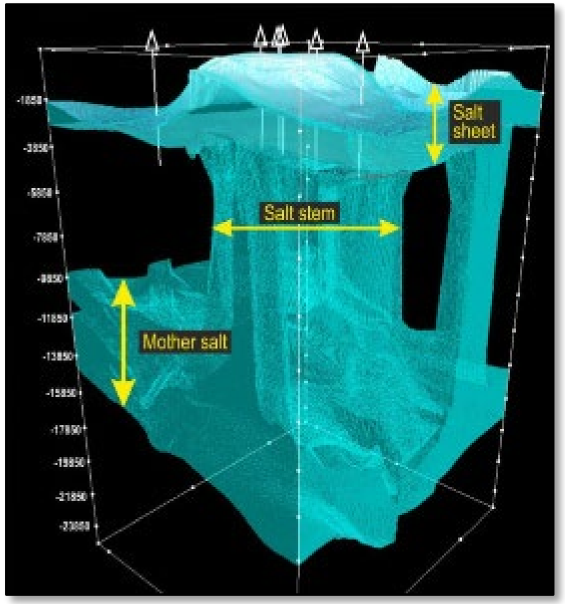
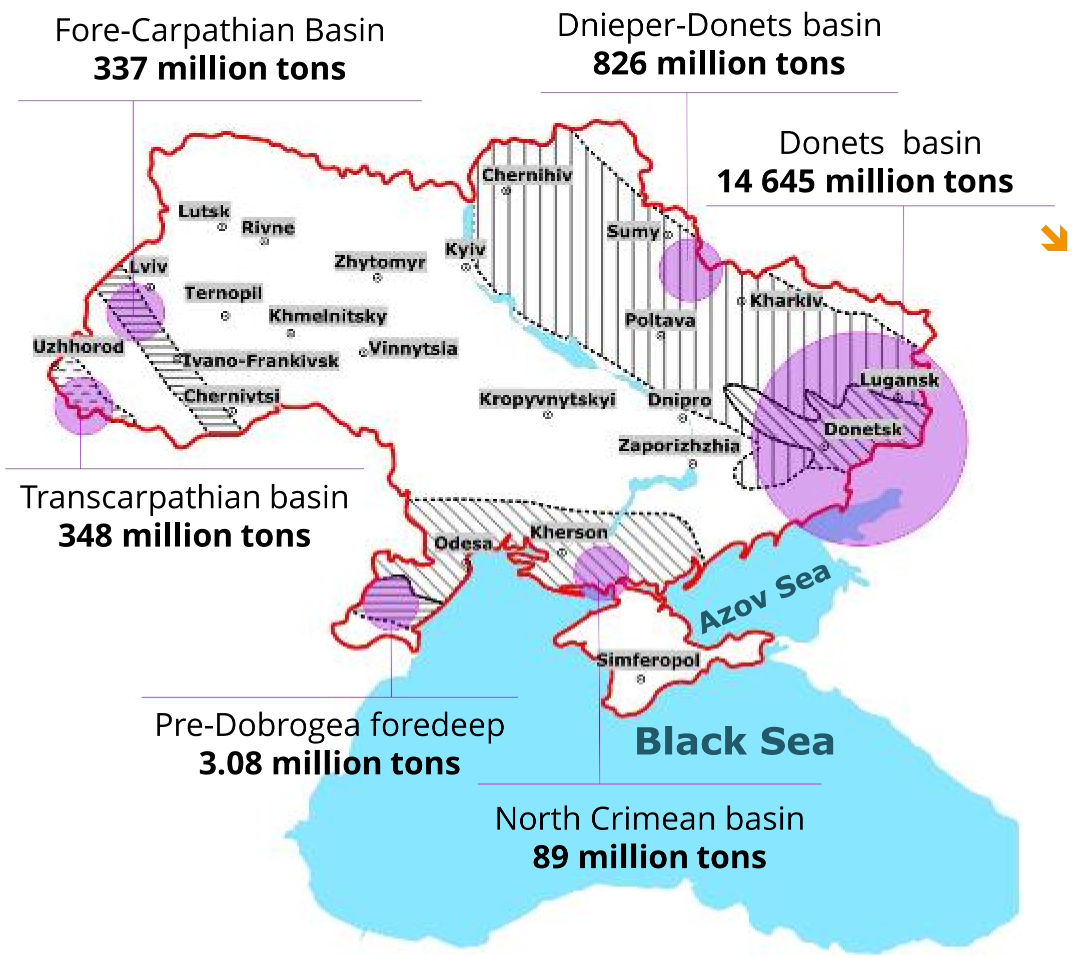


TECHNOLOGY FOR COMMERCIAL SALT DEPOSITS MAPPING BY 3D GRAVITY, WELL LOG AND SEISMIC DATA INVERSION

DEPROIL
DETAILED OIL & GAS PROSPECTING

SALT PRODUCTION IN UKRAINE

SALT RESERVES – SODIUM CHLORIDE*



SALT PRODUCTION

In 2020-2021, Ukraine produced **2 M tons** of rock salt, making it the 21st largest salt producer in the world and 9th in Europe.

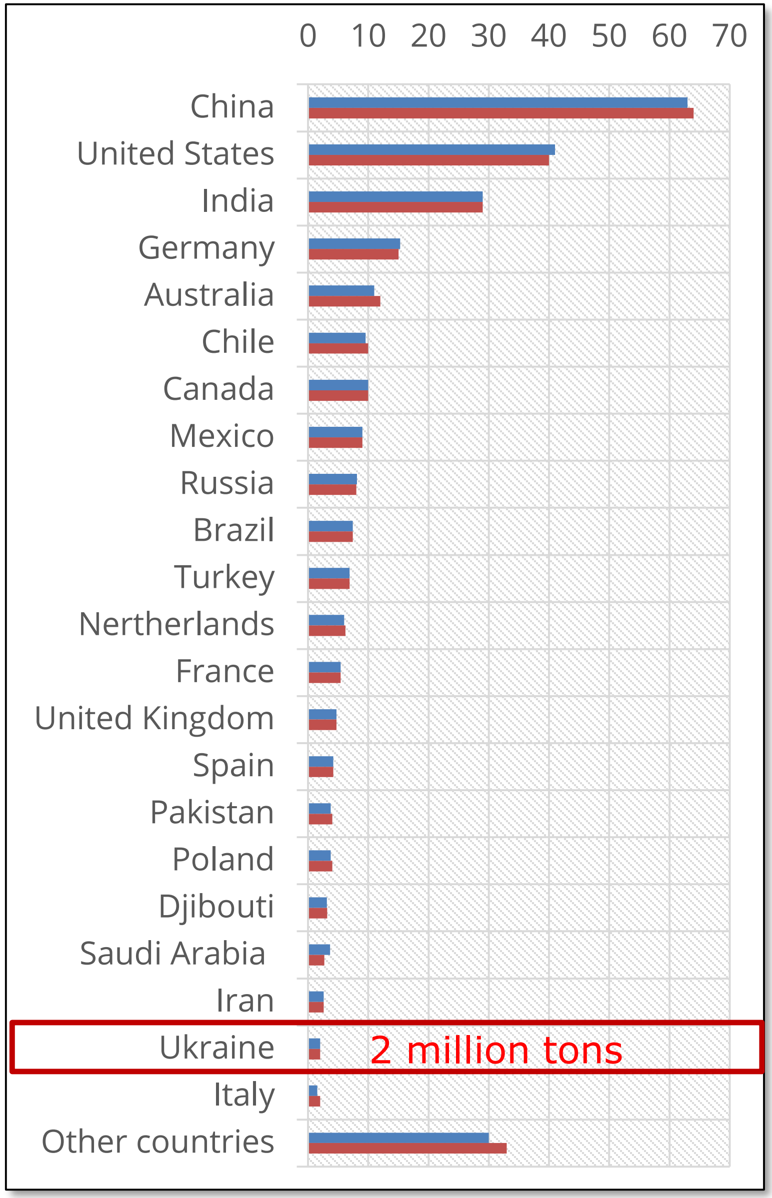
OPERATING SALT MINES

Artemsil (Soledar) salt mine:
Location – Donets basin
Reserves – 5 000 M tons
Production – 90-95% of total salt production in Ukraine

* Geography of Mineral Resources in Ukraine. M. Syvyi, I. Paranko, Ye.Ivanov. 2013

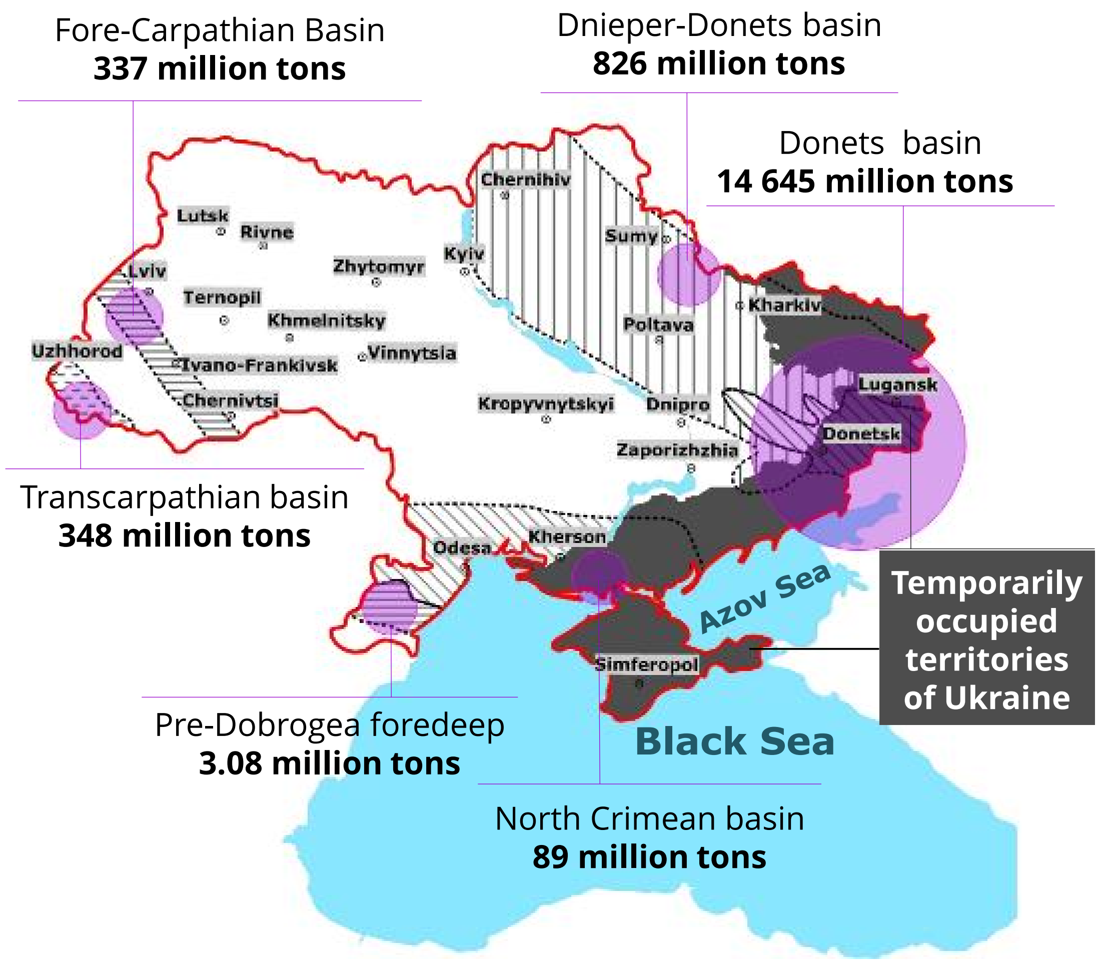
** https://www.statista.com/global-production-output-of-salt

Major countries in salt production worldwide (in 1,000 000 (M) metric tons)**



SALT PRODUCTION IN UKRAINE

SALT RESERVES – SODIUM CHLORIDE



Daily News

News from non-English countries

TXT Home News Life Sports Tech

Europe's largest salt producer Artemsil shut down due to fighting in Donbass

26.05.2022, 15:21:25

Now in Ukraine and some European countries began a shortage of salt, this product has risen significantly.

SALT PRODUCTION IN UKRAINE

SALT RESERVES – POTASSIUM SALTS

Fore-Carpathian Basin
384 million tons*

SALT PRODUCTION

Due to obsolete production technologies and significant environmental pollutions, potassium salt has not been produced in Ukraine since 2007.

MEASURES TO RESUME PRODUCTION

- Exploration activities in order to define areas with favorable mining and geological conditions;
- Recalculation of potassium salt reserves (current reserves estimation is dated by 1948-1960)

* Mineral resources of Ukraine. Annual addition. State Geological Fund of Ukraine. 2018

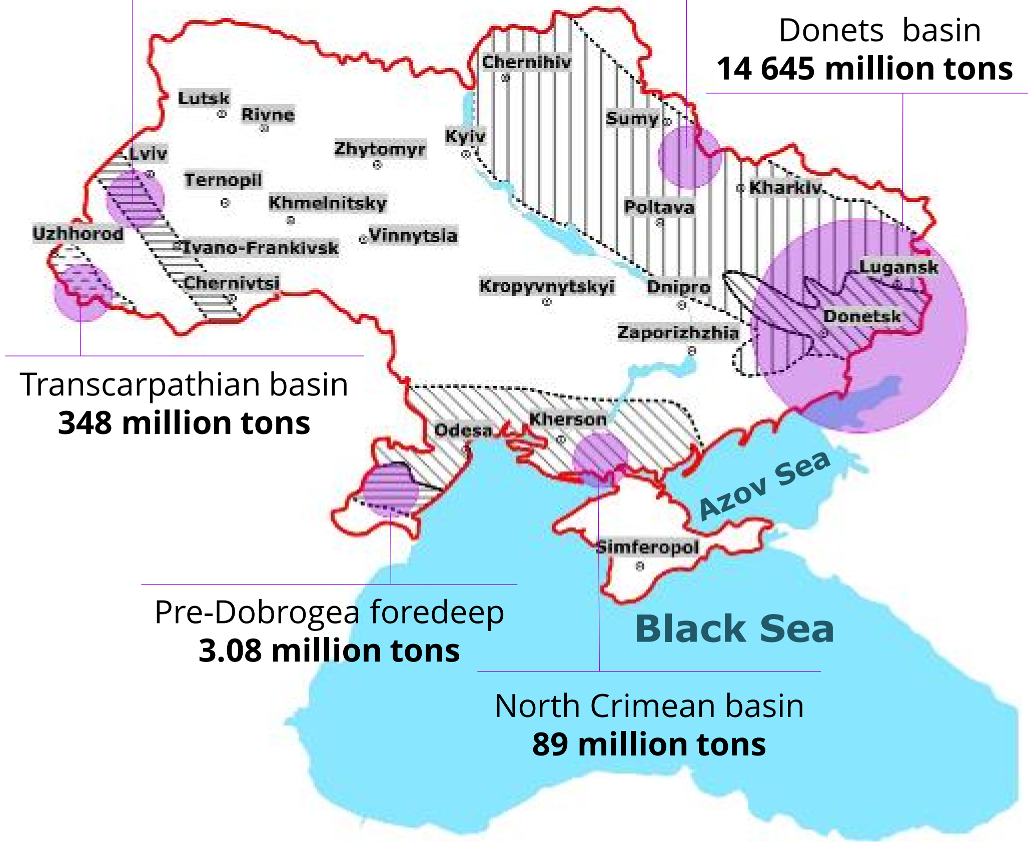
CHALLENGES OF SALT PRODUCTION IN UKRAINE

CHALLENGES

- "Artemsil" shutdown in Eastern Ukraine due to mines' and infrastructure damage caused by missile attack
- Providing Ukrainian households and industry with domestic salt
- To start salt production in Western Ukraine in short terms

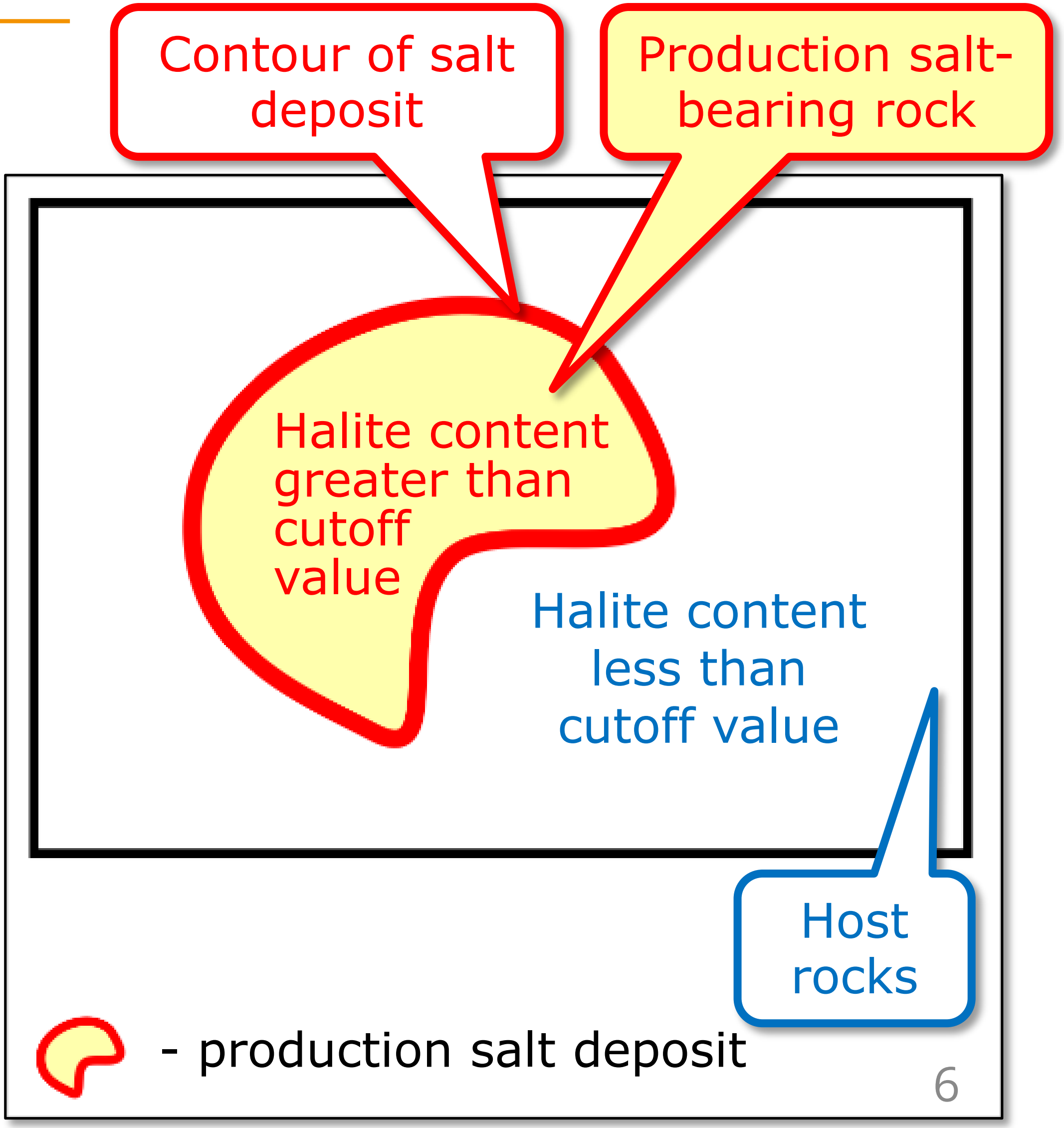
WAYS TO OVERCOME CHALLENGES

- To restore salt production in old salt deposits (if possible)
  To map new commercial salt deposits and to start salt production from these deposits



PRODUCTION SALT-BEARING ROCK AND PRODUCTION SALT DEPOSIT

- PRODUCTION SALT-BEARING ROCK – an isolated subsurface body of rock having halite content greater than the cutoff value (>90%)
- CONTOUR OF THE PRODUCTION SALT-BEARING ROCK is mapped as a closed contour, which includes all salt-bearing rocks
- PRODUCTION SALT DEPOSIT – closed set in 3D space, which includes production salt-bearing rocks and is associated with the contour of the production salt-bearing rock



DENSITY OF PRODUCTION SALT-BEARING ROCK FOR MAPPING OF PRODUCTION SALT DEPOSITS

DEPROIL
DETAILED OIL & GAS PROSPECTING

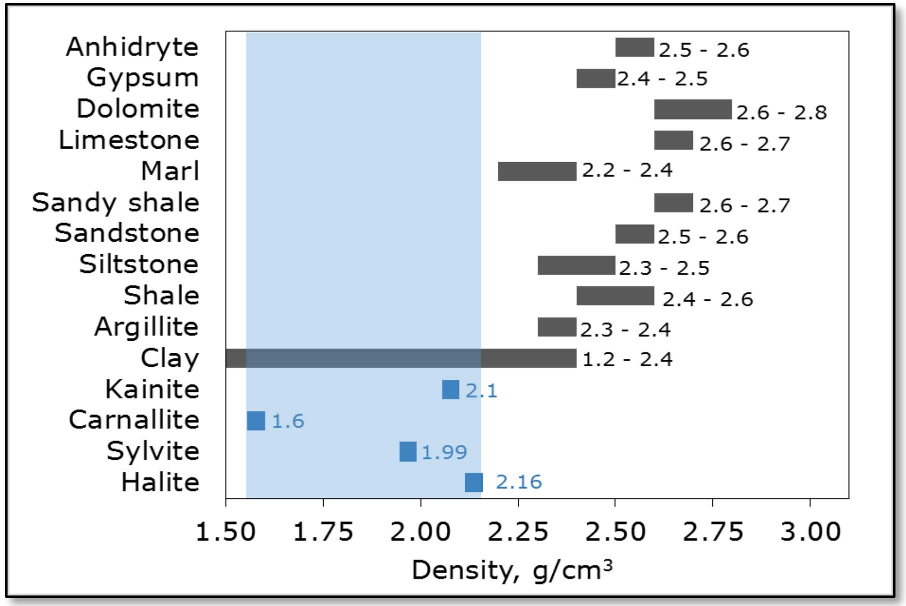
- DENSITY OF THE ROCKS is the most sensitive physical properties of the salt deposits rocks which depends on halite content
- **Salt rock density:**

$$\sigma = K_{h.c.} * \delta_{salt} + (1 - K_{h.c.}) * \delta_{h.r.}$$

$K_{h.c.}$ – halite content,

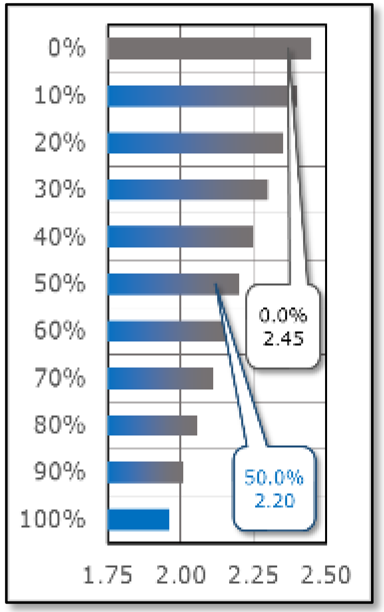
$\delta_{salt}, \delta_{h.r.}$ – density of halite minerals and host rocks

Halite minerals and host rocks most common density*



* Dortman, 1976

Density of Salt-bearing rock

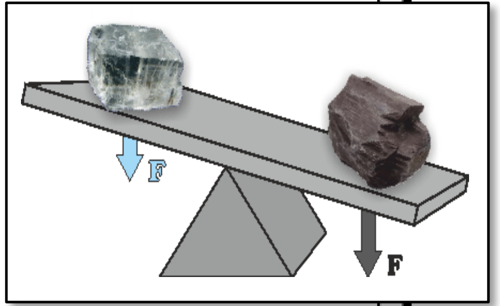


Halite minerals and host rocks density

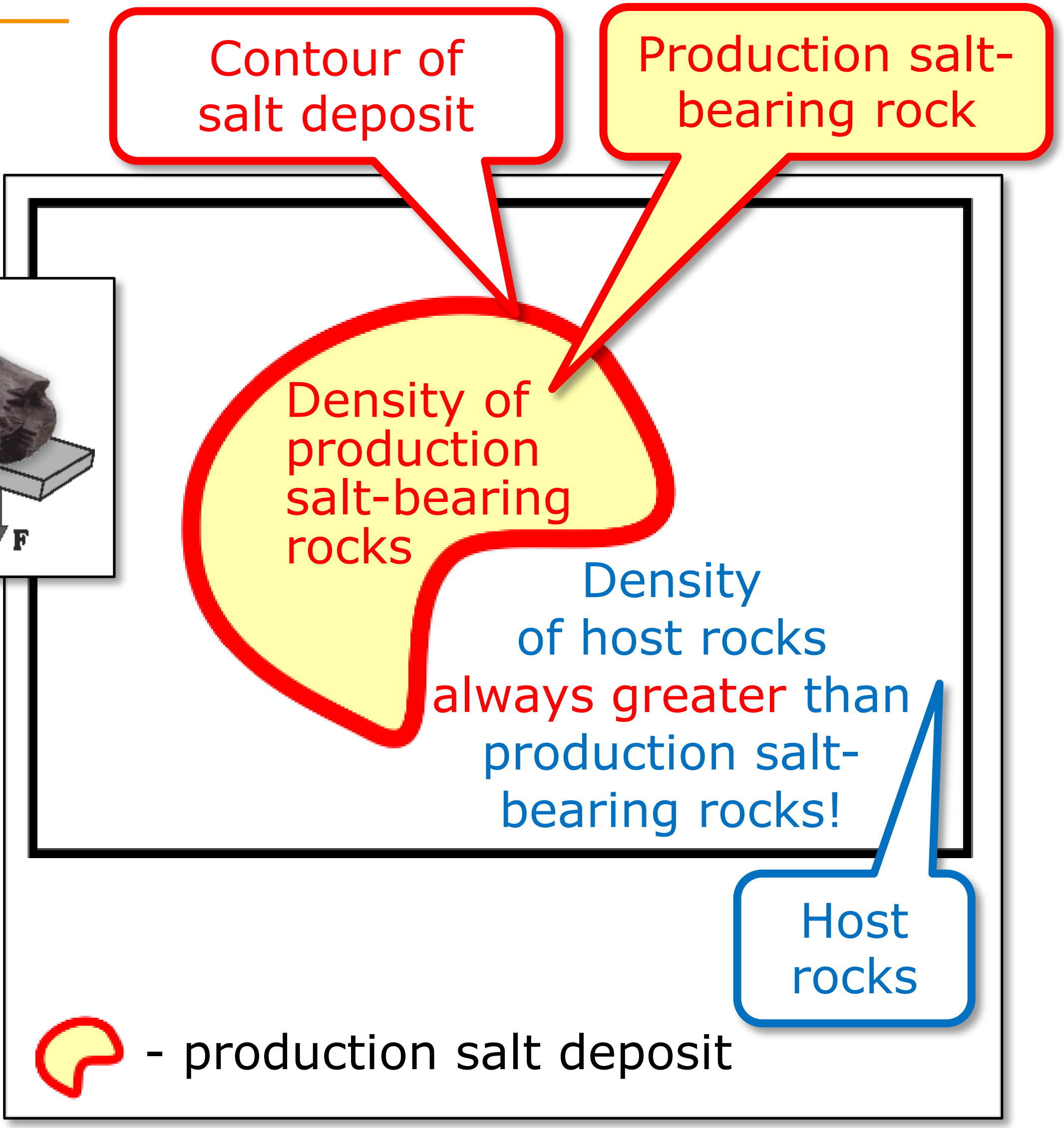
Mineral Rock type	Range, g/cm³	Most common range, g/cm³
Halide minerals		
Halite	–	2.16
Sylvite	–	1.99
Carnallite	–	1.60
Kainite	–	2.10
Average		**1.96**
Sedimentary rocks		
Clay	1.2 – 2.4	–
Argillite	1.7 – 2.9	2.3 – 2.4
Shale	2.3 – 3.0	2.4 – 2.6
Sand	1.3 – 2.0	1.5 – 1.7
Siltstone	1.8 – 2.8	2.3 – 2.5
Sandstone	2.0 – 2.9	2.5 – 2.6
Sandy shale	2.3 – 3.0	2.6 – 2.7
Marl	1.5 – 2.8	2.2 – 2.4
Limestone	1.8 – 2.9	2.6 – 2.7
Dolomite	1.9 – 3.0	2.6 – 2.8
Gypsum	2.1 – 2. 5	2.4 – 2.5
Anhydrite	2.4 – 2.9	2.5 – 2.6
Average		**2.45**

DENSITY OF PRODUCTION SALT-BEARING ROCK FOR MAPPING OF PRODUCTION SALT DEPOSITS

- DENSITY OF THE ROCKS is the most sensitive physical property of the salt deposit rocks which depends on halite content
- DENSITY OF THE PRODUCTION SALT-BEARING ROCK is ALWAYS LESS than the density of the host rocks



- CONTOUR OF THE PRODUCTION SALT DEPOSIT is mapped as a closed contour, which includes the rocks with the lower densities than on the contour
- GRAVIMETRY is the only geophysical method that gives the possibility to study the density of production salt-bearing rocks



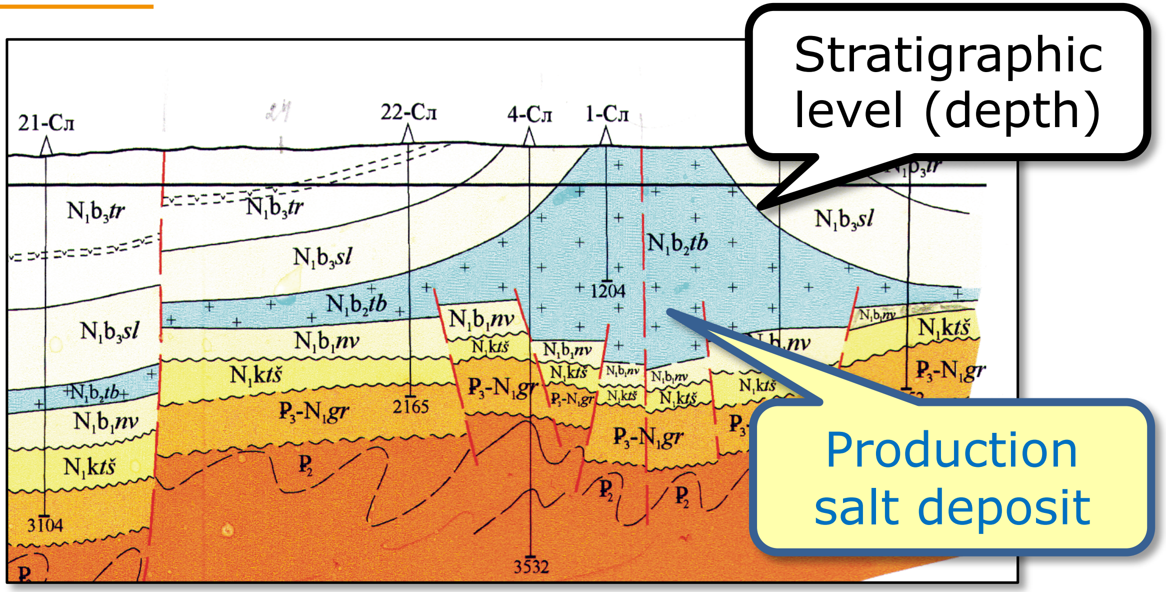
PROPERTIES OF PRODUCTION SALT DEPOSIT FOR FUTURE COMMERCIAL PRODUCTION

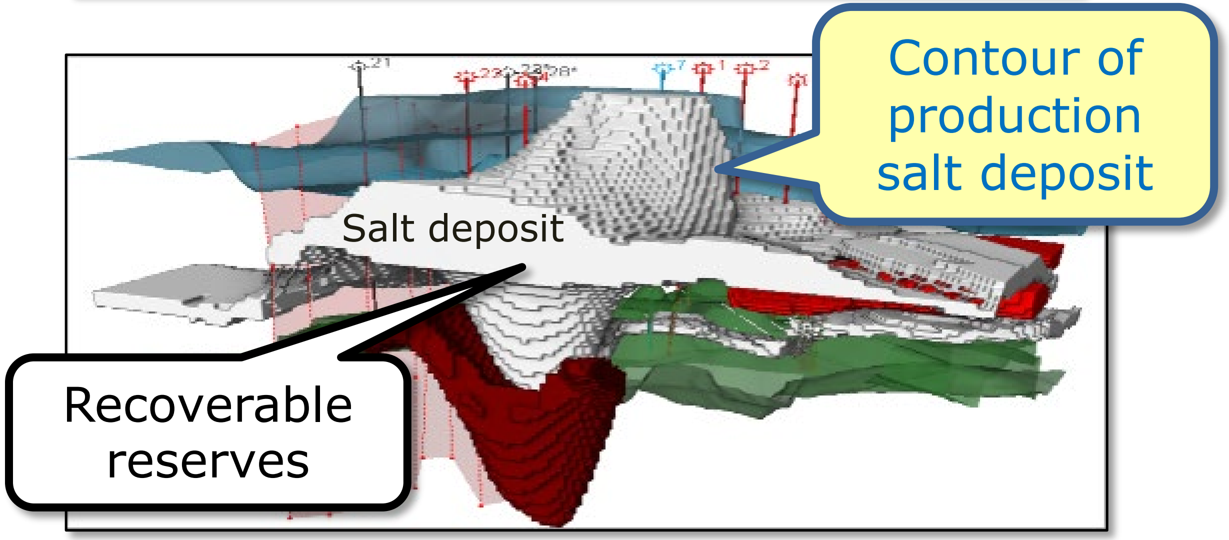
DEPROIL
DETAILED OIL & GAS PROSPECTING

MAIN PROPERTIES OF PRODUCTION SALT DEPOSIT:

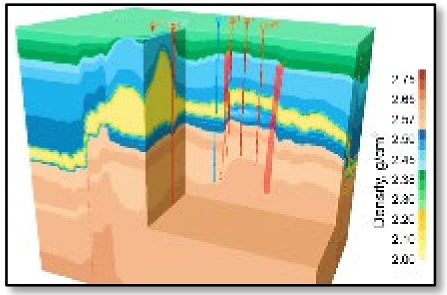
- STRATIGRAPHIC LEVEL (DEPTH)
- 3D CONTOUR (IN-PLANE LOCATION)
- TOTAL AND RECOVERABLE RESERVES
- INITIAL PRODUCTION RATE

THE MAIN TASK - TO ESTIMATE OF THE PROPERTIES WITH MAXIMUM PROBABILITY OF SUCCESS?



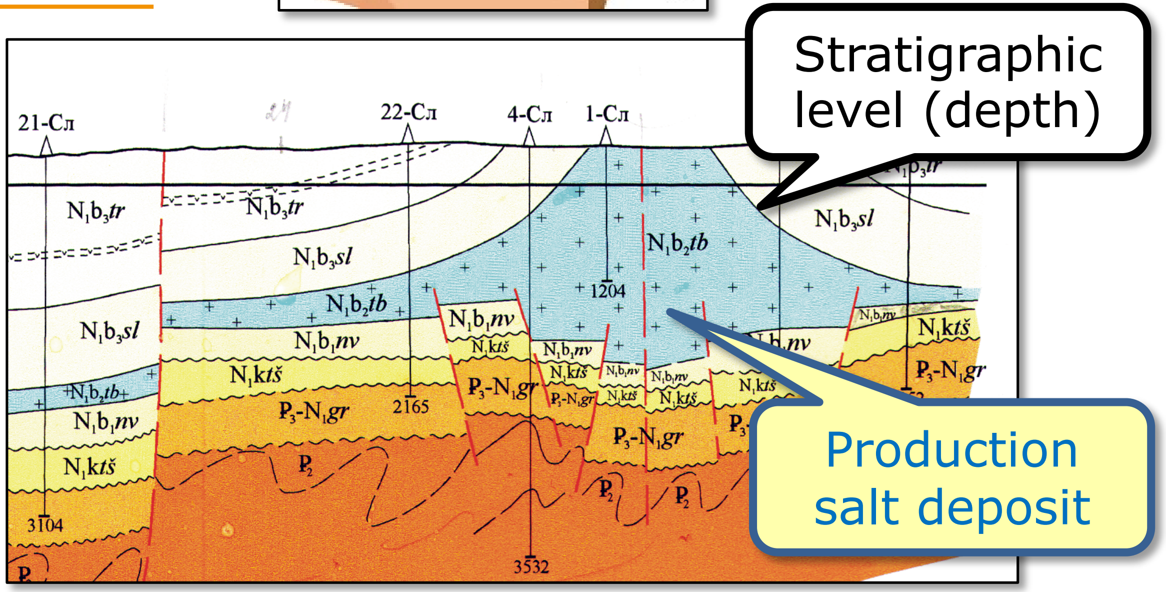


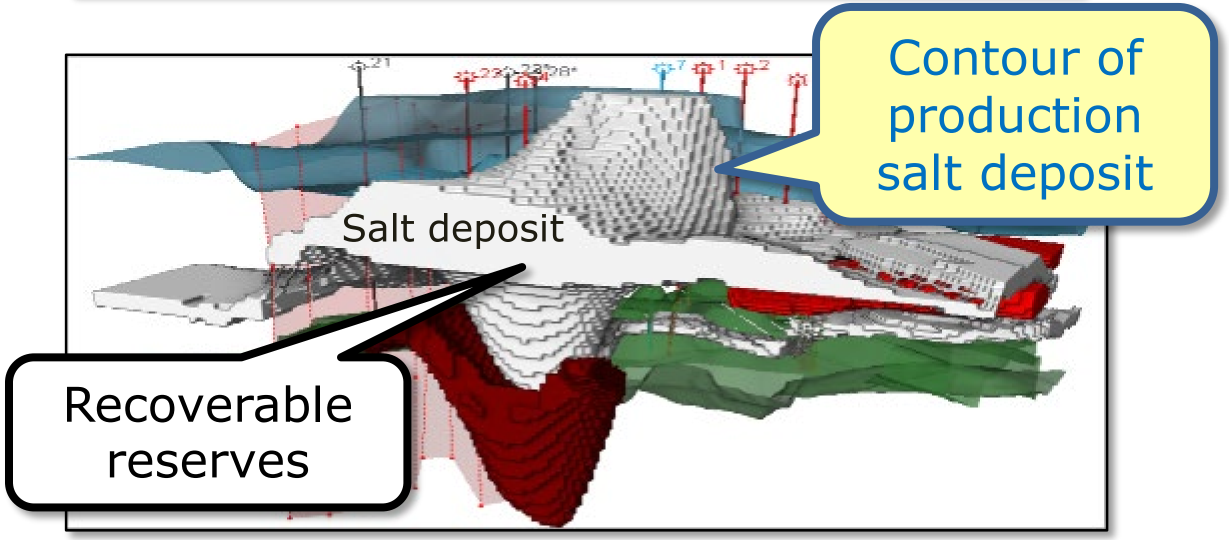
REVOLUTIONARY SOLUTIONS FOR SALT EXPLORATION AND PRODUCTION



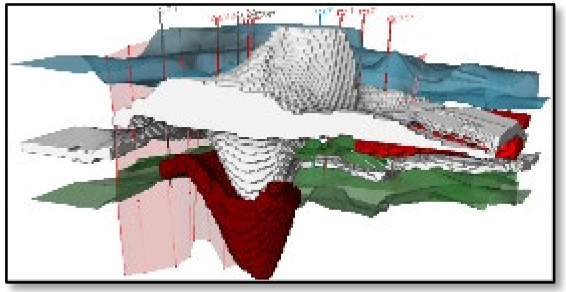
DEPROIL LTD DEVELOPED:

- REVOLUTIONARY TECHNOLOGY for mapping commercial salt deposits of different morphology and origin
- REVOLUTIONARY MATHEMATICAL THEORY for the construction of geologically consistent subsurface models of density based on 3D gravity data inversion with well and seismic acquisitions
- REVOLUTIONARY in-house software GCIS (Geophysical Complex Interpretation System) for support of the TECHNOLOGY



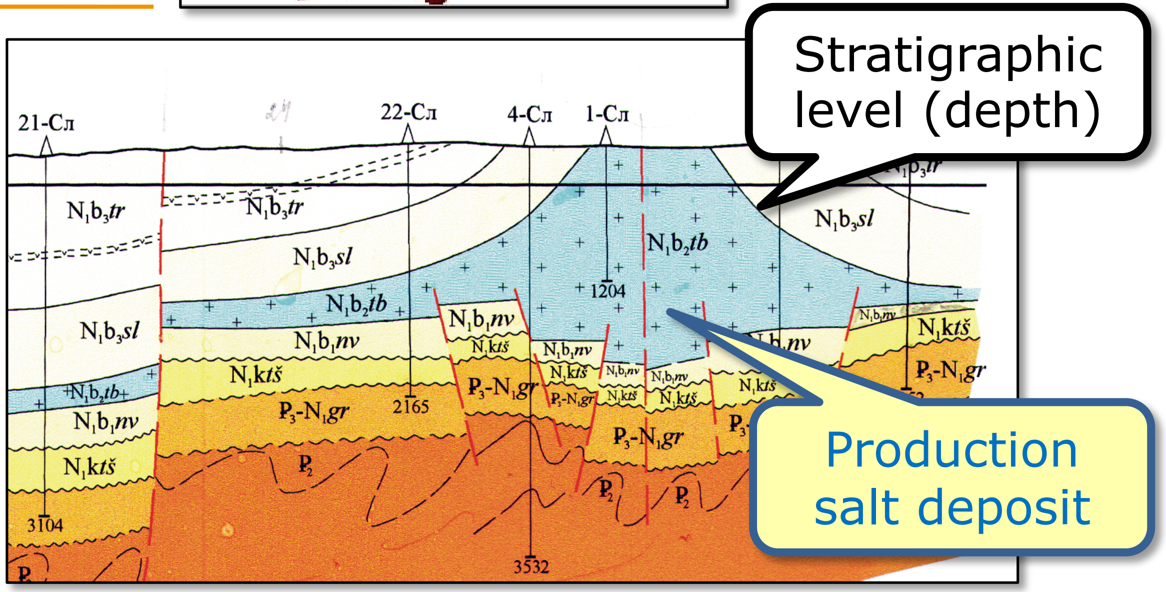


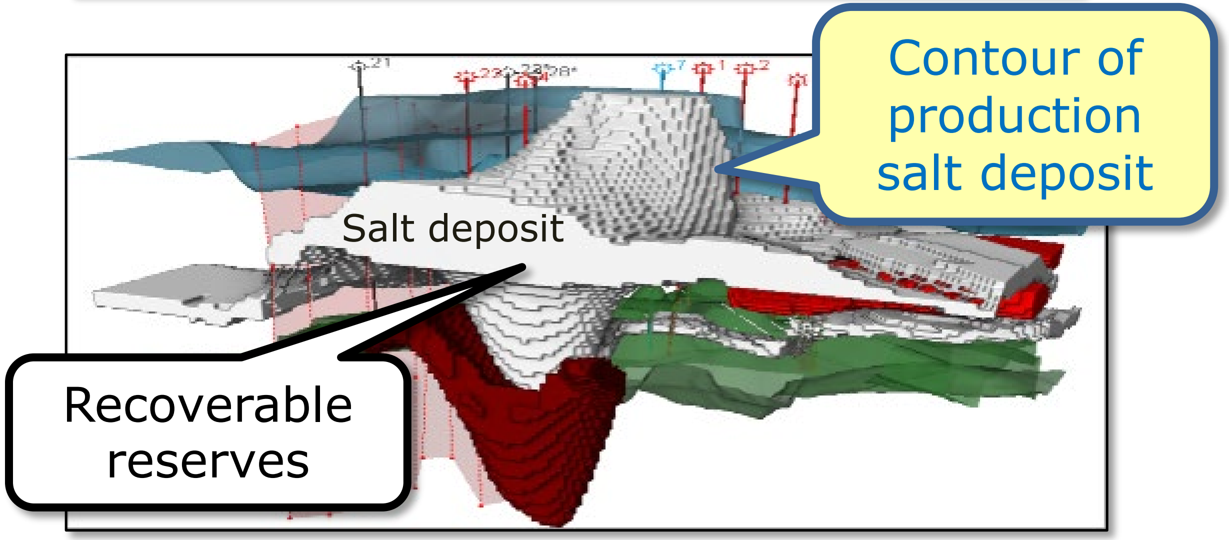
REVOLUTIONARY SOLUTIONS FOR SALT EXPLORATION AND PRODUCTION



DEPROIL LTD DEVELOPED:

- **3D MODEL OF THE DENSITY OF SALT RESERVES** is the most informative property of salt deposit because it include only amount of reserves in one unit of the salt-bearing rocks (BCM of salt in cubic kilometer of rocks)
- **ESTIMATION OF THE TOTAL AND RECOVERABLE RESERVES** based on integrating the 3D model of the density of salt reserves and control by Monte-Carlo simulation





«There is nothing more practical than a good theory» Immanuel Kant

DEPROIL

DETAILED OIL & GAS PROSPECTING

30 YEARS OF RESEARCH

- 1974 – Own mathematical theory of «Criterial Approach to Solve an Incorrect Inverse Geophysical Problem for the Complex 3D Models of Geological Media»
- 1989 – Active model of quantitative joint 2D inversion of gravimetric and seismic data
- 2003 – Mapping the contours of geological body based on 3D model of rock density
- 2004 – Passive model of quantitative joint 3D inversion of gravimetric and well data
- 2010 – Starting field gravimetric observations, 2011 – starting field magnetometric observations
- 2016 – Commercial mineral reserves estimation by Monte-Carlo simulation
- 2017 – 3D model of the spatial density of commercial mineral reserves
- 2018 – Estimation of total commercial reserves on the base of 3D models of the spatial density of commercial mineral reserves and its control by Monte-Carlo simulation
- 2020 – Estimation of the initial production rates for new extraction wells

1974 Idea → 1989 ELENA IBM360 → 2000 GCIS-2D → 2004 GCIS-3D → 2008 GCIS-4D → 2010 GCIS-4D+1D Wells → 2018 GCIS-4D+1D+HC → 2020 Production Rate

«I choose a block of marble and chop off whatever I don't need», Auguste Rodin

INVERSE PROBLEM – SCHEME OF PASSIVE SOLUTION

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

where: $\xi(\mathbf{x})$ – properties of the 3D model – rock density or depth to the geological horizon

$\xi(\mathbf{x}) \in X$ – metric space of the model;

$y(\mathbf{s}) \in U$ – observed geophysical field with error $\boldsymbol{\varepsilon}$;

U – metric space of geophysical fields;

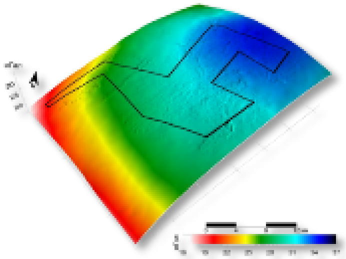
$A(.): X \to U$ – operator which connects properties of the model $\xi(\mathbf{x})$ with geophysical field $y(\mathbf{s})$ – non-linear in case of a structural problem and linear in case of modelling inhomogeneous distribution of properties;

$D(A)$ – set of operator determination $A(.)$ – open half-space in space X, wide enough to approximate real geological models;

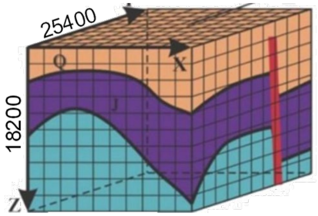
$Im(A)$ – set of the operator A values in space Y, wide enough to approximate observed geophysical fields M – set of geologically meaningful models of the subsurface;

$J(.): X \to R$ – convex functional which provides choosing the best geologically meaningful model;

$\xi_I(\mathbf{x}), \xi_F(\mathbf{x})$ – Initial and Final models.

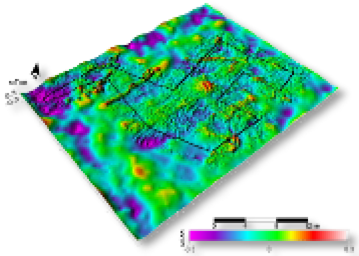


Gravity – $y(\mathbf{s})$



Initial model – $\xi_I(\mathbf{x})$

Passive inverse problem

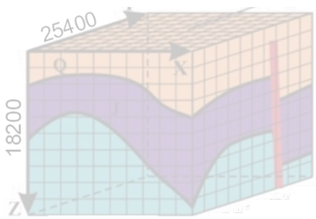


Gravity misfit (Error $\boldsymbol{\mu}(\xi_F(\mathbf{x}))$)

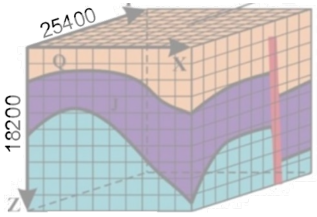
Choosing geologically-consistent model

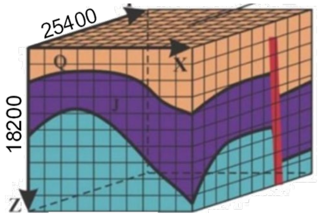
$$J(\xi(\mathbf{x}) - \xi_I(\mathbf{x})) \Rightarrow min$$

Equivalent models ($\mu < \varepsilon$ and $\tau < \delta$)



Dummy model





Geologically consistent

INVERSE PROBLEM – SCHEME OF ACTIVE SOLUTION

$$\begin{cases} A(\xi(\mathbf{x})) = y(\mathbf{s}),\ \xi(\mathbf{x}) \in M \subset D(A) \subset X, y(\mathbf{s}) \in Im(A) \subset Y \\ B(\eta(\mathbf{x})) = u(\mathbf{s}),\ \eta(\mathbf{x}) \in N \subset D(B) \subset X, u(\mathbf{s}) \in Im(B) \subset U \\ J(\xi(\mathbf{x}) - \eta(\mathbf{x})) \to min,\ \mu = \|y(\mathbf{s}) - A(\xi(\mathbf{x}))\|,\ \tau = \|u(\mathbf{s}) - B(\eta(\mathbf{x}))\| \end{cases}$$

where: $\xi(\mathbf{x}),\eta(\mathbf{x})$ – properties of the 3D model – rock density or depth to the geological horizon;

$\xi(\mathbf{x}),\eta(\mathbf{x}) \in X$ – metric sgeophysical field with error $\boldsymbol{\varepsilon}$ and $\boldsymbol{\delta}$;

$y(\mathbf{s}) \in Y, u(\mathbf{s}) \in U$ – metric sppace of the model;

$y(\mathbf{s}), u(\mathbf{s})$ – observed ace of geophysical fields;

$A(.): X \to Y,\ \ B(.): X \to U$ – operator which connects properties of the models $(\xi(\mathbf{x}),\eta(\mathbf{x}))(\mathbf{x})$ with geophysical fields $(y(\mathbf{s}), u(\mathbf{s}))$;

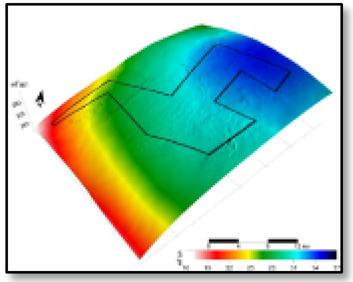
$D(A), D(B)$ – sets of operators determinations $A(.), B(.)$ – open half-space in space X, wide enough to approximate real geological models;

$Im(A), Im(B)$ – sets of operators A and B, wide enough to approximate observed geophysical fields;

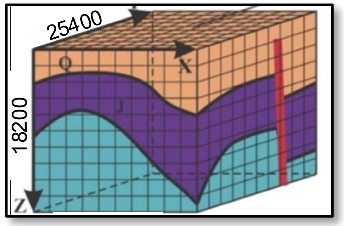
M, N – sets of geologically meaningful models of the environment

$J(.): X \to R$ – convex functional which effects X and provides choosing the best geologically meaningful model;

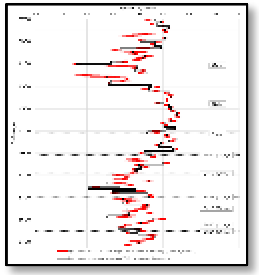
$\xi_I(\mathbf{x}), \xi_F(\mathbf{x}), \eta_F(\mathbf{x})$ – Initial and Final models.



Gravity – $y(\mathbf{s})$

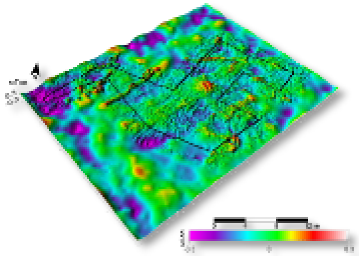


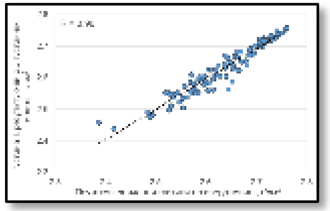
Initial model – $\xi_I(\mathbf{x})$



Well log data – $u(\mathbf{s})$

Active inverse problem





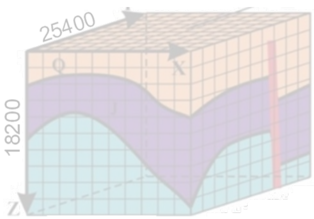
Well

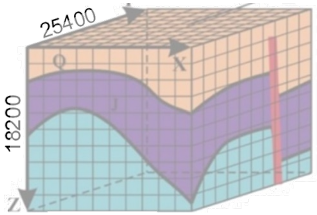
Gravity misfit (Errors $\boldsymbol{\mu}(\xi_F(\mathbf{x}))$ and $\boldsymbol{\tau}(\eta_F(\mathbf{x}))$)

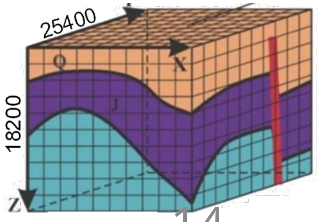
Choosing geologically-consistent model

$J(\xi_F(\mathbf{x}) - \eta_F(\mathbf{x})) \Rightarrow min$

Equivalent models ($\mu < \varepsilon$ and $\tau < \delta$)

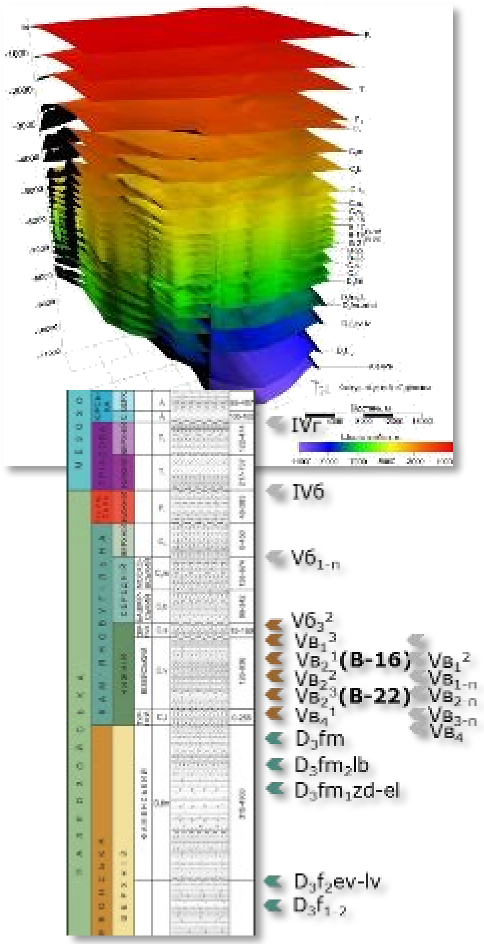


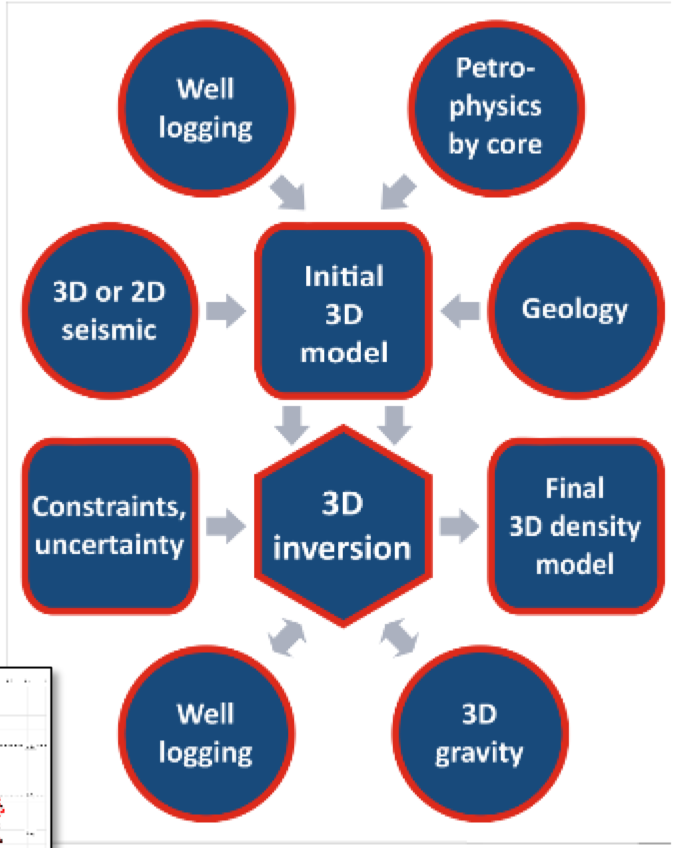


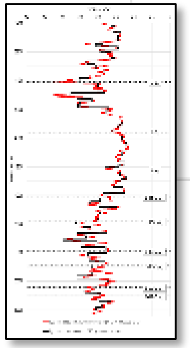


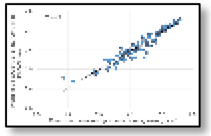
Dummy model   Geologically consistent

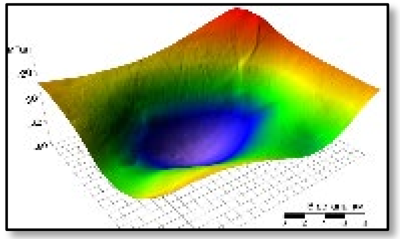
THE ALGORITHM OF 3D GRAVITY INVERSION

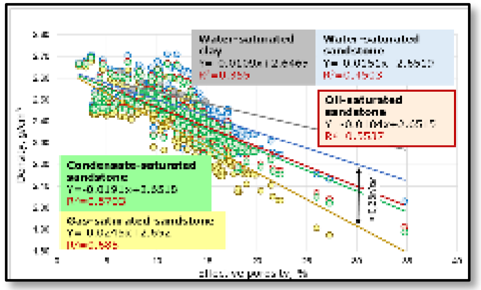


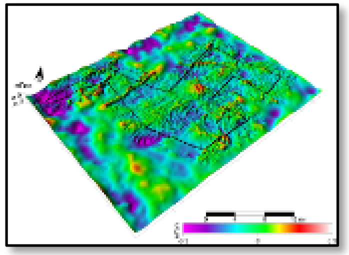


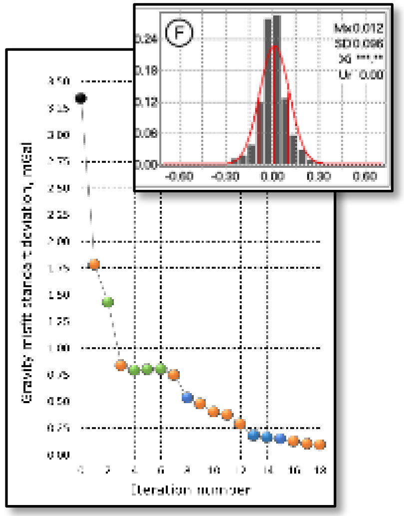


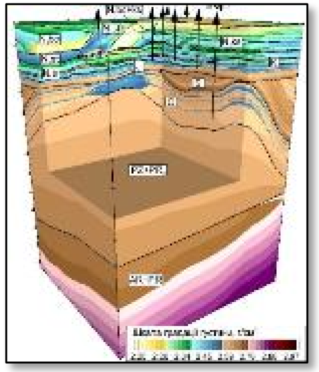


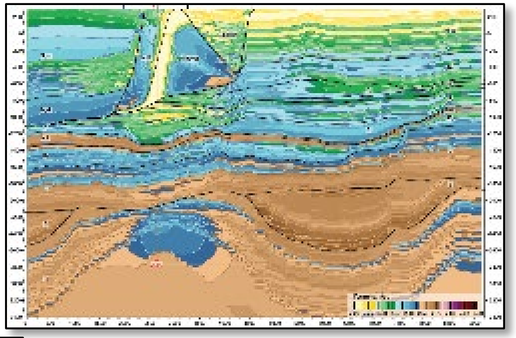


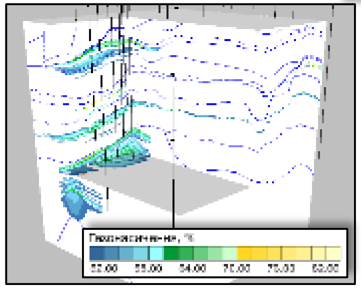


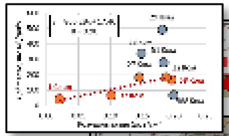


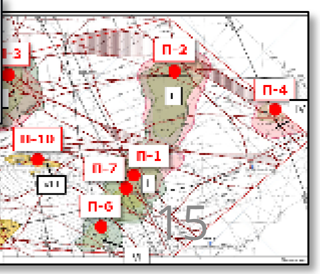












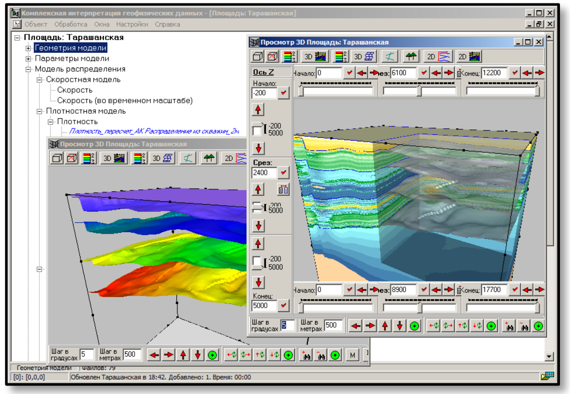
TECHNICAL CAPABILITIES

GRAVITY AND MAGNETIC SURVEY EQUIPMENT

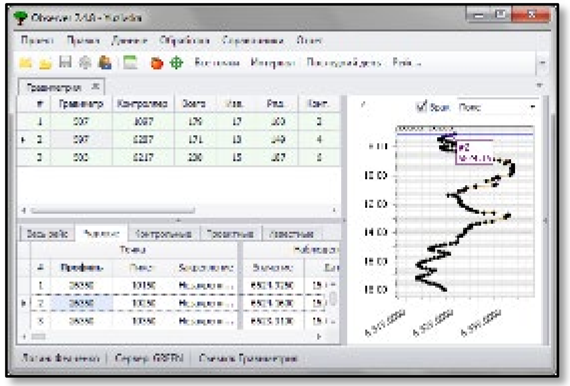
- SCINTREX CG-5 (Canada) – 6 units of digital gravimeters
- GEOMETRICS G-859SX Mining Mag (USA) – 4 units of digital cesium magnetometers
- GEOMETRICS G-856AX Memory-Mag (USA) – proton magnetometer (base-station)
- Gravity field observation error – <6.5 µGal
- Magnetic field observation error - <0.8 nT
- Trimble GPS R-10, R-8, 5700 – 10 units GNSS
- Computer cluster with 342 cores

PROPRIETARY SOFTWARES

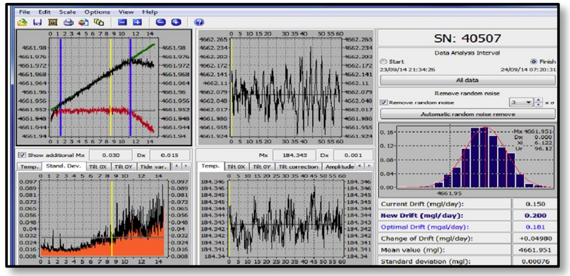
- **GCIS** – automated computer system, aimed at creating, storing and defining optimal density properties of 1D, 2D, 3D models



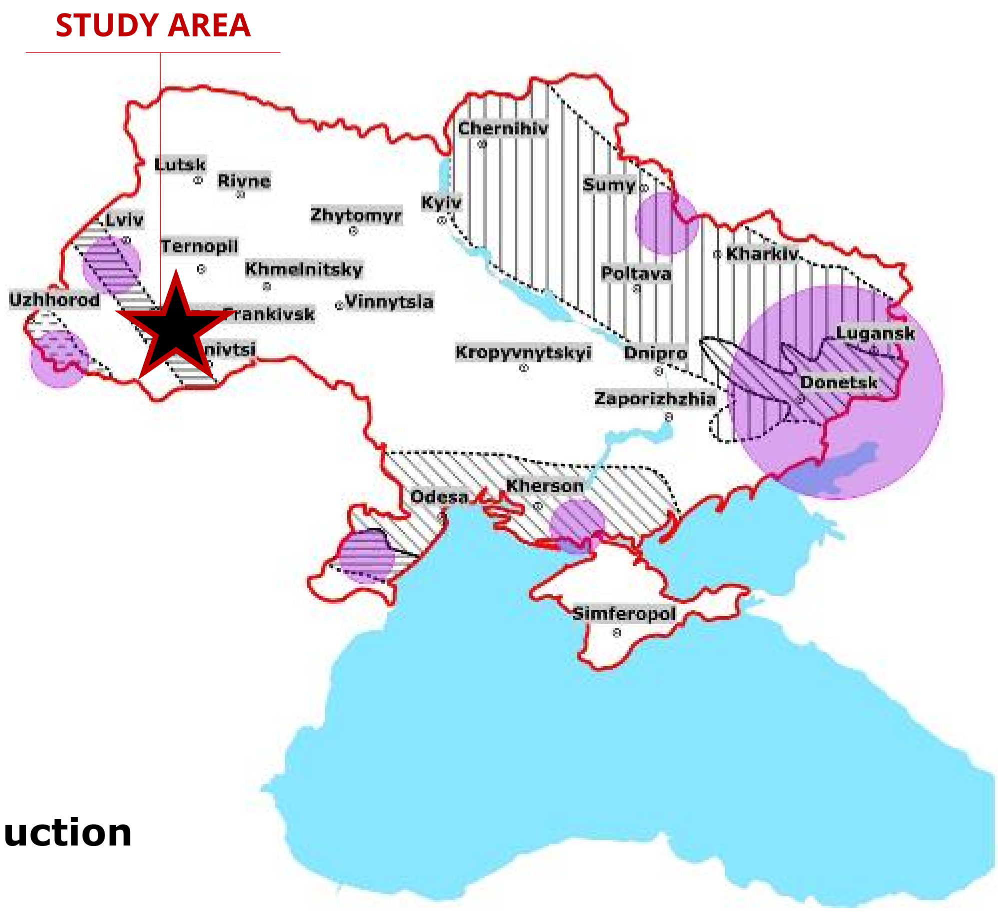
- **OBSERVER** – Client-server software aimed at operative storing and processing of gravimetric and magneto-metric data and real-time quality control



- **GRAVITYDRIFT** – software aimed at control and setting to optimal parameters of SCINTREX CG-5 gravimeters



DEPROIL
DETAILED OIL & GAS PROSPECTING



CASE STUDY
FORE-CARPATHIAN THROUGH, UKRAINE

New Halite Deposit!

Total halite reserves: **3.25** - **3.81** – **4.77** billion tons

Cost of reserves depending on halite content for **rock salt production** (56$ per ton*) **–** **182** – **214** – **267** billion $,

for **vacuum and open pan salt** production (220$ per ton*) **–** **715** – **839** – **1050** billion $

CASE STUDY
FORE-CARPATHIAN THROUGH

The study was performed in 2021-2022 as a part of hydrocarbon exploration project

Study area:

- Location – Fore-Carpathian Through
- Size – 80.99 km^2 (8.9 x 9.1 km)
- Depth to the basement (AR-PR) ≈7 km

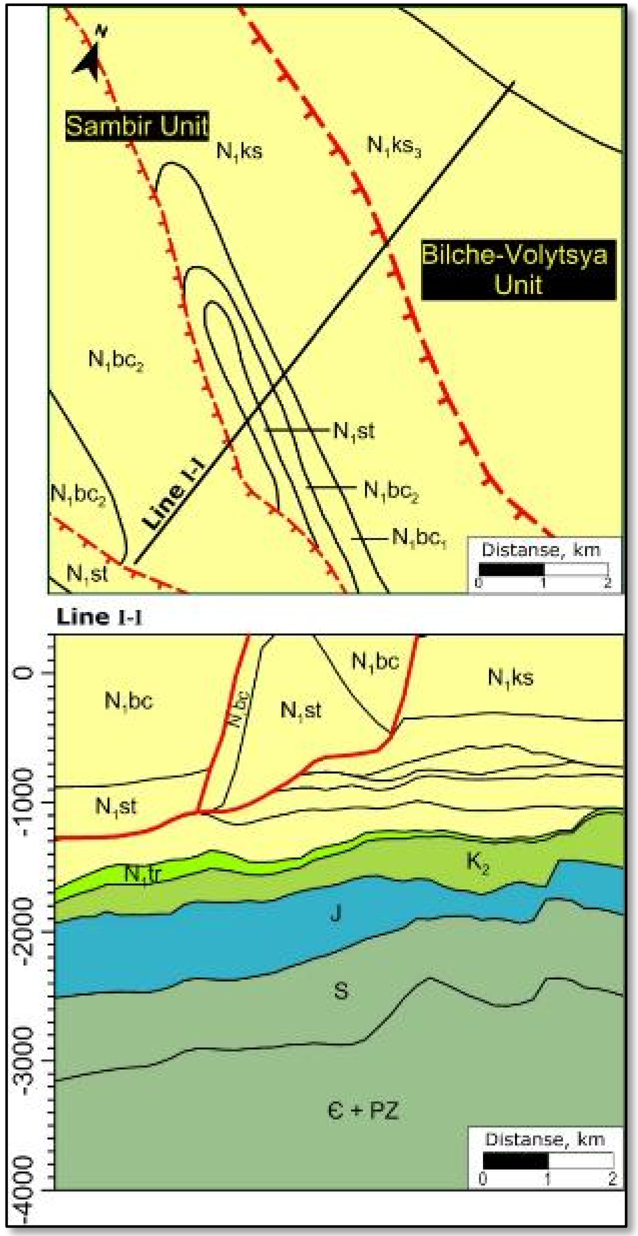
Survey performed:

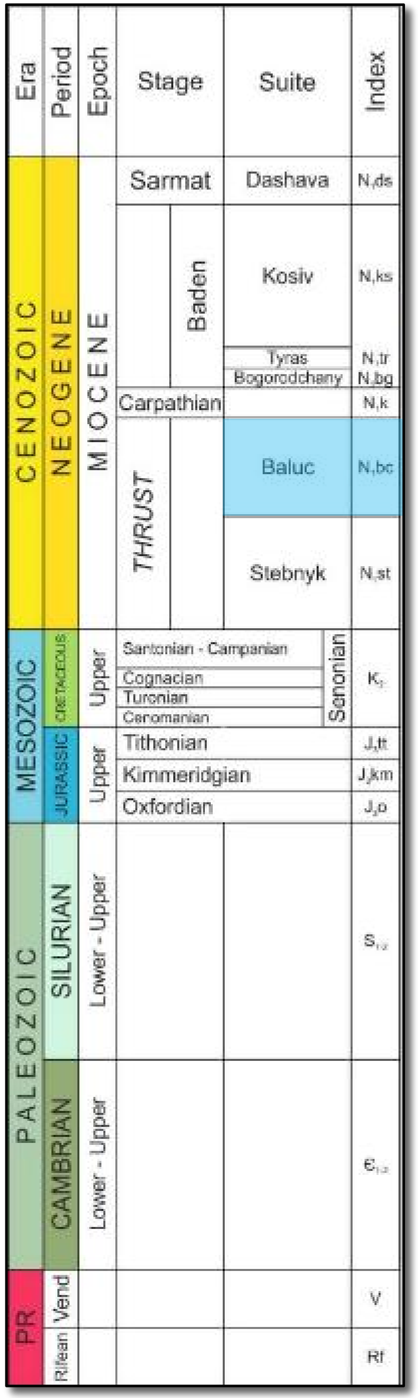
- High-accuracy gravity survey (1:10 000) by digital gravimeters Scintrex CG-5 (Canada).
  Error ± 6.5 µkGal
- High-accuracy magnetic survey (1:10 000) by cesium magnetometers Geometries G-859 (USA).
  Error ± 0.71 nTl

Study objectives:

- Commercial gas-bearing pools mapping

Geological sketch map
(by V.Glushko, 1968)





- Salt rock

CASE STUDY

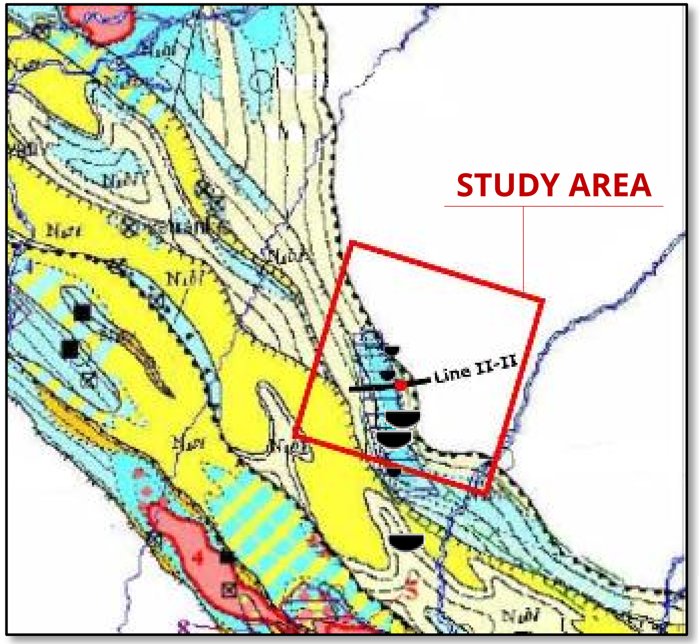
FORE-CARPATHIAN THROUGH

Salt deposits:

- Study area belongs to one of the most prospective parts of Fore-Carpathian Salt-Bearing Basin
- Rock salt batches are encountered in Balytska Suite (N_1bc) of Neogene with maximum thickness 500 m (Chapowski, 2009)
- Average NaCl content changed from 70.7% to 95.46%

Well #1:

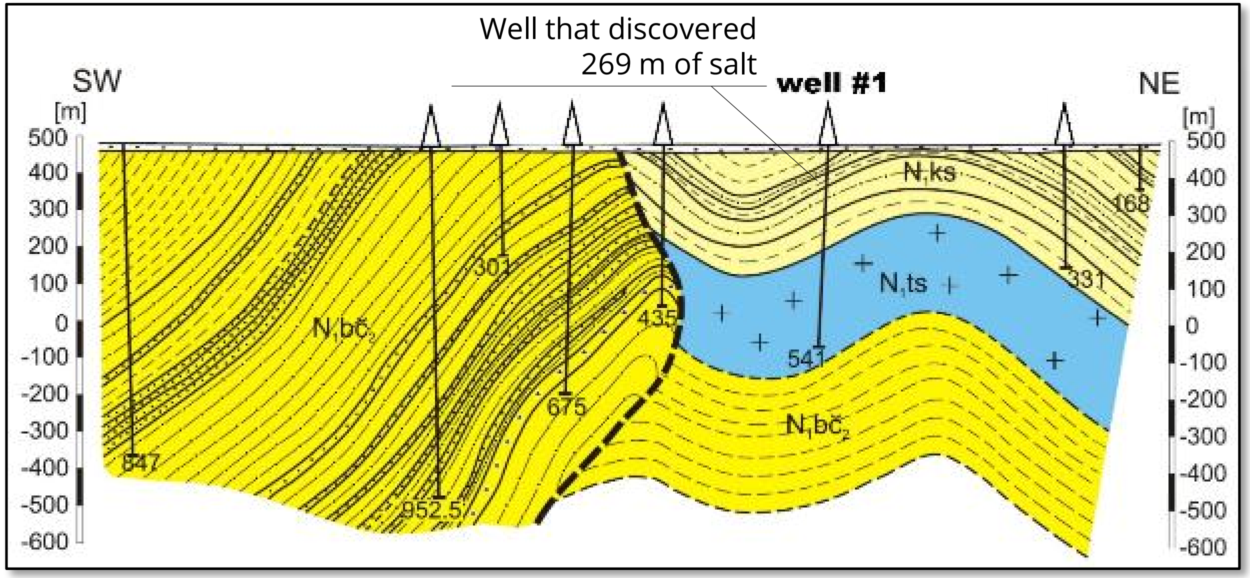
- The well was drilled as a part of exploration project for potassium salt
- It revealed 269 m of salt (the maximum thickness within the study area) with average NaCl content of 76.3%
- Considering the angle of syncline limb dipping (30°) true thickness of revealed saline formation might be 232 m
- Drilling rig malfunction at 541 m, the salt bed bottom was not reached and thickness of salt bed is unknown



Distribution scheme of Lower Miocene salt-bearing sediments and regularities in salt location within Fore-Carpathian salt-bearing basin (by V.O. Vashchenko, 2007)

- salt-bearing formation with halite rock beds
- sodium salt deposits

Geological cross-section along line II–II by well drilling results (by Stupnitskiy et al., 1978)



CASE STUDY
FORE-CARPATHIAN THROUGH

Model dimensions:

- Lateral 8.9 x 9.1 km
- Depth 12 km

Input data:

- 3D seismic cube
- 2D legacy seismic data
- High precision gravity data
- Well logs
- Petrophysics by core

Initial density of rock properties

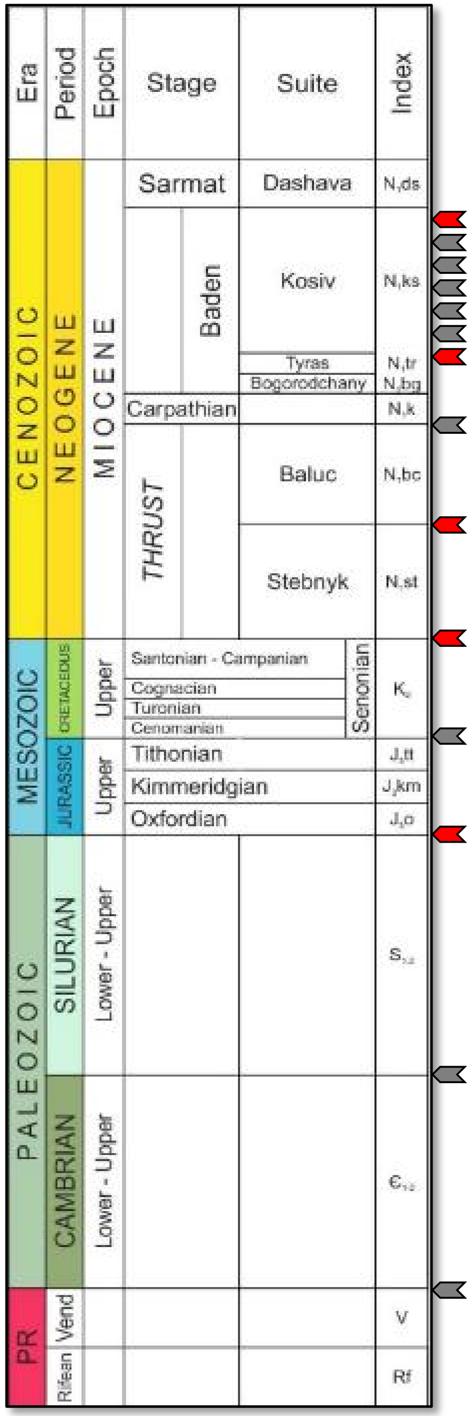
- Generalized core data
- Sonic log
- Lithology and saturation by well log interpretation

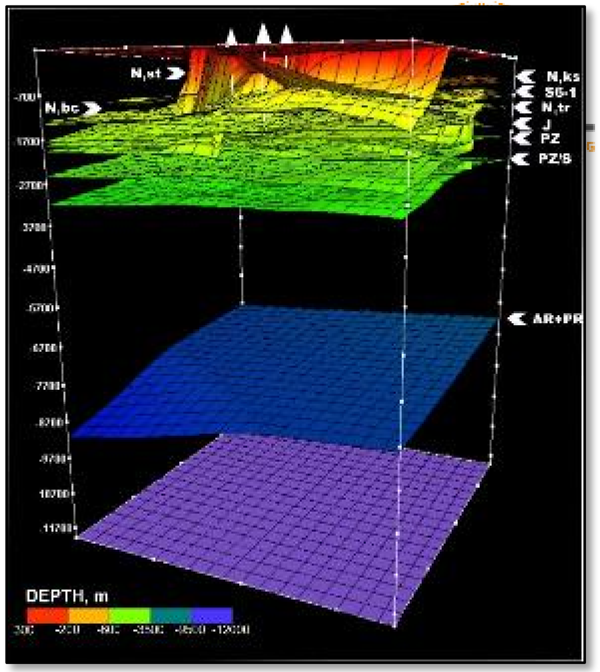
3D structural model

- **15** structural surfaces:
- 6 basic stratigraphic surfaces: N_1st (W), N_1st (E), N_1tr, J, PZ, AR+PR,
- 3 intermediate stratigraphic surfaces: N_1bc, N_1ks, K_2
- 6 intermediate seismic surfaces within Kosiv suite of Neogene (N_1ks) and Paleozoic: S-6, S-5,S-3,S-2-2, S-1, PZ-S

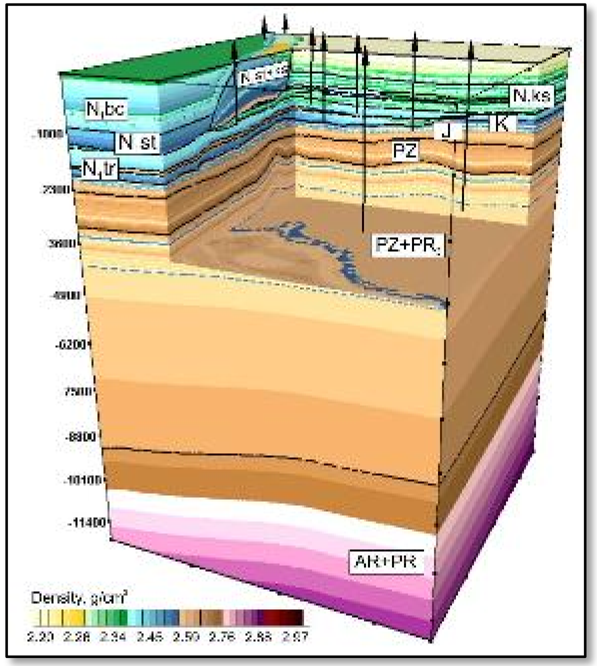
3D property model

- Parallelepiped as elementary cell, 100 m x 100 m x 5 m in size
- Voxel model consisting of 19.9 million of cells





Initial 3D density model



CASE STUDY
FORE-CARPATHIAN THROUGH

Algorithm for rocks density calculation by well log data

- Acoustic log data quality control and calibration
- Determining of the clay and sand content by the Larionov equation (1969).
- Determining of the density of rocks based on the velocity data by acoustic log and modified Gardner's equation
- Calibration of Gardner's coefficients to match mean values of density by well logging with density by core data analysis for each lithological and stratigraphical group of sediments

Modified Gardner's equation for rock density:

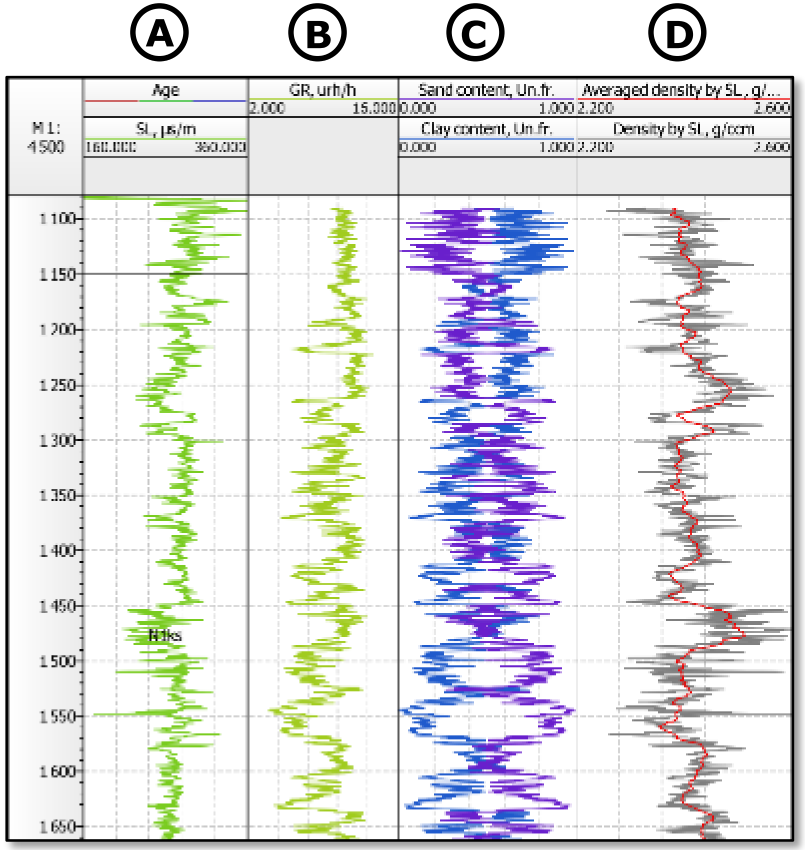
$$\sigma = (K_c * a_c + K_{sand} * a_{sand} + K_{cl} * a_{cl} +$$

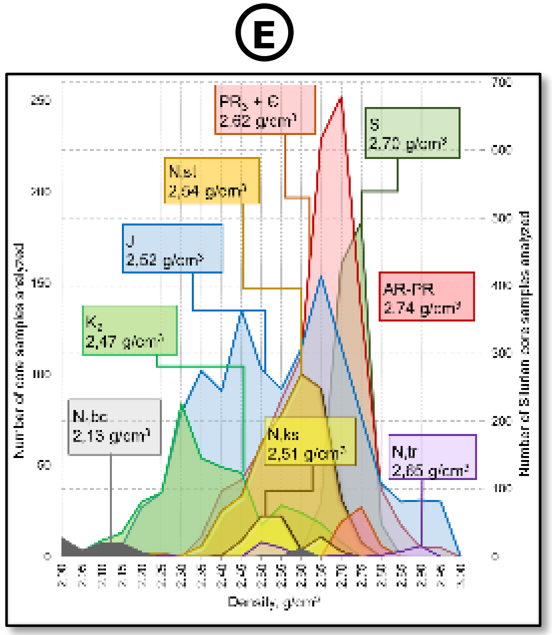
* Modified Gardner equation for evaluation of rock density basing on velocity data for Dnipro-Donets depression O. Petrovskyy, T. Petrovska, A. Borozdina (DEPROIL), M. Firman (UKRGAZVYDOBUVANNIA (Poltava)), I. Gafych, I. Solodkyy (DTEK Oil & Gas) 18th International Conference on Geoinformatics - Theoretical and Applied Aspects | 13-16 May 2019 | Kyiv, Ukraine

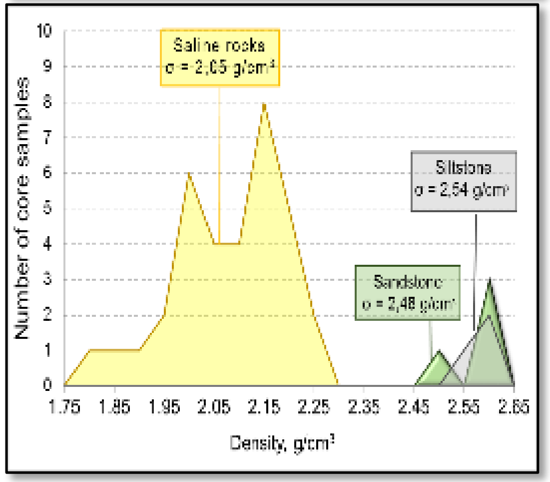
CASE STUDY
FORE-CARPATHIAN THROUGH

Algorithm for rocks density calculation by well log data

- Acoustic log data quality control and calibration (A)
- Determining of the clay and sand content (C) using gamma log data (B) by the Larionov equation (1969)
- Determining of the density of rocks based on the velocity data by acoustic log and modified Gardner's equation (D)
- Calibration of Gardner's indexes (F) to match mean values of density by well logging with density by core data analysis (E) for each lithological and stratigraphical group of sediments







(F) Lithology	Before calibration*		After calibration	
	a	*b*	*a*	*b*
Stebnyk thrust sediments				
Clay	0.3118	0.2515	0.3500	0.2515
Sandstone	0.2309	0.2826	0.3300	0.2380
Salt and saline rocks	0.0022	0.8128	0.2947	0.235557
Other sediments				
Clay	0.3118	0.2515	0.3118	0.2515
Sandstone	0.2309	0.2826	0.2309	0.2826
Carbonates	0.1593	0.3234	0.1593	0.3234
Gypsum and anhydrite	0.7038	0.1634	0.7038	0.1634

CASE STUDY
FORE-CARPATHIAN THROUGH

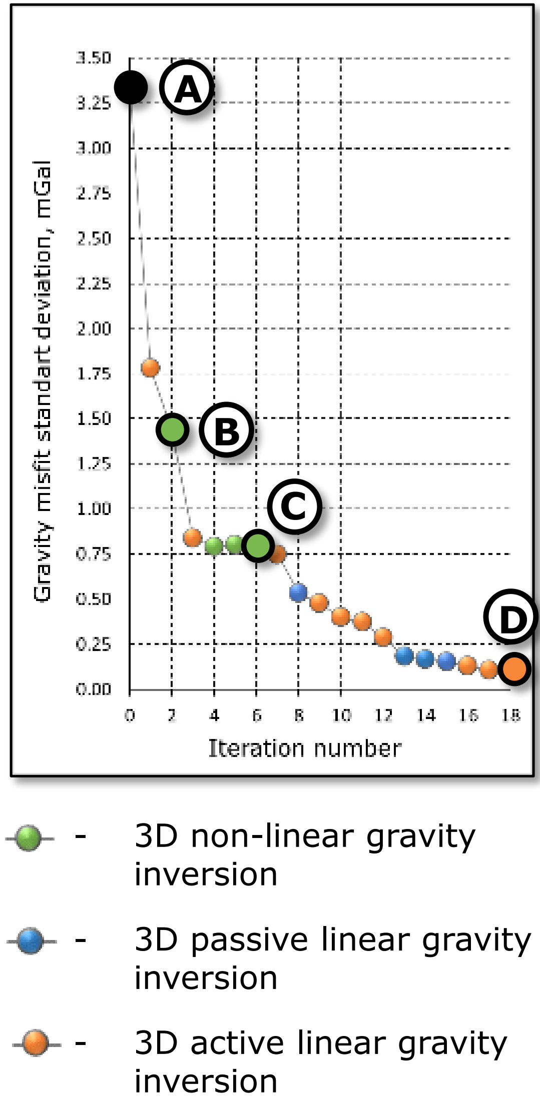
Key steps of the 3D gravity inversion applied:

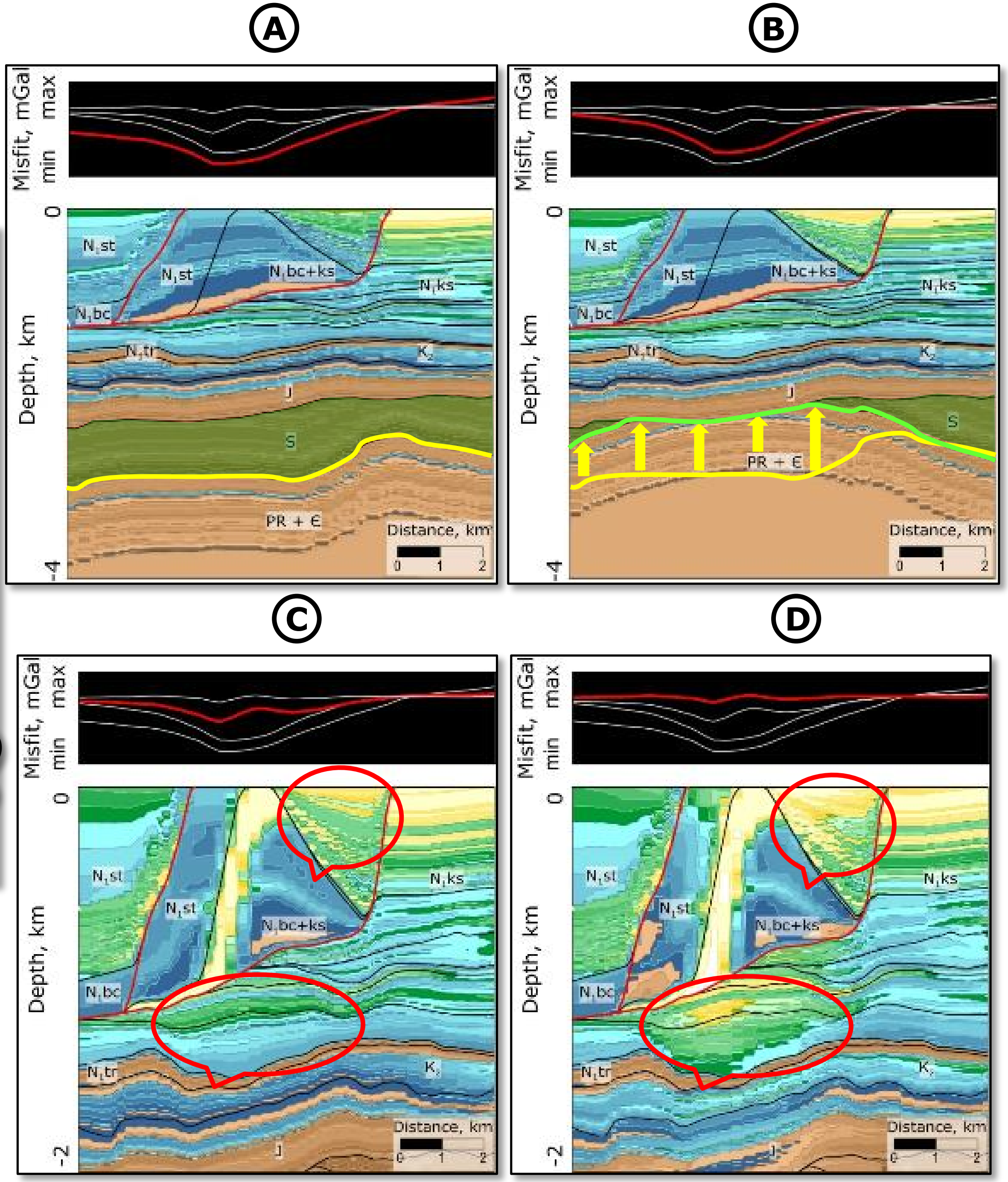
(A) - Creating an initial 3D model of density consistent with all available well log, seismic and geological data set.
SD – 3.340 mGal

(B) - Determine the surface of Paleozoic formation by applying 3D non-linear gravity inversion.
SD = 1.430 mGal

(C) - Determine the shape of salt body within fold in Stebnyk sediments by applying 3D linear gravity inversion.
SD = 0.800 mGal

(D) - Determine the density inhomogeneous of the rock by applying active 3D+1D linear gravity inversion.
SD = 0.096 mGal

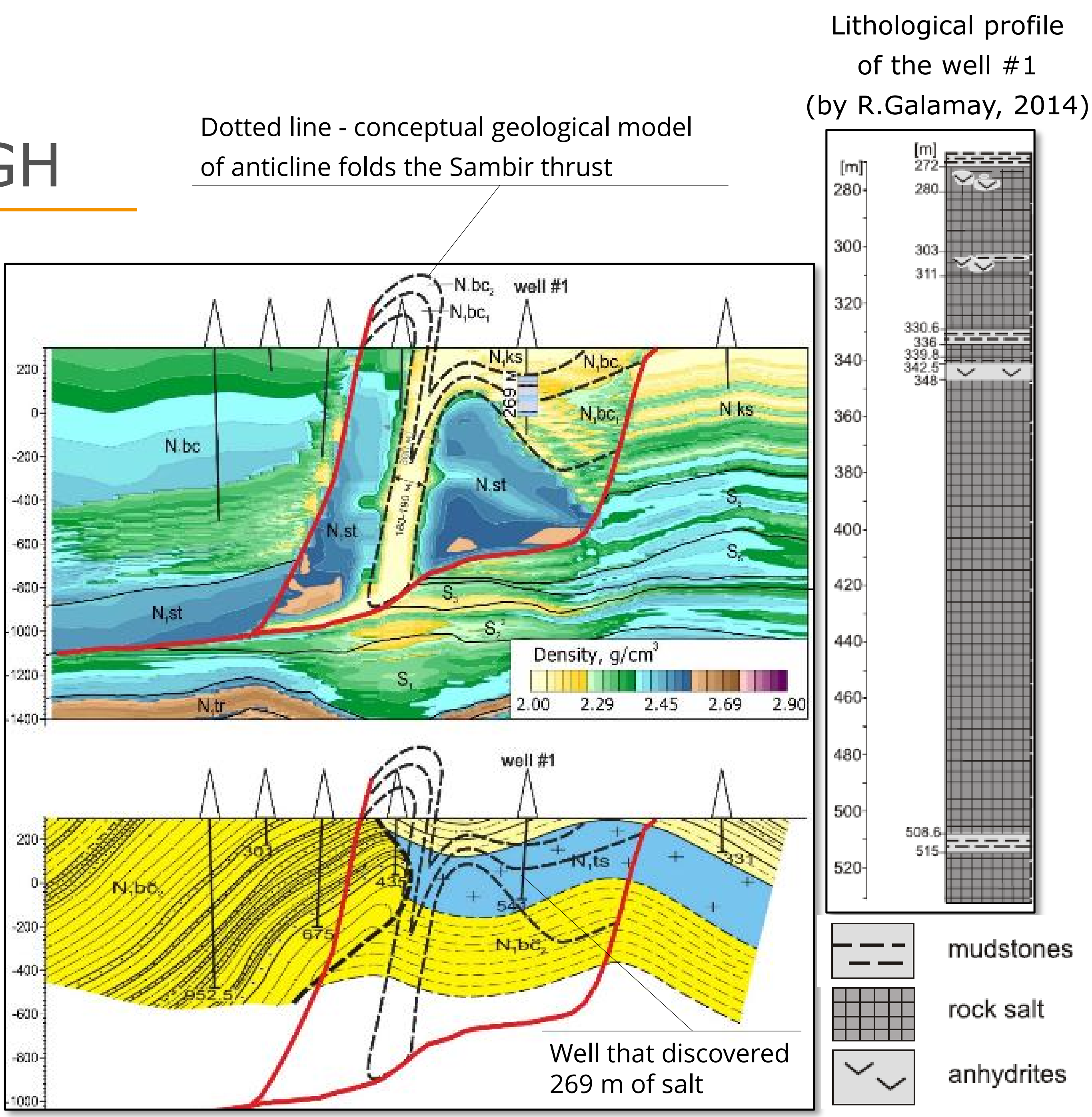




CASE STUDY
FORE-CARPATHIAN THROUGH

Interpretation model of salt by the results of 3D gravity modelling

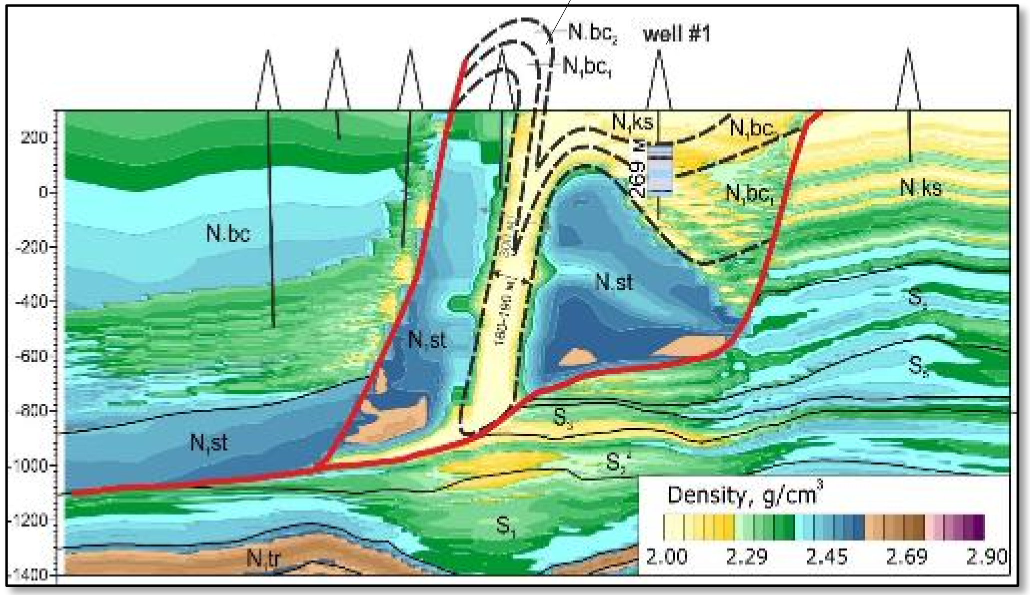
- The salt body was delineated by the contour that includes rocks with density values varying in a range from 2.05 to 2.27 g/cm³ that corresponds to salt-bearing formation with <35% of clayey content
- True thickness of mapped salt-bearing formation is 160 – 190 m
- The model does not contradict with well data collected while exploration project for potassium salt (boreholes shown on the cross sections were note involved into gravity inversion) and explains significant variability of salt thickness in neighboring boreholes



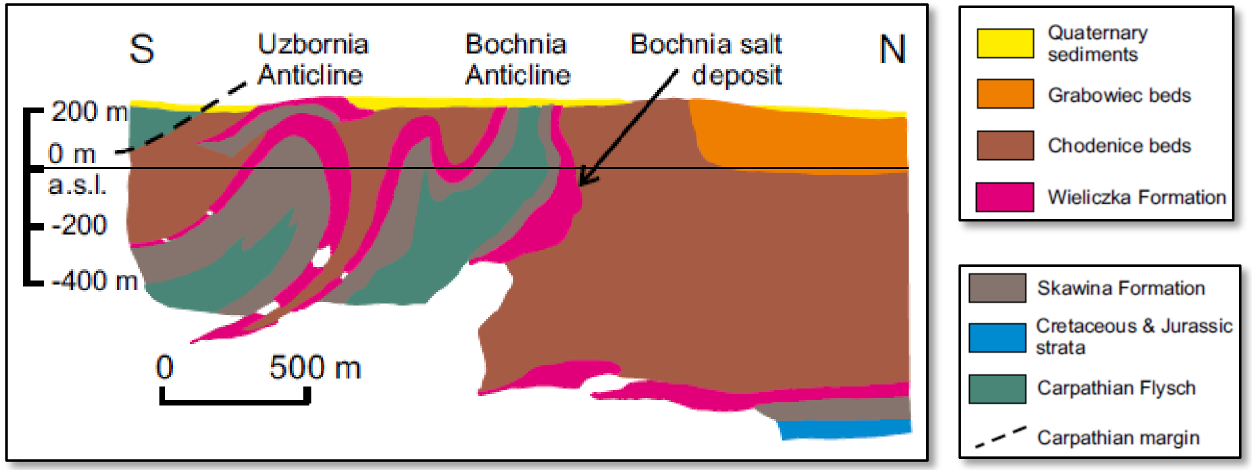
CASE STUDY
FORE-CARPATHIAN THROUGH

- **The Badenian salt deposits in the Carpathian Foredeep in the southern part of Poland**
  - Most of the deposits are intensively folded and imbricated in front of the Carpathian nappes.
  - Deposits of the salt-bearing formation occur at a depth from 50 to 800 m.
  - The salt layers are from several to several hundred (via tectonic duplication) meters thick and include a considerable admixture of clay and anhydrite.

Dotted line - conceptual geological model of anticline folds the Sambir thrust



Geological cross-section of the Bochnia salt deposit (cited from J.Wiewiórka, 2008, by Poborski, 1952 Garlicki, 2008)



CASE STUDY
FORE-CARPATHIAN THROUGH

Dependence of salt reserves on maximum production depth

- The salt body was delineated by the contour that includes rocks with density values varying in a range from 2.05 to 2.27 g/cm^3
- Minimum absolute depth to the salt top: +297 m
- Maximum absolute depth to the salt top: -1137.5 m
- Planar area: 9 km^2
- Total volume of the production salt-bearing rock – 2.44 km^3
- Total salt reserves: **3.25** **-** **3.81** **–** **4.77** billion tons
- Cost of reserves depending on halite content

  for **rock salt** (56$ per ton*) **–**

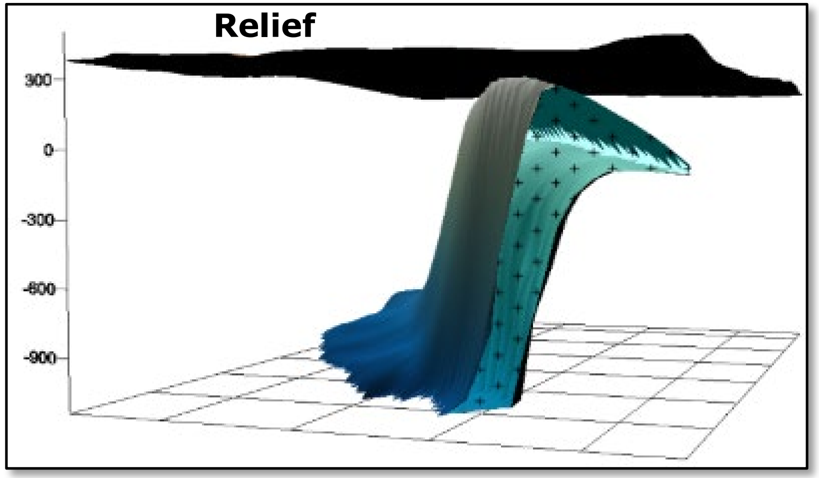
  182 – **214** – **267** billion $,

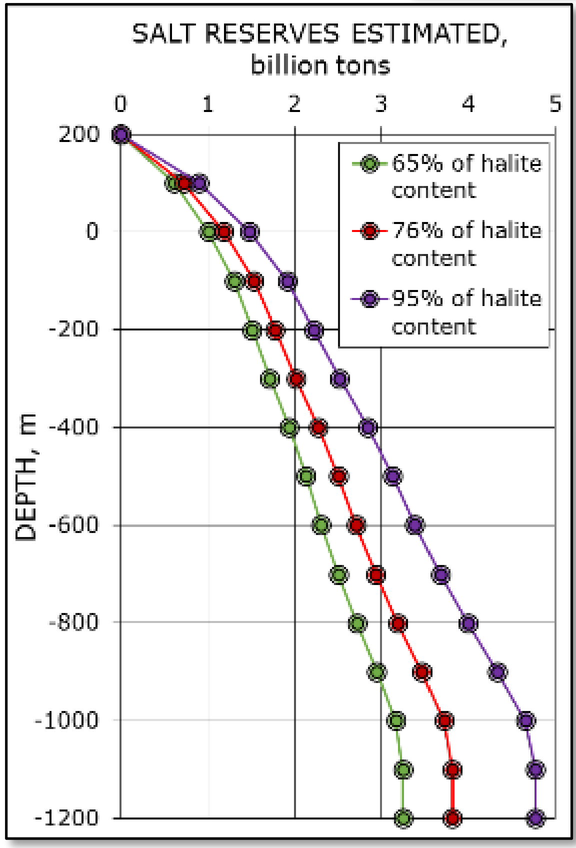
  for **vacuum and open pan salt** (220$ per ton*) **–**

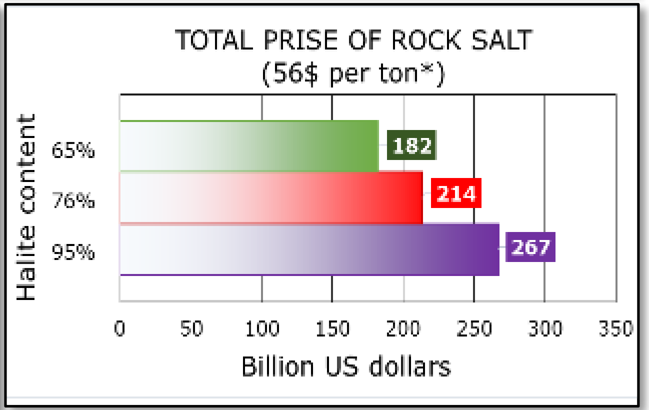
  715 – **839** – **1050** billion $

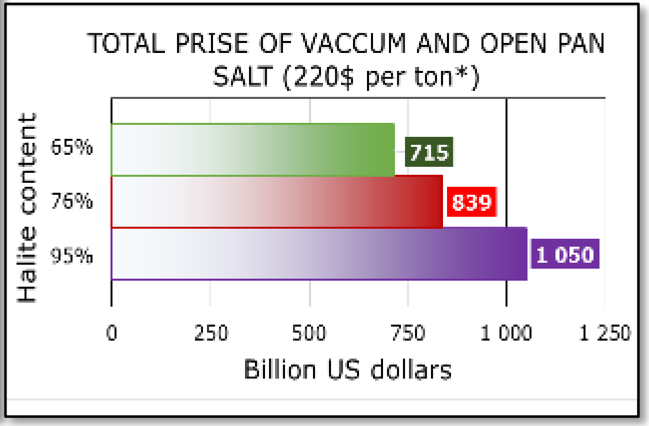
* https://www.statista.com/statistics/916733/us-salt-prices-by-type/

3D shape of the salt-bearing formation









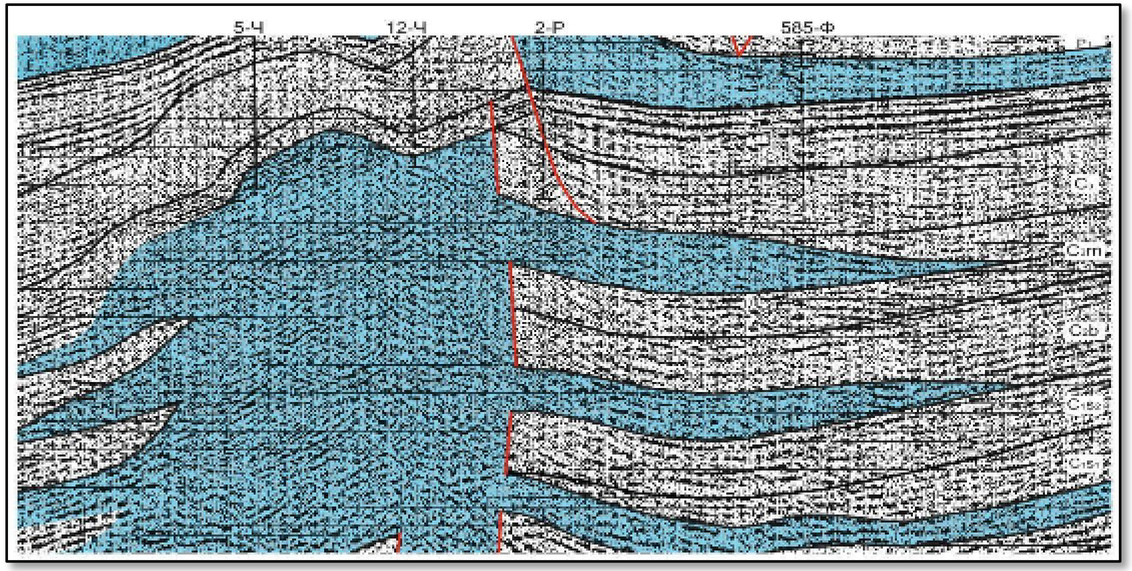
CASE STUDY
DNIEPER-DONETS BASIN, UKRAINE

CASE STUDY
DNIEPER-DONETS BASIN

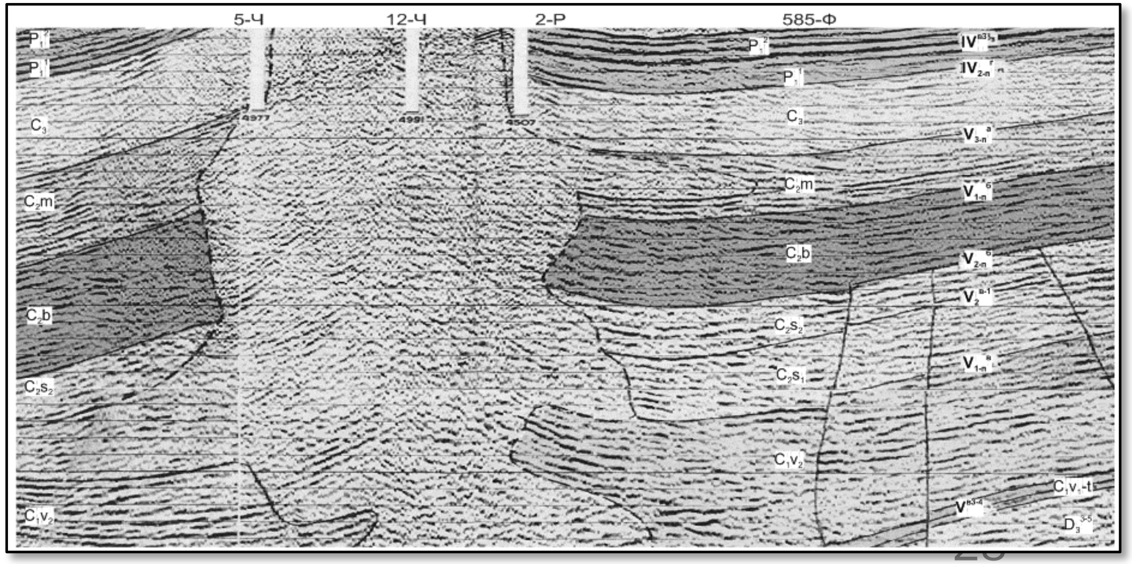
The study was performed in 2019 as a part of hydrocarbon exploration program on 2 old hydrocarbon fields being in the final stage of development

- **Study area:**
  - Size – 548 sq. km (25.5 x 21.5 km)
  - Depth to basement (AR-PR) ≈20 km
- **Survey performed:**
  - high-accuracy gravity survey (1:10 000) by digital gravimeters Scintrex CG-5 (Canada)
    Error ± 5.7 μkGal
  - high-accuracy magnetic survey (1:10 000) by cesium magnetometers Geometries G-859 (USA)
    Error ± 1.25 nTl
- **Study objectives:**
  - Commercial gas-bearing pools mapping
- **Salt deposits:**
  - Salt diapir in central part of the study area breaches over 10 km of Carboniferous-Permian sequence. The top of the salt (by borehole data) is -150 m below sea level

Interpretation models of salt diapir



by Larin S., UkrDGRI



by SE Ukrgeofizyka

CASE STUDY
DNIEPER-DONETS BASIN

Model dimensions

- Lateral – 25.5 x 21.5 km
- Depth – 25 km

Input data

- 2D legacy seismic data
- High precision gravity data
- Well logs
- Petrophysics by core

Initial density properties

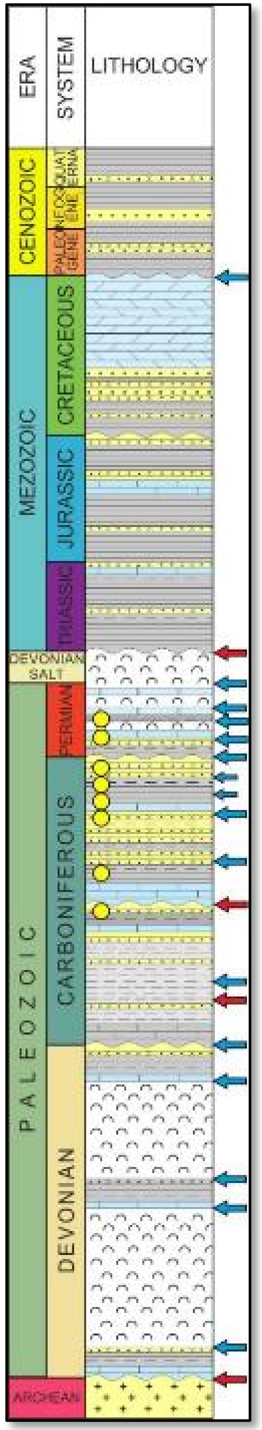
- Generalized core data
- Sonic log
- Lithology and saturation by well log interpretation

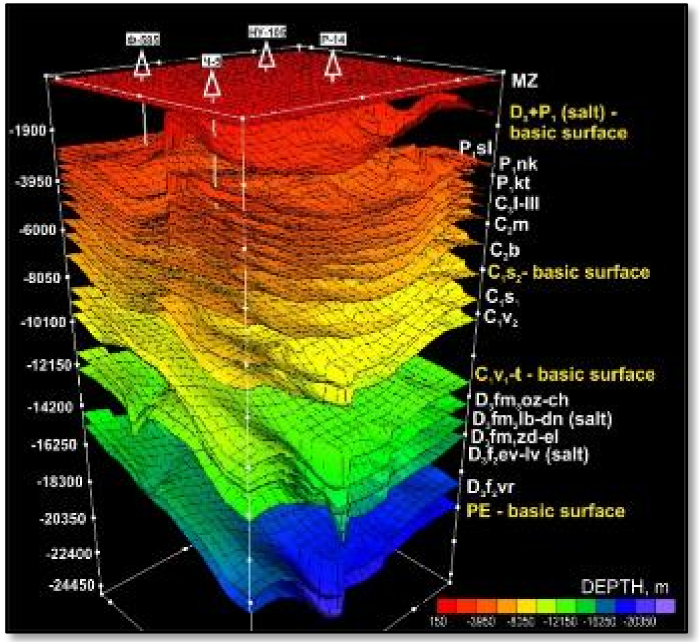
3D structural model

- **20** structural surfaces based on 2D seismic data and well tops:
- **4** basic stratigraphic surfaces: PE, C1t-v1, C1s2, D3+P1(salt)
- **16** intermediate stratigraphic surfaces: D_3f_2vr, $D_3f_2ev\text{-}lv$ (salt), $D_3fm1zd\text{-}el$, $D_3fm_2lb\text{-}dn$ (salt), $D_3fm_3oz\text{-}ch$, C_1v_2, C_1s_1, C_2b, C_2m, C_3-III, C_3-II, C_3-I, P_1kt, P_1nk, P_1sl+km, MZ

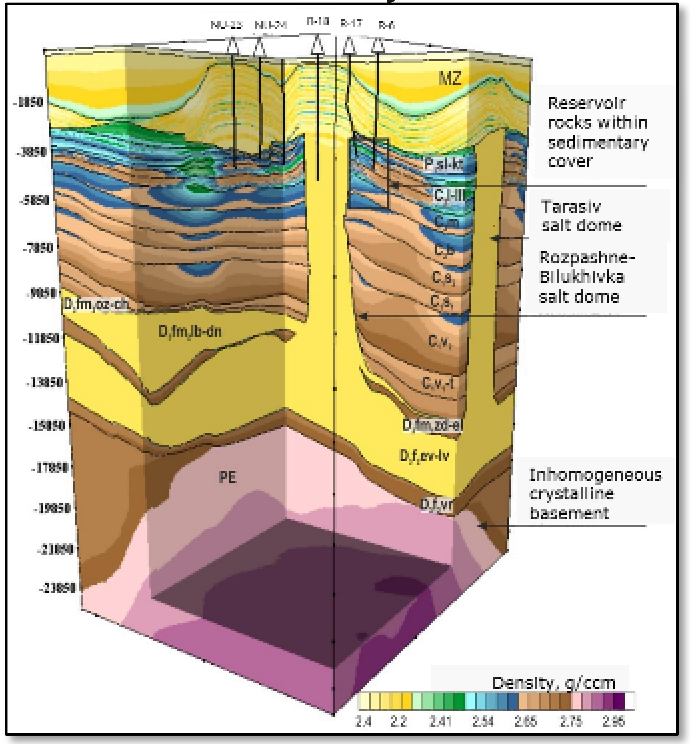
3D property model

- Parallelepiped as elementary cell, 100 m x 100 m x 20 m
- Voxel model consisting of 68.9 million of cells





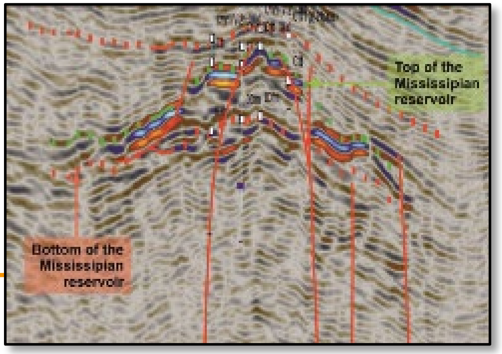
Final 3D density model

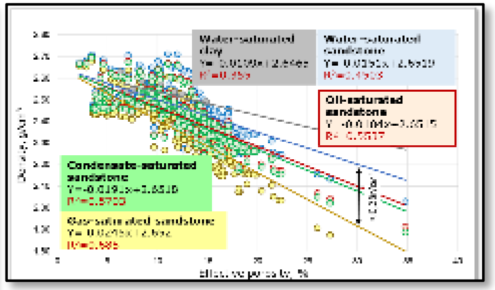


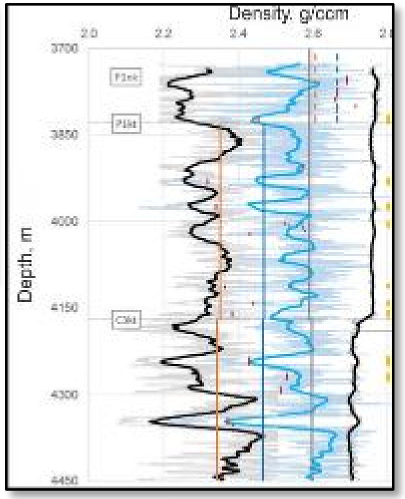
CASE STUDY
DNIEPER-DONETS BASIN

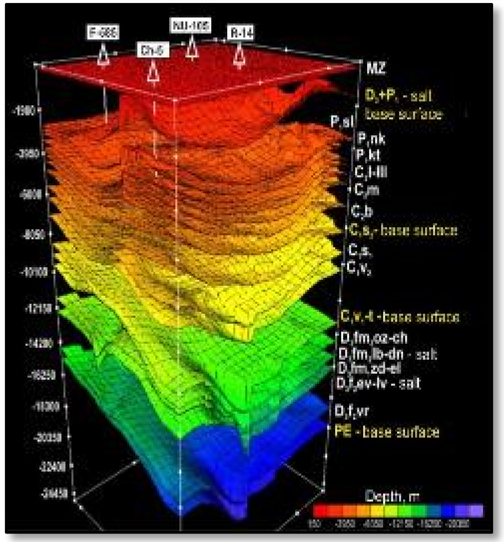
- **In order to solve geological tasks exploration activities involved:**
  - Comprehensive analysis and generalization of all available geophysical data set.
  - Creation of 3D density model based on the joint inversion of gravity, well log, seismic, well production and additional geological data.*
  - Final 3D structural model and 3D model of rock density were used to determine the shape of salt body, to trace new tectonic elements around the salt dome and to predict distribution of known and new gas-bearing reservoirs.

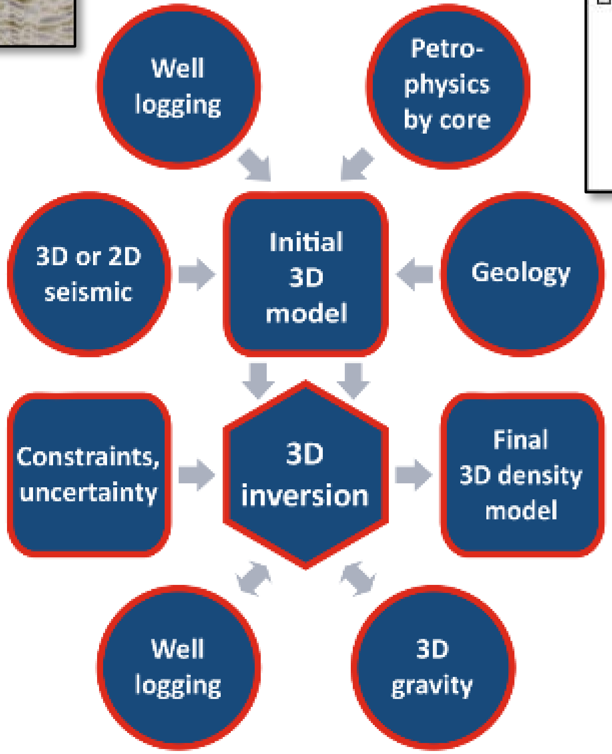
* Petrovskyy, 2005

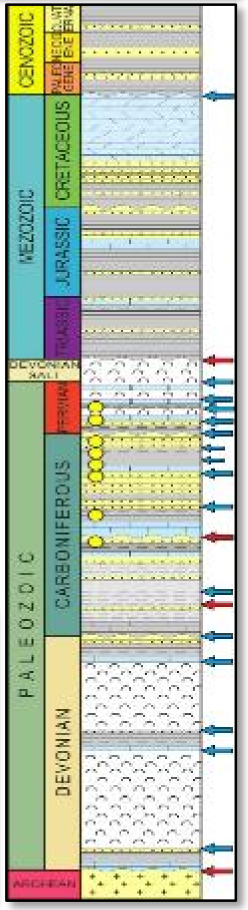




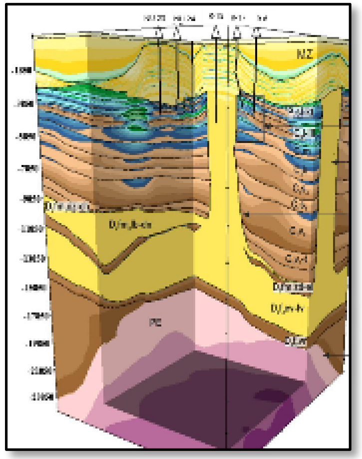


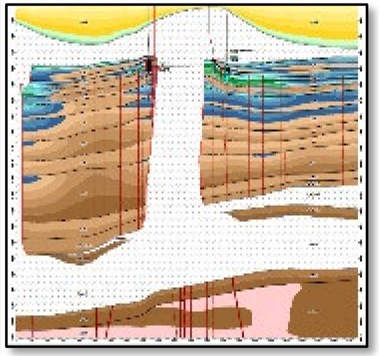




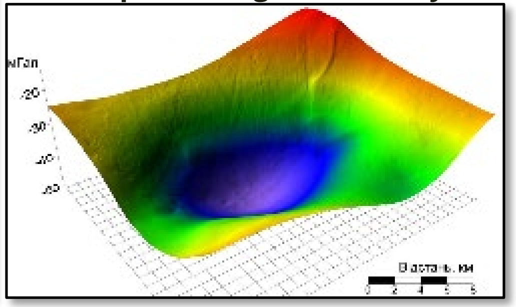


Final 3D density model



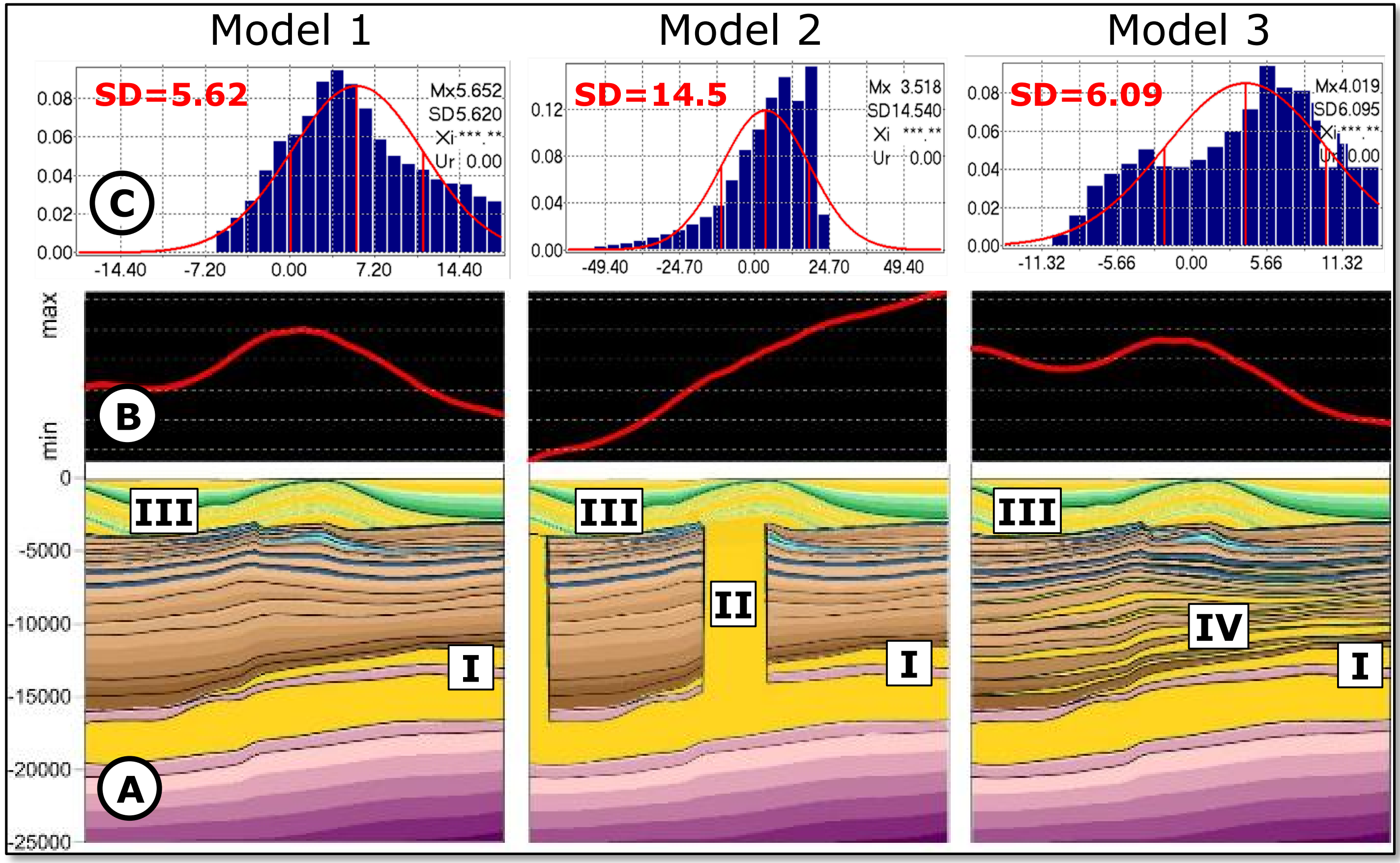


Complete Bouguer anomaly



CASE STUDY
DNIEPER-DONETS BASIN

- **Geologically consistent initial 3D models of rock density gravity verification for different cases of initial salt body shapes**
  - Due to significant uncertainties of salt mapping by seismic, three different models were considered as a basic model for further 3D gravity inversion
- **Base elements of the salt body shape**
  - **I** – Autochthonous salt layers in the Frasnian and Famennian formations of the Upper Devonian
  - **II** - Salt stem breaching Carboniferous-Permian overburden
  - **III** – Allochthonous salt sheet in Lower Permian formations
  - **IV** - Salt wings in the Middle and Lower Carboniferous formations



A – 3D model of rocks density cross-section

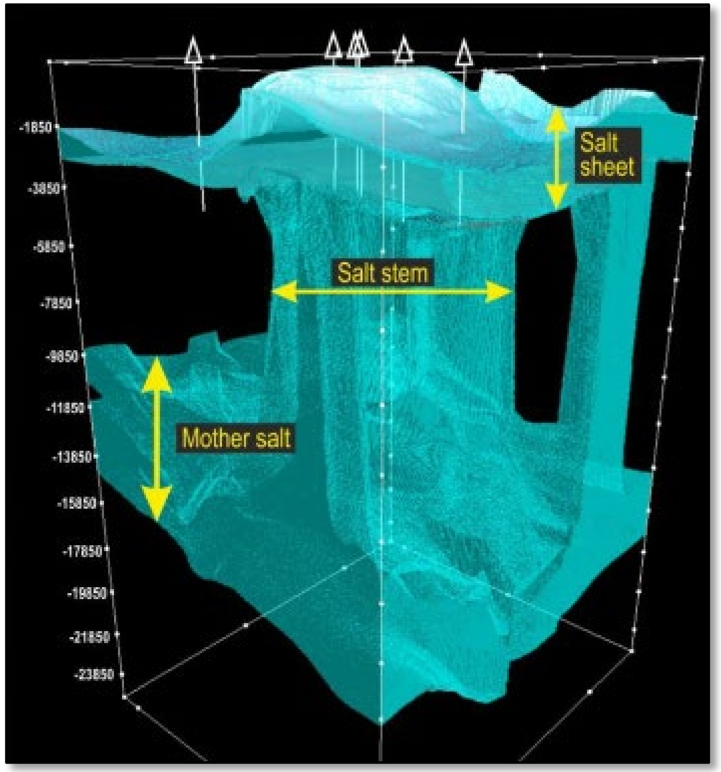
B – Observed and calculated gravity fields misfit

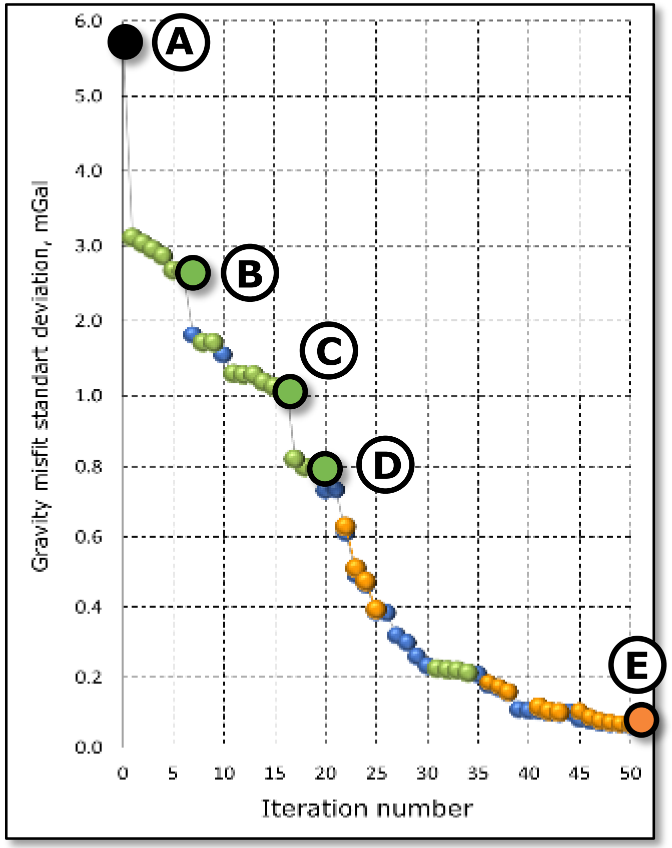
C – Gravity misfit histogram and standard deviation (SD) for normal distribution of a random variable (red line)

CASE STUDY
DNIEPER-DONETS BASIN

- **Determining the salt body shape by applying 3D non-linear gravity inversion**

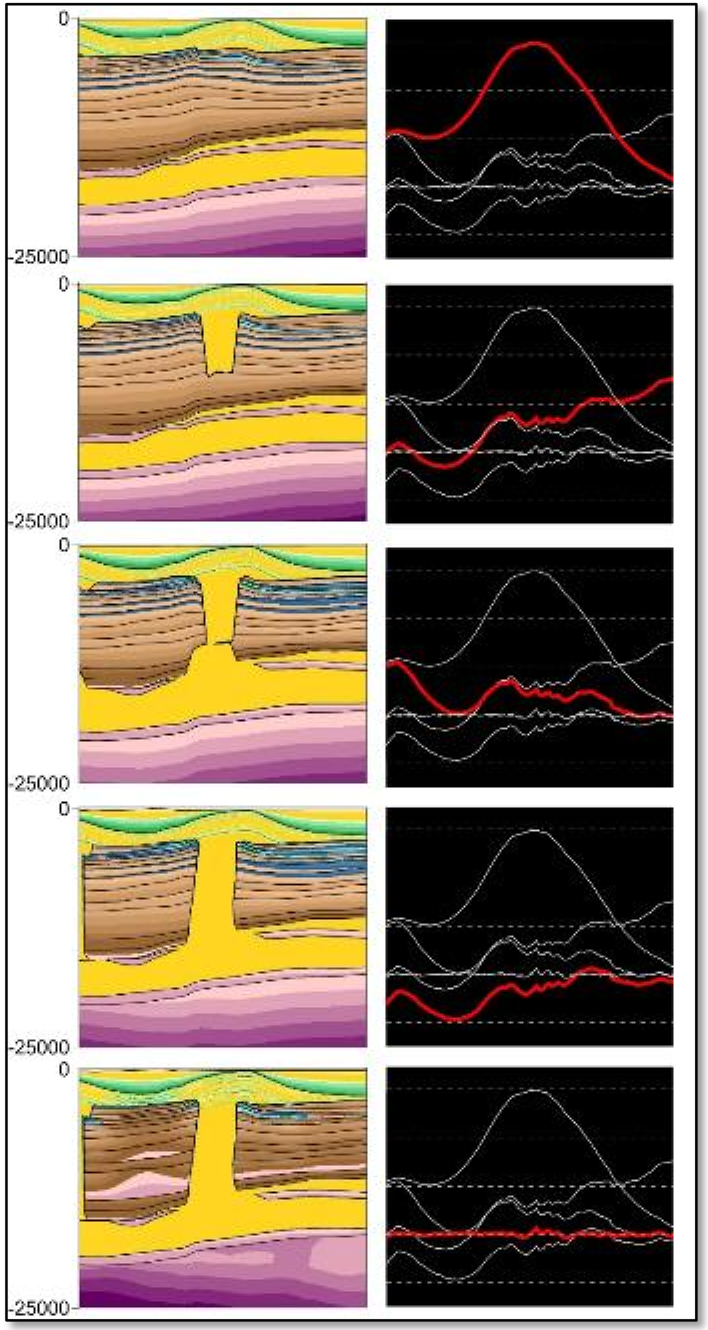
3D shape of salt body





- 3D non-linear gravity inversion
- 3D passive linear gravity inversion
- 3D active linear gravity inversion

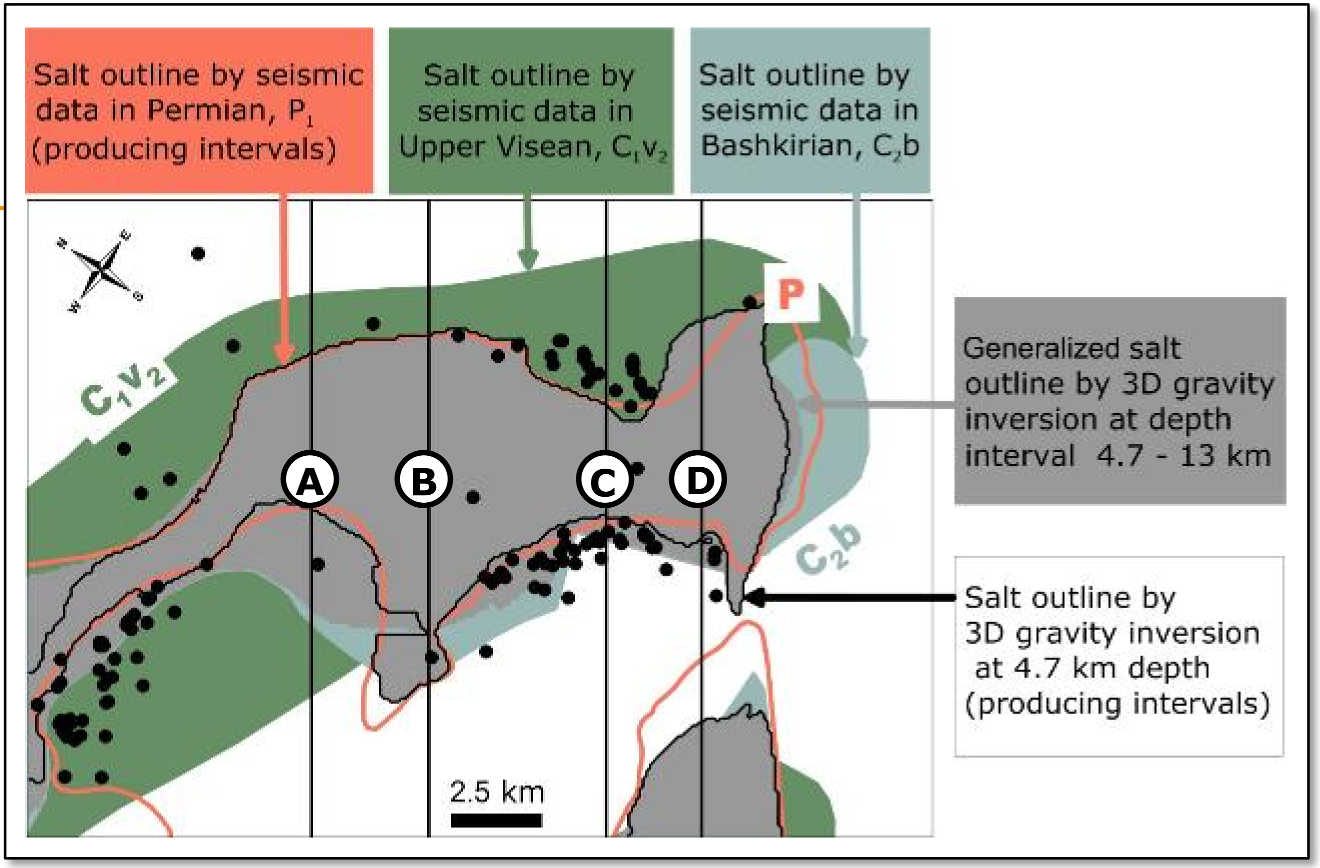
	3D model of rock density changes	Gravity misfit changes
A Initial model without salt dom. SD – 5.620 mGal		
B Model after Iteration 6. SD – 2.660 mGal		
C Model after Iteration 16. SD – 1.050 mGal		
D Model after Iteration 19. SD – 0.790 mGal		
E Final model after Iteration 52 with salt dom. SD – 0.065 mGal		



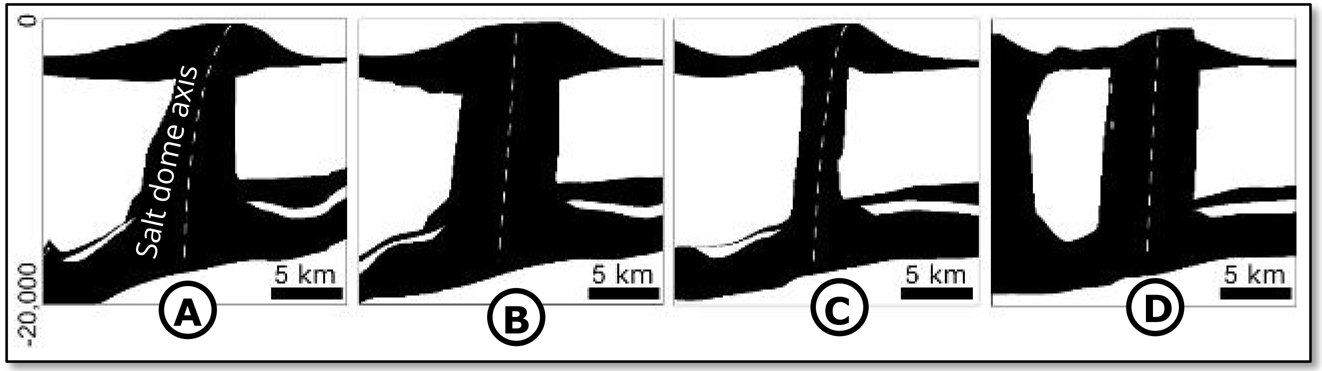
CASE STUDY
DNIEPER-DONETS BASIN

Comparison of the final 3D model of rock density with previous 2D seismic data interpretation

- Compare to the seismic data size of the salt dome:
- For the Visean strata is smaller
- For Permian and Upper Carboniferous is similar but there are two location where it is larger
- The axis of salt dome is inclined towards the Northern flank of Dnieper-Donets depression
- Southwestern wall of the salt dome is more gently slopped, northeastern wall is sub-vertical (with negative angle)



A – cross-sections



CASE STUDY
TRANSCARPATHIAN BASIN, UKRAINE

CASE STUDY
TRANSCARPATHIAN THROUGH

The study was performed in 2010 as a part of hydrocarbon re-exploration project within two operating gas fields

Study area:

- Location – Transcarpathian Through
- Size – 144 km^2 (14.4 x 10 km)
- Depth to the basement ≈7 km

Study objectives:

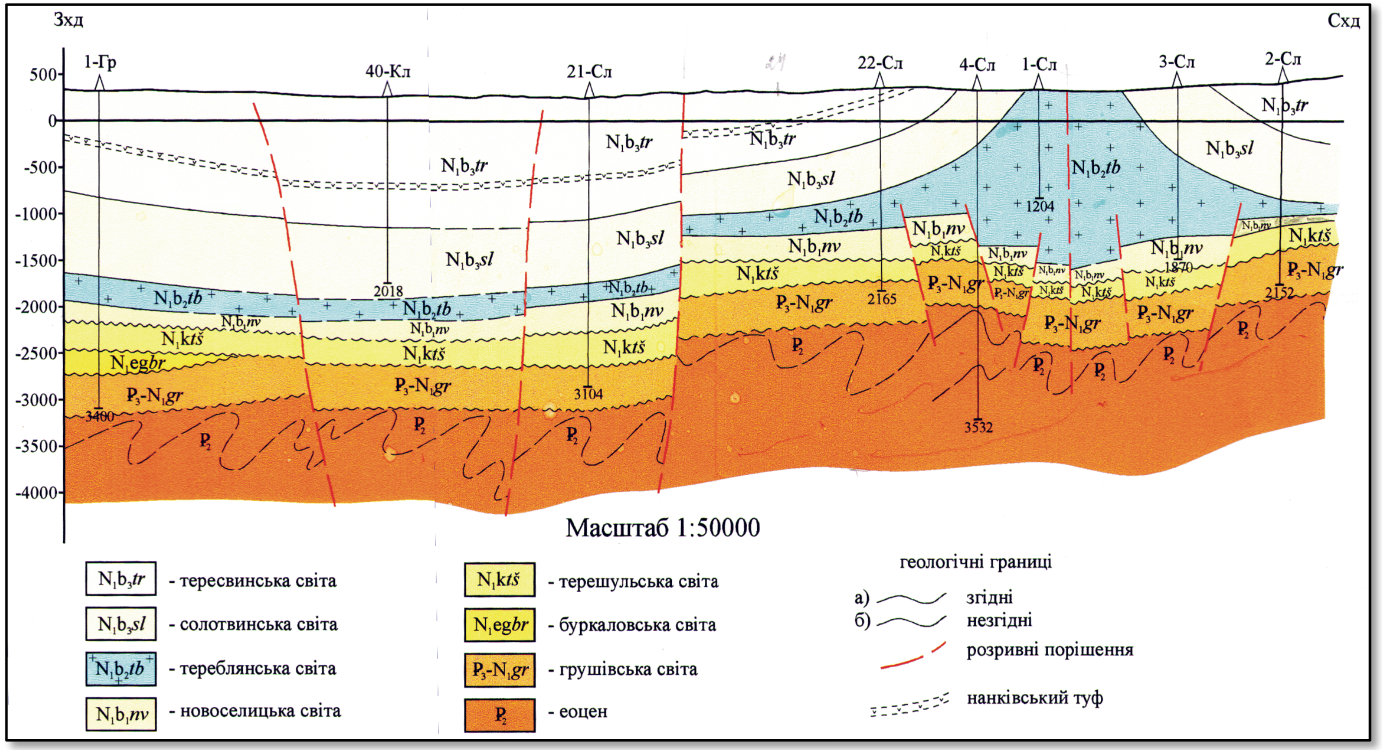
- Commercial gas-bearing pools mapping

Salt:

- Tereblja Formation salt pierces Neogene clastic sequence and outcrops to the west from the field. Due to alternation with clastics rocks on the top and bottom of salty sequence the last is not imaged on the seismic data.

Tectonic scheme of Carpathian region

Geological cross-section by P. Lozyniak, Yu. Malevych, 2005



CASE STUDY
TRANSCARPATHIAN THROUGH

Model dimensions
- Lateral 14.4 x 10 km
- Depth 7 km

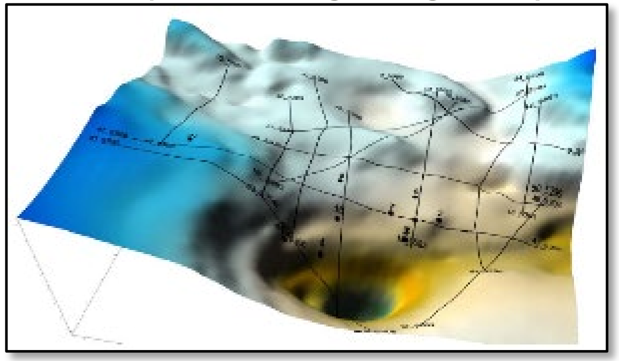
Input data
- 2D legacy seismic
- Complete Bouguer gravity (1:50 000)
- Well logs
- Petrophysics by core

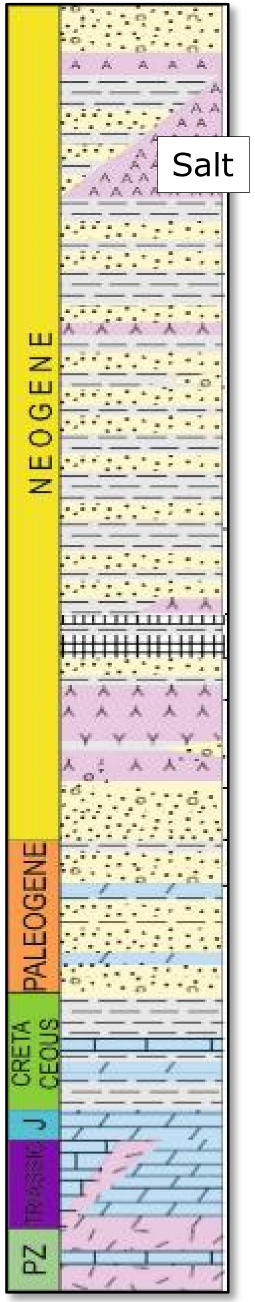
Initial density properties
- Generalized core data
- Sonic log
- Lithology and saturation by well log interpretation

Structural model
- 7 structural surfaces featuring the structure of Neogene and Paleogene formations

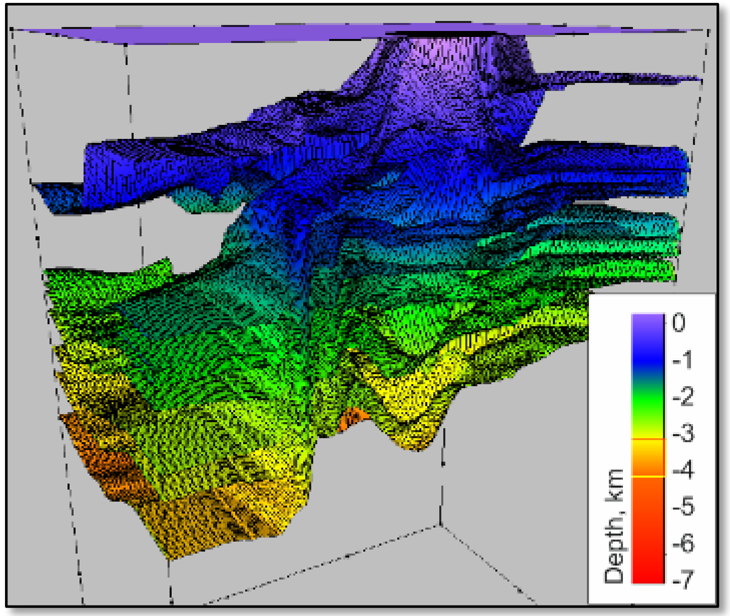
Property model
- Parallelepiped as elementary cell, 100 m x 100 m x 50 m in size
- Voxel model consisting of 2 million of cells

Complete Bouguer gravity

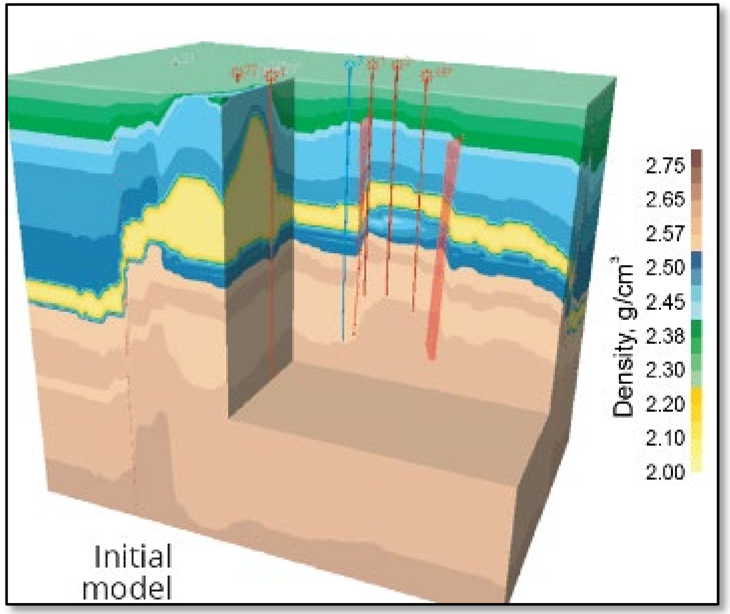




Initial 3D structural model



Initial 3D model of rock density



CASE STUDY
TRANSCARPATHIAN THROUGH

Salt body shape by input data - Ⓐ

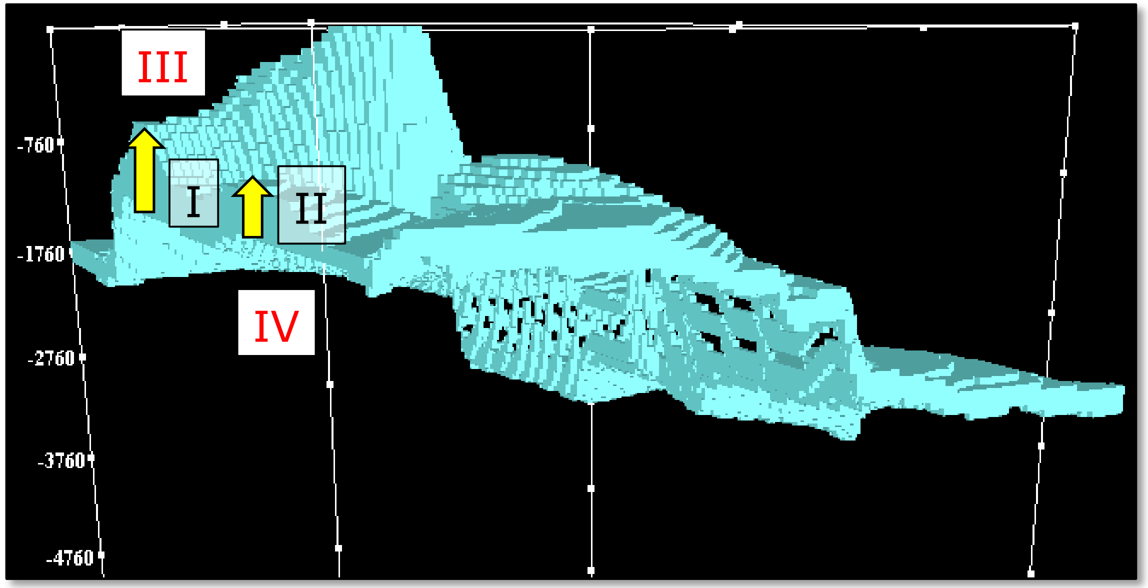
Data used to create the initial 3D structural model of the salt body:

- 2D geological cross-sections
- Salt outcropping contour
- Salt body contour at absolute depth level of 0 m
- Stratigraphic well tops from 3 boreholes

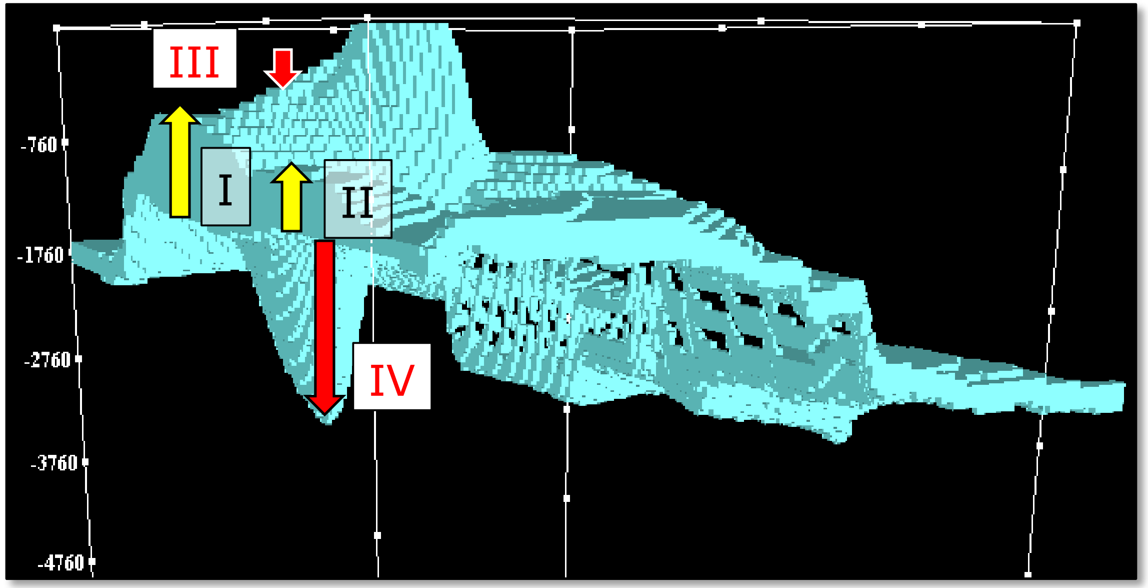
Salt body shape by 3D gravity inversion - Ⓑ

- Significant increase of salt-bearing deposit thickness (I and II)
- Salt bottom reaches -2680 m depth which is 1420 m deeper than in the initial 3D structural model before applying 3D non-linear gravity inversion (IV)

Ⓐ



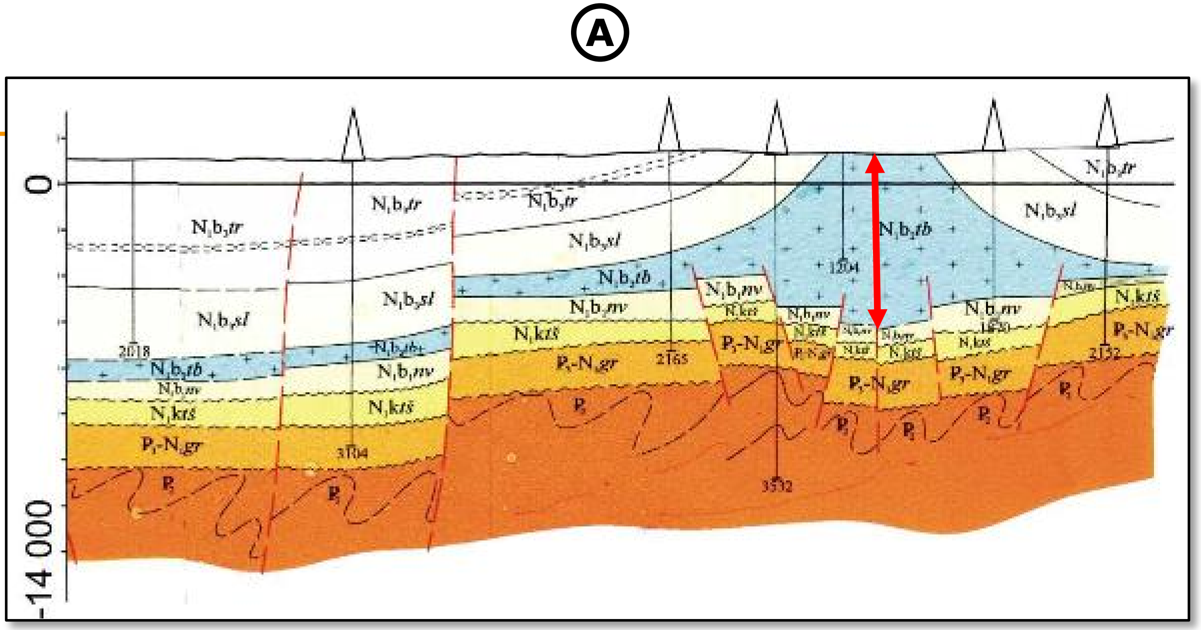
Ⓑ

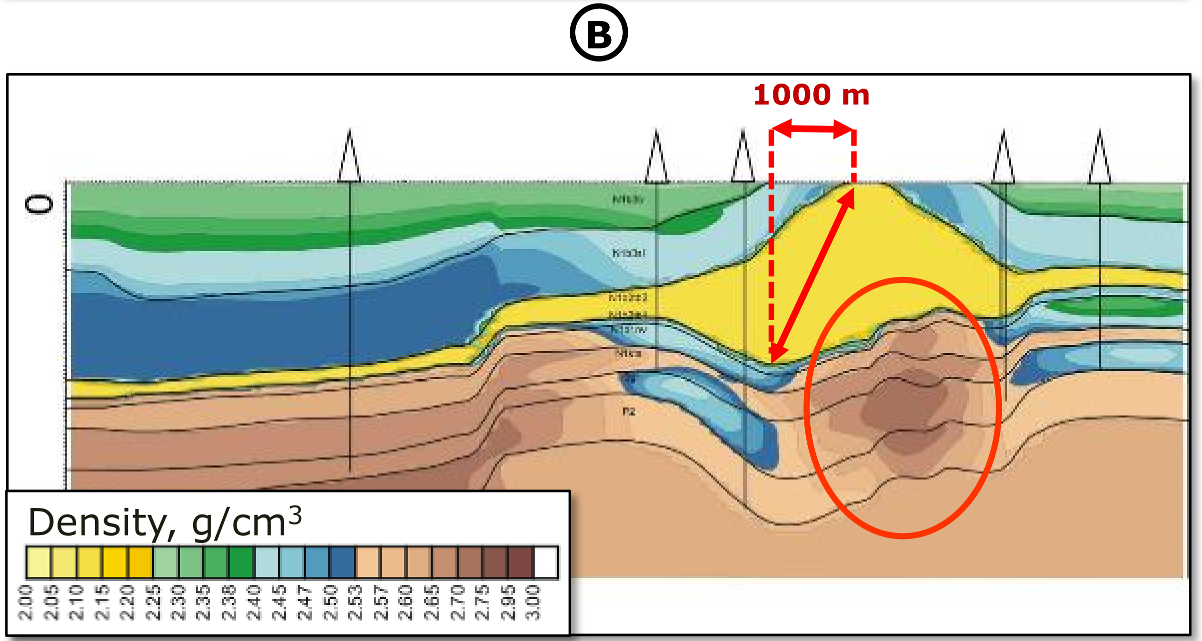


CASE STUDY TRANSCARPATHIAN THROUGH

Conclusion by 3D gravity inversion results

- Unlike the initial geological structure (A), 3D gravity inversion results showed that the horizontal projection of the most deeply buried (>2 km) part of the salt body does not match the position of the salt outcrop.
  There is more than 1000 m lateral shift to the west of structure – read arrow (B)
- An uplifted block of high density rocks has been mapped under the salt-bearing deposit below its outcropping. Apparently, vertical movements of the block caused redistribution of salt and its outcrop placement
- The value of rock density inside mapped block indicates its intrusive origin. This confirmed by the well drilling result. Intrusive vein formations have been opened by the well





CONCLUSIONS AND RECOMMENDATIONS

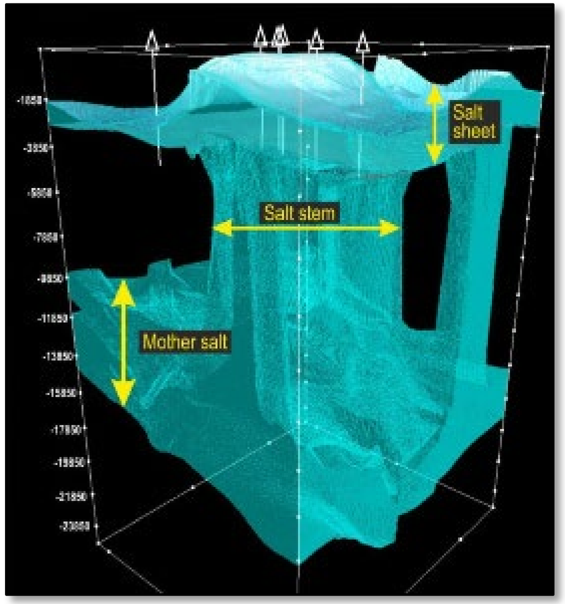
CONCLUSIONS

- The technology for commercial salt deposits mapping by 3D gravity, well log and seismic data inversion has been developed and implemented for exploration with geological success rate over 85%.
- New large deposit of table salt has been mapped in the territory of Ukraine. Estimated salt reserves – 4.77 billion tons. Cost of the reserves with total current price for vacuum and open pan salt production is 1050 billion $.

CONCLUSIONS AND RECOMMENDATIONS

PROPOSALS

- To found a joint venture for salt production fro discovered deposit in Western Ukraine
- To apply the «Technology for commercial salt deposits mapping by 3D gravity, well log and seismic data inversion» for re-exploration of known commercial salt deposits within the licenses owned by the venture
- To apply the «Technology for commercial salt deposits mapping by 3D gravity, well log and seismic data inversion» in order to discover ne commercial salt deposits within the licenses owned by the venture and new prospective areas in Europe and worldwide



TECHNOLOGY FOR COMMERCIAL SALT DEPOSITS MAPPING BY 3D GRAVITY, WELL LOG AND SEISMIC DATA INVERSION

DEPROIL
DETAILED OIL & GAS PROSPECTING