[PS]Geologically Driven Joint Inversion of Gravity, Seismic and Well Data: A Step Forward in Understanding of Geological Structure and Reducing E&P Risks*

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Abstract

In spite of being the first geophysical method to be used in oil and gas exploration, gravity is practically not used today for detailed study of subsurface structure and oil and gas prospecting. This is the result of huge advances in seismics, which began with introduction of the CDP method, leading to a chasm between the geological outcome of seismic vs. gravity data interpretation. Recent publications evidence that during the last decades we saw considerable advances in gravity instruments and field survey techniques, but not so big advances in the interpretation techniques. Thus filtration, regional-residual separation, analytical upward-downward continuation, Fourier and wavelet transforms are still used for gravity data interpretation in attempt to link directly gravity anomalies with target geological objects or features, which fundamentally cannot be done due to additive character of gravity field and nonuniqueness of geophysical inversion. More sophisticated approaches, which use physical modeling of the subsurface either stop on forward modeling with partial gravity fit to local/regional anomalies, or construct inversion algorithms using A. M. Tikhonov's regularization theory to obtain stable solution. Inappropriateness of the last one is caused by exotic properties of harmonic function as the natural uniqueness class. Instead, the inverse problem should be redefined so the inversion is not only constrained by prior information, but also driven by it, so that additional geological information is used as a guiding rule to select the single geologically meaningful model from a space of all possible solutions. Such reformulation of gravity inversion implies fulfillment of the following conditions: full-earth (from top to basement) real density inversion, using observed gravity, quantifying uncertainties for all the geological sequence and involving maximum additional data like structure by seismic, petrophysics, logs, layering according to expected stratigraphy etc. Described approach was implemented in the proprietary Technology and Software of joint inversion of gravity, seismic and well data. Efficiency of the approach is illustrated by case studies for Ukraine, including near-salt exploration in Dniper-Donets Basin, under-salt gas pools delineation in Transcarpathian Trough, study of oil pool in basement of the Northern Flank of Dniper-Donets Basin, and offshore the Black Sea, all of those post-verified by drilling.

INTRODUCTION

In spite of being the first geophysical method to be used in oil & gas exploration, gravity is practically not used today for detailed study of subsurface structure and oil and gas prospecting. This is the result of huge advances in seismics, which began with introduction of the CDP method, leading to a chasm between geological outcome of seismic vs. gravity data interpretation. Recent publications evidence that during the last decades we saw considerable advances in gravity instruments and field survey techniques, but not so big advances in the interpretation techniques. Thus filtration, regional-residual separation, analytical upward-downward continuation, Fourier and wavelet transforms are still used for gravity data interpretation in attempt to link directly gravity anomalies with target geological objects or features, which fundamentally cannot be done due to additive character of gravity field and nonuniqueness of geophysical inversion. More sophisticated approaches, which use physical modelling of the subsurface either stop on forward modelling with partial gravity fit to local/regional anomalies, or construct inversion algorithms using A. M. Tikhonov's regularization theory to obtain stable solution. Inappropriateness of the last one is caused by exotic properties of harmonic function as the natural uniqueness class

CHANGING PARADIGM

To obtaine geologically meaningful results for gravity data inversion, the inverse problem should be redefined so the inversion is not only constrained by prior information, but driven by it, so that additional geological information is used as a guiding rule to select the single geologically meaningful model from a space of all possible solutions.

Inversion of one geophysical field

Inactive inverse problem

$$\begin{cases} A(x) = y,\ x \in D(A) \subset X,\ y \in Im(A) \subset U \\ J(x) \to min \\ x \in M \subset D(A), \end{cases}$$

where:
x – parameters of model (density values or density horizon depth)
X – metric space of models
y – observed geophysical (gravity) field or its functional
U – metric space of geophysical fields
$A(.): X \to U$ – in general case nonlinear for structure task and linear for properties task operator acting from models' space to space of geophysical fields
$D(A)$ – domain of operator $A(.)$ – open subspace in space X, wide enough to ensure adequate approximation of real geological model
$Im(A)$ – open subspace in space Y, wide enough to ensure adequate approximation of geophysical field
M – ensemble of possible geologically meaningful models x
$J(.): X \to R$ – convex functional acting on X, and containing priory geological and geophysical information

Such reformulation of gravity inversion implies fulfillment of the following conditions for inactive scheme:

- full-earth (from top to basement) inversion
- real density for 3D property model and inversion
- using of observed gravity
- quantifying uncertainties for all the geological sequence
- involving maximum additional data into initial property model (like structure by seismic, petrophysics, logs, layering according to expected stratigraphy, well test results etc.)

Inversion of two geophysical field

Active inverse problem

$$\begin{cases} A(\xi(\mathbf{x})) = u(s), \\ B(\eta(\mathbf{x})) = y(s), \\ J(\xi(\mathbf{x}) - \eta(\mathbf{x})) \Rightarrow \min \end{cases}$$

where:
$\xi(x), \eta(x)$ – parameters of model
X – metric space of models
u, y – observed geophysical fields or its functional
U, Y – metric spaces of geophysical fields
$A(.): X \to U, B(.): X \to Y$ – in general case nonlinear operators acting from models' space to space of U, Y geophysical fields
$D(A), D(B)$ – domain of operator $A(.), B(.)$ – open subspace in space X, wide enough to ensure adequate approximation of real geological model
$Im(A), Im(B)$ – open subspace in space U, Y, wide enough to ensure adequate approximation of geophysical field
M, N – set of possible geologically meaningful models $\xi(x), \eta(x)$,
$J(.): X \to R$ – convex functional acting on X, and containing priory geological and geophysical information

...for the active inversion this additionally implies:

- simultanious (active) use of gravity and seismic data for inversion to refine the shape of geological structures, including top and bottom of the salt bodies
- simultanious (active) use of well logs (including gravity, density log) for high accuracy models of up to 1 meter depth resolution, prediction of porosity, current oil and gas saturation

MAPPING TOP AND BOTTOM OF THE SALT DOME AND DELINEATION OF SUB-SALT HC POOLS BY 3D JOINT INVERSION OF GRAVITY FIELD WITH SEISMIC AND WELL DATA

DECADE OF EXPLORATION DRILLING CONFIRMS 100 % OF SUCCESS IN PREDICTION OF SUBSALT GAS POOLS

Case study for Transcarpathian Trough, Ukraine (2005)

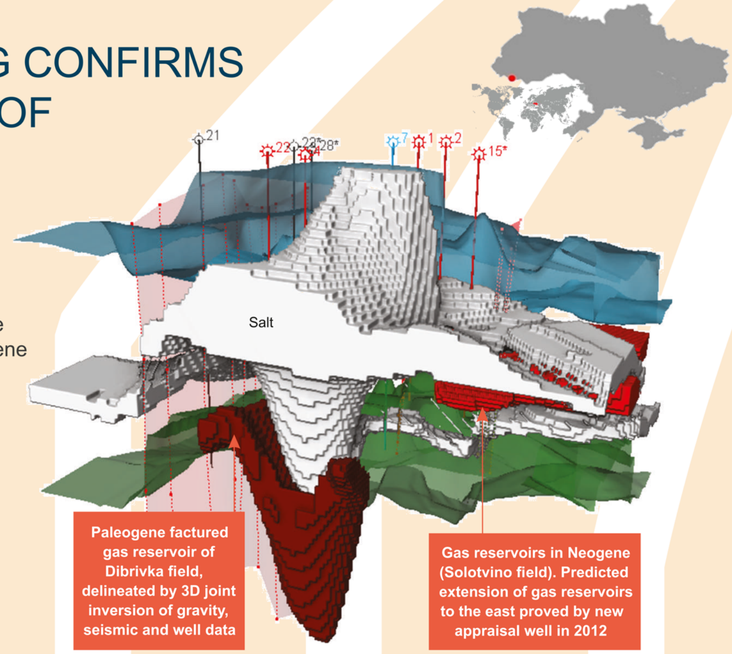


Figure 11. Neogene salt (in gray), Neogene and Paleogene gas pools (in red and dark red respectively), extracted in form of bodies from the inverted 3D density model

BACKGROUND INFORMATION

Transcarpathian Trough is Miocene molasse basin, underlayed by Paleogene-Mezozoic basement. Few gas accumulations known at the time. Within the study area producing reservoir intervals of Solotvino gas field confined to Neogene tuffs below salty-clastic sequence of Tereblja Formation. Salt pierces Neogene clastic sequence and outcrops to the west from the field. Due to alternation with clastics top and bottom of salty sequence are not imaged on the seismic data.

To the west from in proximity to the salt dome two wells #4 and #22 penetrated gas reservoir in Paleogene (Dibrivka gas field). Structurally wells were placed in south periclinal part of the four-way dip closure. Main objective of the study was to delineate extension of Paleogene pool.

INVERSION WORKFLOW

3D structural framework was built using 20 2D seismic lines. Structural model consisted of 7 surfaces, featuring the structure of Neogene and Paleogene.

3D property model (Figure 9) was build using generalized petrophysical dependencies and consisted of 2 million cells (single cell dimensions were 100x100x50 meters). Initial misfit between observed and calculated gravity by forward problem solution was 3.7 mGal (Figure 12). Salt dome and salt bed were refined through 3D structural (nonlinear) inversion of gravity data. That reduced deviation between observed and calculated gravity fields to 1.15 mGal. At the next step full-depth 3D linear inversion of gravity data for property model was run, resulting final misfit of gravity fields' less then 0.3 mGal (Figure 12)

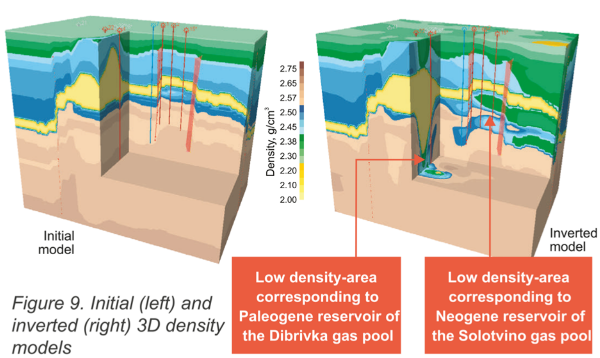


Figure 9. Initial (left) and inverted (right) 3D density models

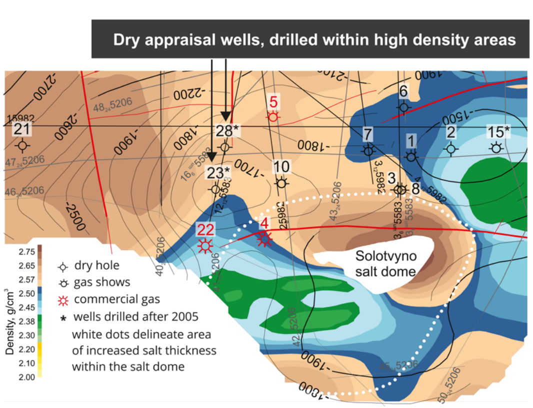


Figure 10. Conformal density slice within Paleogene

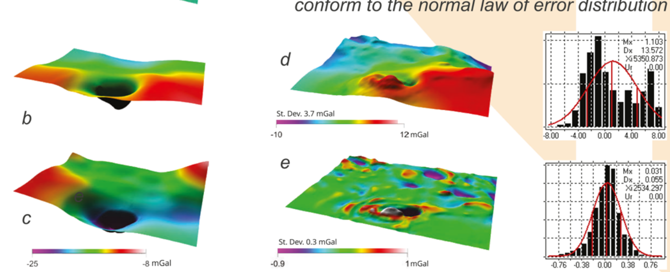
EXPLORATION RESULTS

In the result of the inversion salt dome shape was refined. In the inverted 3D property model areas of low density were mapped in Neogene and Paleogene, indicating presence of quality reservoir with gas saturation (Figure 9).

It was determined that gas pool in Paleogene is confined to fractured reservoir and is distributed in immediate proximity to the wall of the salt dome and beneath the salt (Figures 9-11). In 2005 new appraisal well #23 was drilled in the crest of the anticline structure, at the distance from the salt body. No HC inflow obtained during well testing. In 2011 another appraisal well #28 was drilled in similar structural position to that of the well #22, in the northern periclinal part of the structure. The well was dry. According to the density model of Paleogene sequence (Figure 10). Both wells were placed within the areas of high density, which evidences tighten of rocks and absence of quality reservoirs. Thus drilling results have fully confirmed accuracy of 3D model, built in 2005.

In 2012 new appraisal well #15 was drilled within the Solotvino field. The well was located in the area of low density, corresponding to quality HC reservoir. Commercial gas inflow from Neogene reservoir confirmed the density model of Neogene gas pool (2005), which have showed wider extension of gas saturated reservoirs to the east.

Figure 12. Correspondence between observed gravity field (a) and gravity fields, calculated from the initial 3D density model (b) and final inverted 3D density model (c). Gravity fields' misfit for the initial model (d) contains systematic components, while for the inverted model deviation (e) is random and conform to the normal law of error distribution



IDENTIFYING OIL POOLS UNDER THE SALT WING BY 3D JOINT INVERSION OF GRAVITY DATA WITH SEISMIC AND WELL INFORMATION

Case study for Dnieper-Donets Basin, Ukraine (2012)

BACKGROUND INFORMATION

Central part of Dnieper-Donets Basin is characterized by active salt tectonics. HC accumulations are conined to Carboniferous sediments, which are pierced by Devonian salt. Within the investigated area HC pools were expected near the salt wall and under the salt wing , which shadowed seismic image, obtained here by 3D survey. The task of gravity was to validate and reine the shape of the salt and identify HC reservoirs around the salt dome.

Within the study area shallow gas pool of Runivshchyna ield was discovered earli er in Triassic just above the salt dome. Besides investigated area includes marginal part of nearby Matviivka oil-gas-condensate ield with pools in Carboniferous.

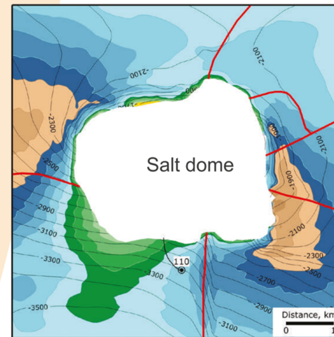


Figure 7. Conformal to bedding density slice within Lower Permian – Upper Carboniferous. Light green areas mark oil pool, identi-ied in the result of gravity inversion and penetrated by irst exploration well

INVERSION WORKFLOW

Structural framework was built using 3D seismic data interpretation for target horizons in Carboniferous. Structure of underlaying Devonian sequence (including mother salt) and basement was built using regional 2D seismic lines. Wells from nearby ields used to deine property model of target Carboniferous interval. Generalized petrophysical dependencies used for deeper horizons.

Structural model consisted of 16 surfaces. Dimensions of 3D density model were 43x25.5x20 km. Voxel property model discretization (cell size) 100x100x50 meters. Total number of cells – 32.9 million.

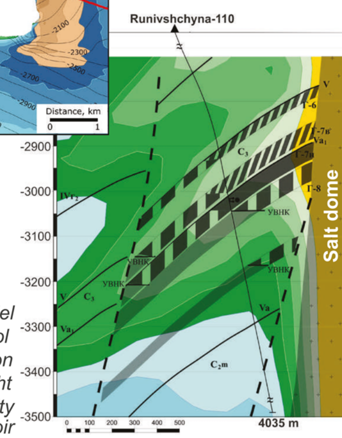


Figure 8. Geological model of discovered oil pool overlaid with cross-section of 3D density model. Light green areas of low density mark oil reservoir

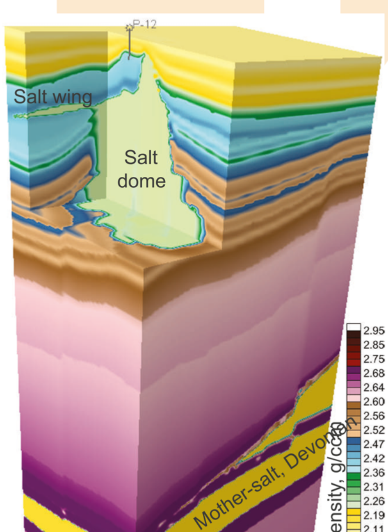
EXPLORATION RESULTS

3D joint inversion of gravity, seismic and well data proved validity of the shape of salt dome and wing. Low density areas associated with known HC Runivshchina and Matviivka ields were clearly identiied in the model (Figure 5).

New HC saturated reservoirs were mapped downdip from the salt dome in Permian-Carboniferous, under the salt wing (Figures 5-8). New mapped HC pools are characterized by low density anomalies. Amplitude of density decrease corresponds to that for HC reservoirs of adjacent fields.

First exploration well #110 drilled in 2012 obtained commercial oil inlow from Permian-Carboniferous (Figure 8). Location and depth of penetrated reservoir agree with location and depth of low density anomalies, thus conirming validity of the 3D density model.

Figure 4. Initial 3D density model by 2D, 3D seismic and well data . Model dimensions: 43x25.5 km, depth 20 km. Cell size 100x100x50 meters. Total number of cells – 32.9 million



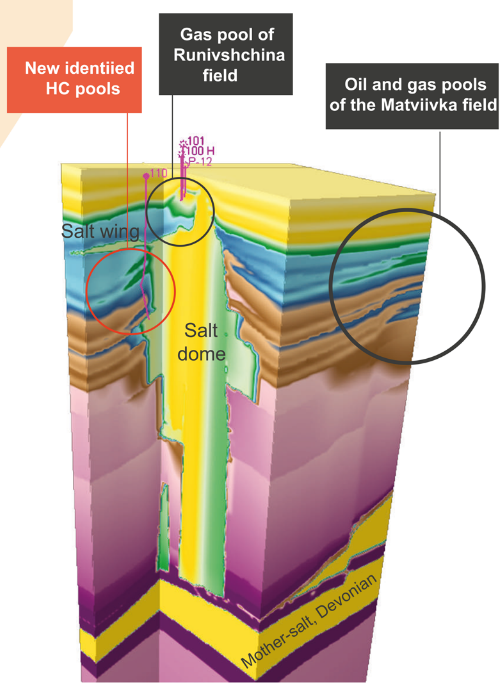


Figure 5. Inverted 3D density model

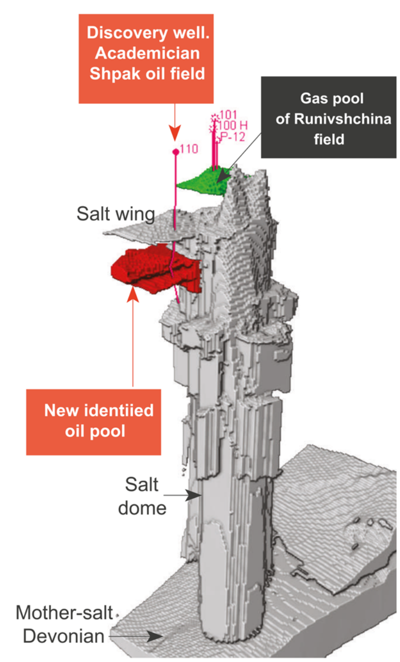


Figure 6. Devonian salt (in gray), Carboniferous oil pool (in red) and shallow Triassic gas pool (in green), extracted in form of bodies from the inverted 3D density model