KMS Technologies – KJT Enterprises Inc.

Presentation

Thomsen, L., Strack, K. – M., Brady, J., Biegert, E.

2003

A Novel Approach to 4D: Full Field Density Monitoring

Society of Exploration Geophysicists, Annual Meeting, Dallas, Invited Paper in workshop “4D Time Lapse Rock Properties”

A Novel Approach to 4D: Full Field Density Monitoring

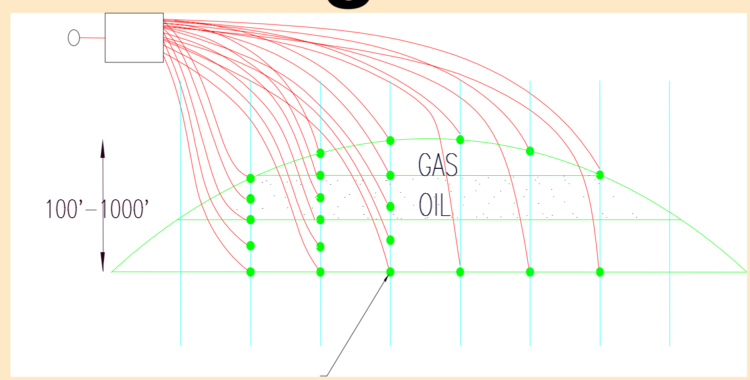
by

Leon Thomsen[1], Kurt Strack[2], Jerry Brady[1], Ed Biegert[3]

[1]BP

[2]KMS Technologies

[3]Shell



SEG Research Workshop

Dallas, Oct. 31, 2003

Outline

- Motivation
- Principles
- Surface
- Borehole
- The Future

The key to effective reservoir management: 4D

4D means:

- **Measurements in 3D + elapsed time**
- **Not necessarily *seismic* monitoring**
- **More frequent is better**
- **Hence, cheaper is better**
- **Boreholes offer *significant* opportunities for monitoring**

4D gravity makes sense when 4D seismics has difficulty

- **Surface difficulties:**
  - **Permafrost, sand, swamp, …**
  - **Infrastructure**
  - **…**
- **Subsurface difficulties:**
  - **Gas cloud**
  - **Salt bodies**
  - **…**

4D gravity makes sense when production makes reservoir density changes

- High porosity
- Gas -> brine (oil -> brine)
- Formation collapse

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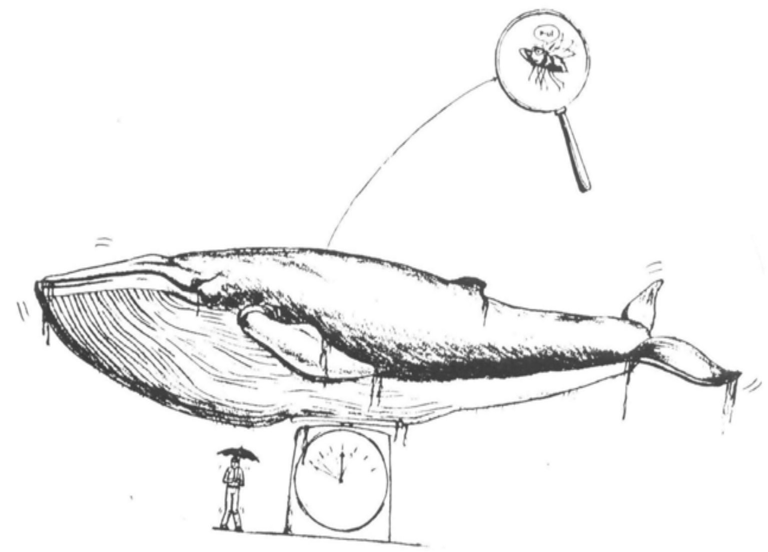
As a reminder…

<u>Every</u> particle in the entire earth pulls on a gravity meter; the sum of all this force is

$$F = mg \quad ;$$

$$g \approx 980 \quad cm/s^2 = 980 \quad Gals$$

Fluid movements make changes in gravity in *micro*-Gals,*ie* in parts per <u>billion</u>!



As a reminder…$_{\text{II}}$

- The direction of gravity *defines* the vertical:

$$g \equiv g_z$$

- In a vertical borehole, we can measure the vertical *gradient* of gravity:

$$g_{z,z} \equiv \frac{\partial g_z}{\partial z}$$

As a reminder…$_{\text{III}}$

- The gravitational attraction of an infinite slab of thickness z is:

$$g_z = 4\pi G\rho\, z$$

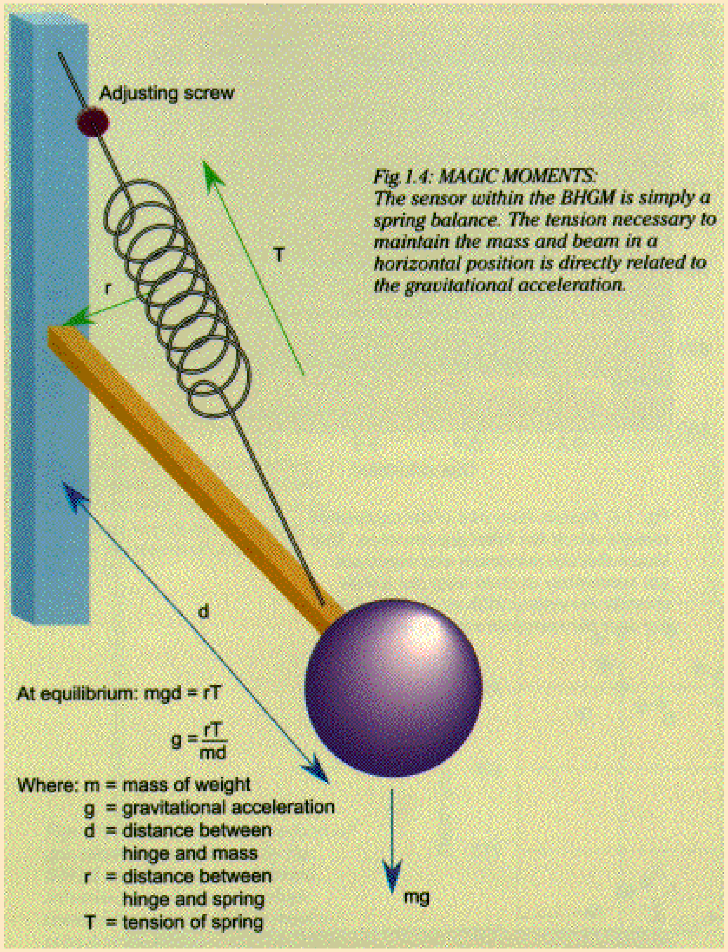
- Hence the measured gravity gradient can be expressed in terms of the *equivalent* density of an infinite slab:

$$\frac{\partial g_z}{\partial z} \equiv 4\pi G\rho_{apparent}$$

We *can* do it because

- Gravity meters are better than when *you* were a student…
- They are getting even *better*!
- We can detect and interpret ***changes*** better than absolute quantities.

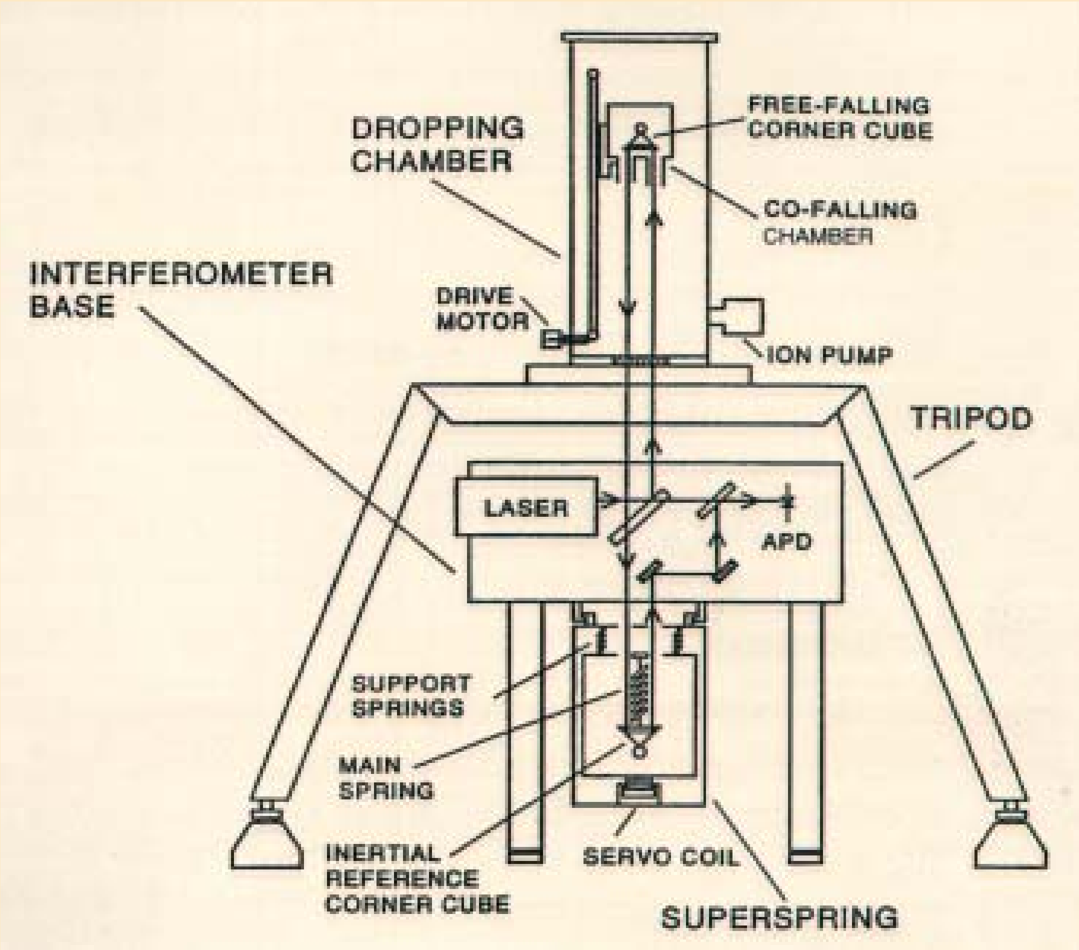
Conventional (relative) gravity meter measures <u>force</u>



Refinements of this basic design have been the state of the art until recently.

But they lack the long-term stability needed for 4D gravity.

Absolute gravity meter measures <u>acceleration</u> *directly*



This design appears to offer more promise for 4D gravity, <u>if</u> sufficient accuracy can be achieved.

FG-5 Absolute Gravimeter courtesy of Micro-G Solutions Inc.

Relative & absolute gravity meters

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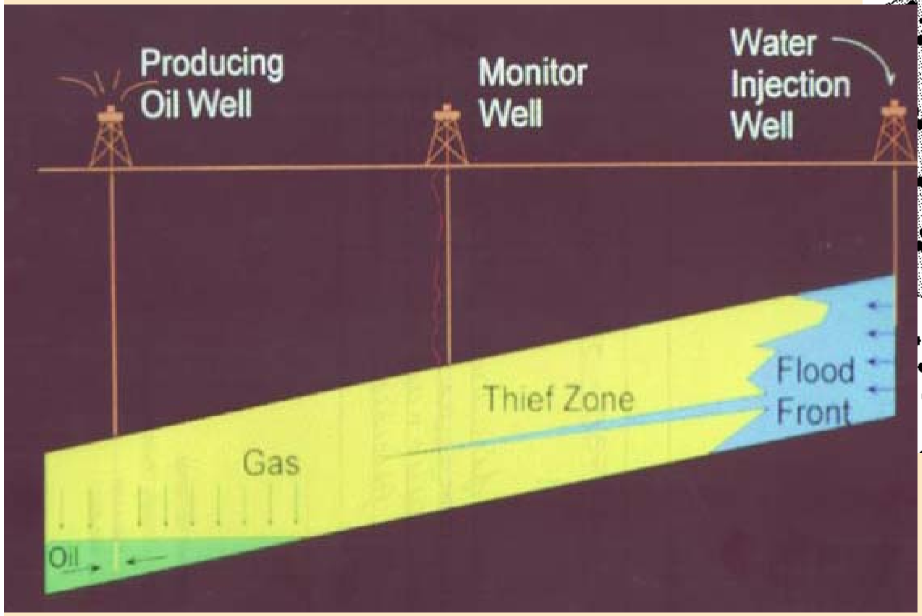
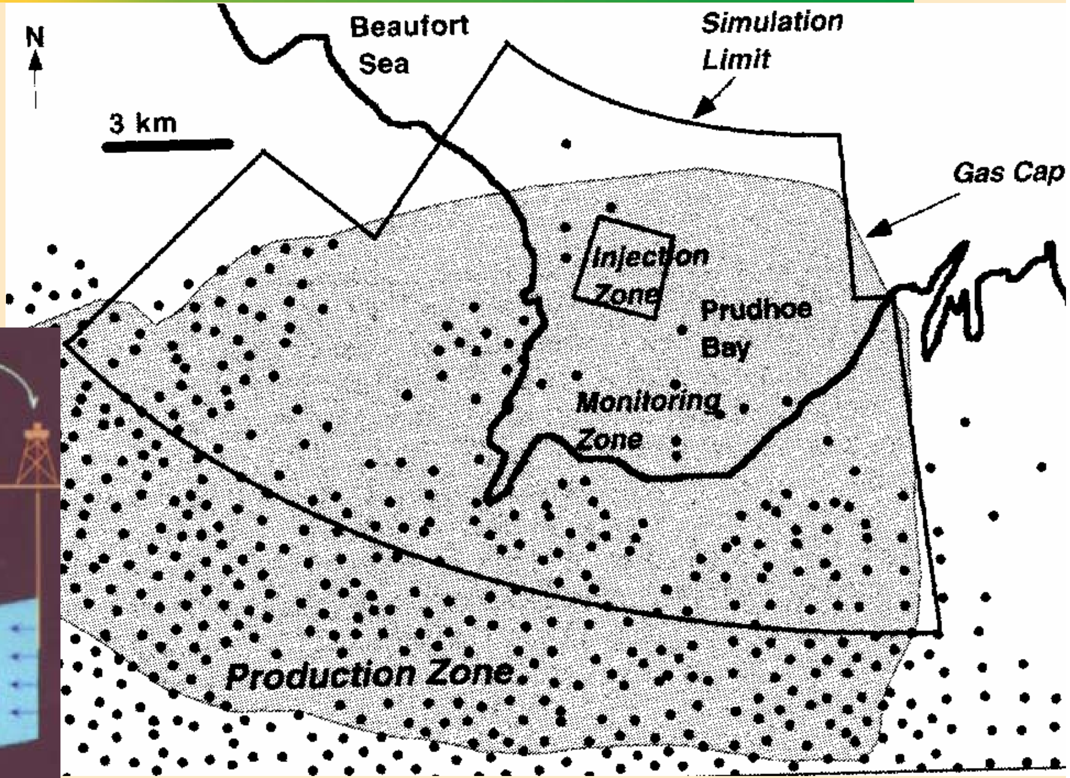
Waterflood Monitoring with 4D Surface Gravity

- Perform baseline gravity survey prior to injection
- Water injection creates a positive gravity anomaly
- Gravity survey repeated yearly
- 4D gravity signal = (repeat – baseline)
- 4D gravity difference inverted for density changes
- Reservoir density change => water movement
- Constraints on the inversion:
  - Changes confined to reservoir
  - Mass balance

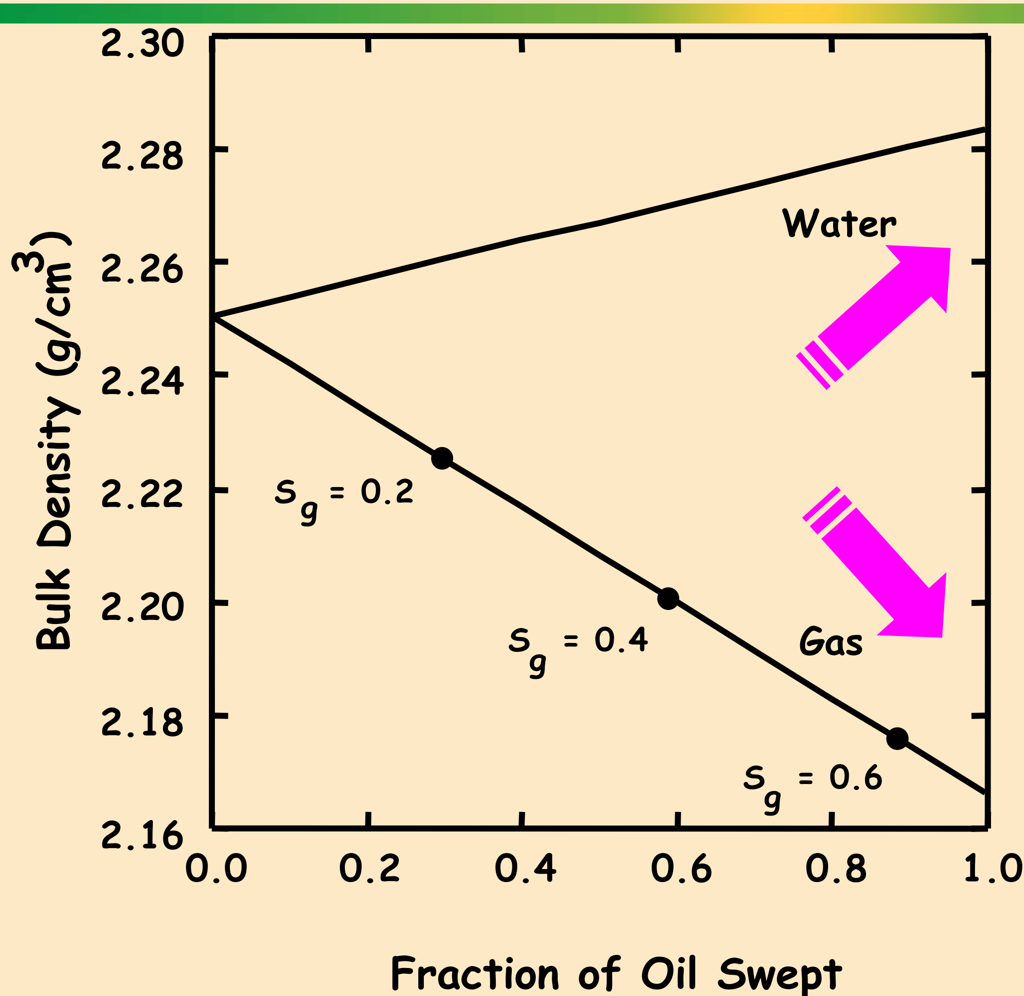
Prudhoe Bay, Alaska





After Hare et al., 1999

Prudhoe Bay: Change in bulk density



ϕ = 0.22

ρ_{ma} = 2.65 g/cm³

ρ_o = 0.762 g/cm³

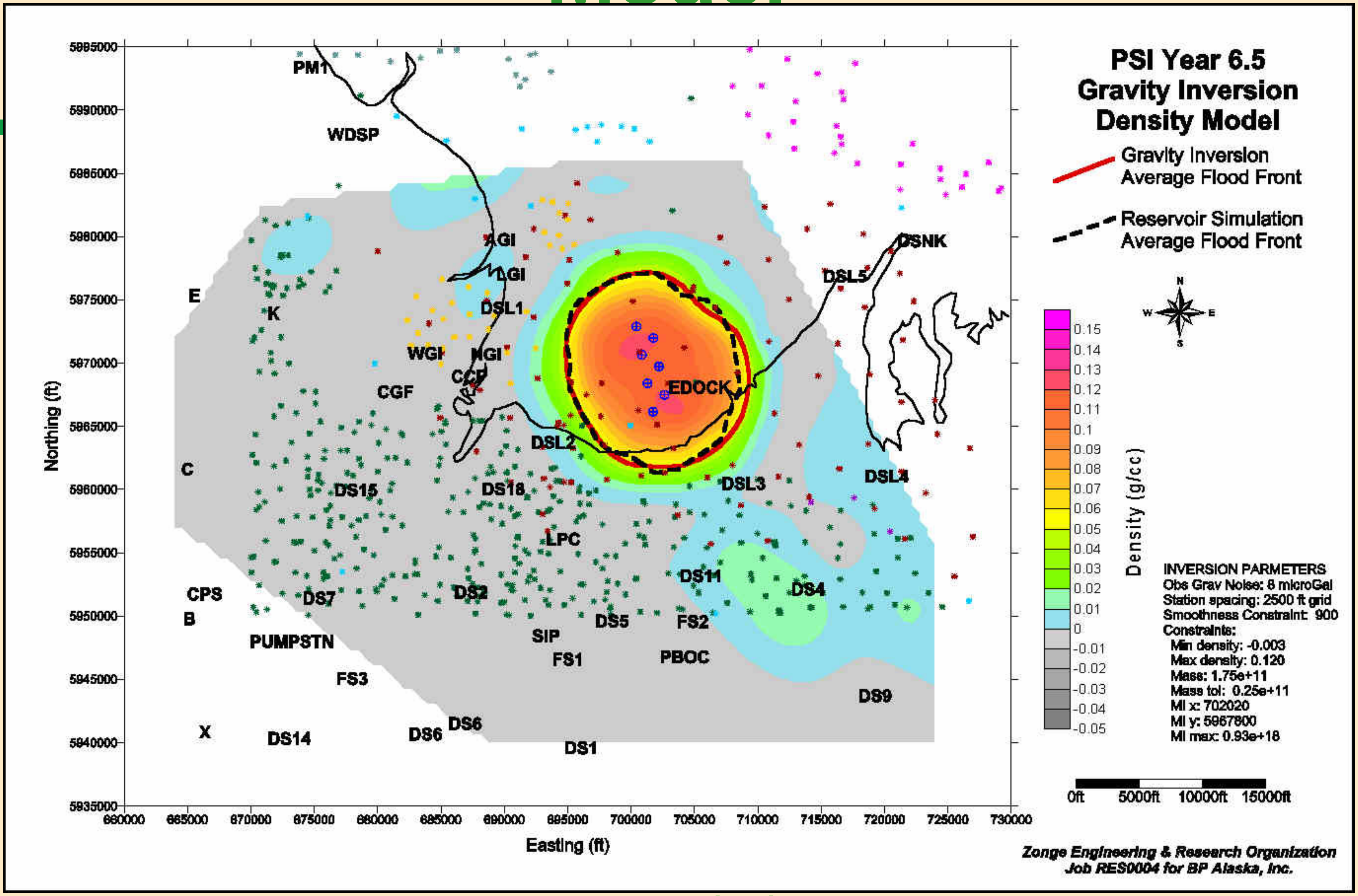
ρ_w = 0.986 g/cm³

ρ_g = 0.198 g/cm³

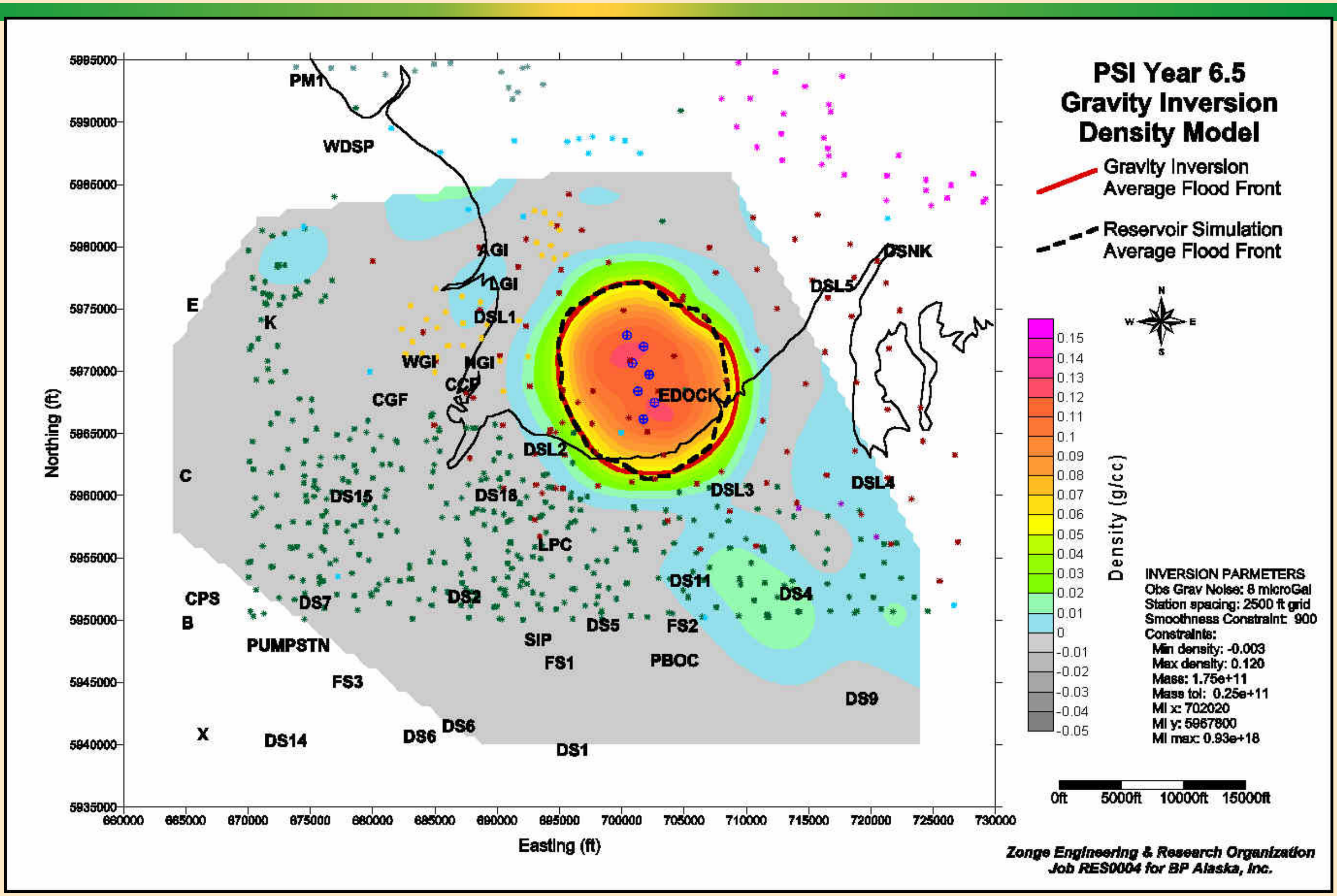
Residual water saturation = 0.32

After Brady, 1998

Gravity Inversion Vs Density Model



Modeling *gravity* is <u>easier</u> than modeling *seismic*

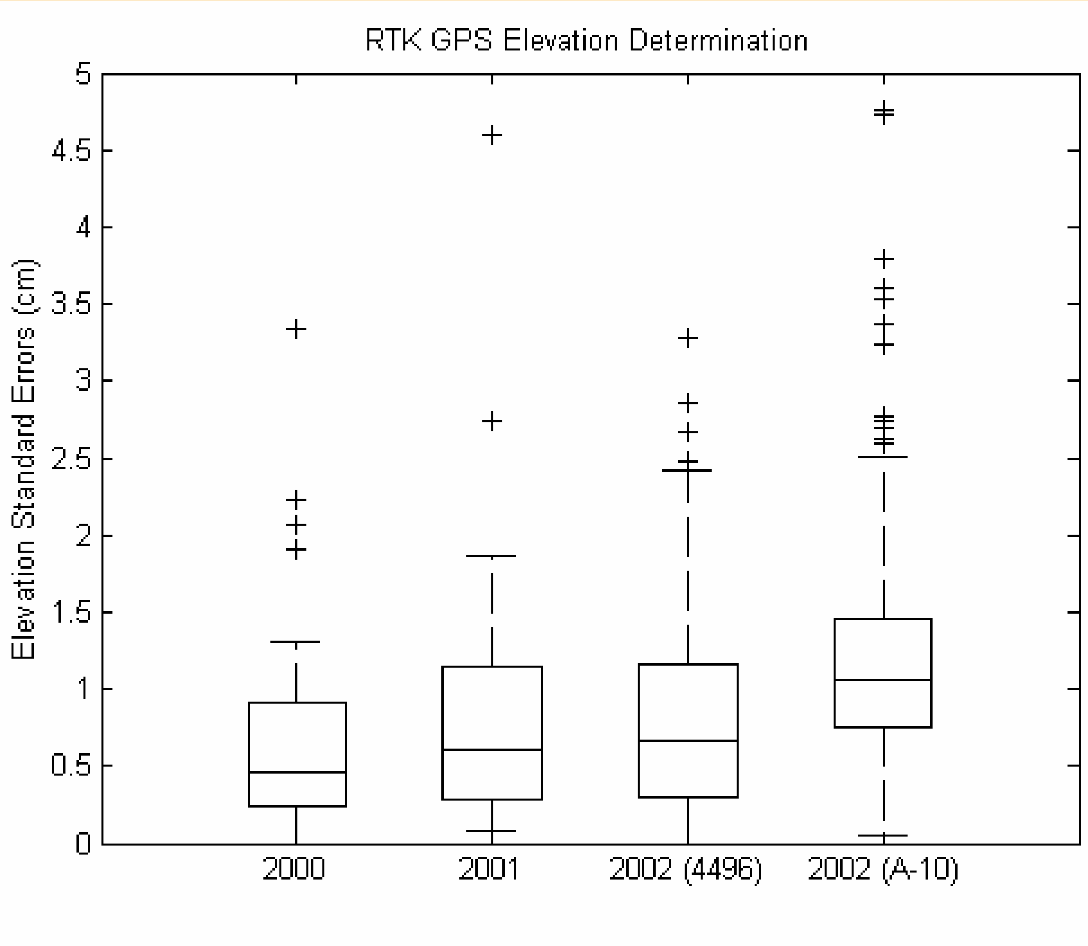


Absolute Gravity Meter Repeats in 2002 Survey

			microgals	
Station	Repeats	Average	Standard Deviation	Standard Error
999	7	470.4	3.1	1.2
102	5	9365.5	5.6	2.5
457	3	4847.3	1.7	1.0
106	2	9895.0	4.7	3.3
406	2	5951.2	0.7	0.5
409	2	5968.3	1.7	1.2
431	2	5609.7	6.0	4.3
458	2	4839.6	2.6	1.9
503	2	3364.7	3.0	2.1
509	2	1906.5	6.4	4.5
		Average	3.5	2.2

The noise floor for repeat surveys is a few microgals.

Preliminary GPS results

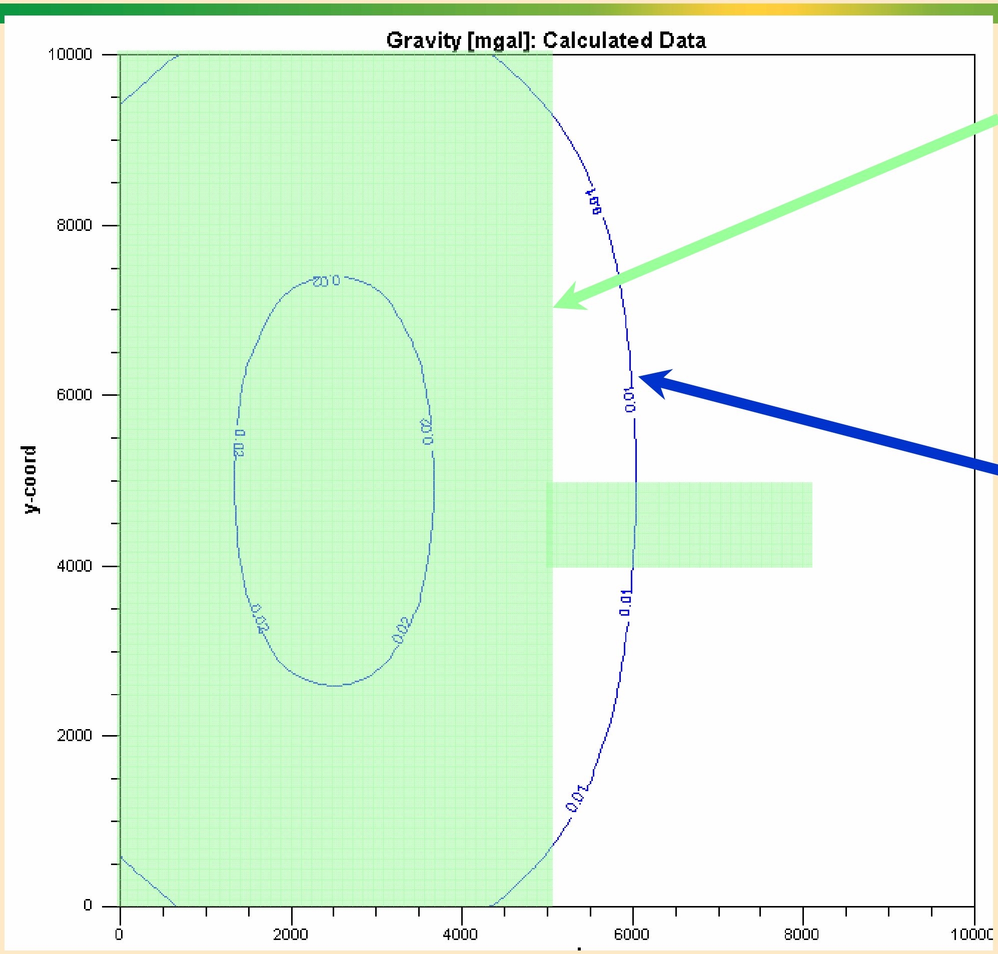


Elevation errors lead to gravity errors: 3 μGals/cm

4D Surface Gravity at Prudhoe Bay: Conclusions

1. **General water front shape and movement can be monitored with the surface gravity technique**
2. **Mass-balance techniques can account for more than 95% of the water added.**
3. **Inversion modeling can determine the average waterflood front and a reasonable location for the leading edge of the waterflood front.**
4. **Absolute gravity meter has been refined to the point that it is a field-worthy tool that can be used as an integral portion of the surface gravity survey.**

Modeling can easily test whether these conclusions apply to another field



Waterflood in reservoir, seen from above

4D gravity anomaly at the surface.

10 μGal contour

Conclusion:
for this field, you <u>can't</u> see the water finger from the surface

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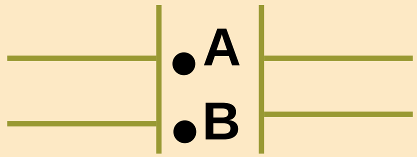
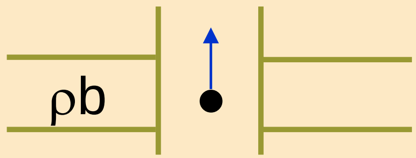
Borehole gravity measurements

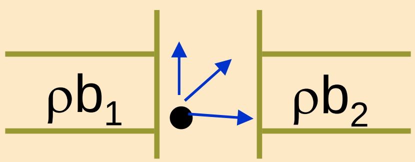
<u>Gravimeter</u>: Very deep investigation; need several boreholes to invert for density. Or, subtract independent readings to derive apparent density.



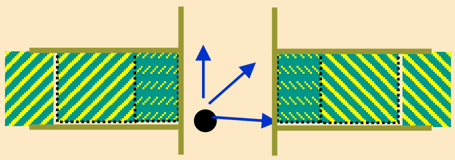
Gravity <u>Gradiometer</u>: Direct measurement of gradient $g_{z,z}$. Fixed frame of reference



<u>Multi-component</u> Gradiometer:
Directional interpretation from $g_{z,x}$, $g_{z,y}$, $g_{z,z}$



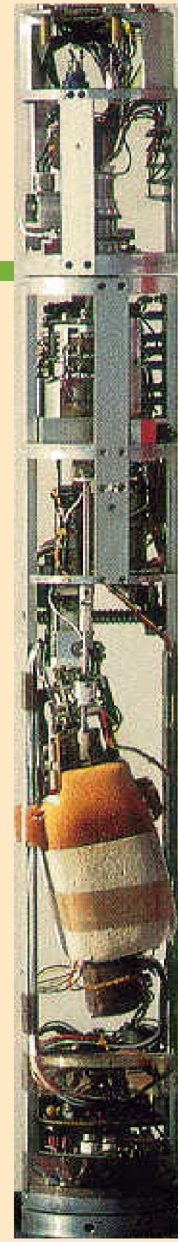
Higher-order derivatives:
Different depths of investigation

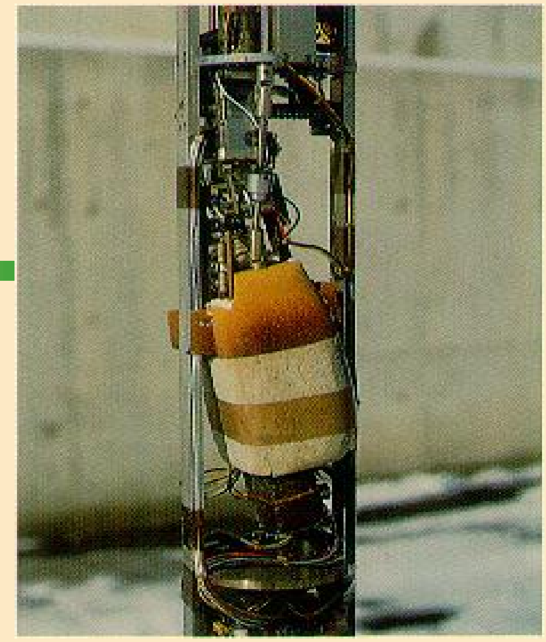


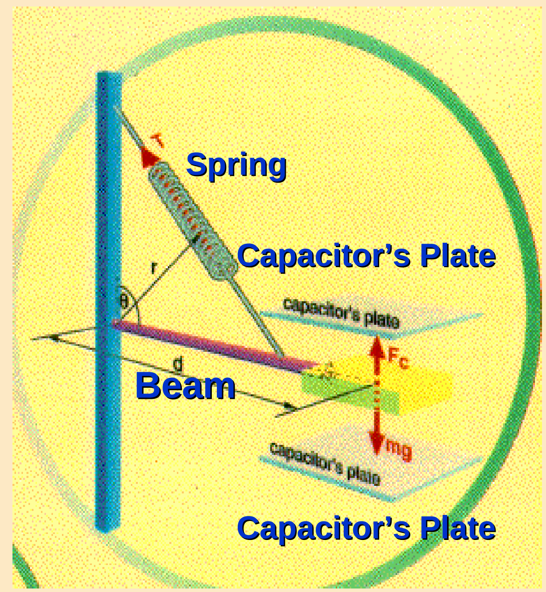
After Strack et al. 1999

Borehole Gravimeter (BHGM)

- LaCoste & Romberg "zero-length" spring balance
- Capacitor force related to gravitational acceleration
- Standard deviation:
  3 µGal.





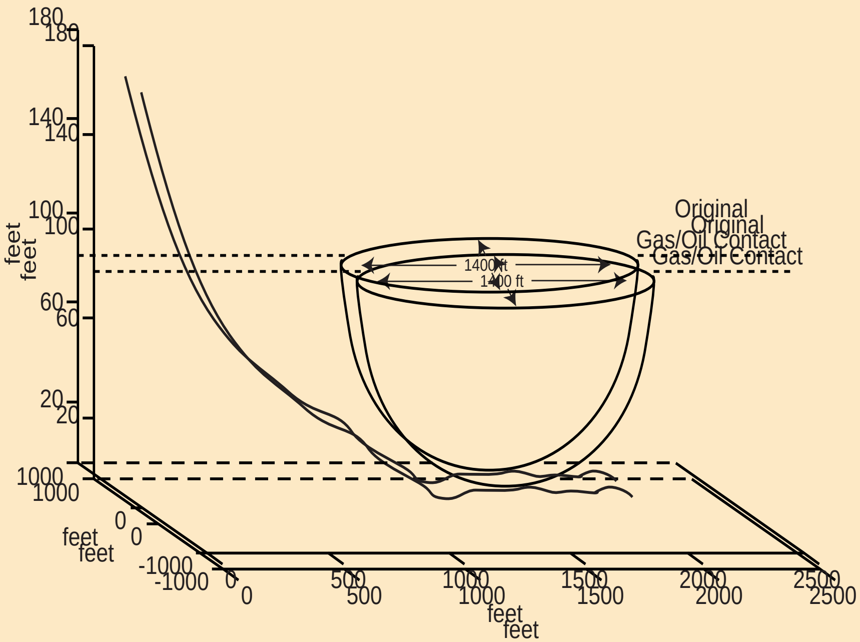


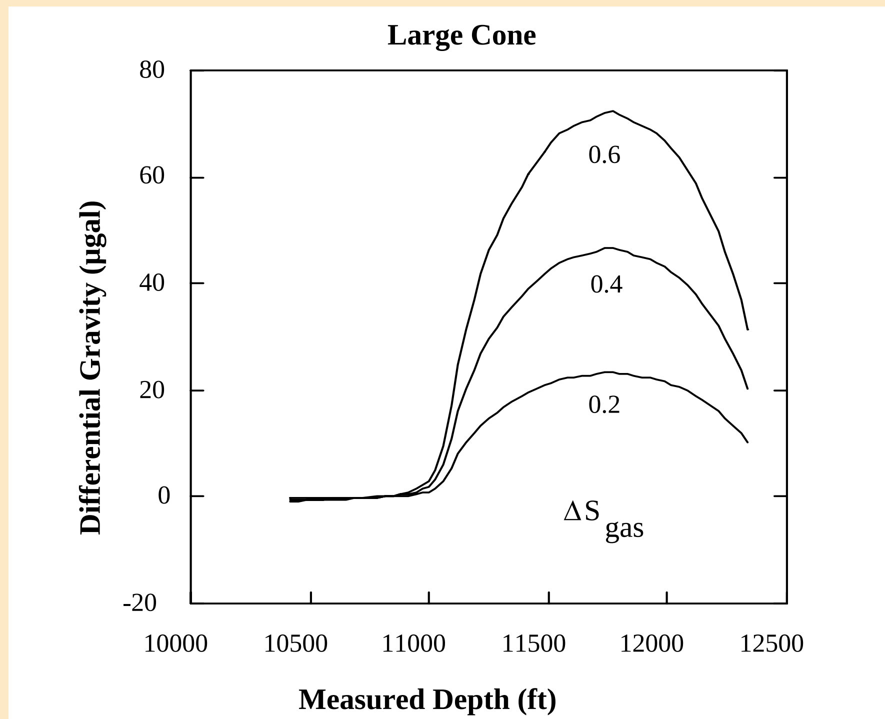
Courtesy Edcon Inc.

Borehole Gravity Used for Reservoir Surveillance

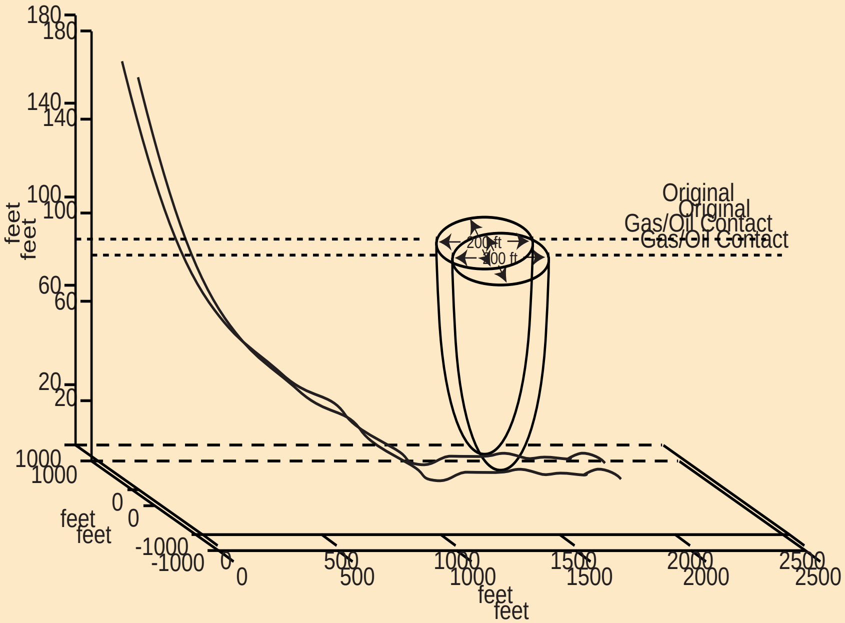
- **Problems with *current* borehole surveillance tools:**
  <u>All</u> shallow-reading devices have problems with:
  - **- Straddles, Scab liners, Gas channels, Gas cones, Perforations**
- **Primary *Advantage* of Borehole Gravity:**
  A very <u>deep</u>-reading tool
  - **Gravity meter reaches a few hundred meters**
  - **Gradiometer: lateral reach ~5X vertical spacing**
- **Primary *Disadvantage* of the BHGM tool:**
  - **- The tool has never been developed for <u>surveillance</u>**
  - **- Tool OD is too large**
  - **- Only works in near-vertical wells**
  - **- Depth control is difficult to achieve**

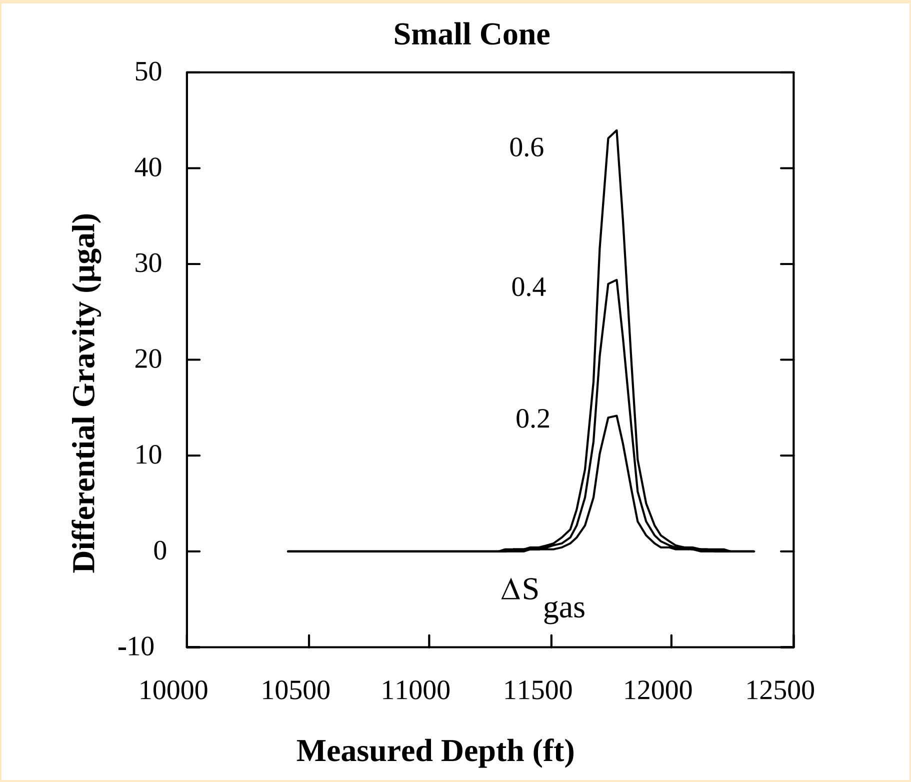
Borehole Gravity Applications: Large Gas Cone



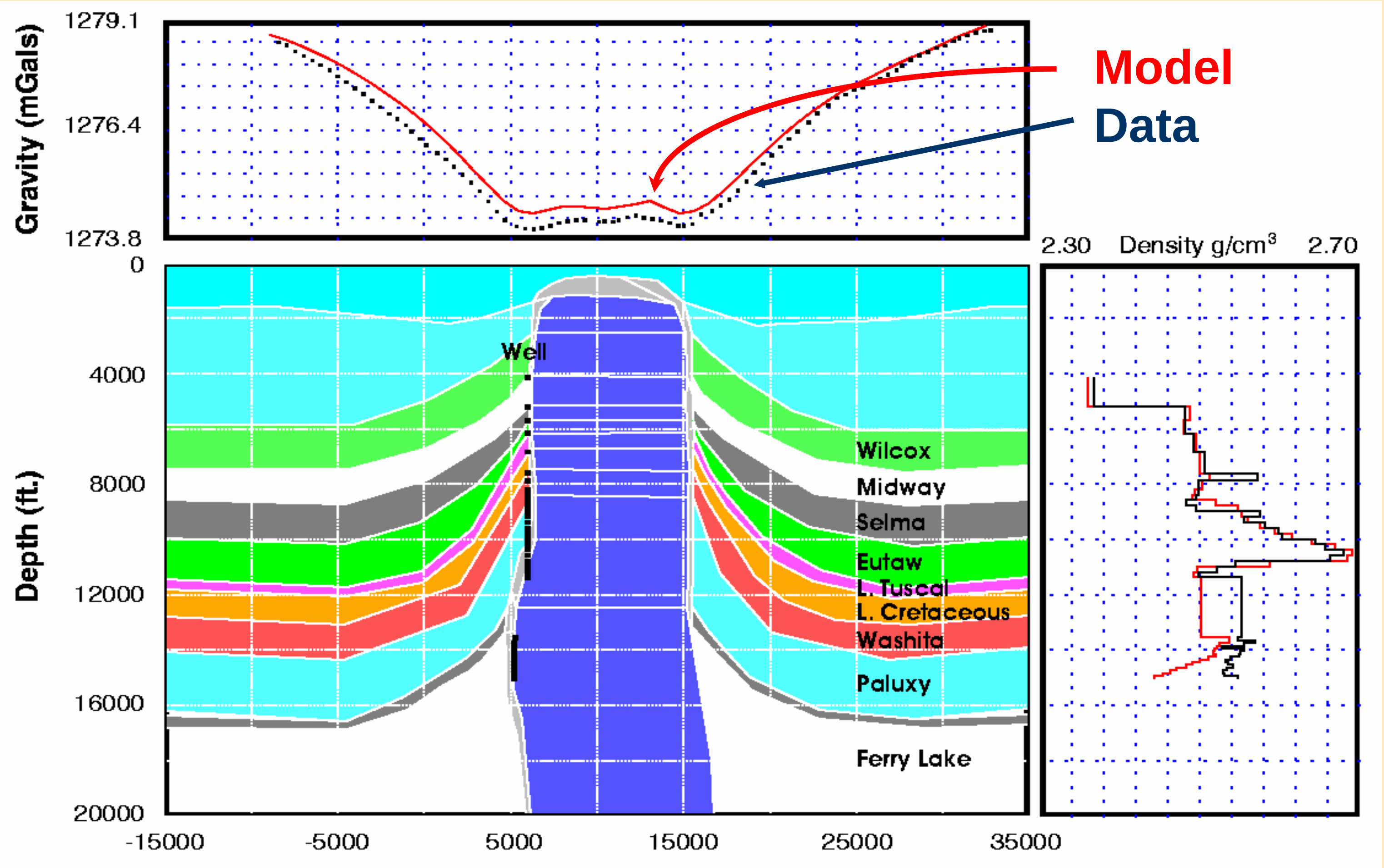


Borehole Gravity Applications: Small Gas Cone



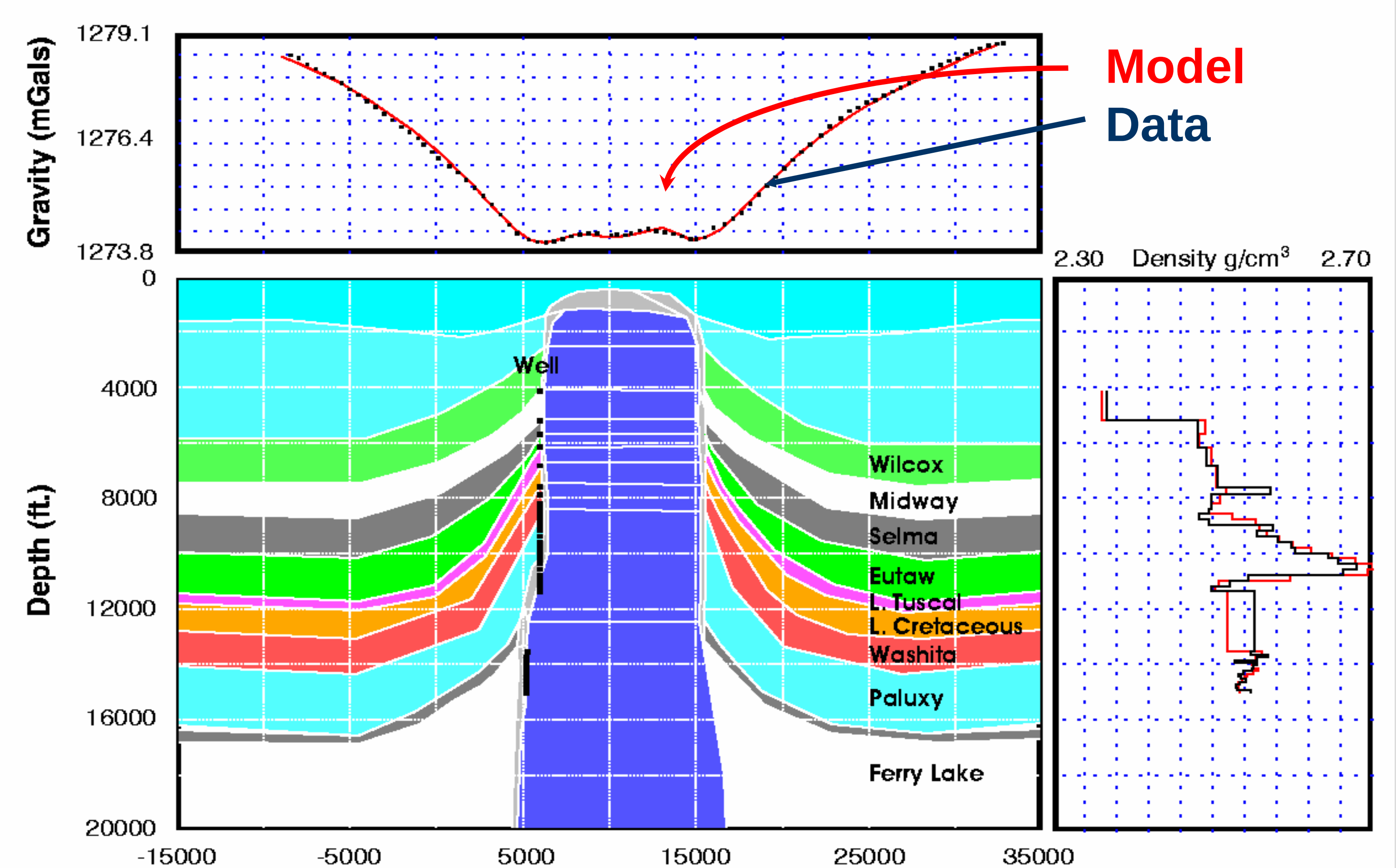


Borehole Gravity Applications: Salt dome overhang



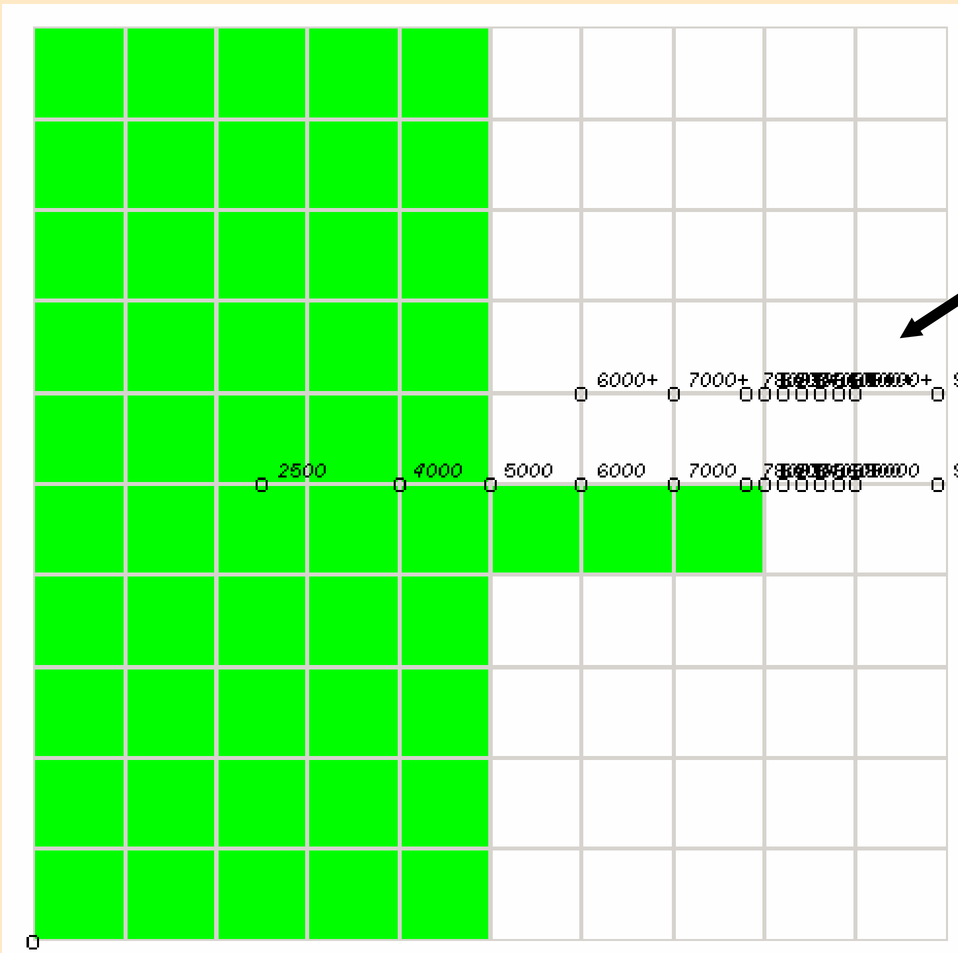
After Black, 1998

Borehole Gravity Applications: Salt dome overhang$_{II}$



After Black, 1998

Borehole Gravity Applications: Waterflood fingering

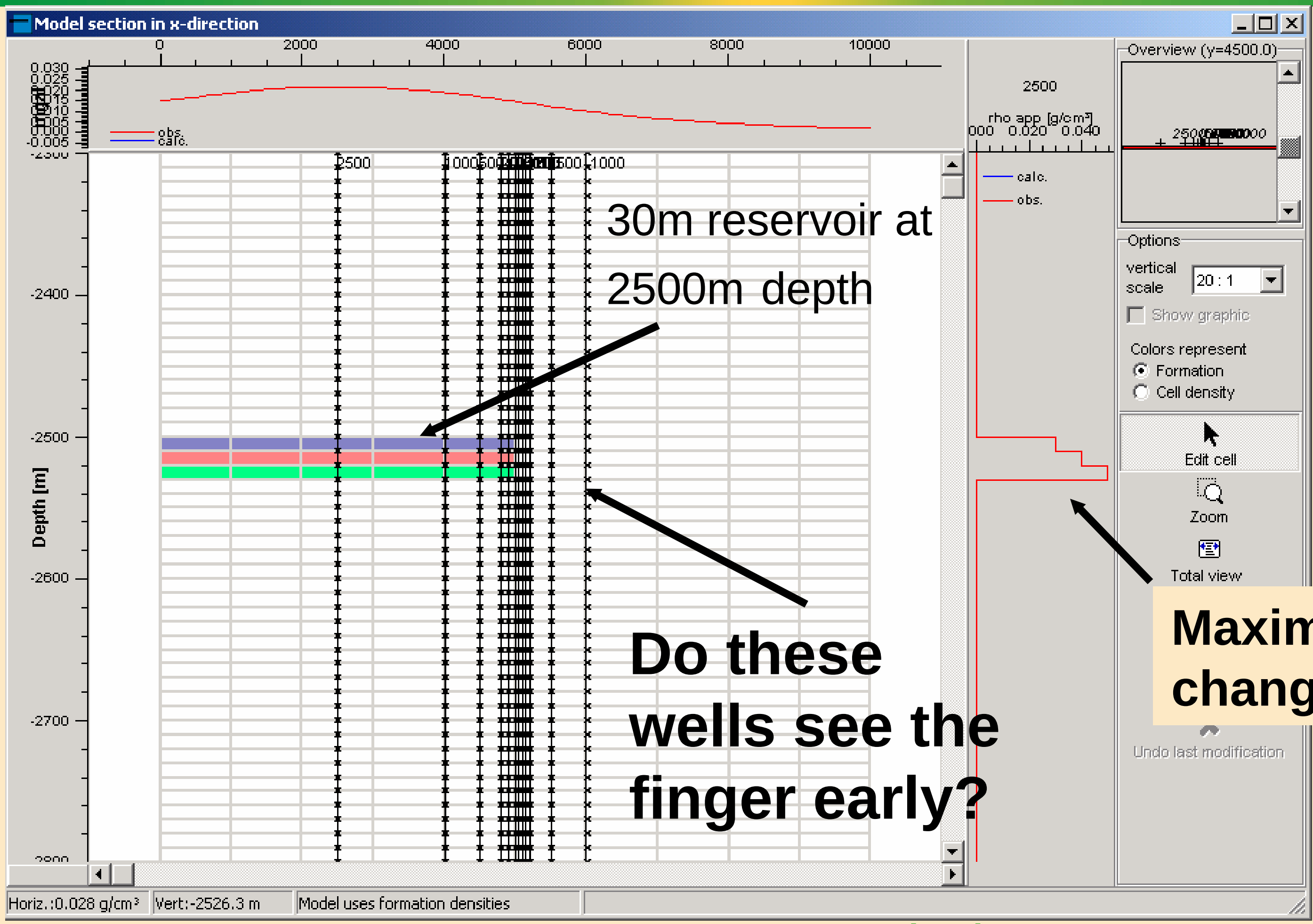


These wells indicate:

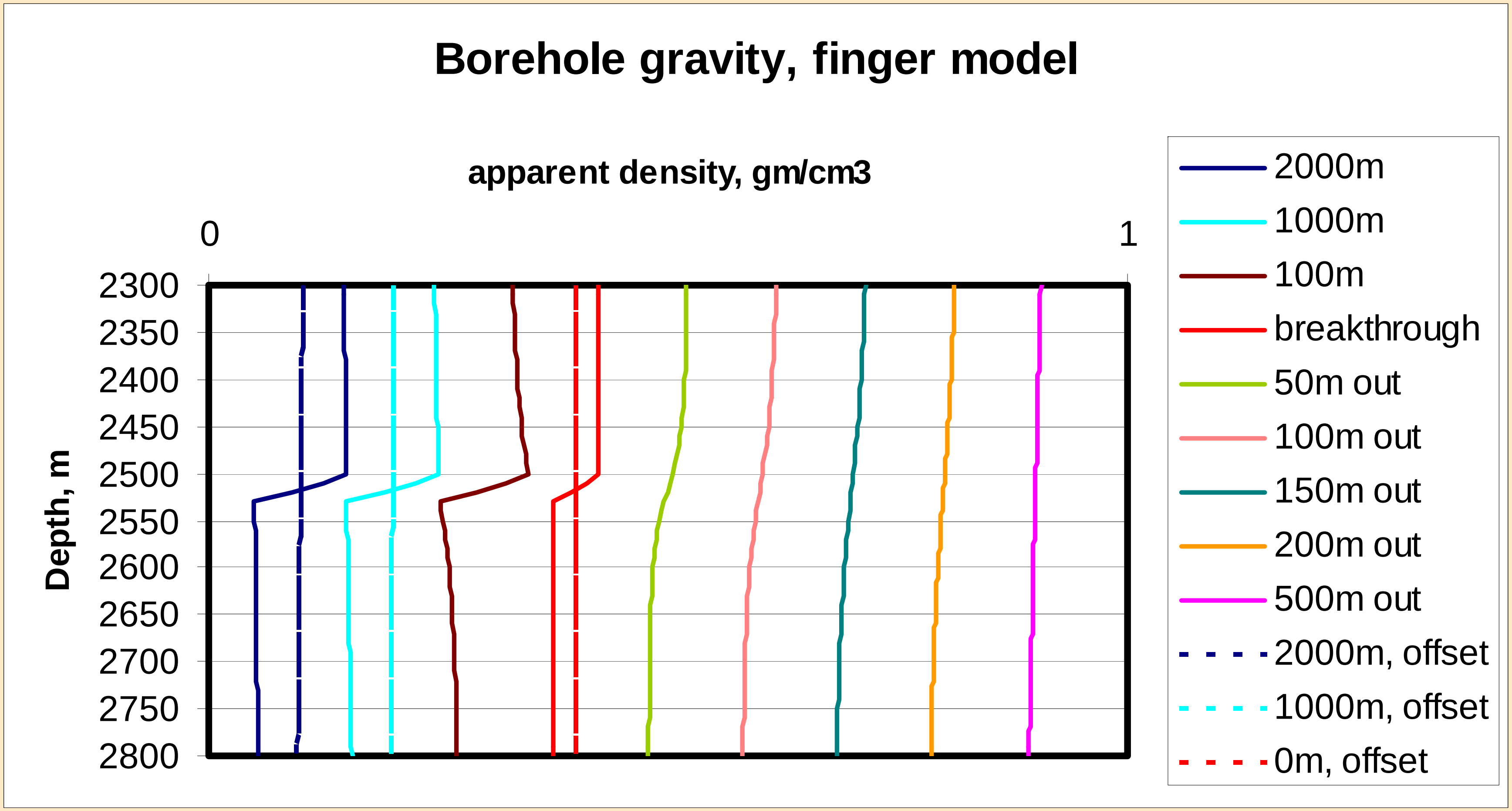
•The <u>spatial</u> variation at any one *time*;

•The <u>temporal</u> variation at a single *place*.

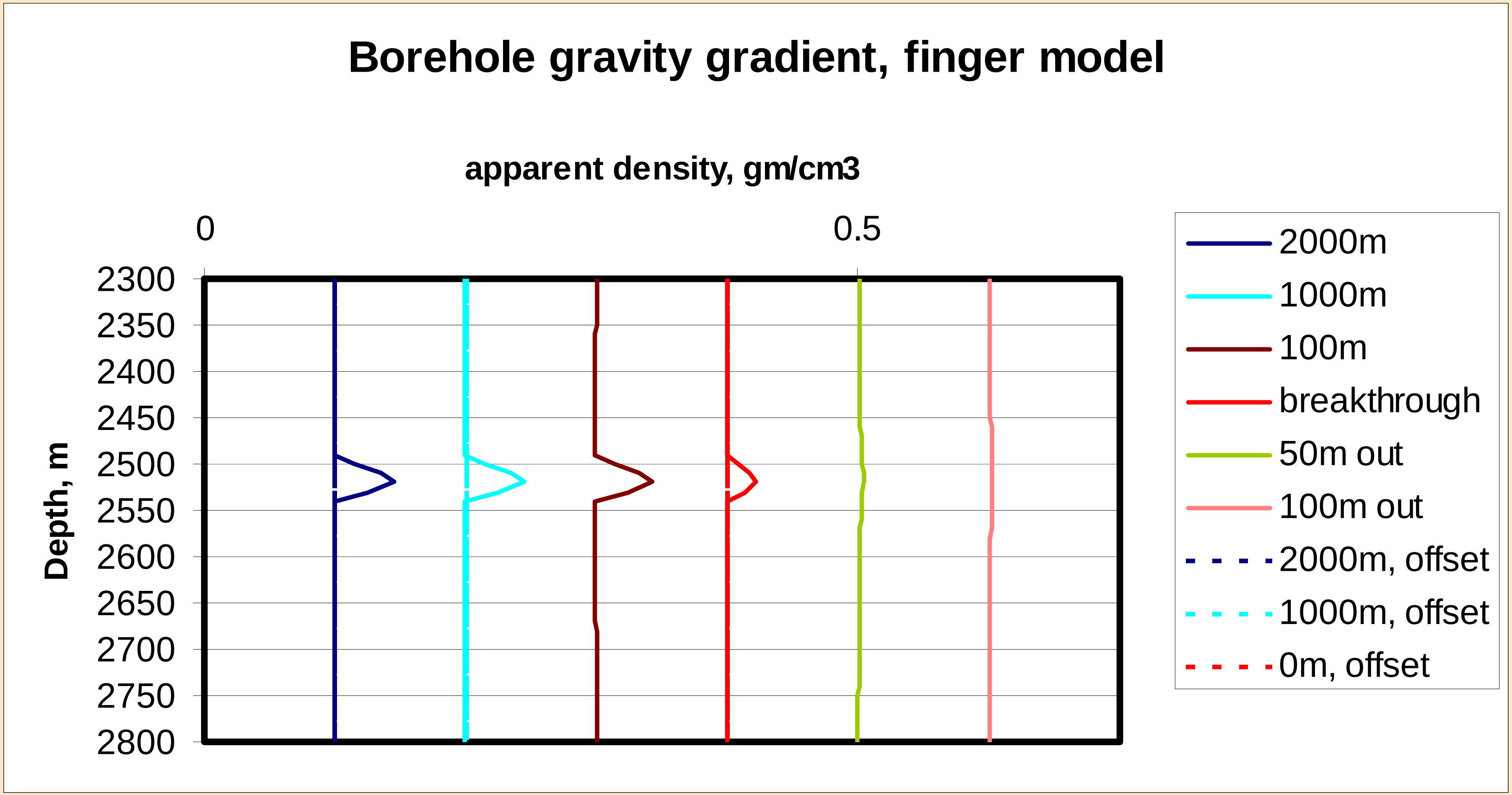
Cross-section though the finger



The 4D gravity signal can be seen for ~ 200m



The gravity gradient signal falls off much faster



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The path to reservoir surveillance through borehole gravity :

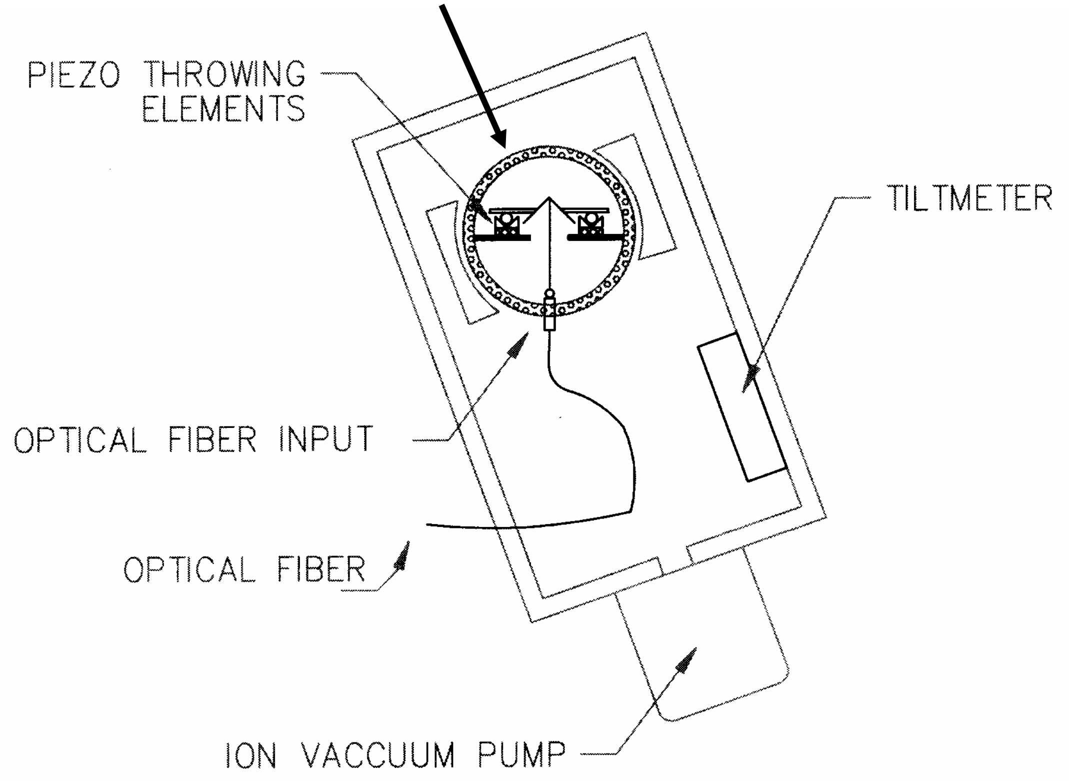
Take <u>new</u> measurements downhole:

- ⊕ **Absolute gravity**
- ⊕ **Optical interferometry**
- ⊕ **Long-term stability-> 4D gravity**
- ⊕ **Cheap, permanent instruments in many wells**
- ⊕ **Active reservoir management**

Borehole Absolute Gravimeter

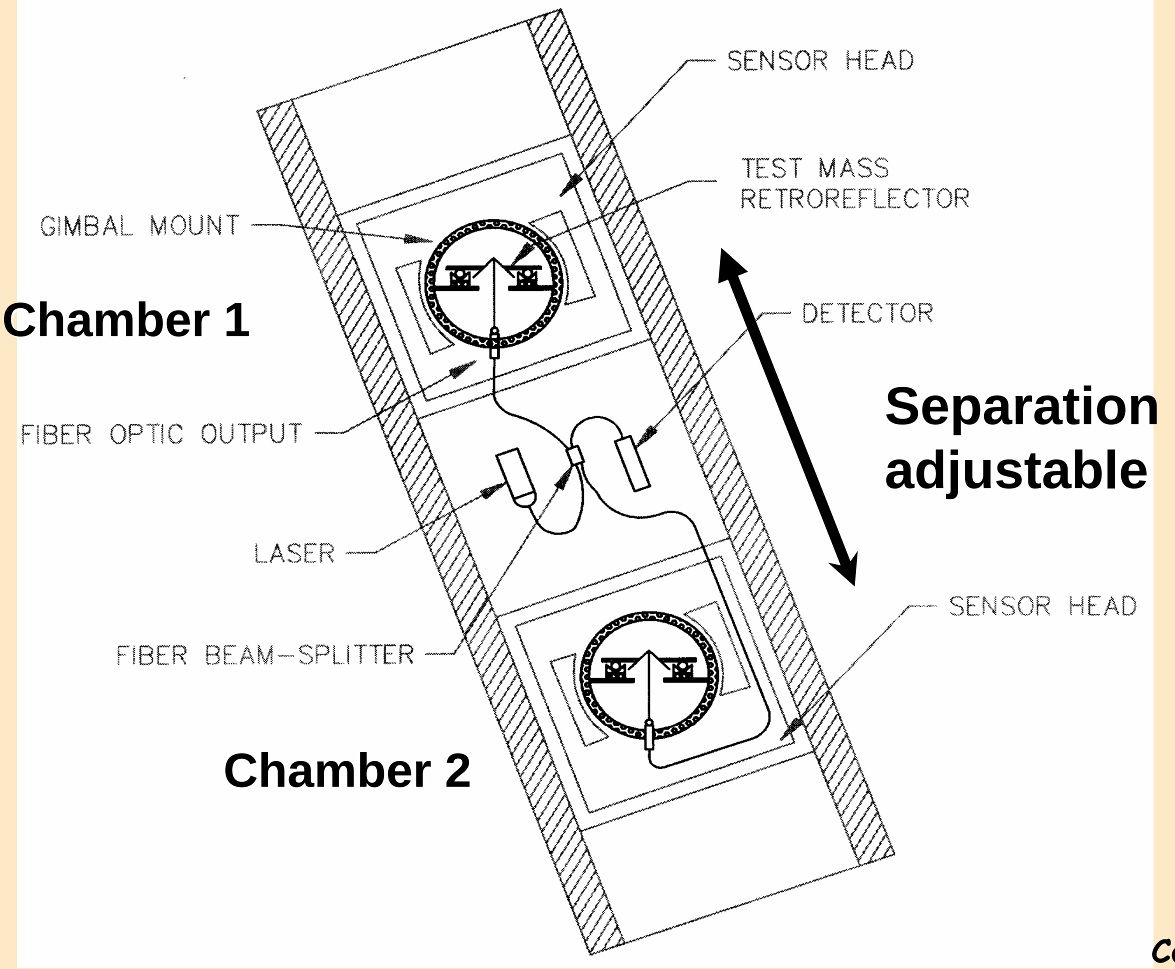
- Evacuated chamber
- Gimbal mount for strongly deviated wells
- Fiber-optic link uphole
- Piezo-launcher
- Small size:
  - Initially 2.5"-3.5"
  - Ultimately 1-11/16"
- Very inexpensive
  - Sensors < $5000
  - Laser = $100s
  - Fiber Optics = $10s

Note: accuracy does <u>not</u> reduce as the size is reduced.



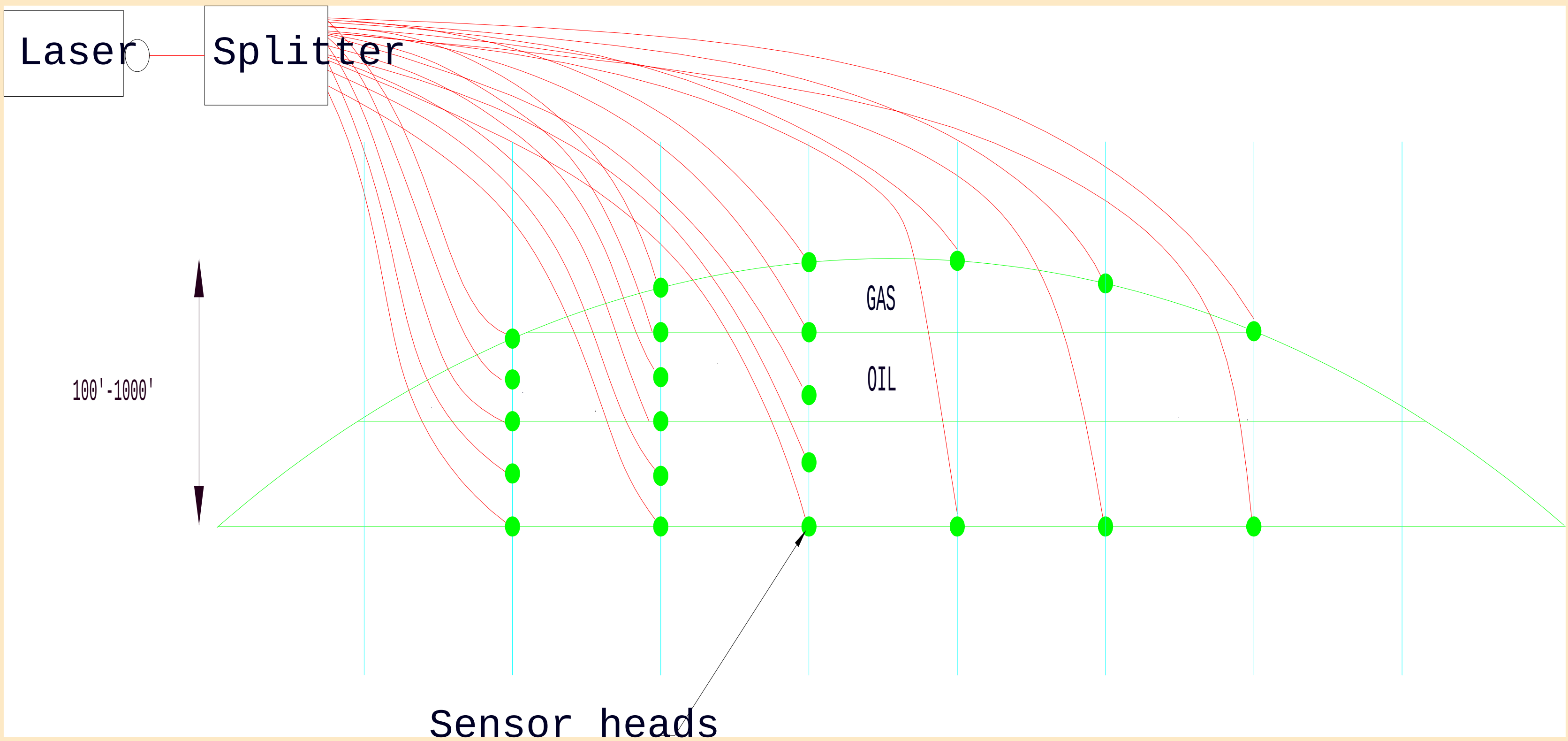
After Strack et al. 1999

Borehole Absolute Gravity Gradiometer



Courtesy EMG Inc.

Multiple Absolute Station System "MASS"



- Multiple Stations provide monitoring network
- Drift-free instruments allow long term monitoring

This system does not yet exist

- Now in engineering phase
- No significant problems loom
- Manufacturing phase in ~ 1 year

We welcome partners in the development and early application of this new means for 4D active reservoir management.

Acknowledgements

We thank:

- BP
- KMS Technologies
- Shell
- and their technology partners

for making this development possible.

KMS Technologies – KJT Enterprises Inc.
6420 Richmond Ave., Suite 610
Houston, Texas, 77057, USA
Tel: 713.532.8144

info@kmstechnologies.com

Please visit us
http://www.kmstechnologies.com//