

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

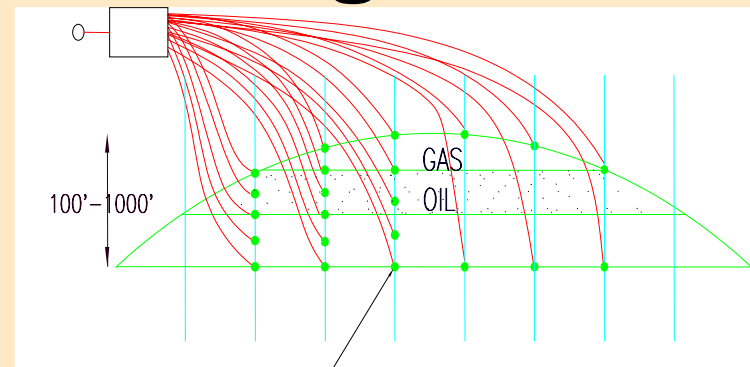
by

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³Shell



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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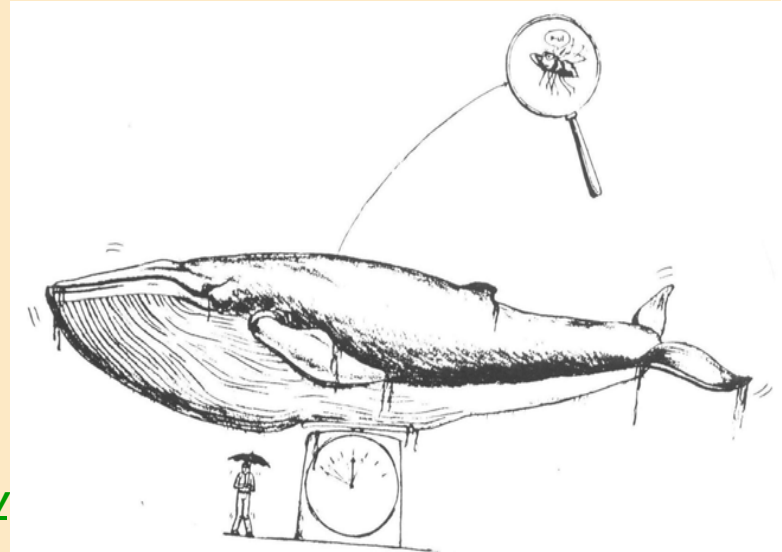
As a reminder...

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

$$F = mg \quad ;$$

$$g \approx 980 \text{ cm} / \text{s}^2 = 980 \text{ Gals}$$

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



As a reminder...||

- 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...|||

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

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

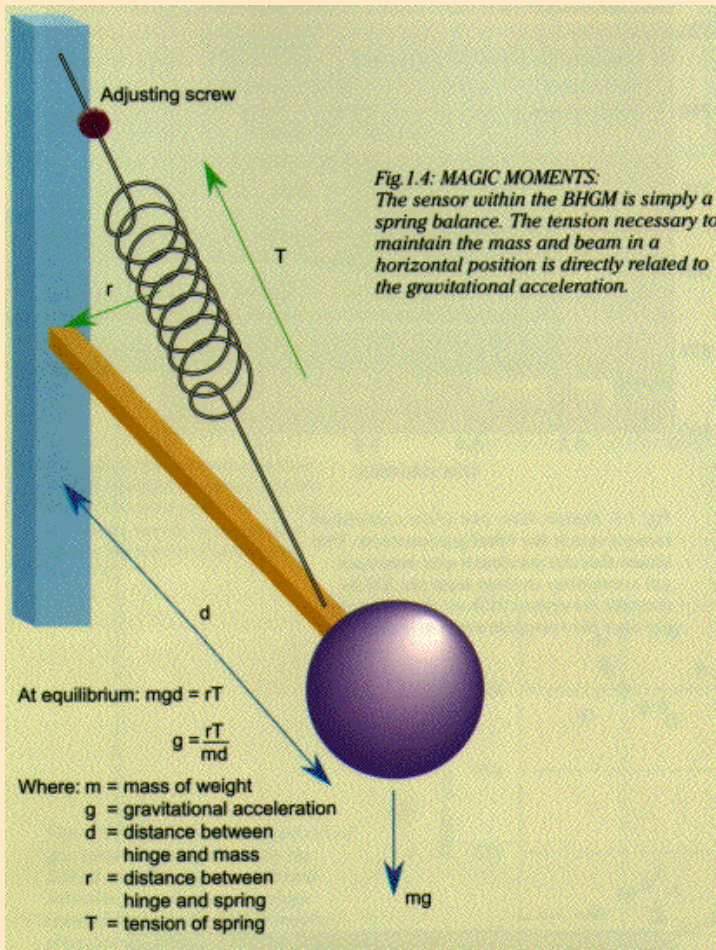
- ◆ Hence the measured gravity gradient can be expressed in terms of the *equivalent* density of an infinite slab:

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

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.

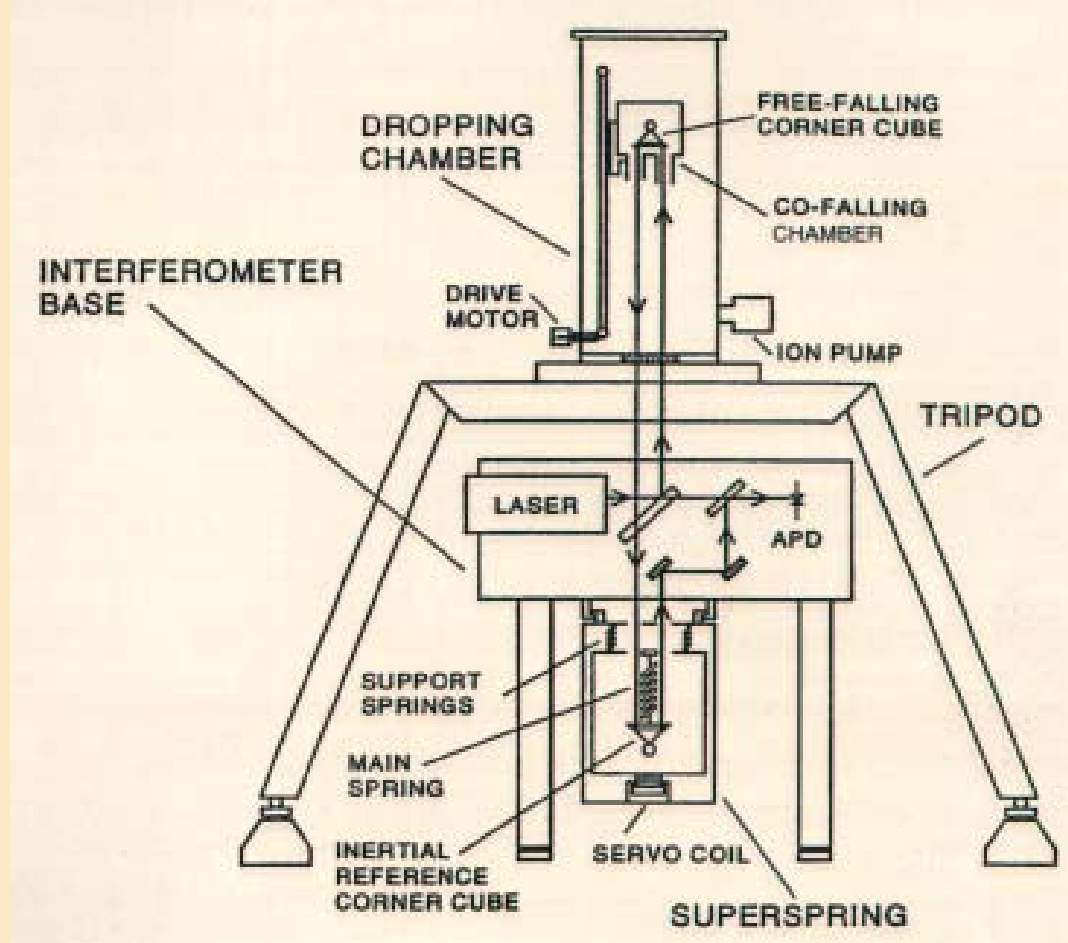
Conventional (relative) gravity meter measures force



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 acceleration *directly*



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

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

Relative & absolute gravity meters



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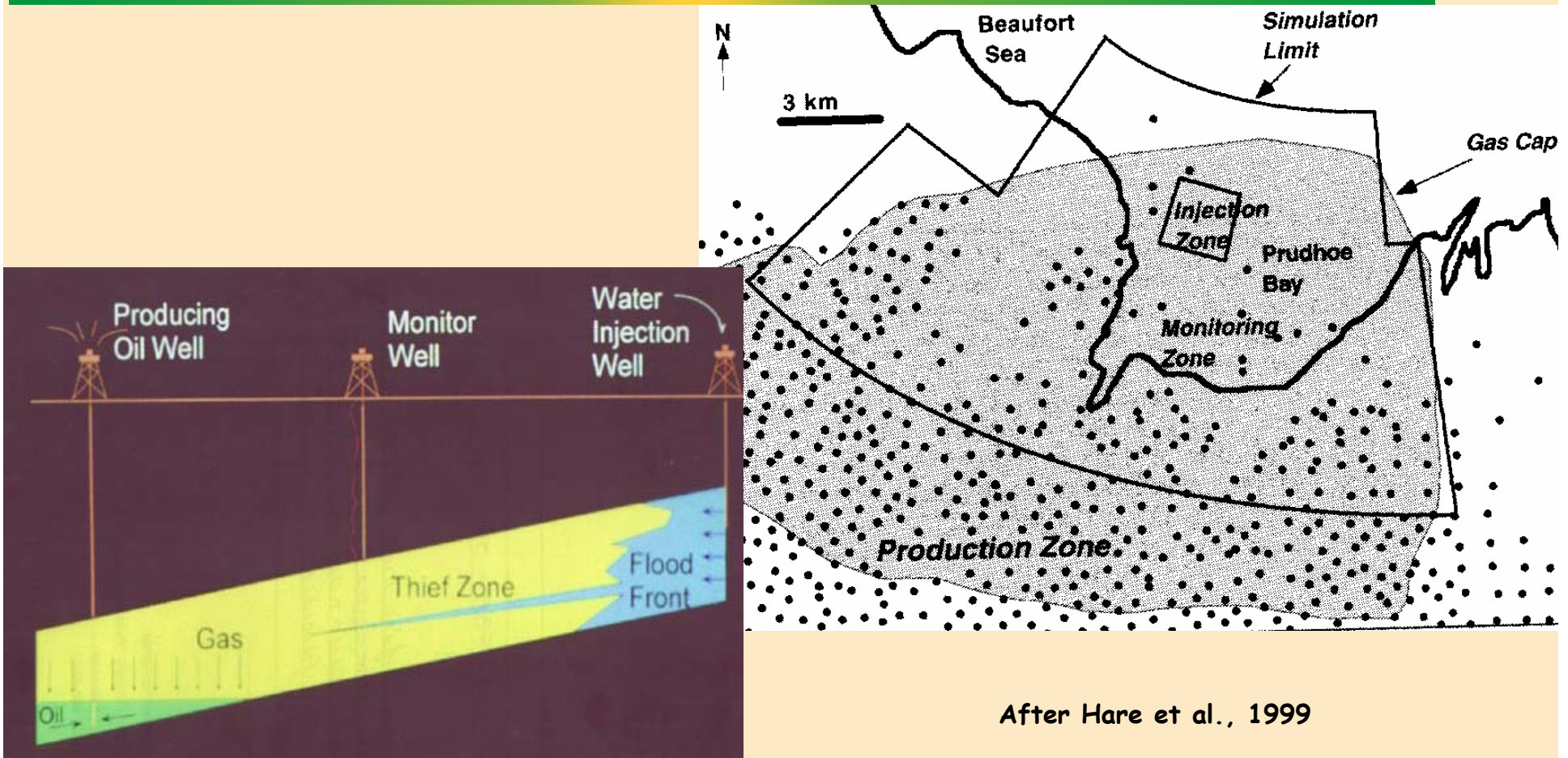
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Waterflood Monitoring with 4D Surface Gravity

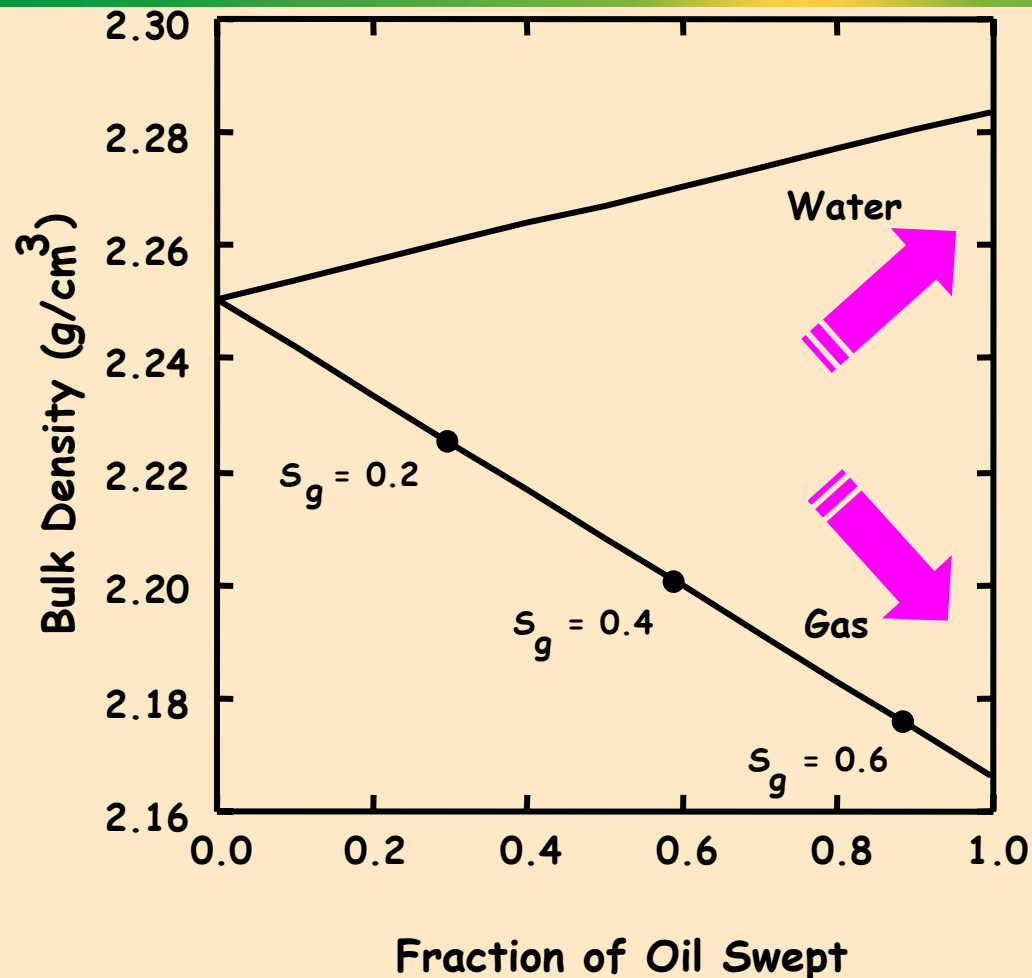
- ◆ Perform baseline gravity survey prior to injection
- ◆ Water injection creates a positive gravity anomaly
- ◆ Gravity survey repeated yearly
- ◆ 4D gravity signal = (repeat – baseline)
- ◆ 4D gravity difference inverted for density changes
- ◆ Reservoir density change => water movement
- ◆ Constraints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

Prudhoe Bay, Alaska



After Hare et al., 1999

Prudhoe Bay: Change in bulk density



$$\phi = 0.22$$

$$\rho_{ma} = 2.65 \text{ g/cm}^3$$

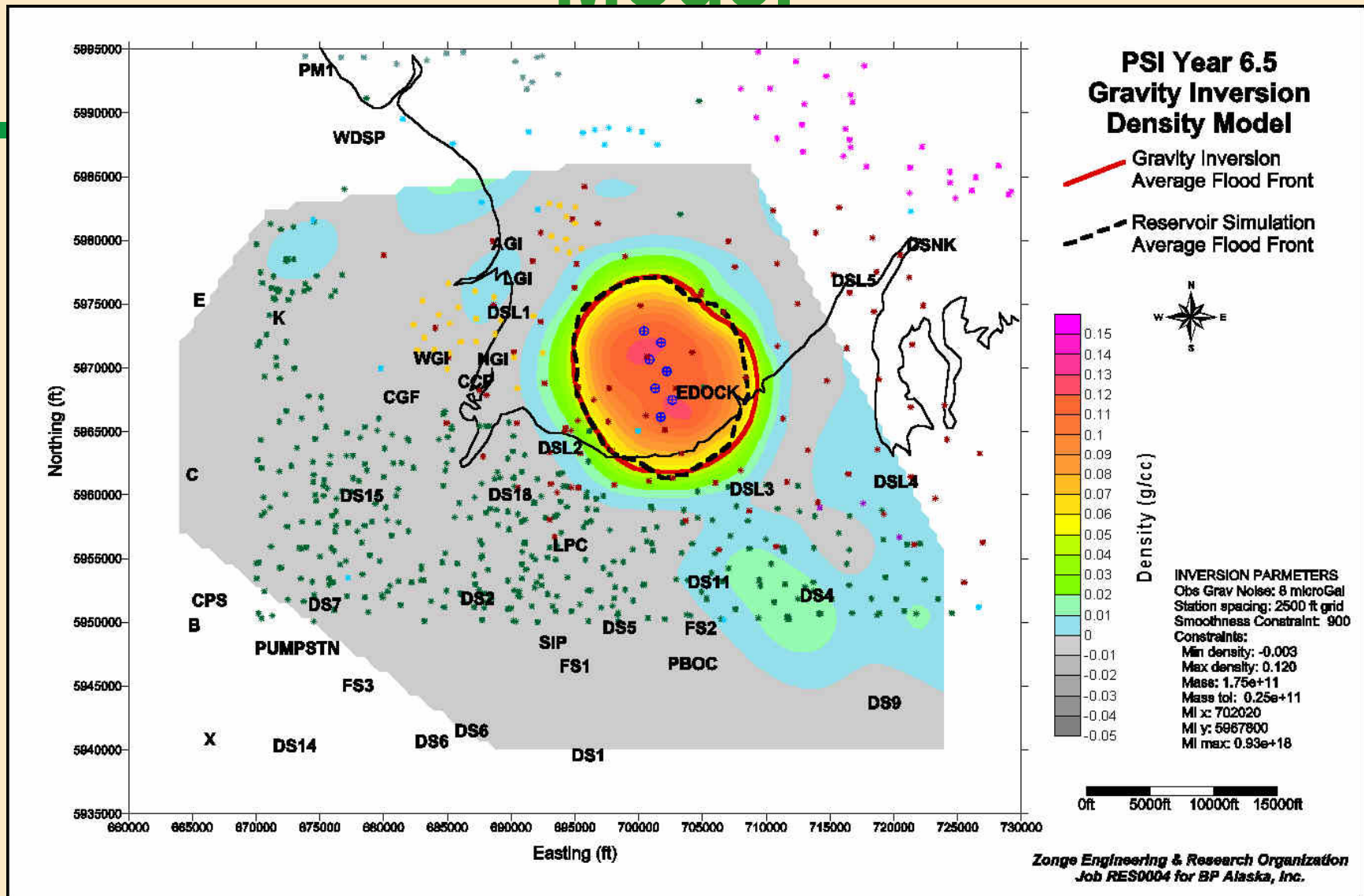
$$\rho_o = 0.762 \text{ g/cm}^3$$

$$\rho_w = 0.986 \text{ g/cm}^3$$

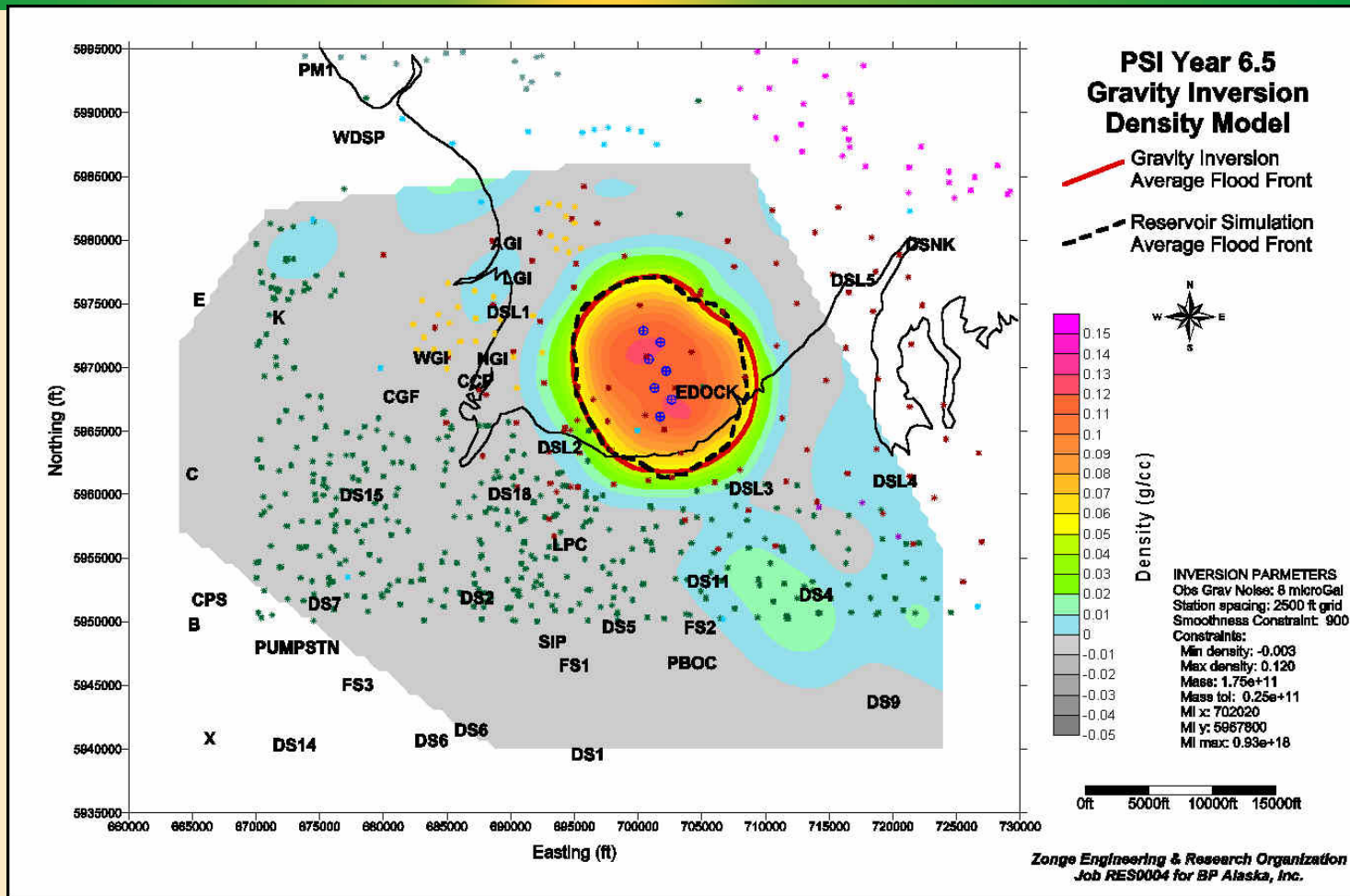
$$\rho_g = 0.198 \text{ g/cm}^3$$

$$\text{Residual water saturation} = 0.32$$

Gravity Inversion Vs Density Model



Modeling *gravity* is easier than modeling *seismic*



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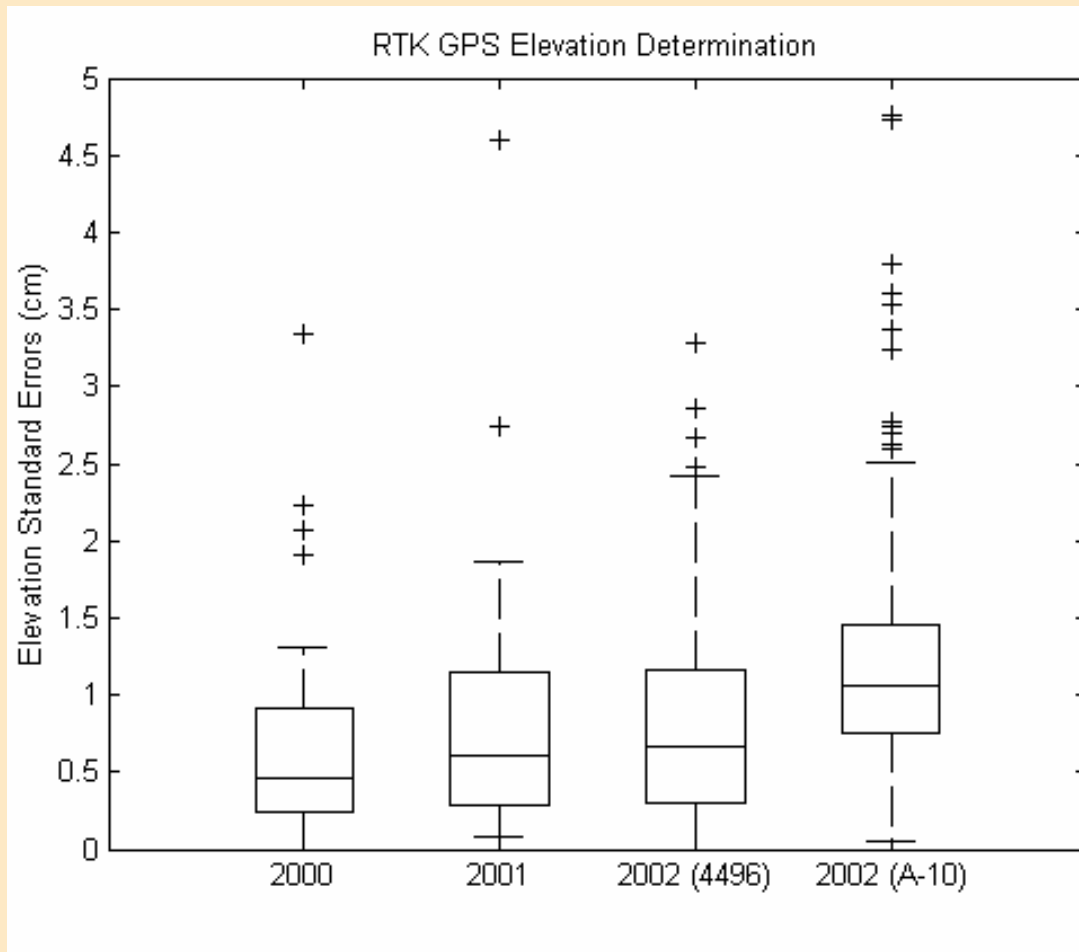
Absolute Gravity Meter Repeats in 2002 Survey

Station	Repeats	Average	microgals	
			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

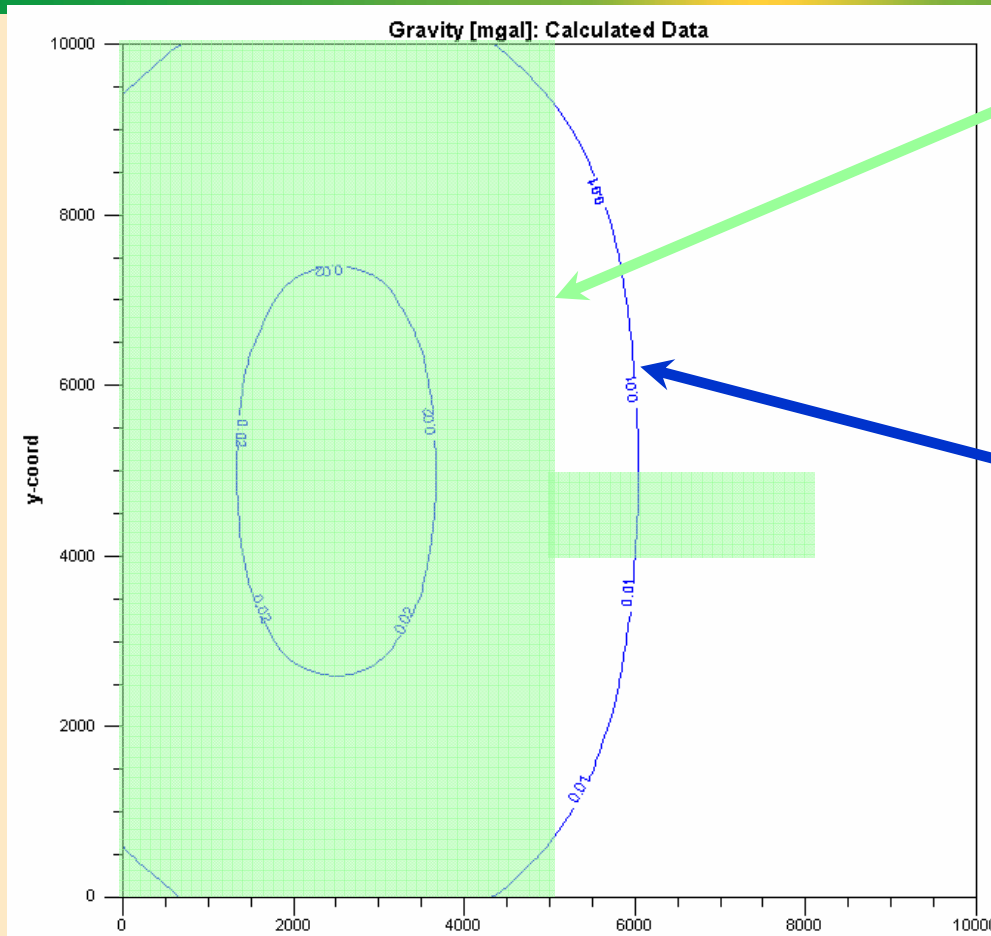


**Elevation errors
lead to
gravity errors:
3 μ Gals/cm**

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 μ Gal contour

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

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Borehole gravity measurements

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

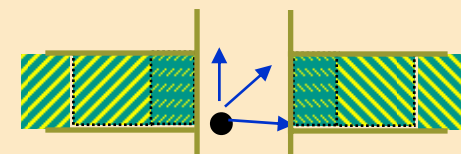
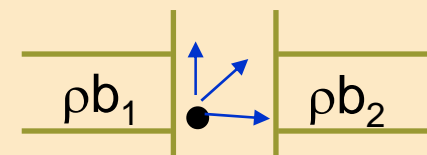
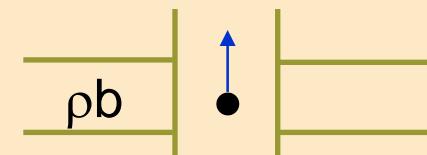
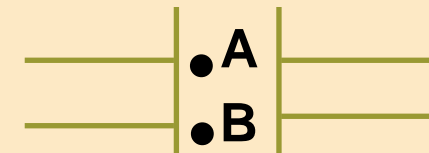
Gravity Gradiometer: Direct measurement of gradient $g_{z,z}$. Fixed frame of reference

Multi-component Gradiometer:

Directional interpretation from $g_{z,x}$, $g_{z,y}$, $g_{z,z}$

Higher-order derivatives:

Different depths of investigation



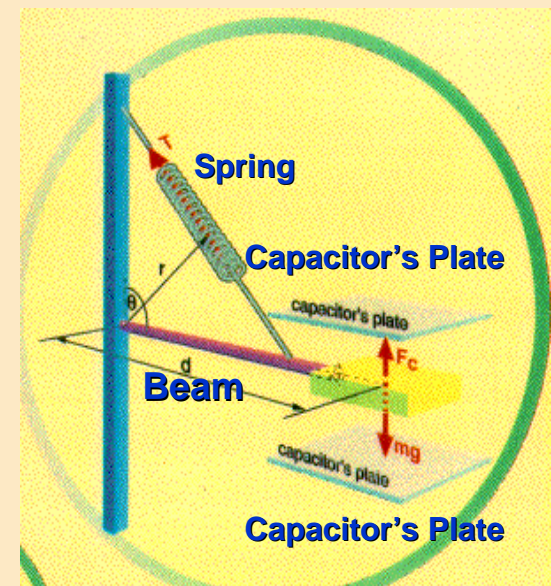
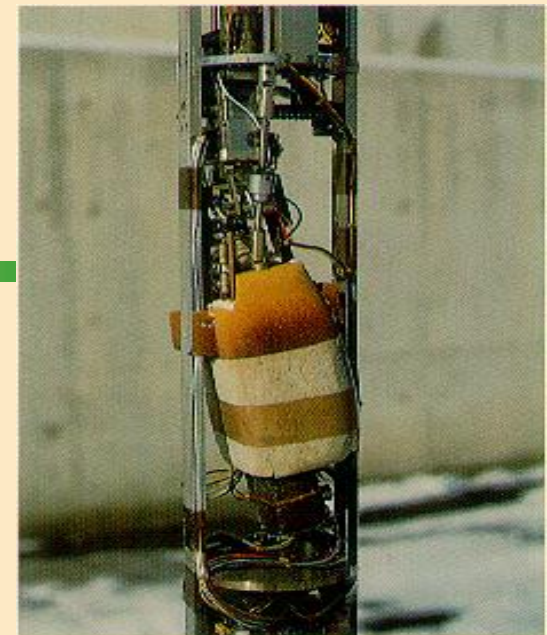
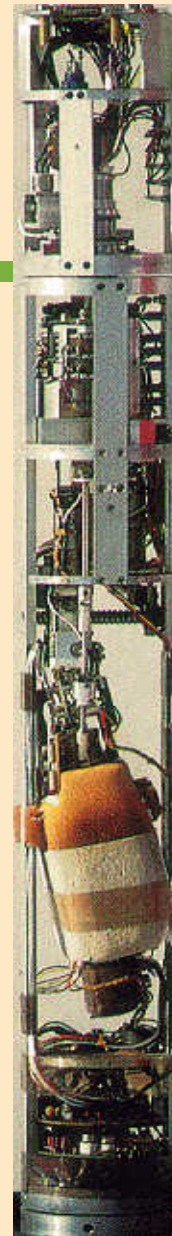
Borehole Gravimeter (BHGM)

- ⊕ LaCoste & Romberg “zero-length” spring balance
- ⊕ Capacitor force related to gravitational acceleration
- ⊕ Standard deviation: $3 \mu\text{Gal}$.

Courtesy Edcon Inc.

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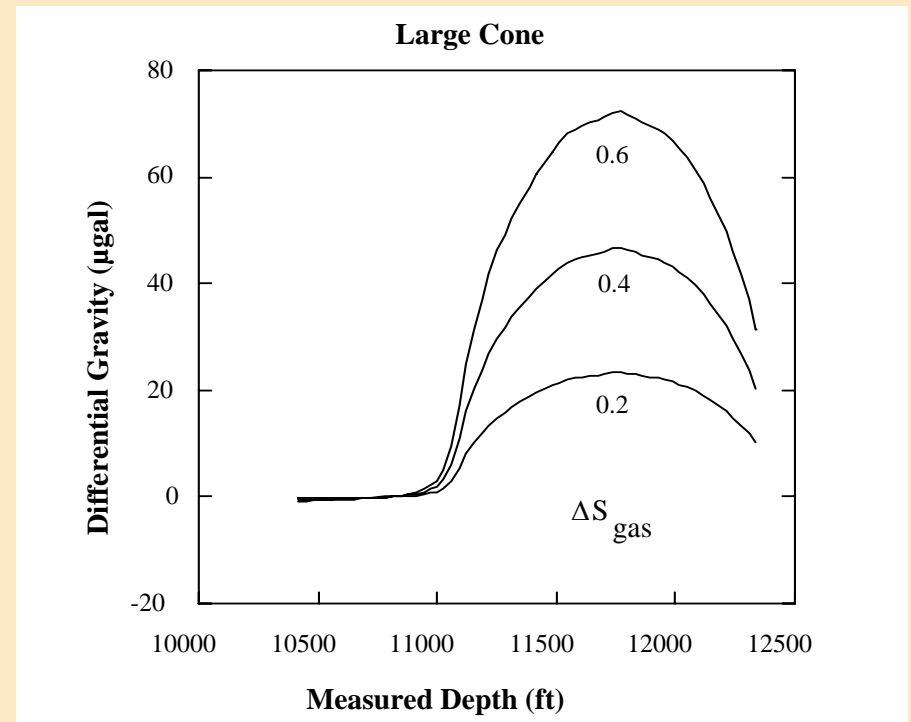
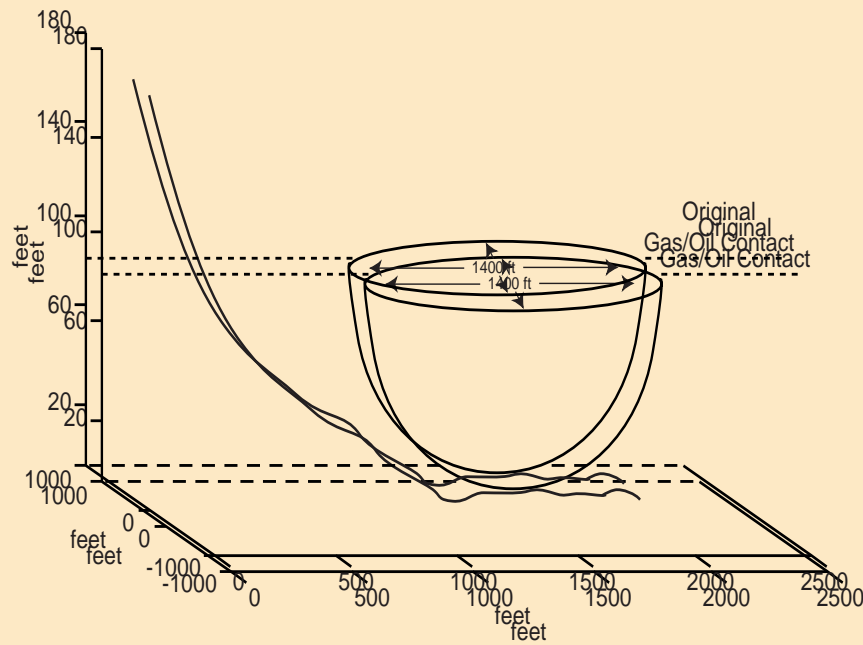
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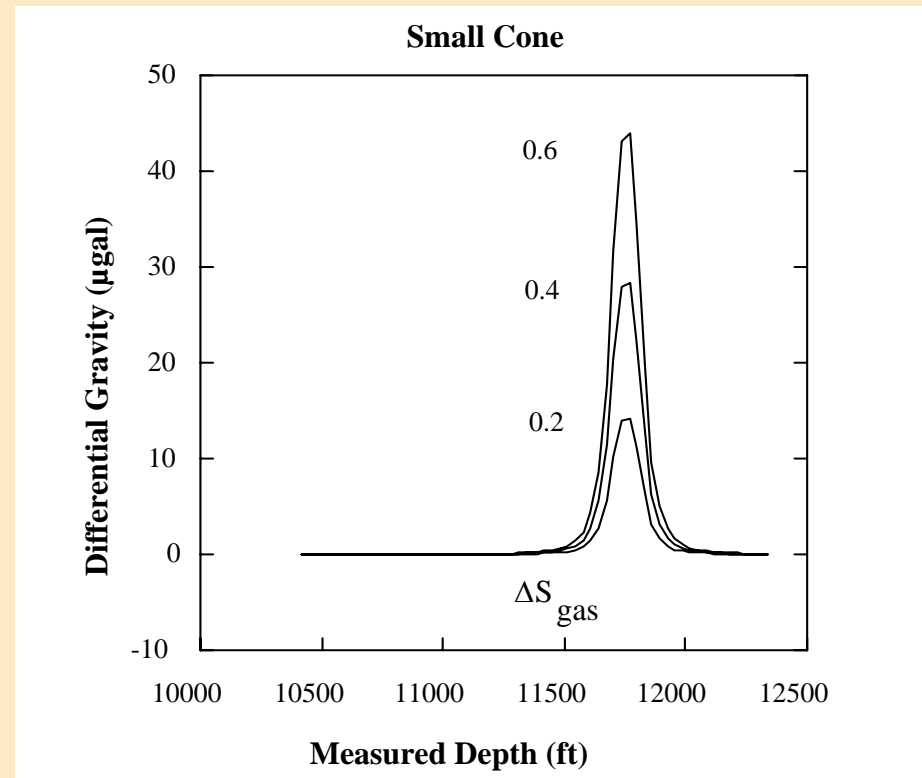
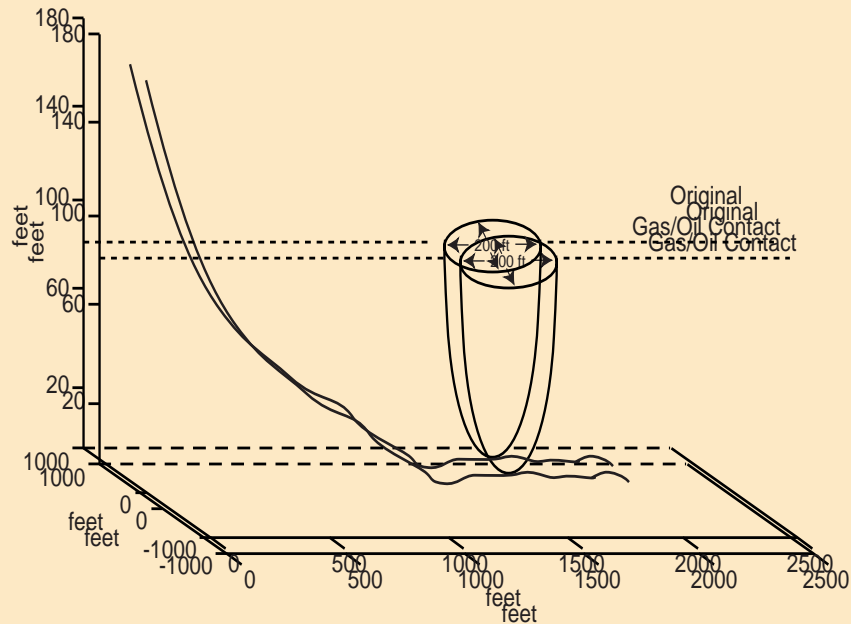
Borehole Gravity Used for Reservoir Surveillance

- ◆ **Problems with *current* borehole surveillance tools:**
All shallow-reading devices have problems with:
 - ⊕ - Straddles, Scab liners, Gas channels, Gas cones, Perforations
- ◆ **Primary *Advantage* of Borehole Gravity:**
A very deep-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 surveillance
 - ⊕ - Tool OD is too large
 - ⊕ - Only works in near-vertical wells
 - ⊕ - Depth control is difficult to achieve

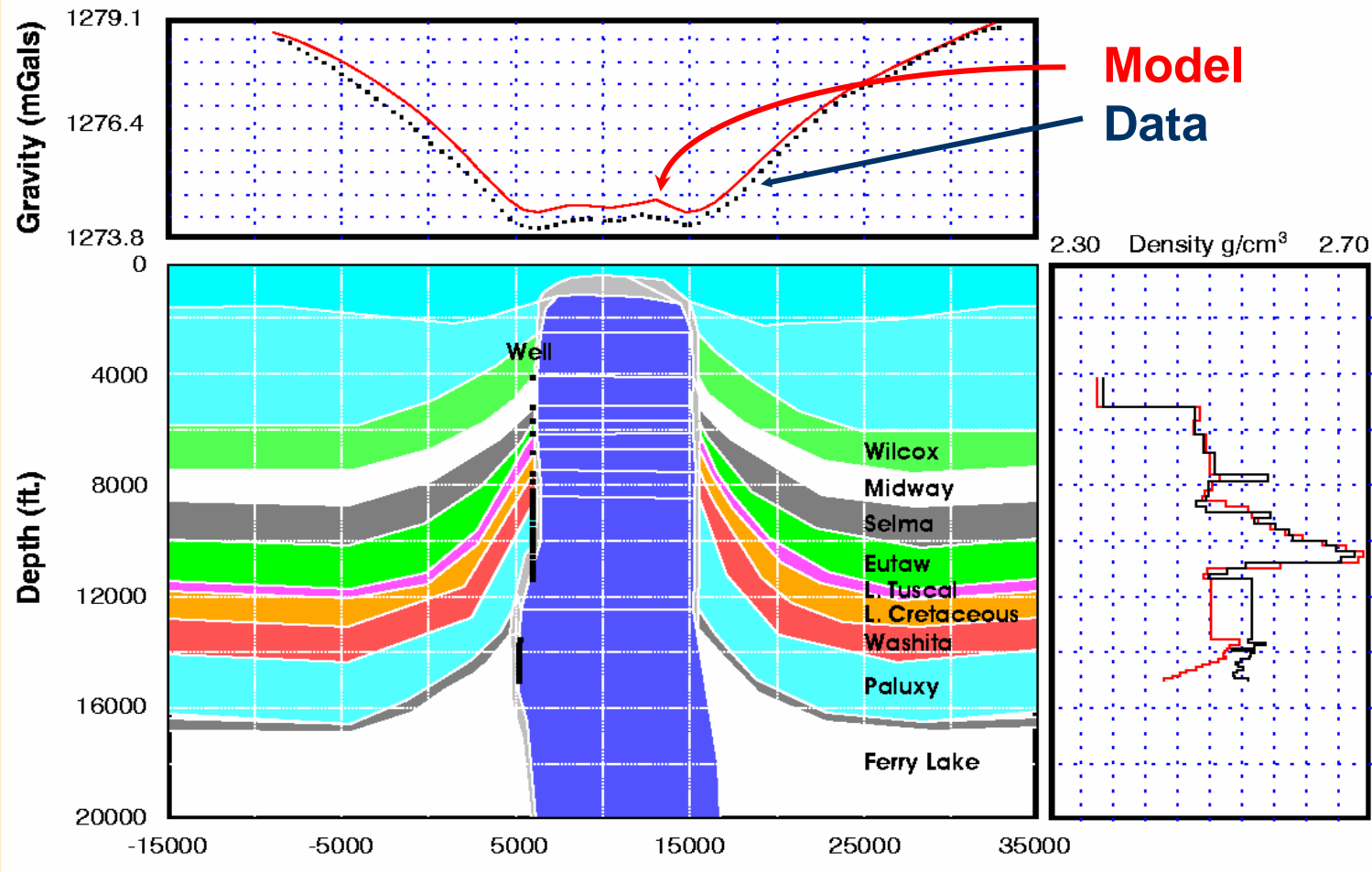
Borehole Gravity Applications: Large Gas Cone



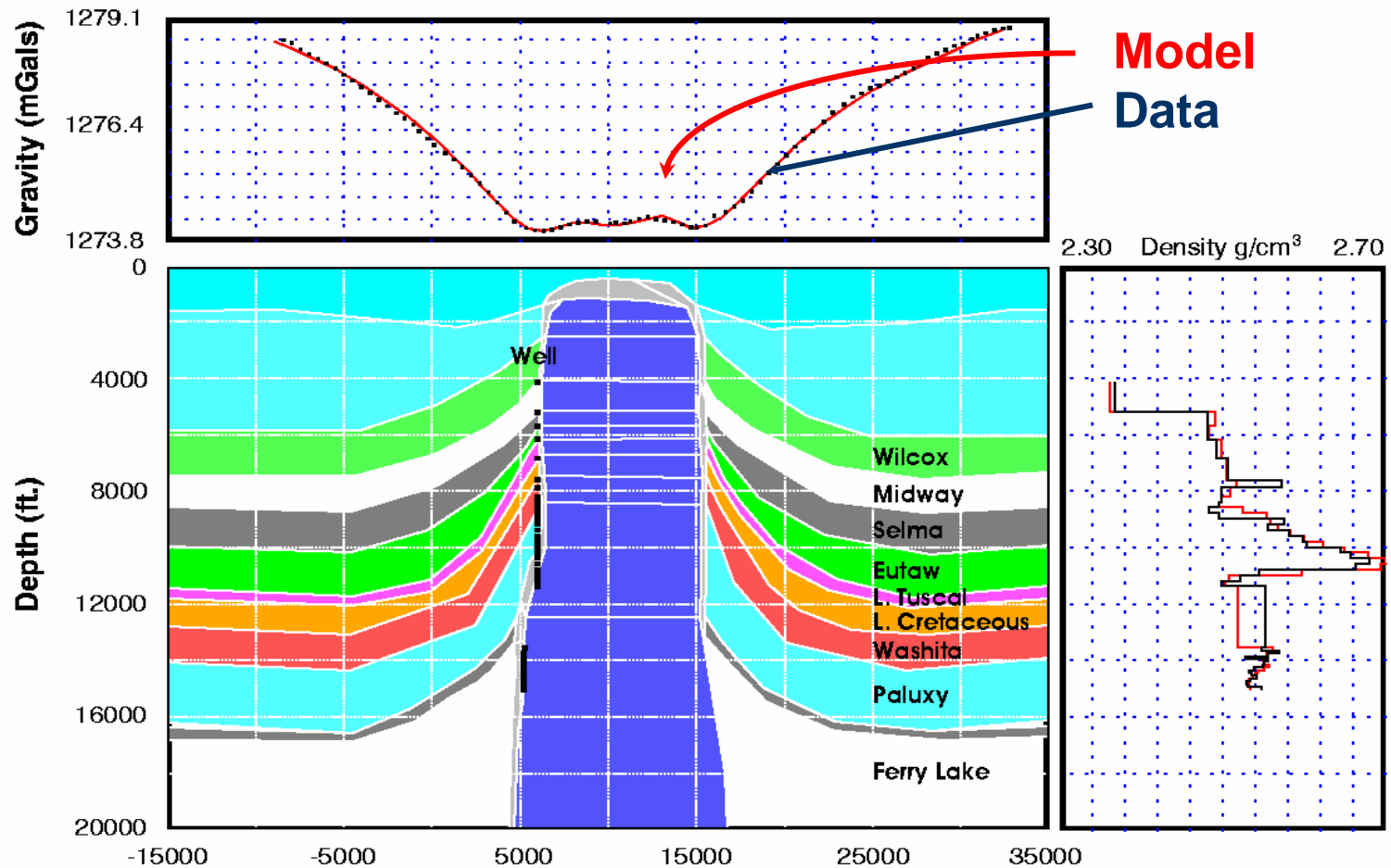
Borehole Gravity Applications: Small Gas Cone



Borehole Gravity Applications: Salt dome overhang



Borehole Gravity Applications: Salt dome overhang

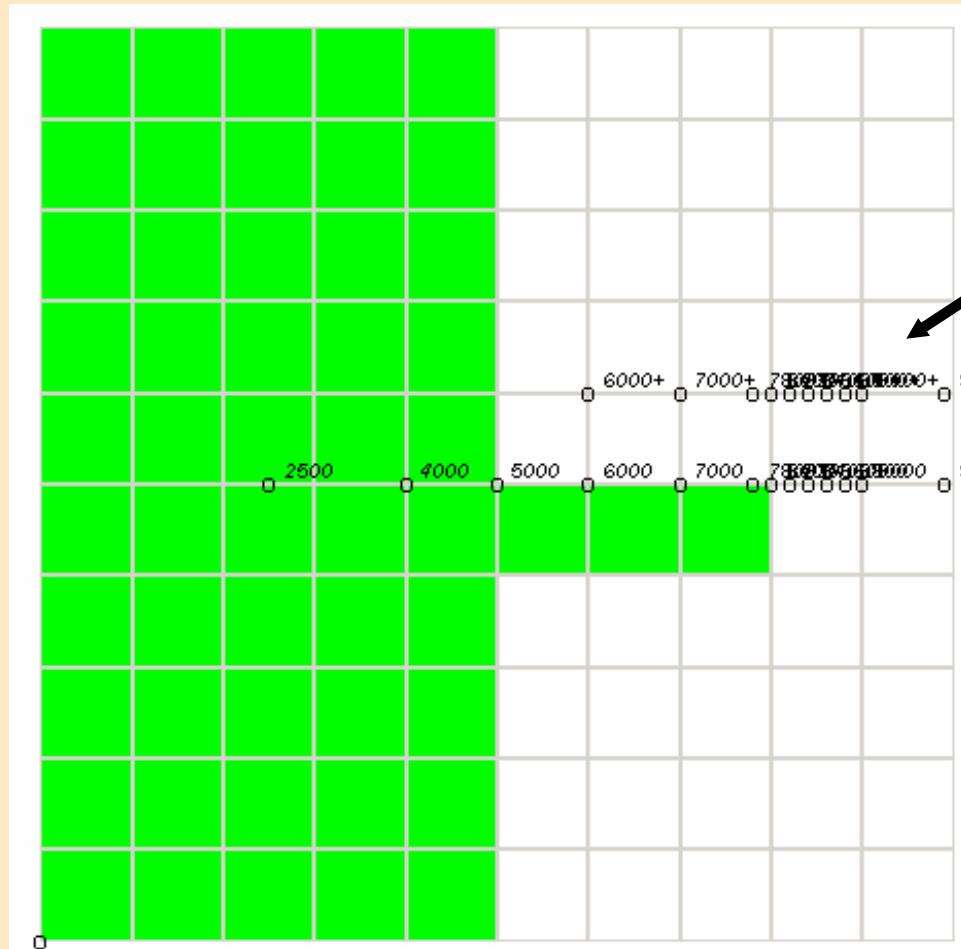


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After Black, 1998

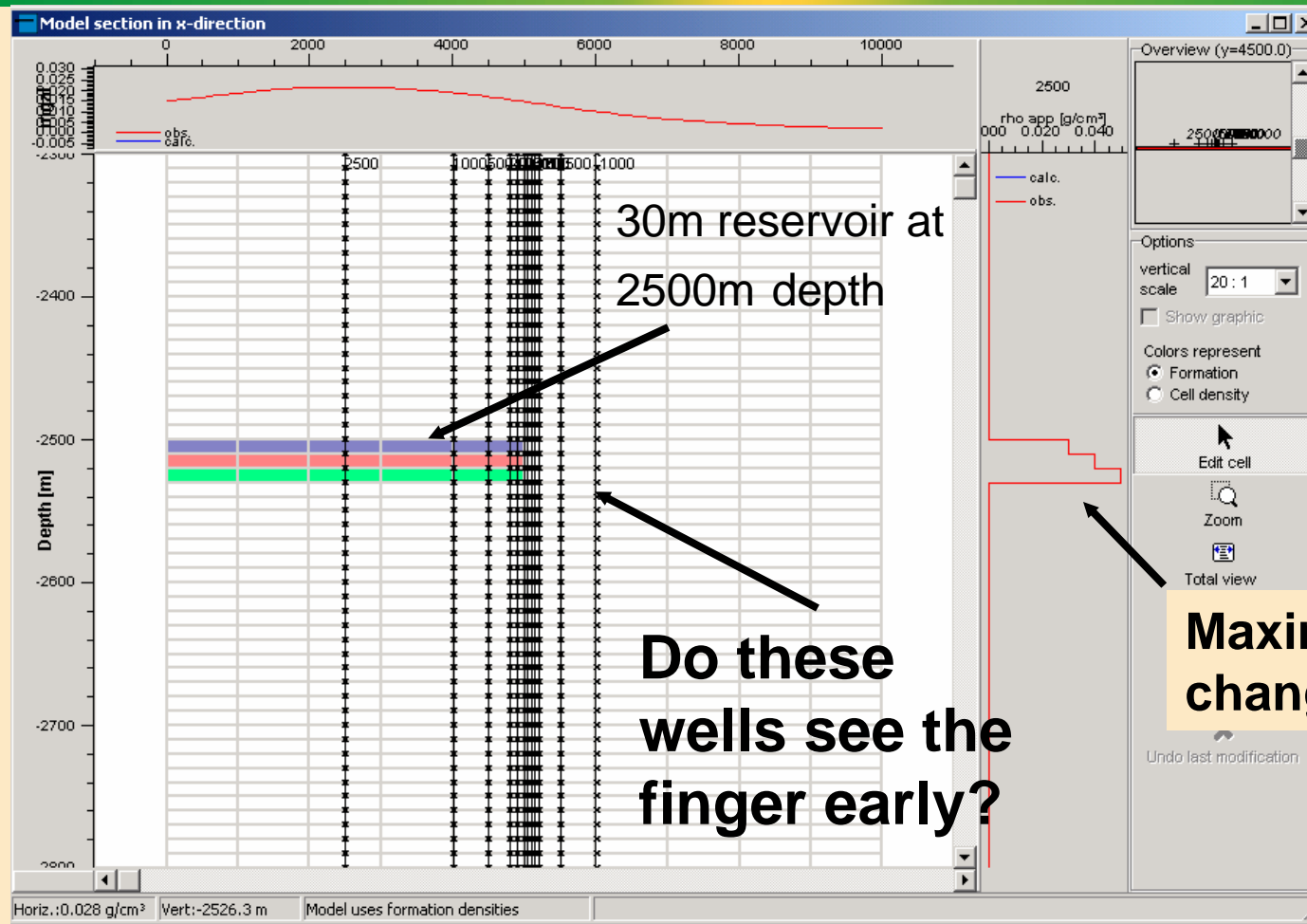
Borehole Gravity Applications: Waterflood fingering



These wells indicate:

- The spatial variation at any one *time*;
- The temporal variation at a single *place*.

Cross-section through the finger

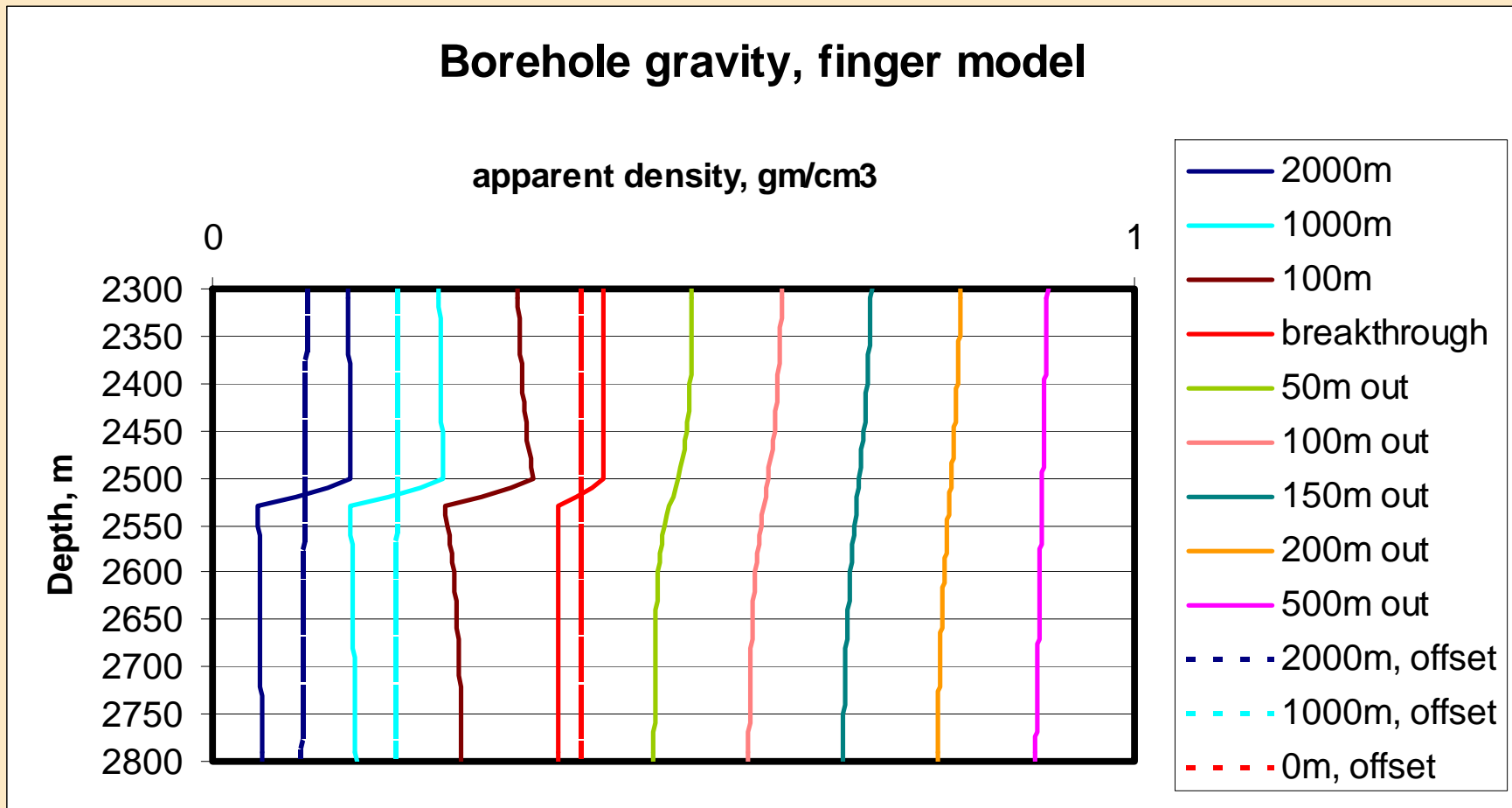


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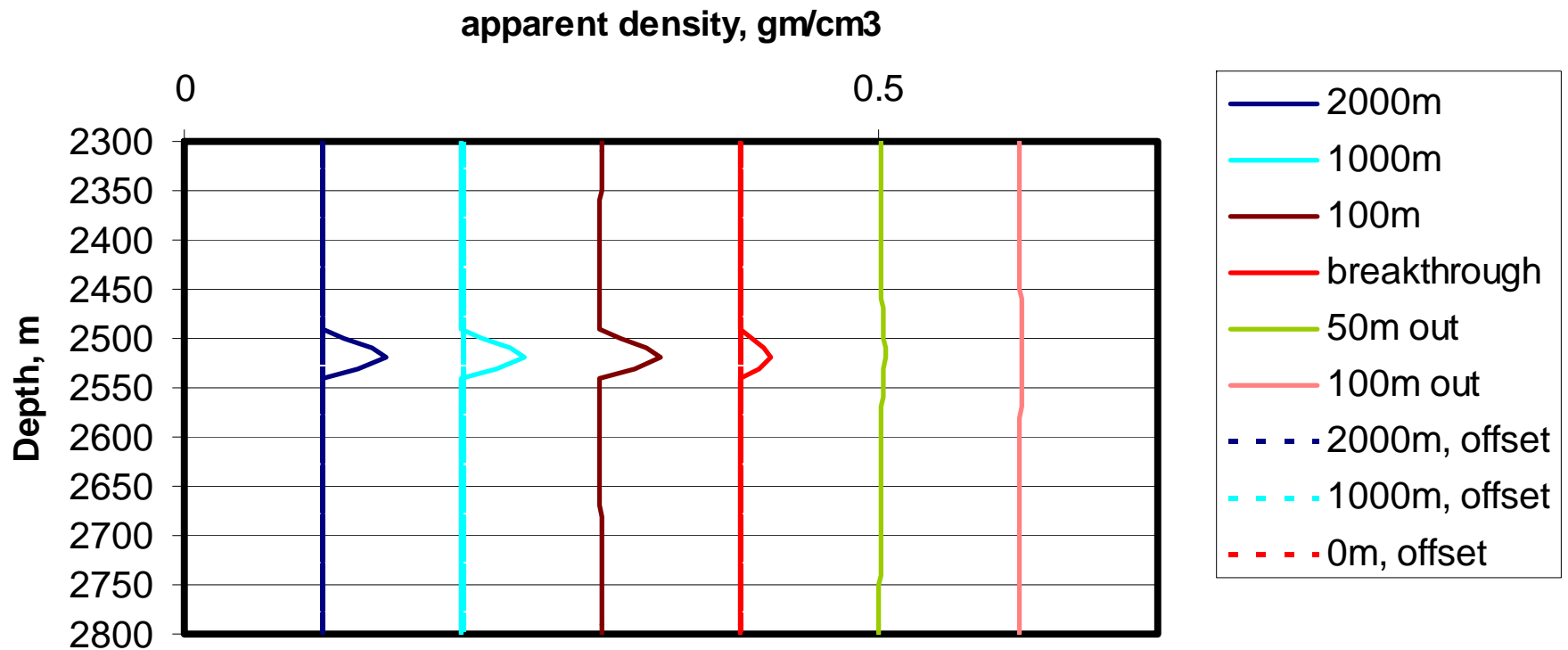
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The 4D gravity signal can be seen for ~ 200m



The gravity gradient signal falls off much faster

Borehole gravity gradient, finger model



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The path to reservoir surveillance through borehole gravity :

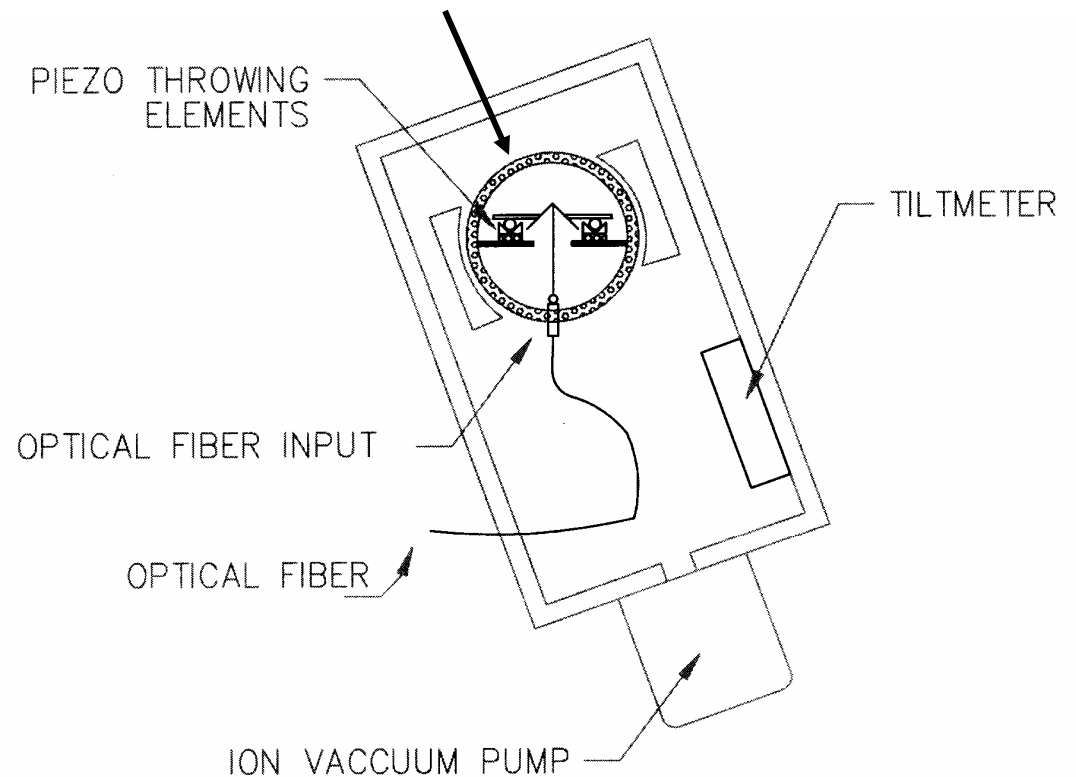
Take new measurements downhole:

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

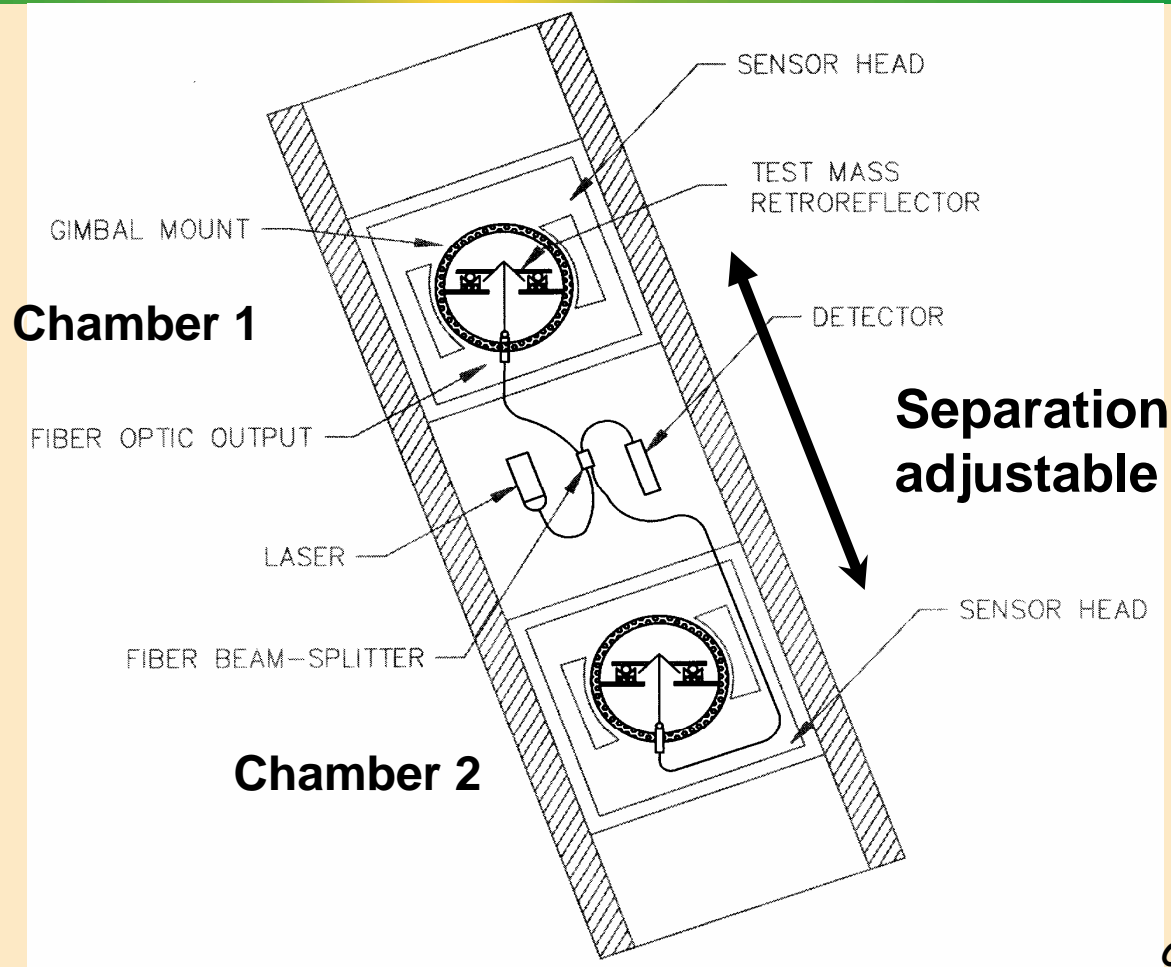
Borehole Absolute Gravimeter

- 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

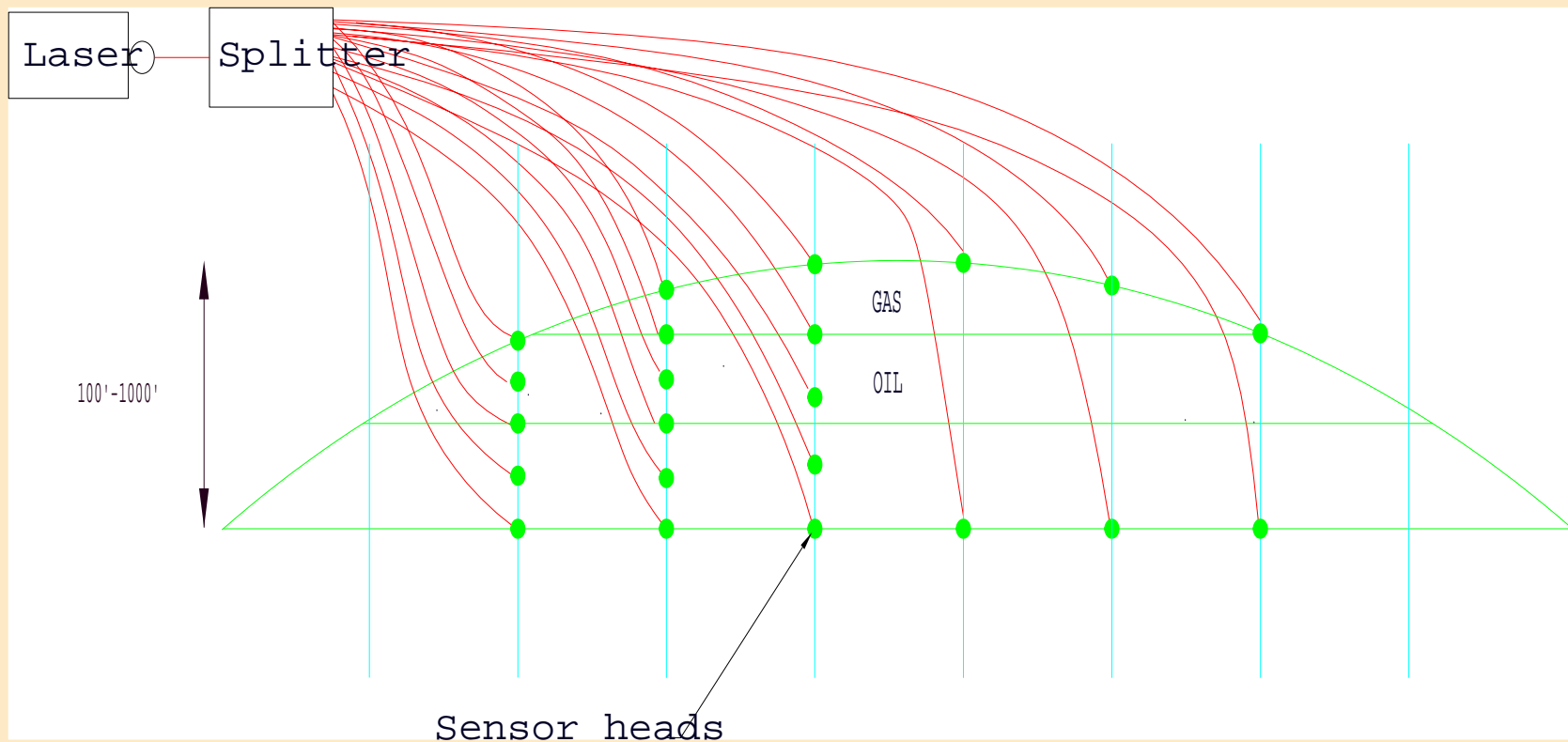
Note: accuracy does not reduce as the size is reduced.



Borehole Absolute Gravity Gradiometer



Multiple Absolute Station System "MASS"



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

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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.**

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