Downhole Gravity Gradiometry: A New Technique for Prospect and Reservoir Modeling?*

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Abstract

With modern E&P geophysics, potential field methods have overcome their classic limitation to reconnaissance surveys; nowadays they are standard procedures for prospect level applications, and reservoir scale studies are no longer exotic.

Over the last decade new tools for measuring gravity gradients emerged on the oil and gas exploration market. As their focus lies particularly on detecting rock density contrasts in short to medium distances, borehole utilizations are obvious. Compared to surface measurements gradient surveys in a well would benefit from the closer distance of the instrument to the causative sources, i.e. to the geological targets.

Gravity gradiometry in boreholes was described first in 1989, and a few studies addressed possible applications. However, motivated by novel downhole instrument developments, and with advanced 3-D modeling, inversion and visualization tools available, the integration of gradient data from wells into modern interpretation workflows can be realized, and their benefits for geological reliability evaluated.

Thus the focus of our study is on the interpretation side, and a couple of scenarios aiming to reduce subsurface uncertainty (or model ambiguity) will be presented. All forward calculations and inversion routines are based on a 3-D voxel model with a flexible density allocation and an adaptive geometry definition by horizon grids and triangulated geobodies.

In the first case we discuss 4-D reservoir monitoring applications with borehole gravity gradients, and why the expected results are feasible up to distances of 10s to 100s of meters. The second example demonstrates the value of surveying directional gradients in the

well, particularly for identification of dipping horizons. Finally, the benefits of integrating downhole gravity tensor data into classic 3-D structural interpretation are estimated by applying advanced inversion evaluation tools. It is shown that a typical base of salt horizon could be defined significantly better if gradient data from a well were available.

This study's results show that subsurface modeling can increasingly benefit from borehole gravity gradiometry, not only due to the decreased distance to the target, but also due to its lateral sensitivity. Proper constraints and parameter correlations as well as appropriate modeling and inversion tools are required to gain maximum advantage of the method, extend its limitations and fully integrate it into joint interpretation workflows.

Reference

Nekut, A.G., 1989, Borehole gravity gradiometry: Geophysics, v. 54/2, p. 225-334.

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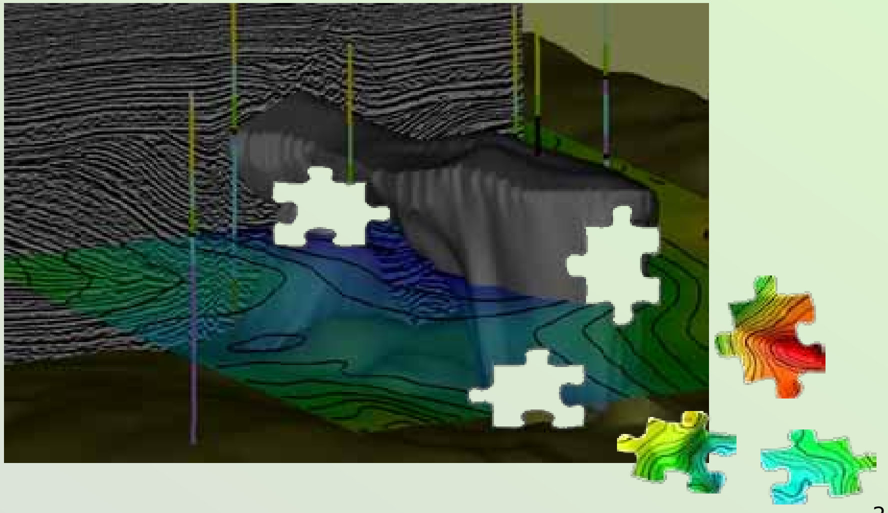
Outline

- Introduction
- Case A: Reservoir Monitoring (OWC/GWC Prediction)
- Case B: Dipping Horizon Recognition
- Case C: Integration with 3D Structural Interpretation
- Conclusions



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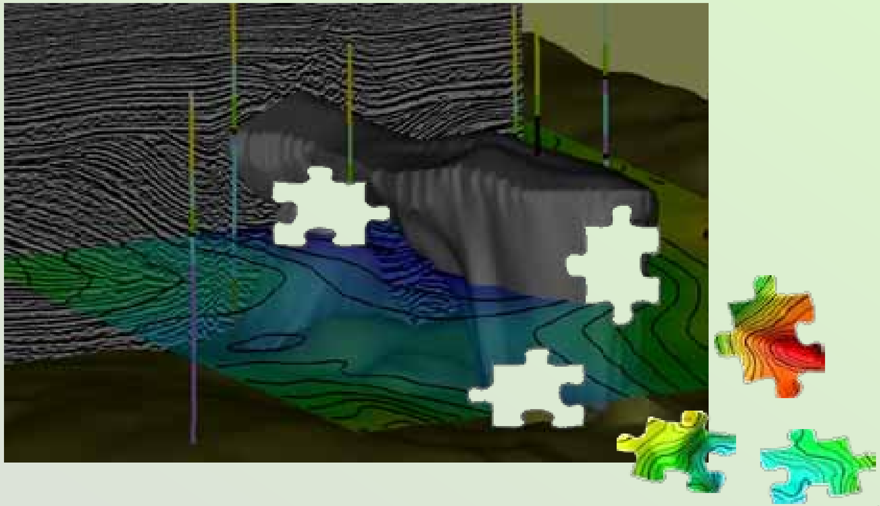
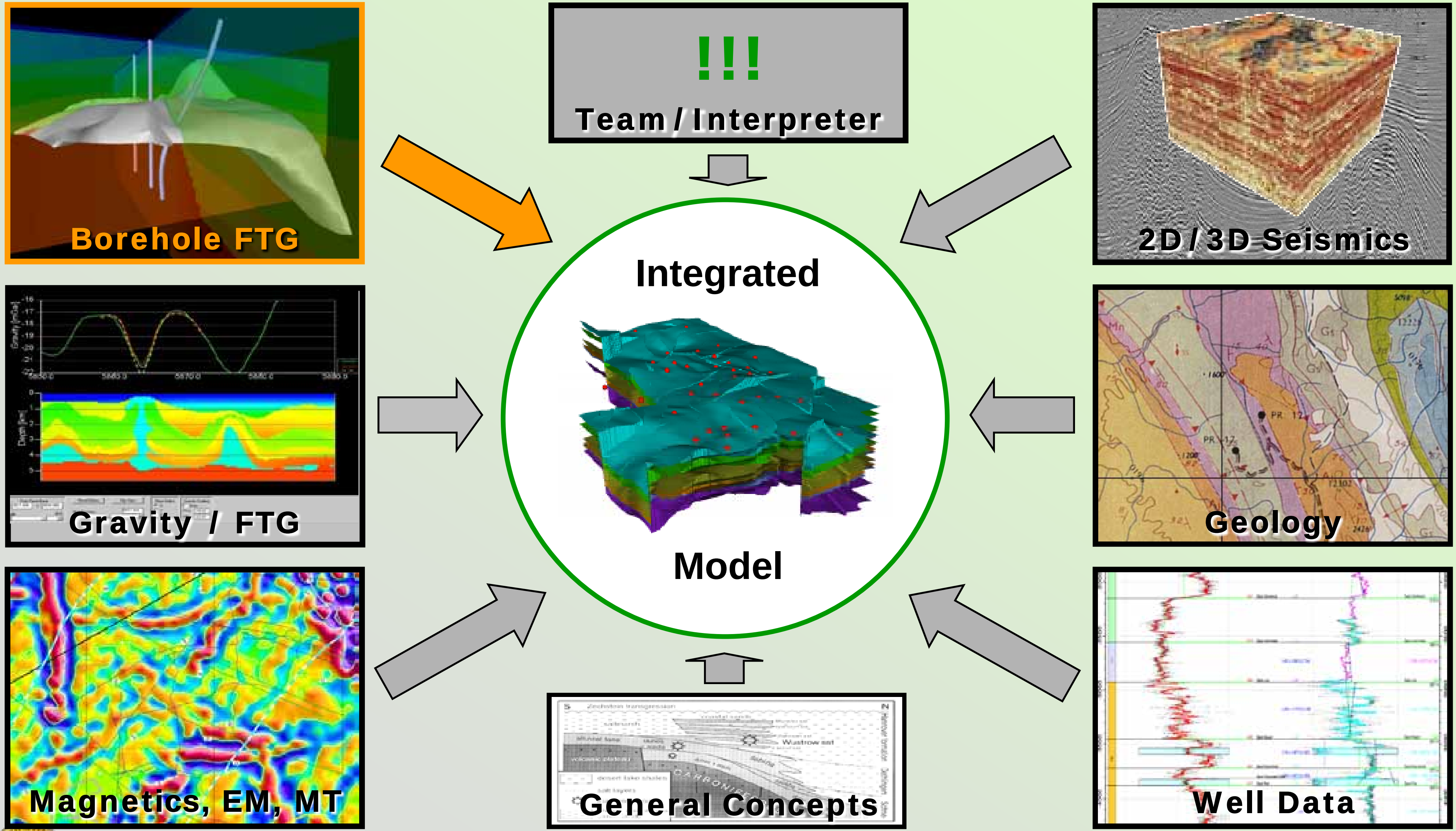


Introduction

- Borehole Gravity Gradiometer Measurements (BGGM) will be available soon
- Appropriate modeling, inversion and interpretation techniques are being developed and evaluated
- For different applications this method’s specific benefits and limitations need to be addressed
- Three scenarios will be discussed here

Enhance Interpretation with Gravity & FTG



!!!

Team / Interpreter

Borehole FTG

2D / 3D Seismics

Integrated Model

Gravity / FTG

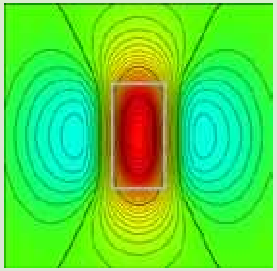
Geology

Magnetics, EM, MT

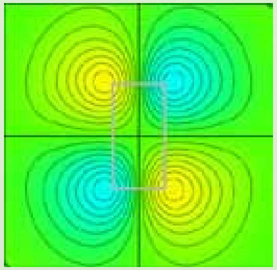
General Concepts

Well Data

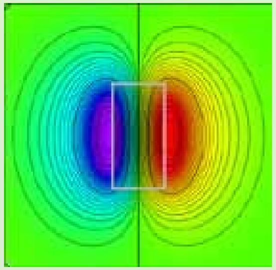
Surface FTG – Information



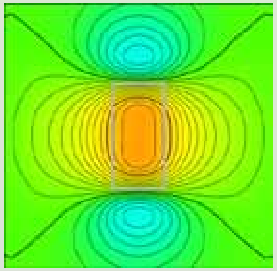
Gxx
Edges



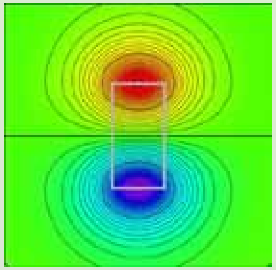
Gxy
Corners



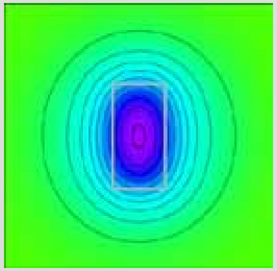
Gxz
Edges



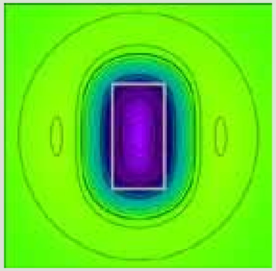
Gyy
Edges



Gyz
Edges

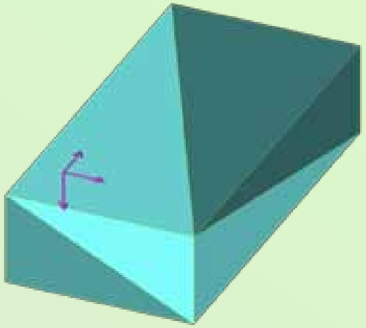


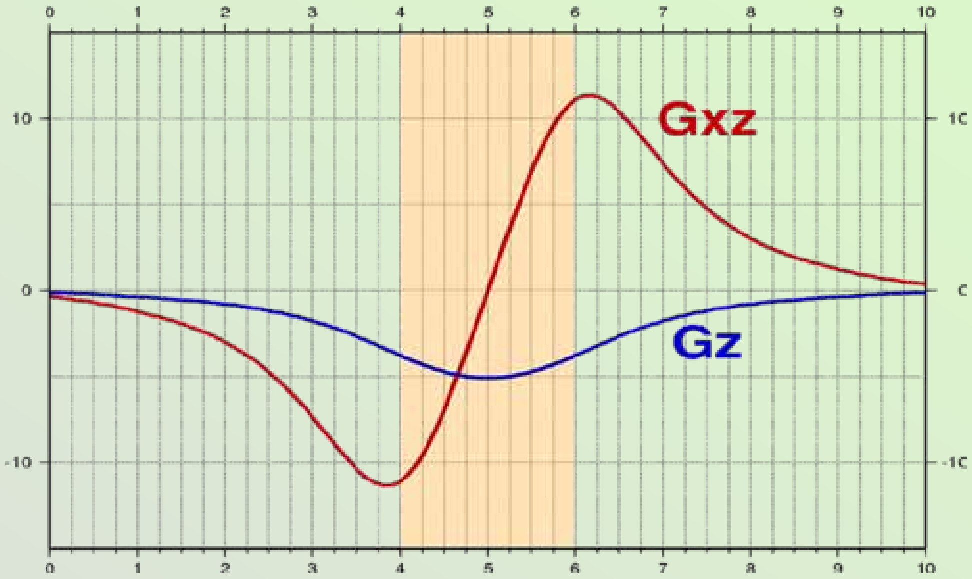
Gz



Gzz
Body

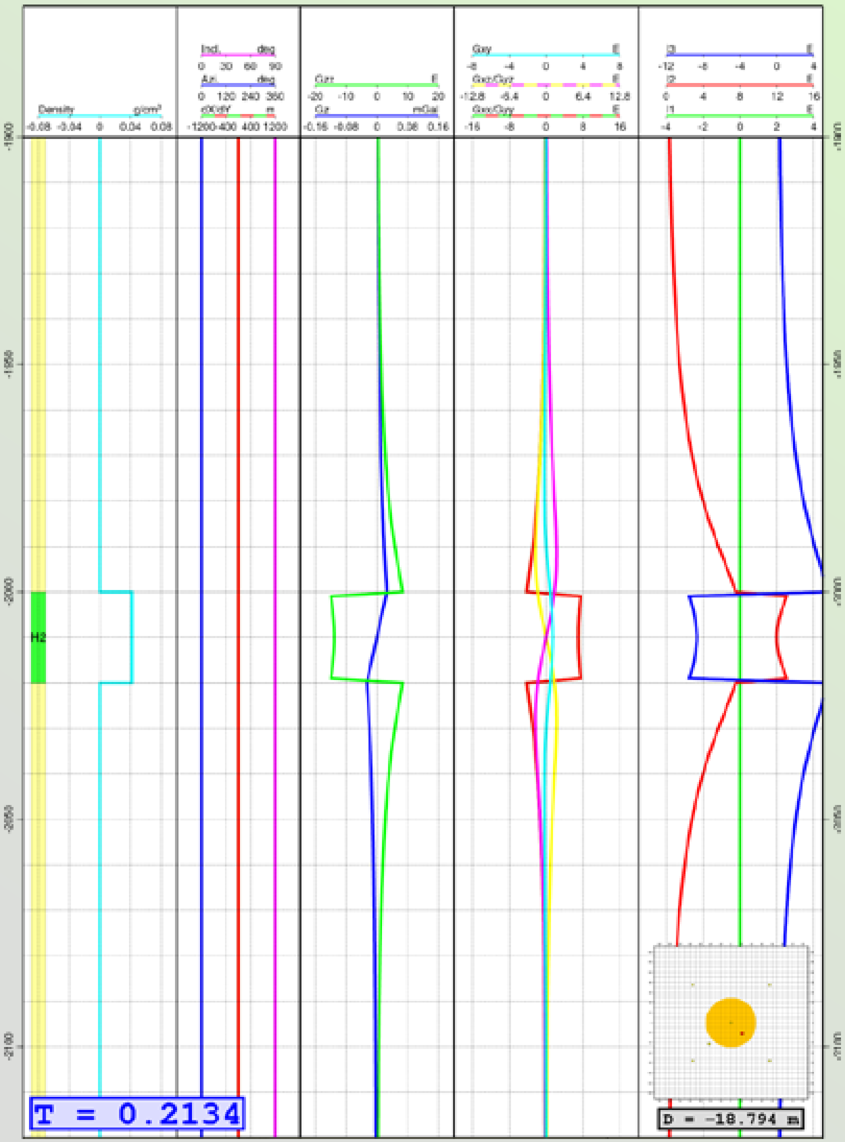
Example: Cuboid 2 x 4 x 1 units





Eötvös (E) 1 E = 10^{-9} (m/s^2)/m = 10^{-4} mGal/m
= 0.1 mGal/km = 0.1 µGal/m

FTG – Well Log Measurements



Deviation data if applicable is indicated in the second column, showing azimuth, inclination and deviation in the x and y direction.

The calculated gravity/gradient values are drawn in columns three (G_z: blue, G_{zz}: green) and four (G_{xx}: green, G_{yy}: red, G_{xz}: yellow, G_{yz}: magenta, G_{xy}: cyan).

All components of the FTG tensor and G_z are plotted to show the complete picture, as well as three rotational invariants shown in the right-most column.

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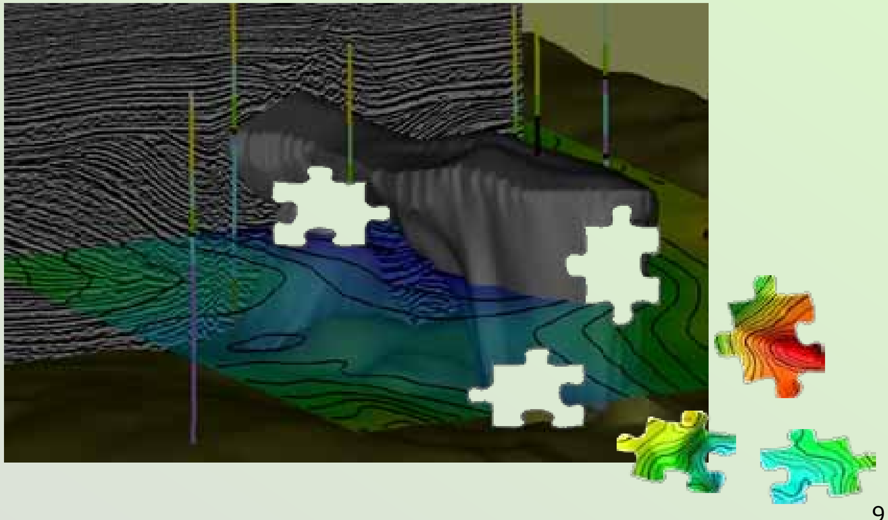
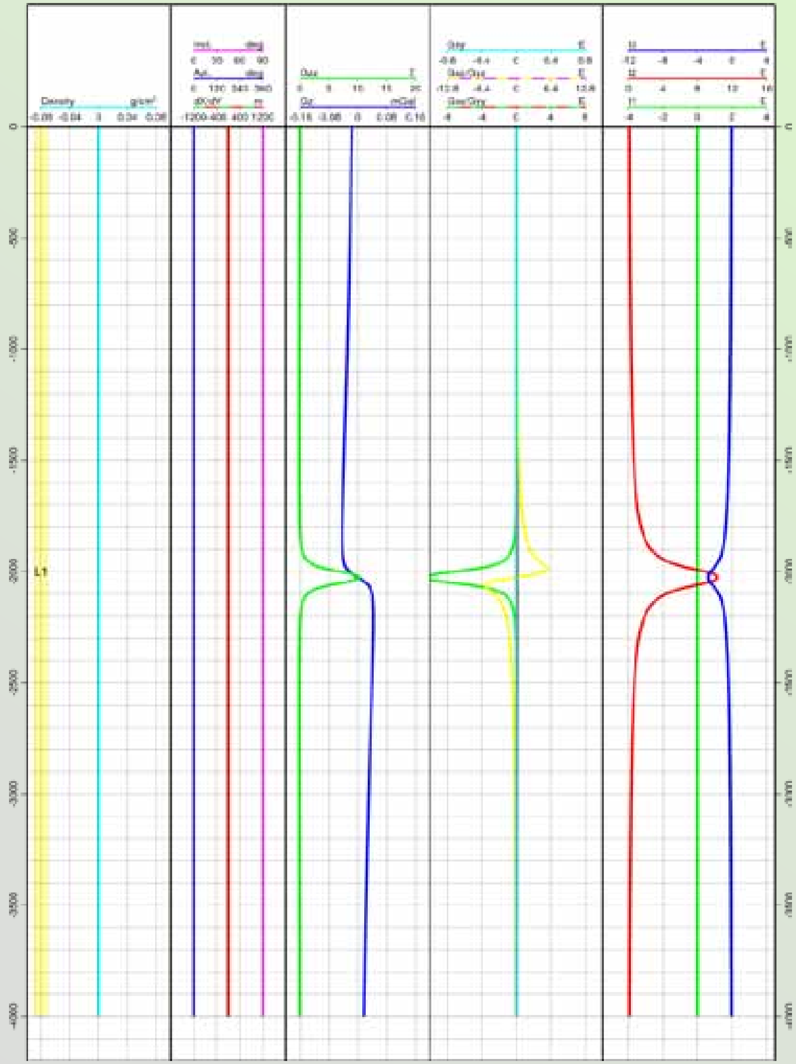


Case A: Reservoir Monitoring (OWC Prediction)

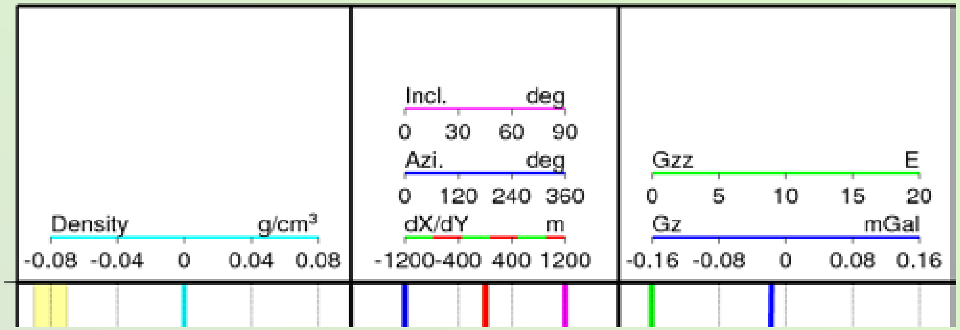
- Reservoir extension of 3 km x 3 km with 50 m thickness at 2000 m depth (top)
- Density contrast inside to outside of reservoir: 50 kg/m^3 based on assumed porosity of 22% and an oil-water density contrast of 225 kg/m^3
- Array of 15 wells placed along the x-axis from x=-1.500 km (center of reservoir) to x=+1.500 km with the OWC at x=0
- Gz, FTG components and 3 rotational invariants (I1-I3) are calculated from the surface down to 4000 m depth.

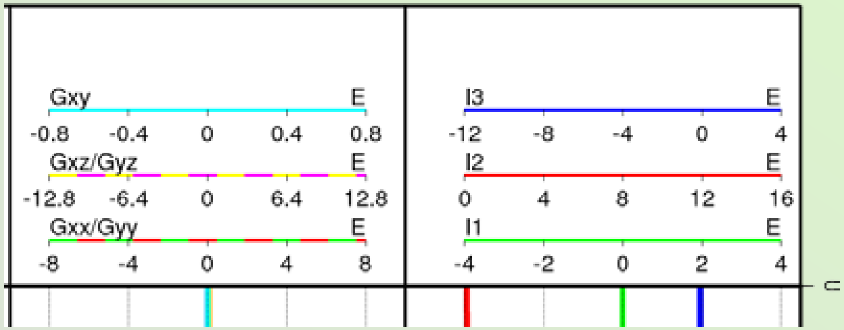
Case A: OWC Model Effect



x=+0.025 km

Zoom-in:





Case A: OWC Model Effect

	x=-1.500 km	x=-0.125 km	x=+0.005 km	**x=+0.025 km**	x=+0.100 km
Gz [mGal]	-0.103/0.103	-0.095/0.098	-0.048/0.048	**-0.043/0.043**	-0.035/0.035
Gzz [E]	-0.629/41.299	-2.799/39.068	-0.222/17.979	**-0.191/10.102**	-0.140/3.022
Gxx [E]	0.081/0.315	0.036/2.675	-18.177/0.043	**-10.298/0.036**	-3.208/0.025
Gyy [E]	0.081/0.315	0.063/0.216	0.060/0.198	**0.060/0.196**	0.058/0.185
Gxz [E]	-0.000/0.000	-1.314/1.314	-15.396/15.396	**-5.878/5.878**	-1.642/1.642
Gyz [E]	-0.000/0.000	-0.000/0.000	-0.000/0.000	**-0.000/0.000**	-0.000/0.000
Gxy [E]	-0.000/0.000	-0.000/0.000	-0.000/0.000	**-0.000/0.000**	-0.000/0.000
I2 [E]	0.140/5.107	0.116/10.649	0.111/18.935	**0.110/10.287**	0.108/3.123
I3 [E]	-0.396/1.599	-1.172/2.824	-4.142/-0.081	**-2.745/-0.080**	-1.217/-0.078

Case A: GWC Model Effect

x=+0.250 km

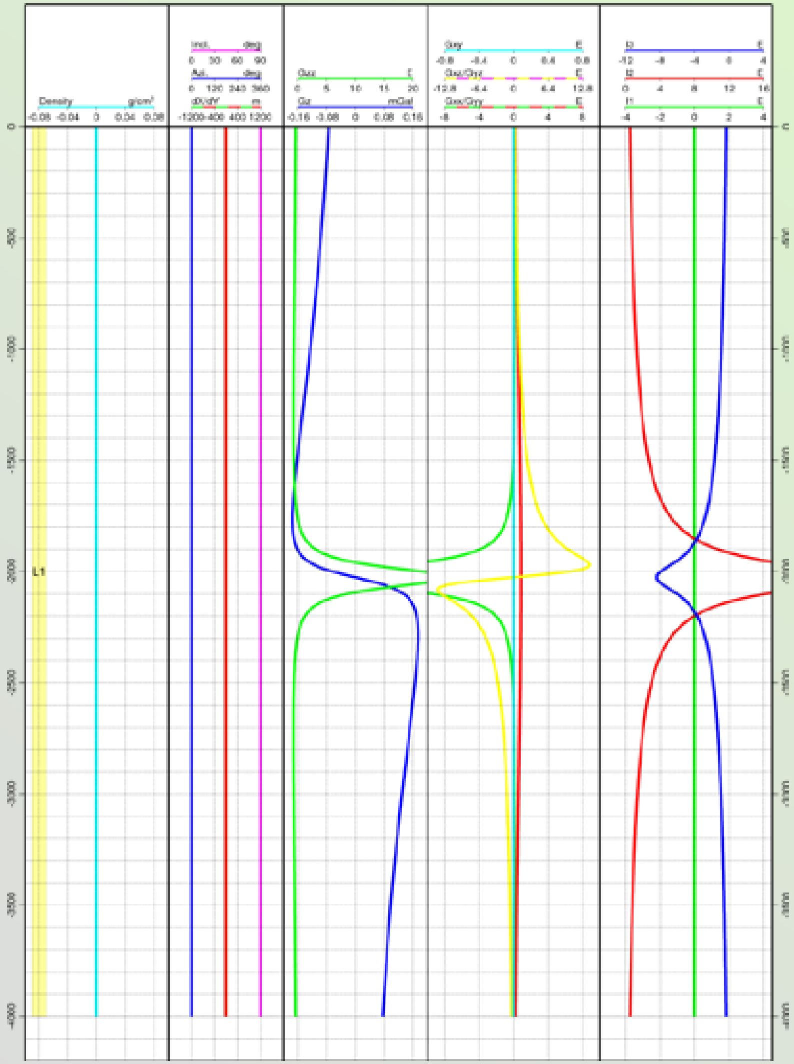
Case A: GWC Model Effect

	x=-1.500 km	x=+0.005 km	x=+0.025 km	**x=+0.250 km**	x=+0.500 km
Gz [mGal]	-0.454/0.452	-0.212/0.212	-0.191/0.191	**-0.115/0.115**	-0.081/0.081
Gzz [E]	-2.767/120.221	-0.979/79.273	-0.842/44.661	**-0.406/4.854**	-0.239/2.028
Gxx [E]	-60.110/1.383	-80.145/0.189	-45.521/0.157	**-5.582/0.066**	-2.618/0.011
Gyy [E]	-60.110/1.383	0.265/0.872	0.263/0.860	**0.240/0.728**	0.214/0.590
Gxz [E]	-0.000/0.000	-66.580/67.743	-25.833/25.857	**-2.839/2.839**	-1.311/1.311
Gyz [E]	-0.000/0.000	-0.000/0.000	-0.000/0.000	**-0.000/0.000**	-0.000/0.000
Gxy [E]	-0.000/0.000	-0.000/0.000	-0.000/0.000	**-0.000/0.000**	-0.000/0.000
I2 [E]	0.614/104.114	0.489/83.739	0.485/45.339	**0.447/5.257**	0.401/2.378
I3 [E]	-1.743/75.734	-18.287/-0.355	-12.092/-0.352	**-2.702/-0.324**	-1.463/-0.291

Case A: GWC Model Effect

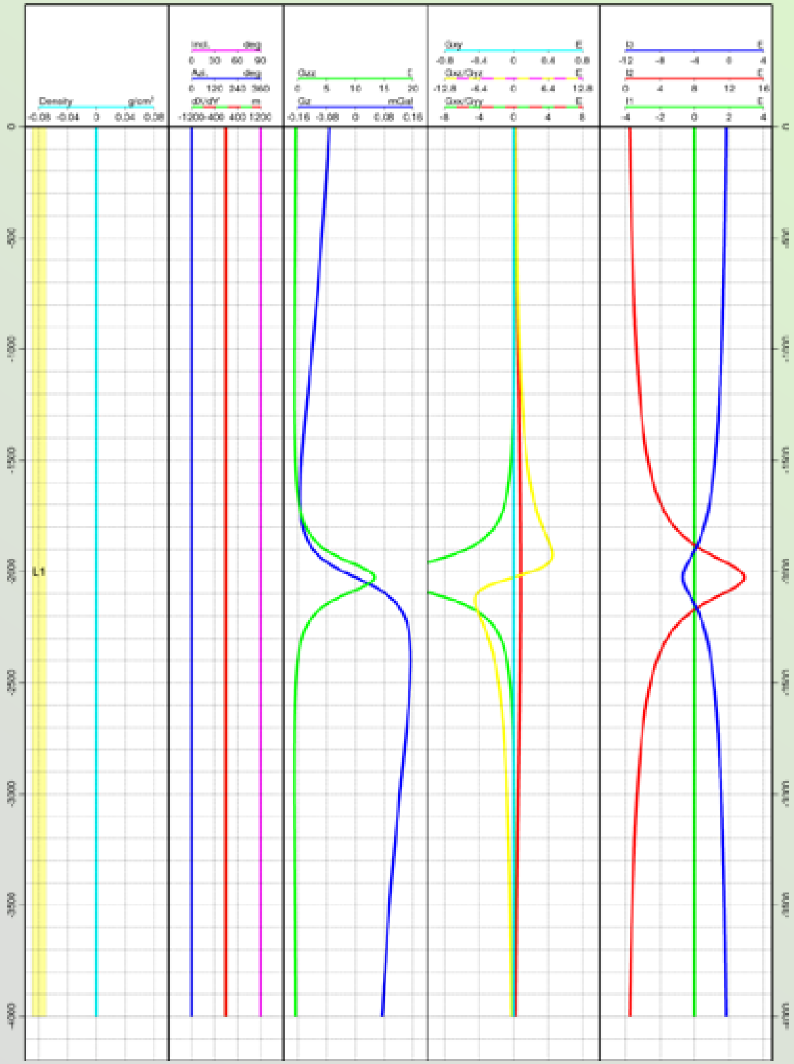
x=+0.025 km

Case A: GWC Model Effect



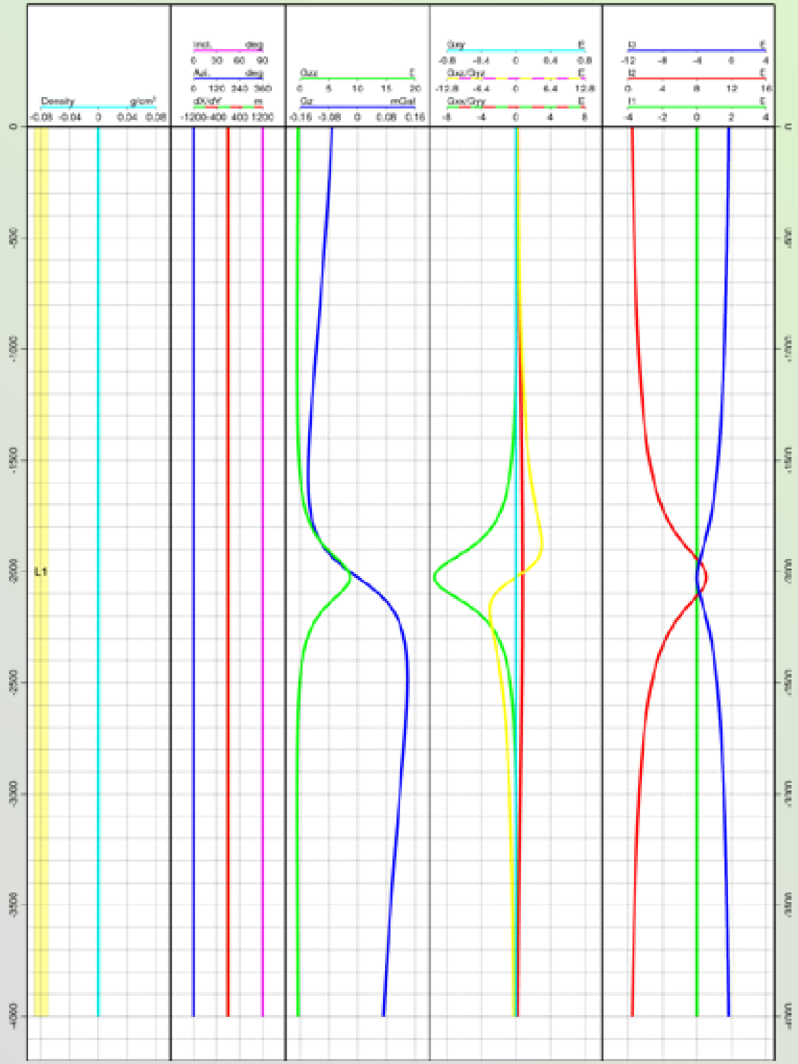
x=+0.050 km

Case A: GWC Model Effect



x=+0.100 km

Case A: GWC Model Effect



x=+0.150 km

Case A: GWC Model Effect

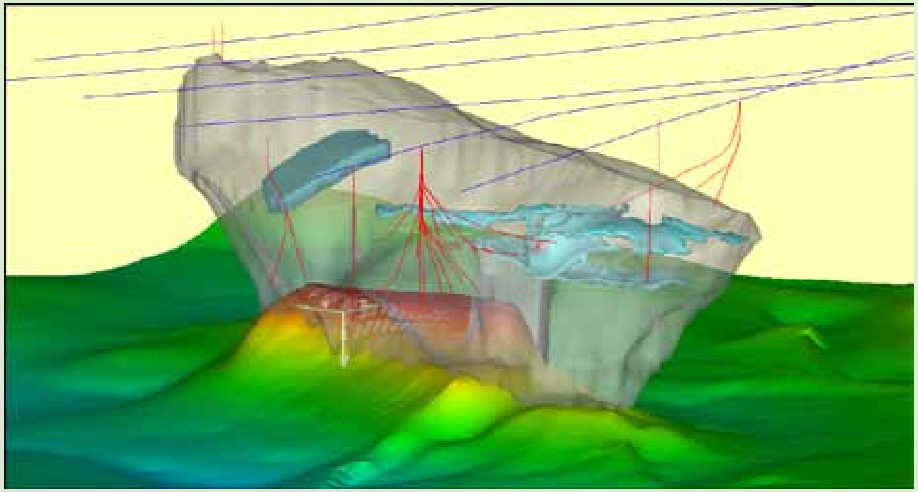
x=+0.250 km

Case A: GWC Model Effect

x=+0.500 km

Case A: Reservoir Monitoring

- Edge of detectability for gravity gradients (approx. 5 E) is reached within 10s of meters from the Oil-Water-Contact
- Monitoring of Gas reservoirs with a higher density contrast is feasible within 100s of meters



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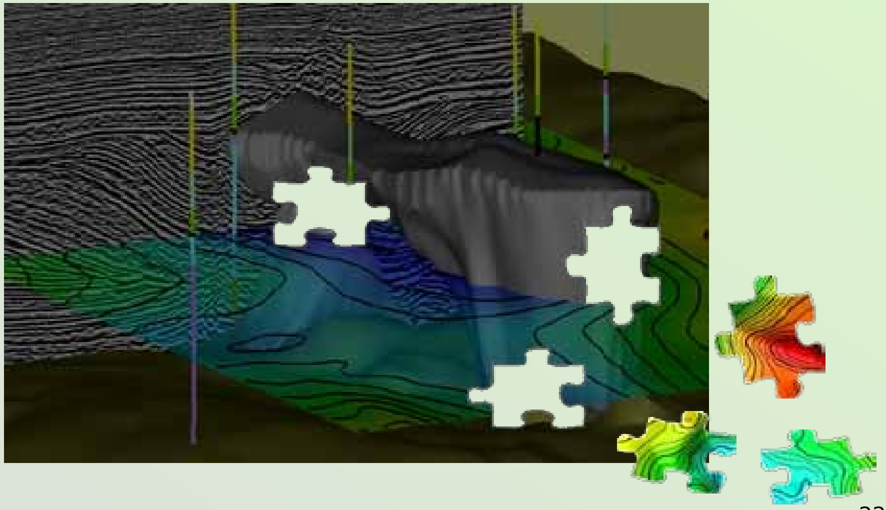
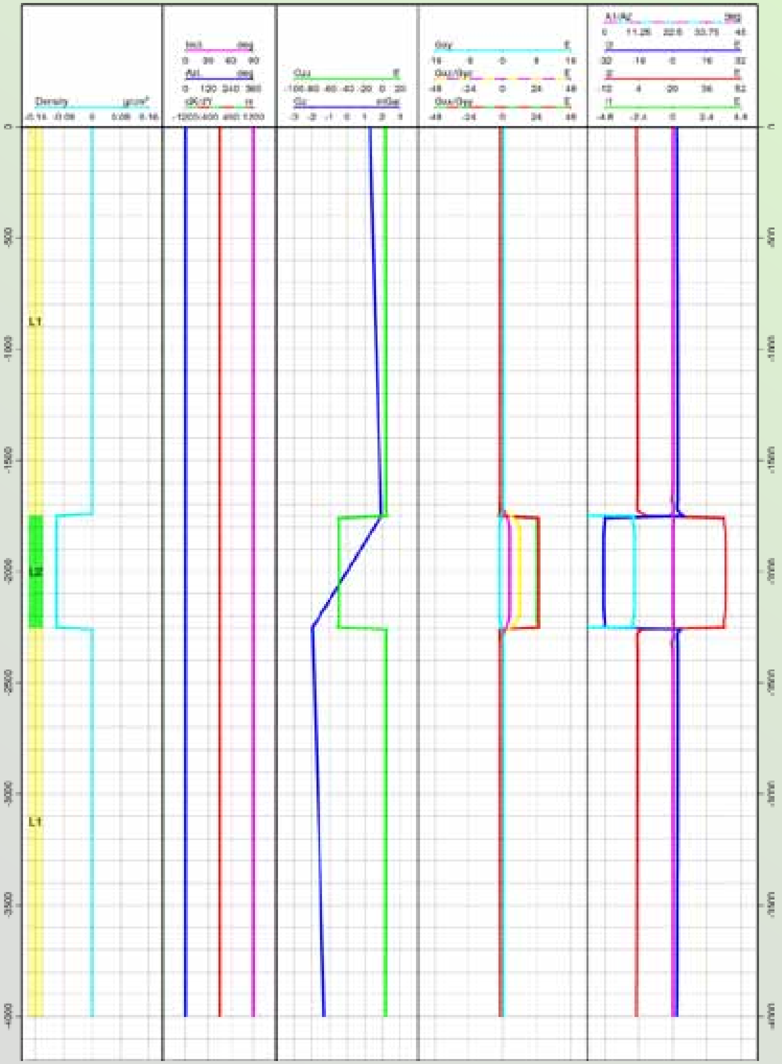


Case B: Dipping Horizon Recognition

- Test horizon of 500 m thickness in 2000 m depth (center)
- Density contrast 100 kg/m^3
- Gxz, Gyz and Gxy components of the tensor can be used to calculate dip φ and azimuth θ of the layer (Nekut, 1989)

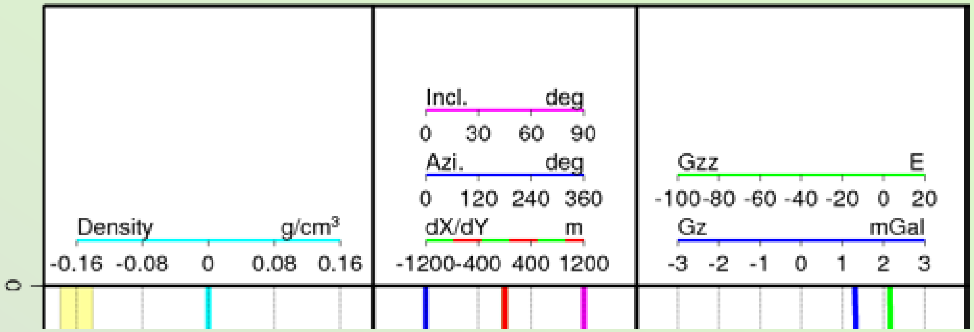
  $\tan(\theta) = G_{xz}/G_{yz}; \quad \tan(\varphi)\cos(\theta) = G_{xy}/G_{xz}$

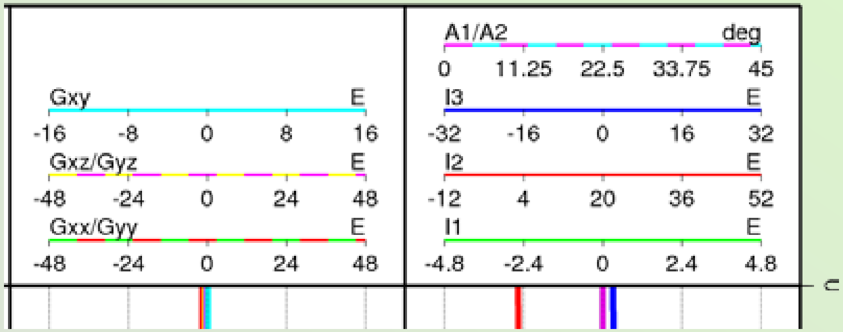
Case B: Dipping Horizon Recognition



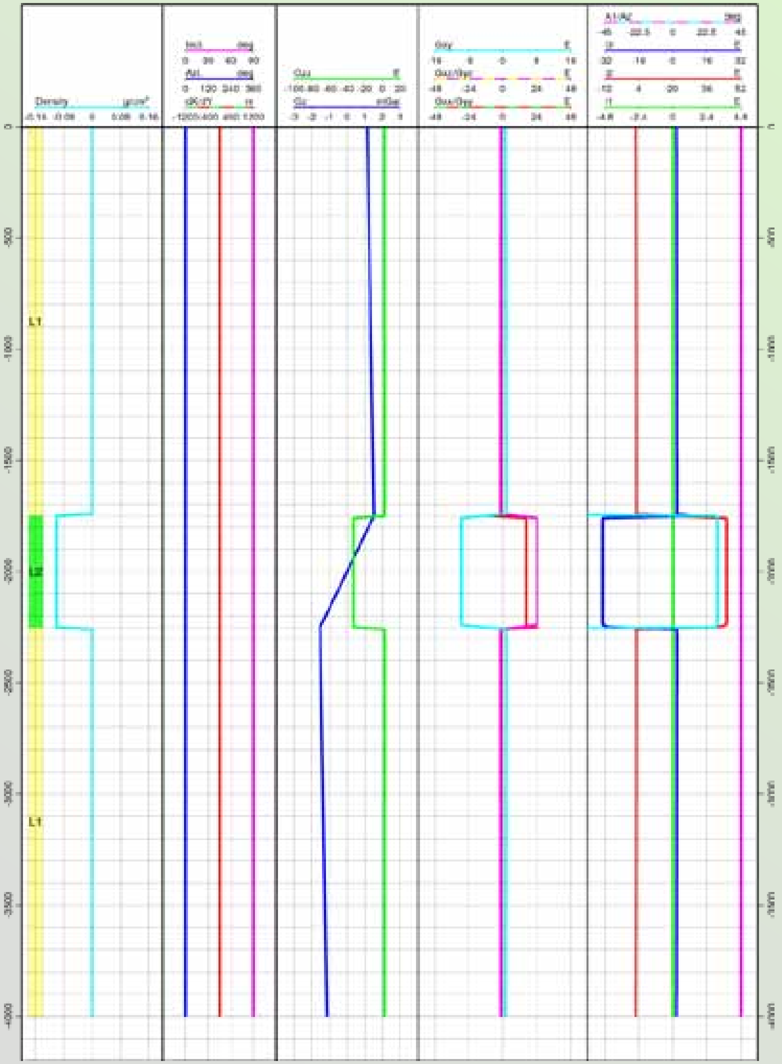
10 dip, 22.5 NNE

Zoom-in:





Case B: Dipping Horizon Recognition



30 dip, 45 NE

Case B: Dipping Horizon Recognition

- Dip and strike of a horizon can be recognized by borehole gravity gradient measurements
- Provides additional value to geological interpretation

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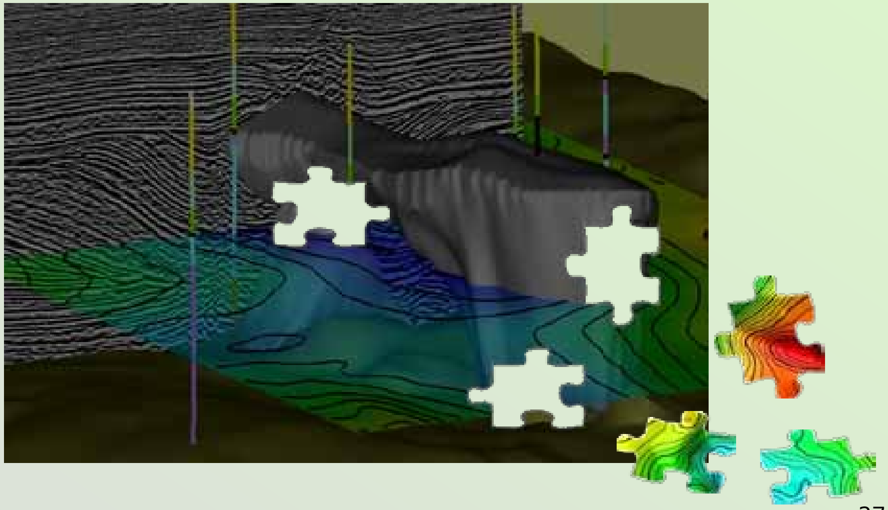
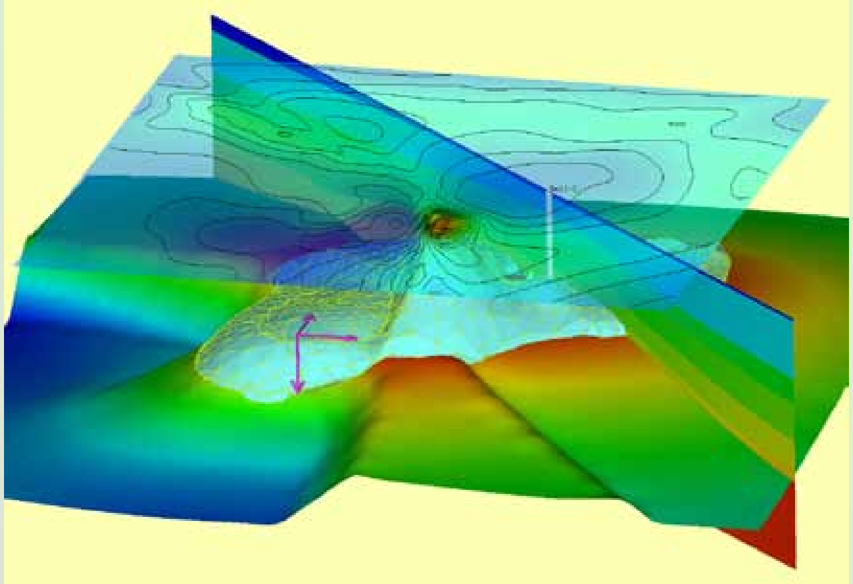
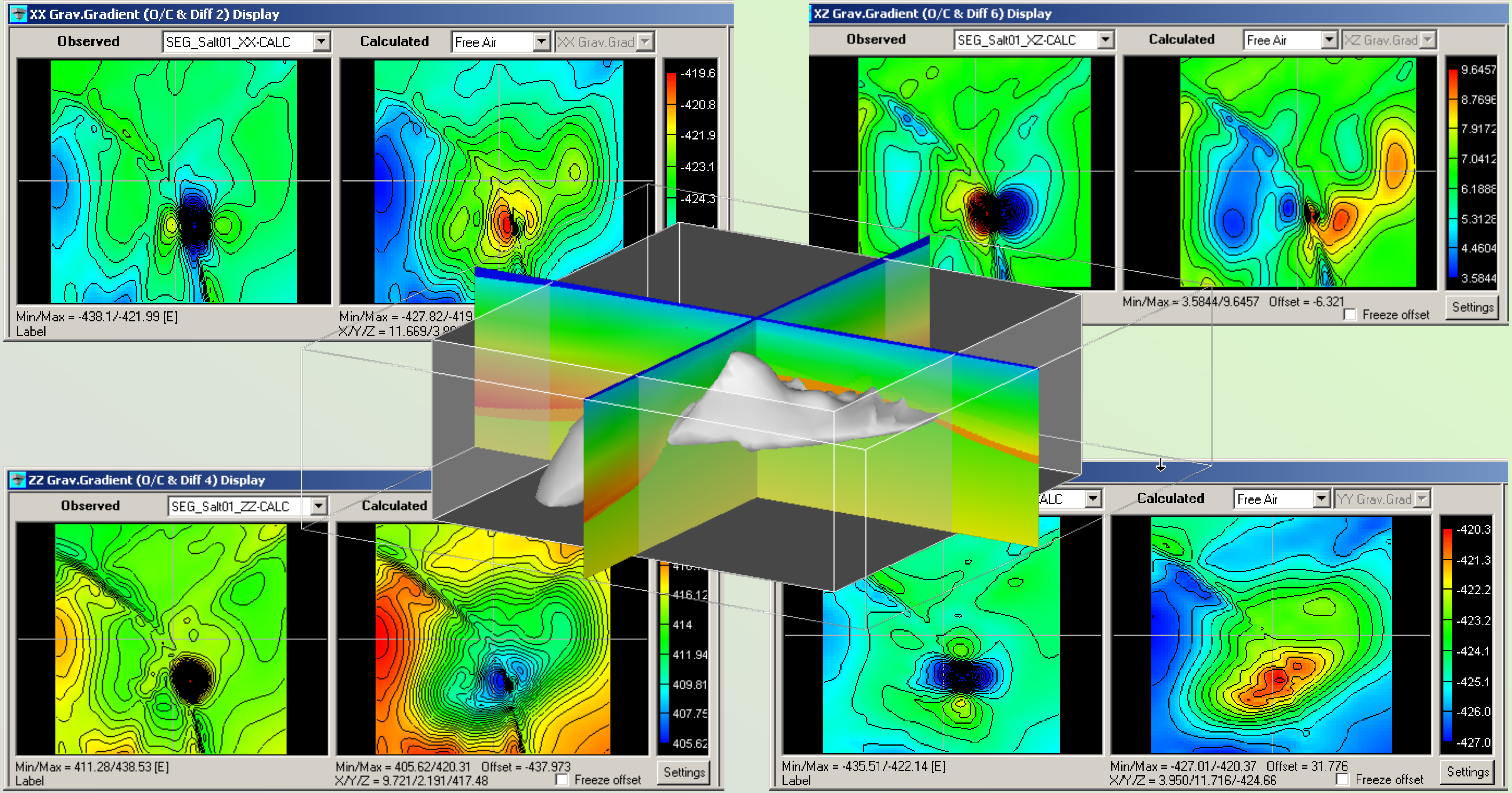


Case C: Integration into 3D Interpretation

- Example: Modeling of complex salt structures
- Test model: SEG/EAGE salt model
- Target: Depth of base of salt
- Layer Densities:
  2000 – 2450 kg/m^3
  Salt density:
  2200 km/m^3
  contrasting 200 kg/m^3
  to underlying sediment



Case C: Surface FTG Variations of SEG Model



XX Grav.Gradient (O/C & Diff 2) Display

Observed SEG_Salt01_XX-CALC

Calculated Free Air XX Grav.Grad

Min/Max = -438.1/-421.99 [E]
Label

Min/Max = -427.82/-419
X/Y/Z = 11.669/3

XZ Grav.Gradient (O/C & Diff 6) Display

Observed SEG_Salt01_XZ-CALC

Calculated Free Air XZ Grav.Grad

Min/Max = 3.5844/9.6457 Offset = -6.321
☐ Freeze offset

ZZ Grav.Gradient (O/C & Diff 4) Display

Observed SEG_Salt01_ZZ-CALC

Calculated

Min/Max = 411.28/438.53 [E]
Label

Min/Max = 405.62/420.31 Offset = -437.973
X/Y/Z = 9.721/2.191/417.48
☐ Freeze offset

ALC

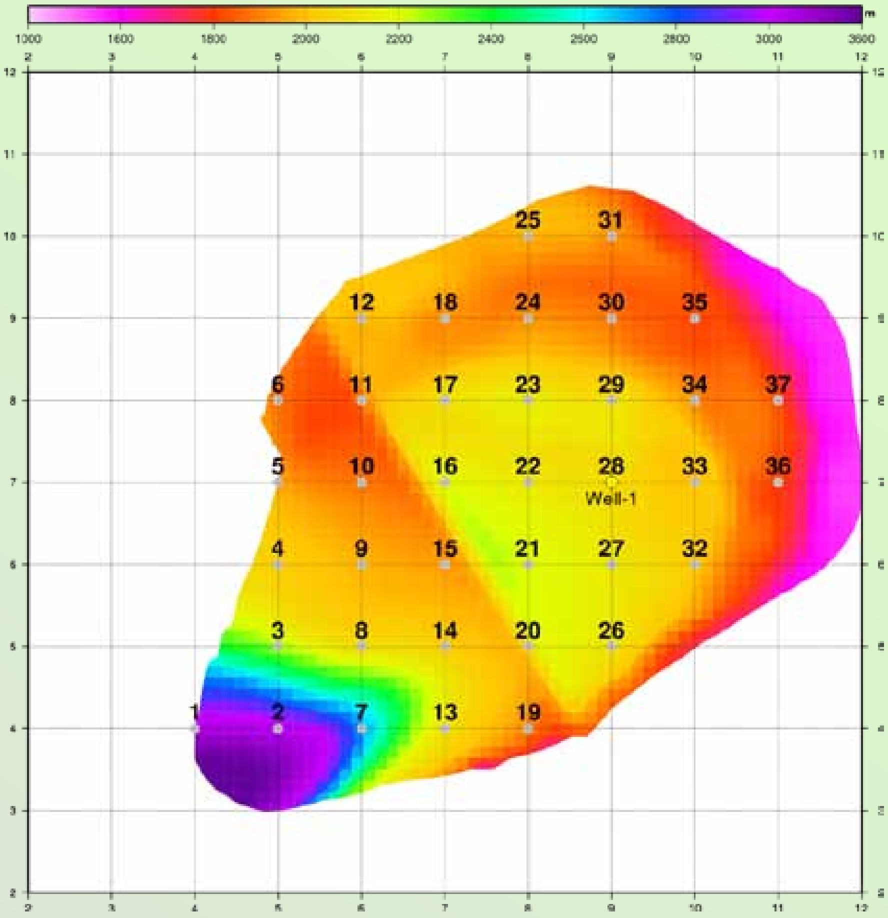
Calculated Free Air YY Grav.Grad

Min/Max = -435.51/-422.14 [E]
Label

Min/Max = -427.01/-420.37 Offset = 31.776
X/Y/Z = 3.950/11.716/-424.66
☐ Freeze offset

Case C: Integration into 3D Interpretation

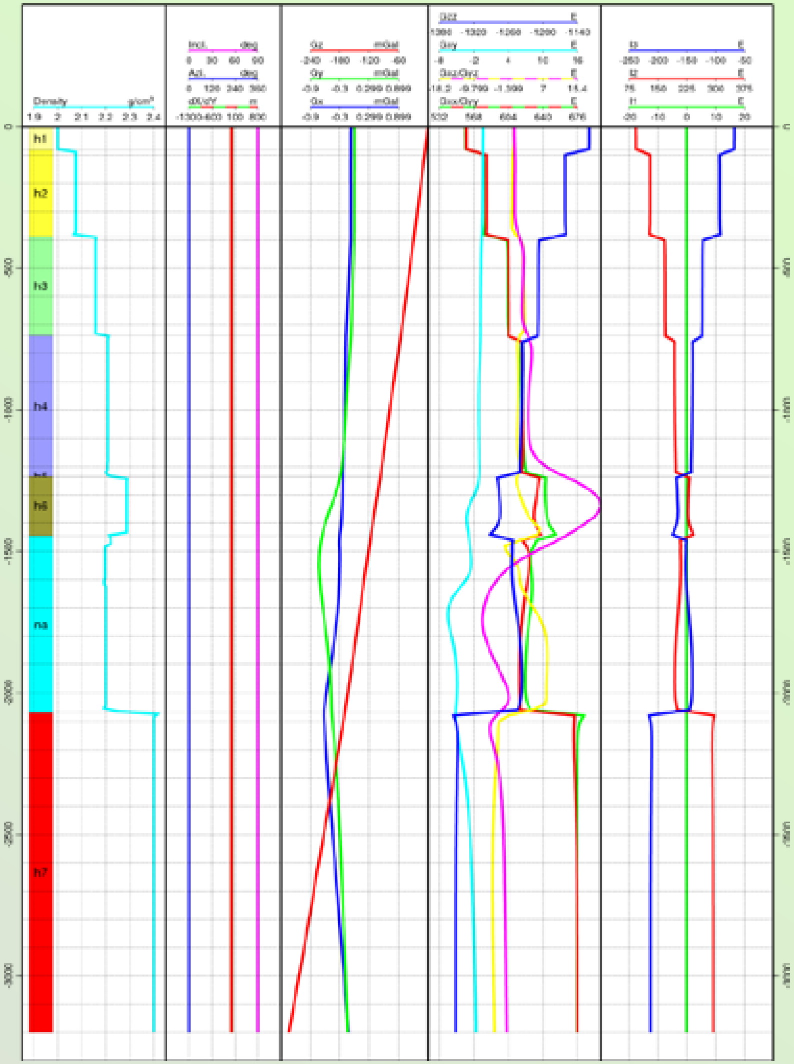
- Definition of 37 control nodes at base of salt surface
- Each node controls the triangulated surface in its neighborhood
- A-priori standard deviation (SD) is set to 1000 m representing low a-priori constraints



Depth to Base of Salt

Case C: Integration into 3D Interpretation

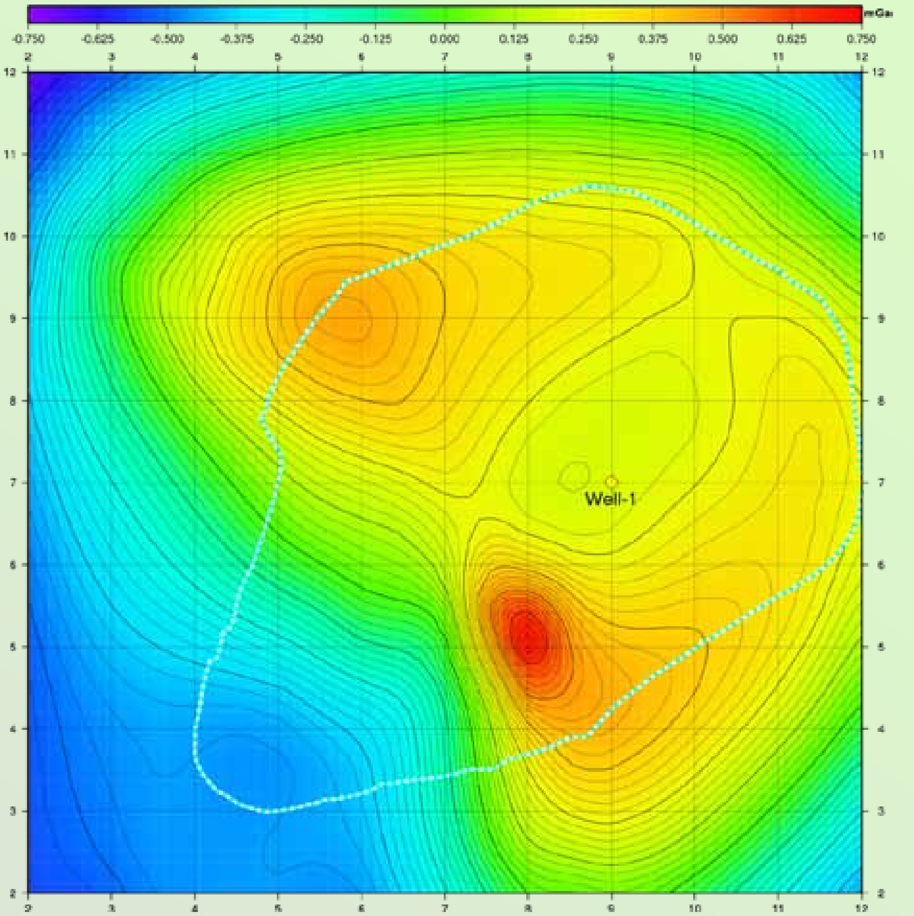
- Calculation of Gz and FTG model effects at surface
- Gz, Gx, Gy and FTG response along path of Well-1



Case C: Integration into 3D Interpretation

- Reference model:
  Gz and FTG observations
  only at surface

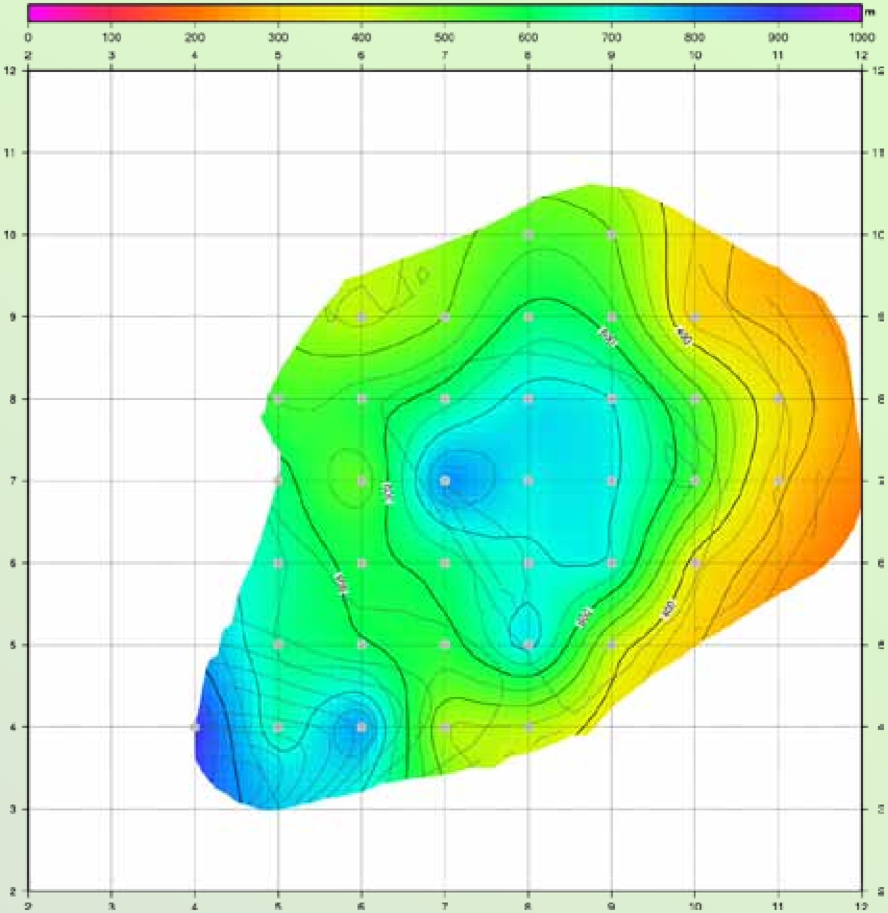
- A-priori SD of observations:
  Gz: 0.05 mGal
  FTG: 5 E



Gz

Case C: Integration into 3D Interpretation

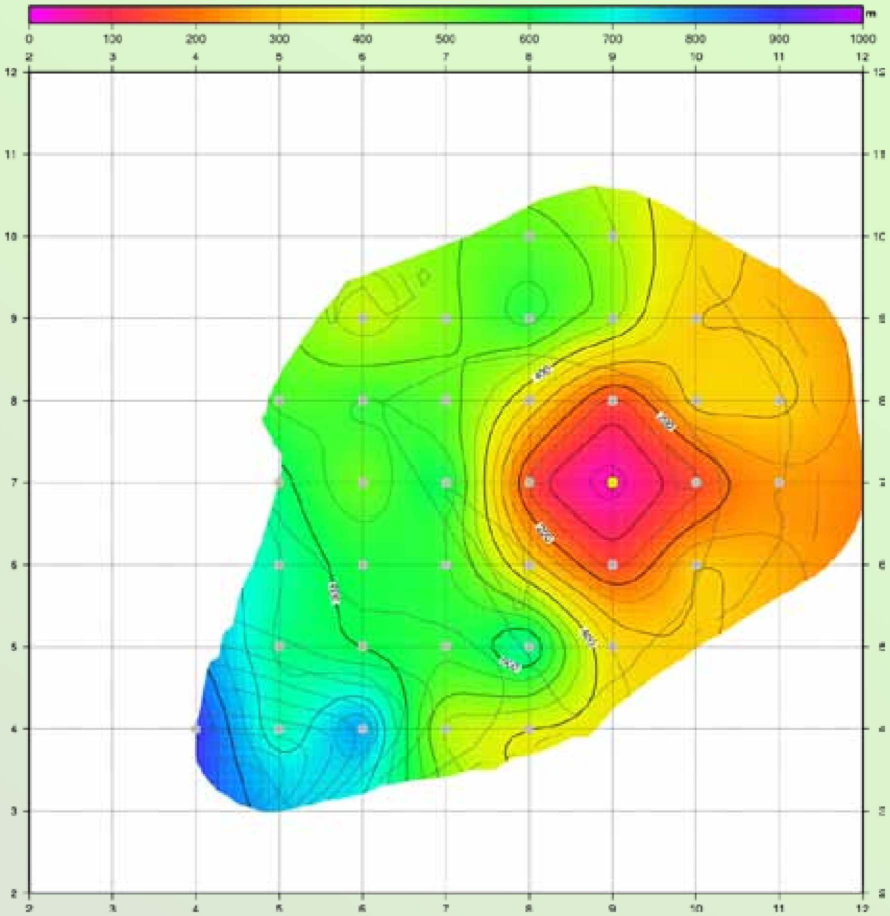
- In an inversion process the a-posteriori standard deviation of the control nodes is determined



A-posteriori standard deviation
using surface Gz/FTG data only

Case C: Integration into 3D Interpretation

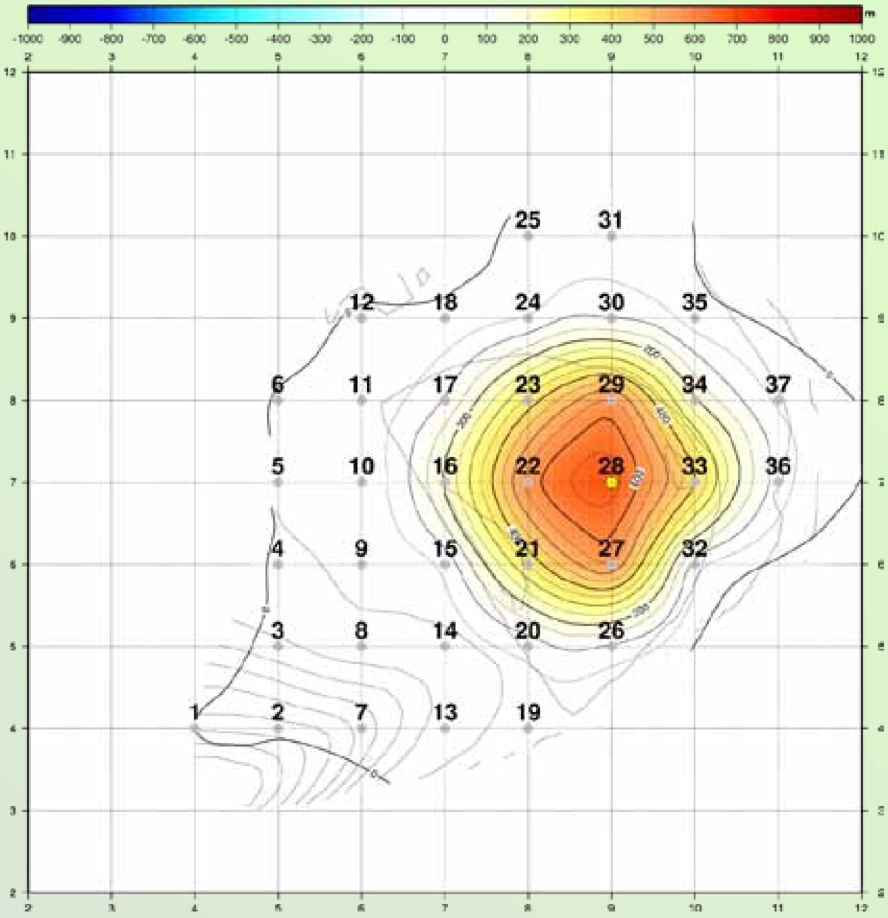
- FTG observations are added along the path of Well-1
- A-priori SD of observations: WFTG: 5 E



A-posteriori standard deviation
using surface Gz/FTG
and FTG data at Well-1

Case C: Integration into 3D Interpretation

- A significant improvement in determination of depth of basement can be achieved
- Maximum improvement: 672 m
- Significant improvements within a radius of 2 km



Difference in a-posteriori standard deviation using surface Gz/FTG and FTG data at Well-1 vs. surface Gz/FTG only

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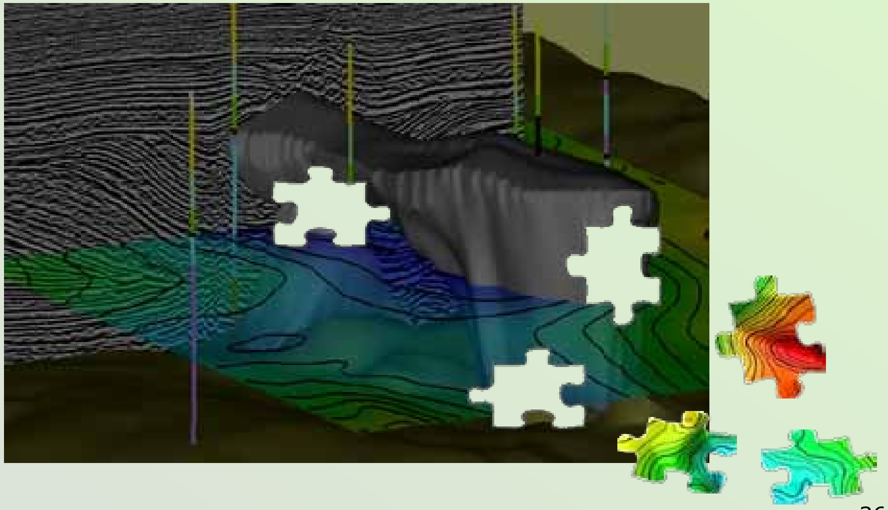

Conclusions

- Borehole Gravity Gradient Measurements (BGGM) provide a complementary type of data for reducing uncertainty in subsurface modeling

- Suitable BGGM applications range from reservoir monitoring to complex structural interpretation

- For integrated geo-modeling and inversion BGGM can …
  … increase resolution (due to near-target measurements)
  … detect lateral changes (due to its directional sensitivity)
  … utilize horizontal wells (due to its dip independence)

Thank you!

We thank you for your precious time !

And we thank our colleagues in Hamburg and Houston
for an excellent cooperation and fruitful discussions