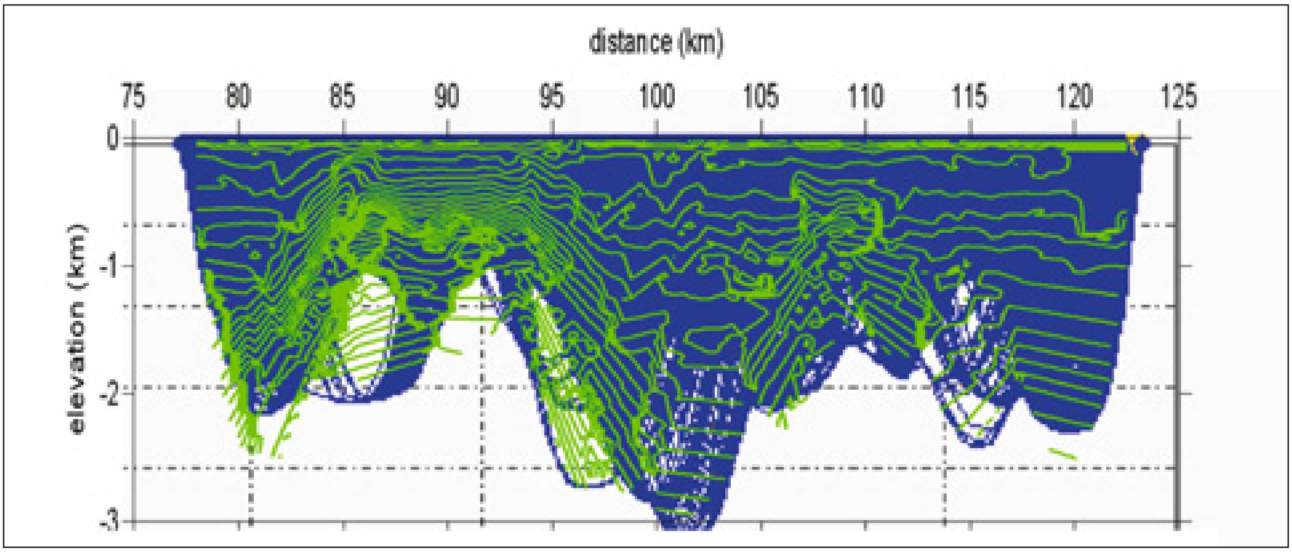

Figure 5 *Calculated rays are shown in blue while velocity contours are in green color.*

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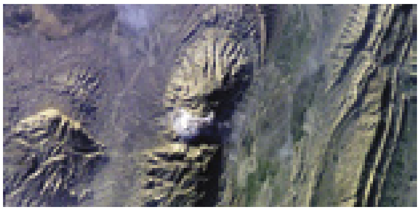

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