Gravimetric monitoring for existing and future use

Adrian Topham, 18th September 2020

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We are a technology platform & data services company & our purpose is to solve complex challenges and create value through the application of gravity

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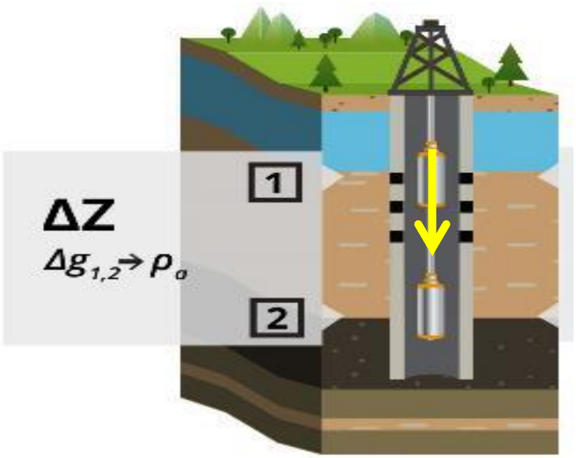
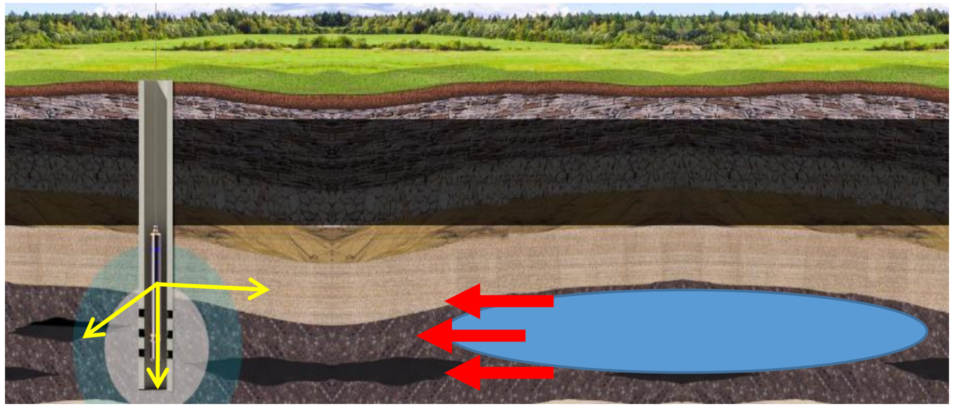
2 Uses of Borehole Gravity Measurements: Apparent density and Time-lapse

- **Apparent density** can represent formation bulk density: we compute an apparent density (ρa, kg/m3) of the layer of rock within the interval ΔZ as the measured difference of single-axis vertical gravity Δg, which is sensitive to the strata away from the borehole.



- **Time-lapse** repeated borehole gravity measurements are taken at the same locations in the well over a time period. The difference of the tri-axial measured gravity Δg over time in a reservoir scenario is directly related to the time-lapse density change caused by the migration of different reservoir fluids such as oil, gas, and/or water.



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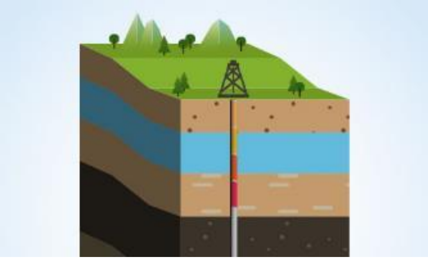
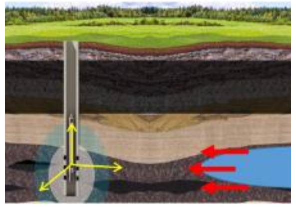
4D time-lapse borehole gravity: What is the problem?

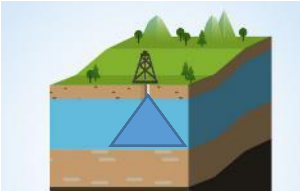
- Few techniques exist to map subsurface fluid movements (100’s ft around a wellbore)
  - Pulsed neutron immediately around a wellbore (10’s cm)
  - Sophisticated seismic surveys attempt to map deeper, costing millions of $$, and are indirect ‘velocity’ measurements
- A gap exists between wellbore centric & 4D seismic survey data. Gravity can fill this gap.
- Huge appetite for time-lapse gravity to reduce uncertainties:
  - O&G reservoir surveillance: Flood front/coning
  - CCS: monitoring storage and CO_2 plume growth
  - Aquifers: Underground water movement
- Appetite for density imaging for mining and civil engineering



Saturation (fluid)
mapping
monitoring



Flood-front
prediction



Monitoring
Water coning

Carbon capture
storage
monitoring
+ EOR

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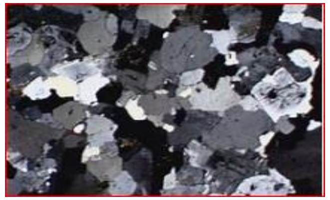
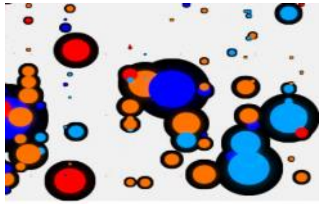
Premise of a time-lapse (4D) gravity survey

- The 3D bulk density distribution within a reservoir at any point in time consists:

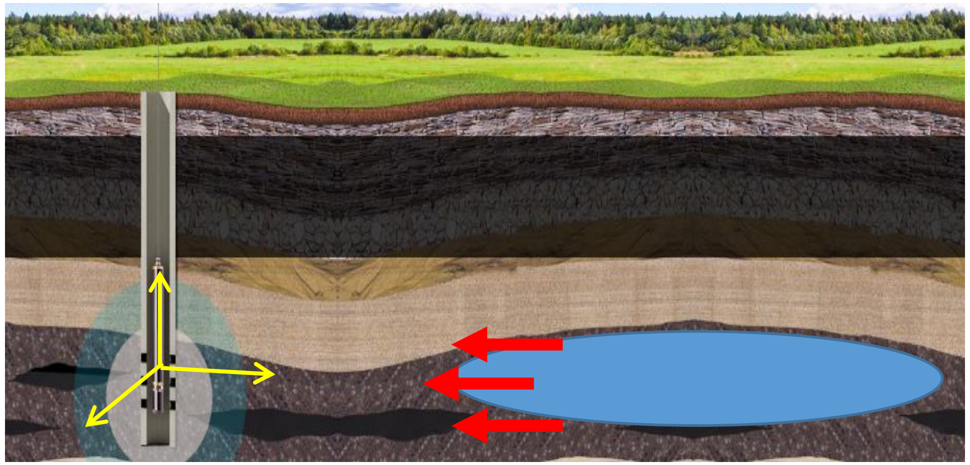
Static element - gross rock volume / density of solid matrix



Dynamic element - saturation / density of fluids within the pore space



- Assume volume of km^3, within this region the mass can be measured by gravity sensor as:
  - Dominant **“background”** gravity field, (spatially constant - static)
  - “**Anomalous”** gravity field (spatially variable, dynamic component)
- Objective of a time-lapse borehole gravity survey is to measure this **anomalous** field, inferring fluid movement/substitution over time
- 3 axes will indicate spatial direction



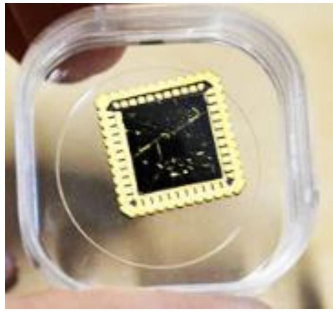
194845 • Three-axis Borehole Gravity Logging for Reservoir Surveillance • Lofts et al.

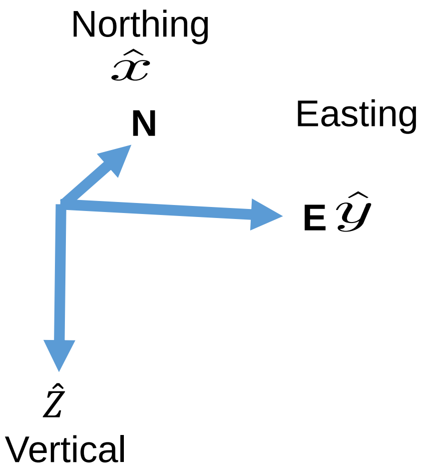
Emerging Wireline Borehole Gravity Technology

Highly sensitive accelerometer

- MEMS technology
- Ultimate resolution of approx. Billionth Earth's gravity
- 3-axis arrangement
- Significant size, weight & power ("SWaP"), 2-1/8" tool
- Wireline provider agnostic, full toolstring provided
- Feasibility modelling & post-acquisition Inversion

	Target Specifications
Outside Ø	Slimhole OD 2-1/8" (54mm), tubing 2 ¼ ID
Temp. / Press.	250 ^{o}F, 125^{o}C / 15,000 psi
Gravity Sensor	3-axis, resolution ~5 μGal





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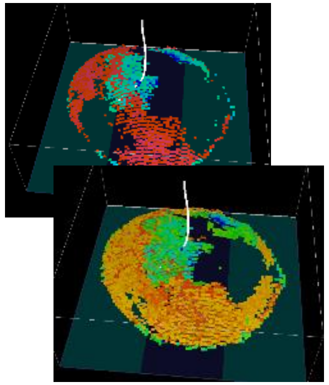
4D gravity time-lapse workflow

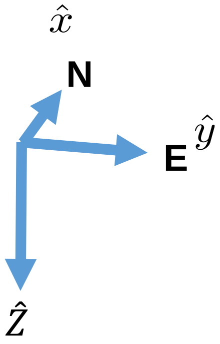
Survey plan/model → Inversion → Model Update → Decisions

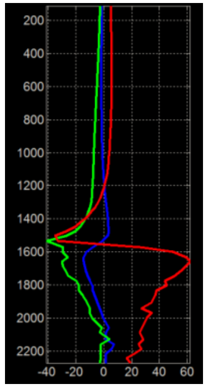
- saturation
- porosity
- density

→ Feasibility MODELLING → AQUIRE Gravity Log → Inversion RESULTS →

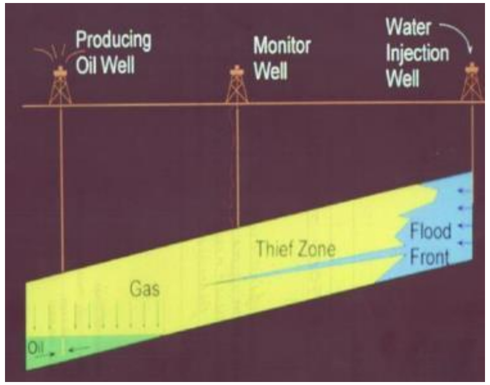
- saturation
- porosity
- density







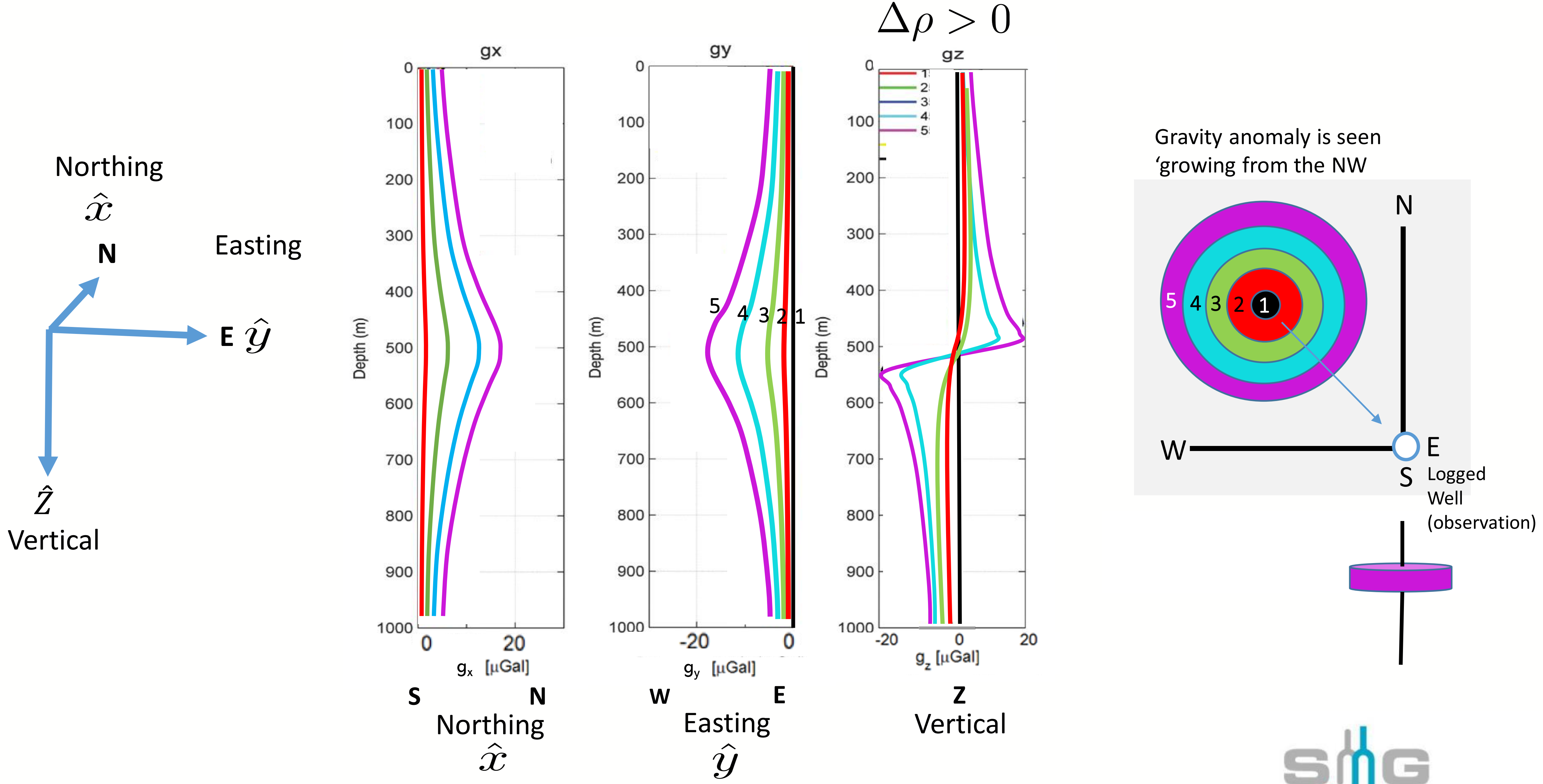
gx, gy, gz (μGal)



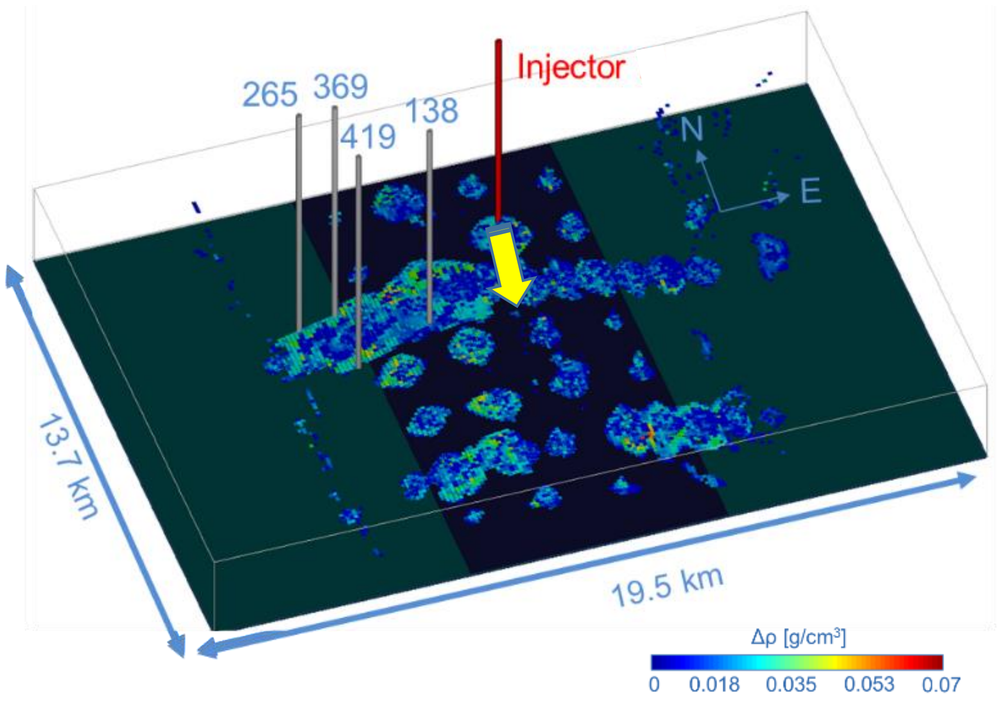
194845 • Three-axis Borehole Gravity Logging for Reservoir Surveillance • Lofts et al.

OTC 10.4043/30626 • Time-lapse borehole gravity survey for pre-salt reservoir monitoring • Du et al.

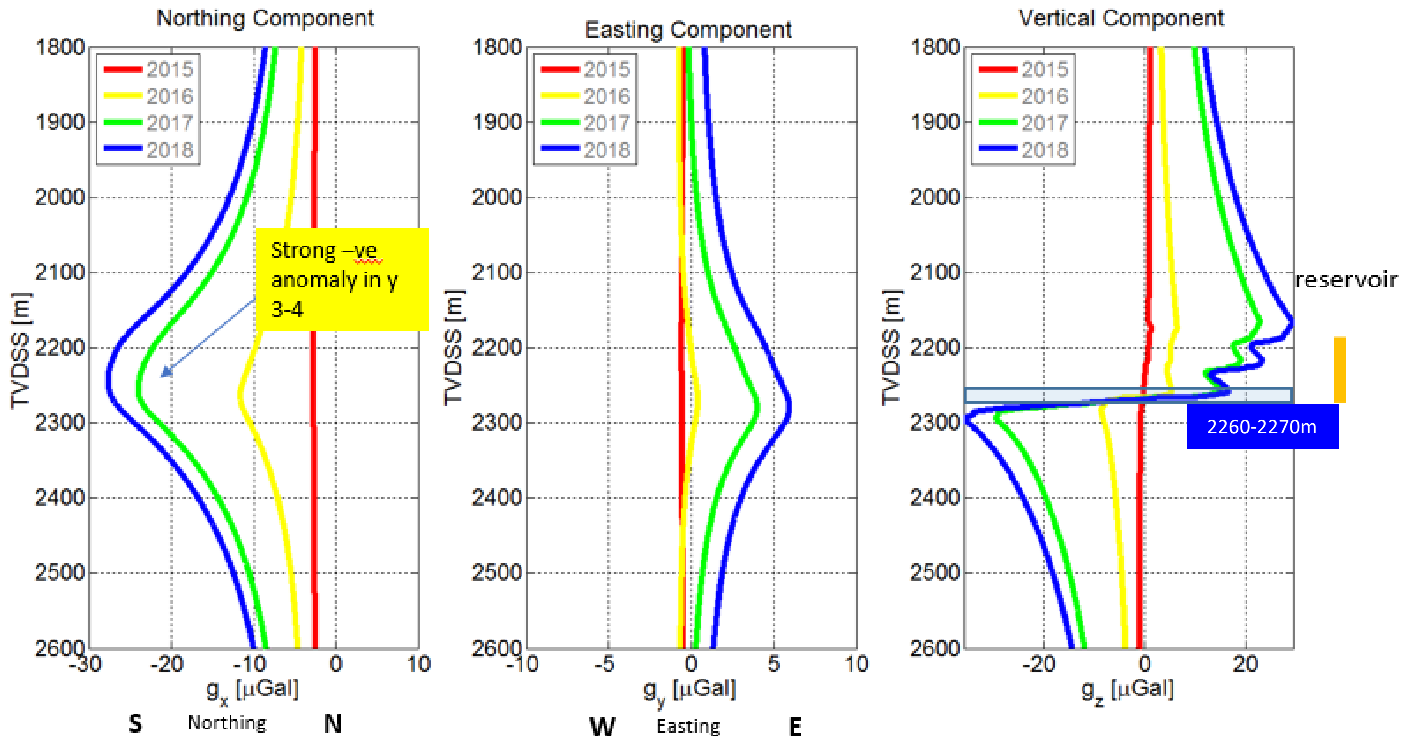
Vector gravity: 3-axis gravimeter measurements



4D gravity time-lapse, Waterflood example
Onshore, Middle East



4d gravity time-lapse in Injector well



- g_z provides info on vertical distribution of water; presence of water close to the well corresponds to a high gradient versus depth of g_z in a zone
- Main injection interval (2260-2270 m) shown by the 2017-2018 responses
- g_x shows southward movement of the water; 3-axes adds important directional information
- Measurement made in producers OR injectors…minimising lost production

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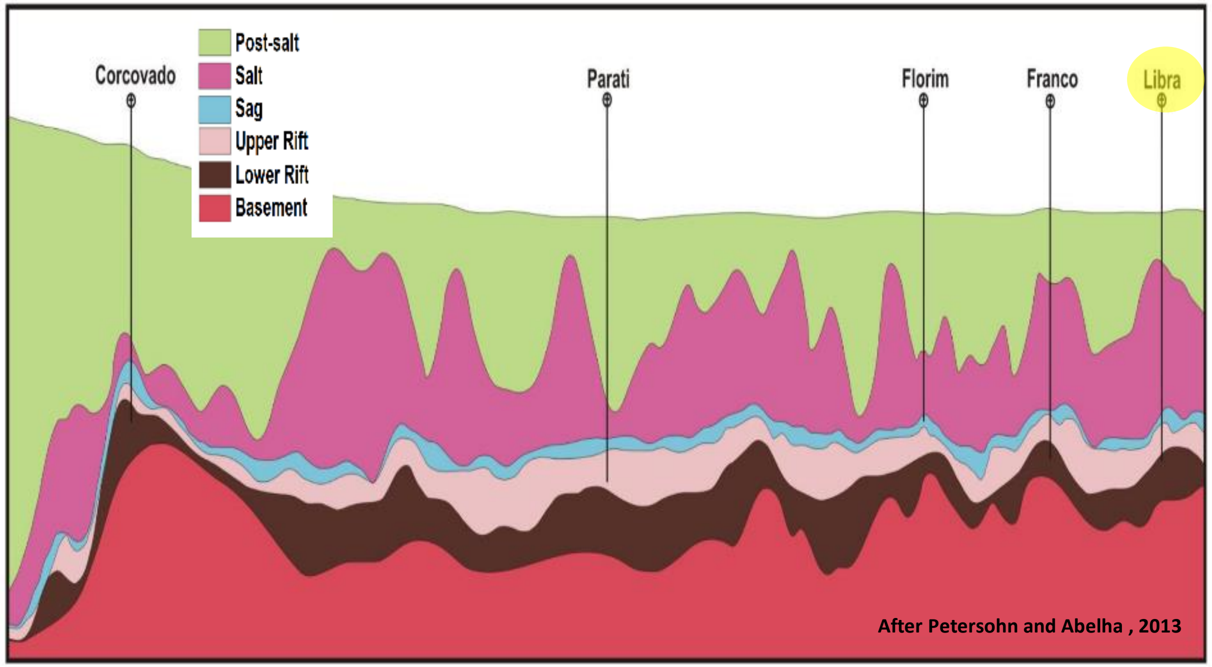
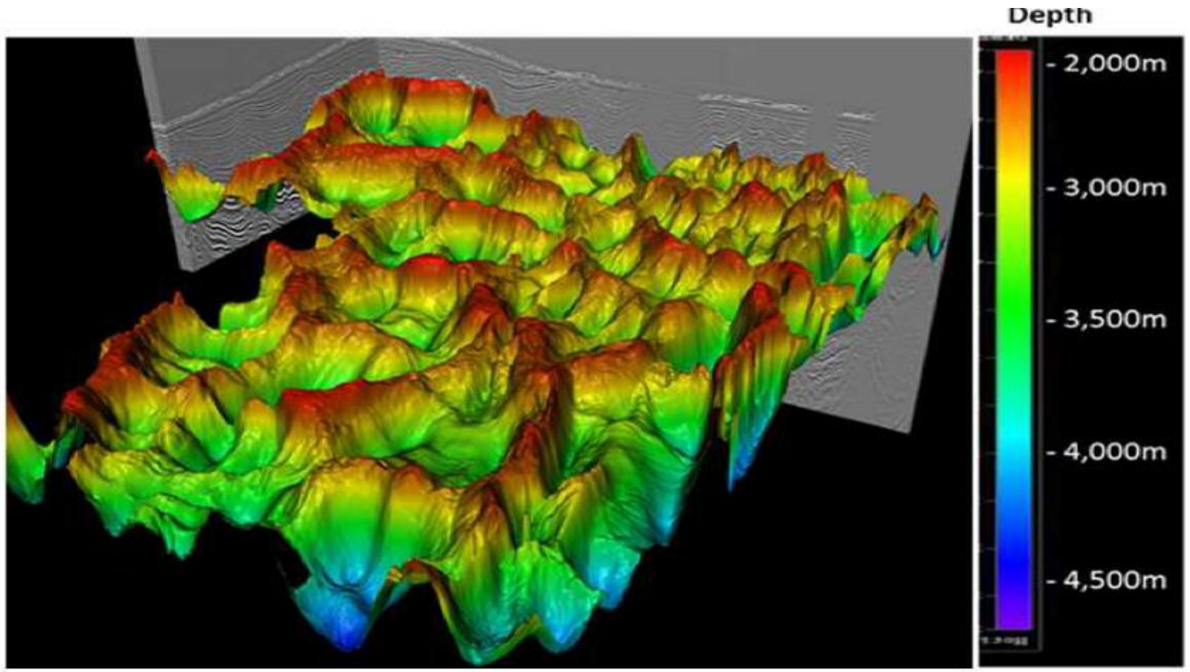
4D gravity time-lapse, Waterflood example
Libra Field, Santos Basin, Brazil

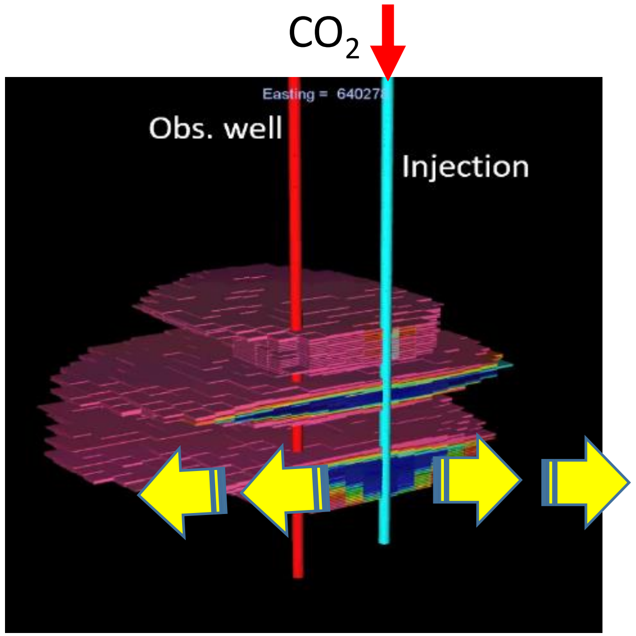


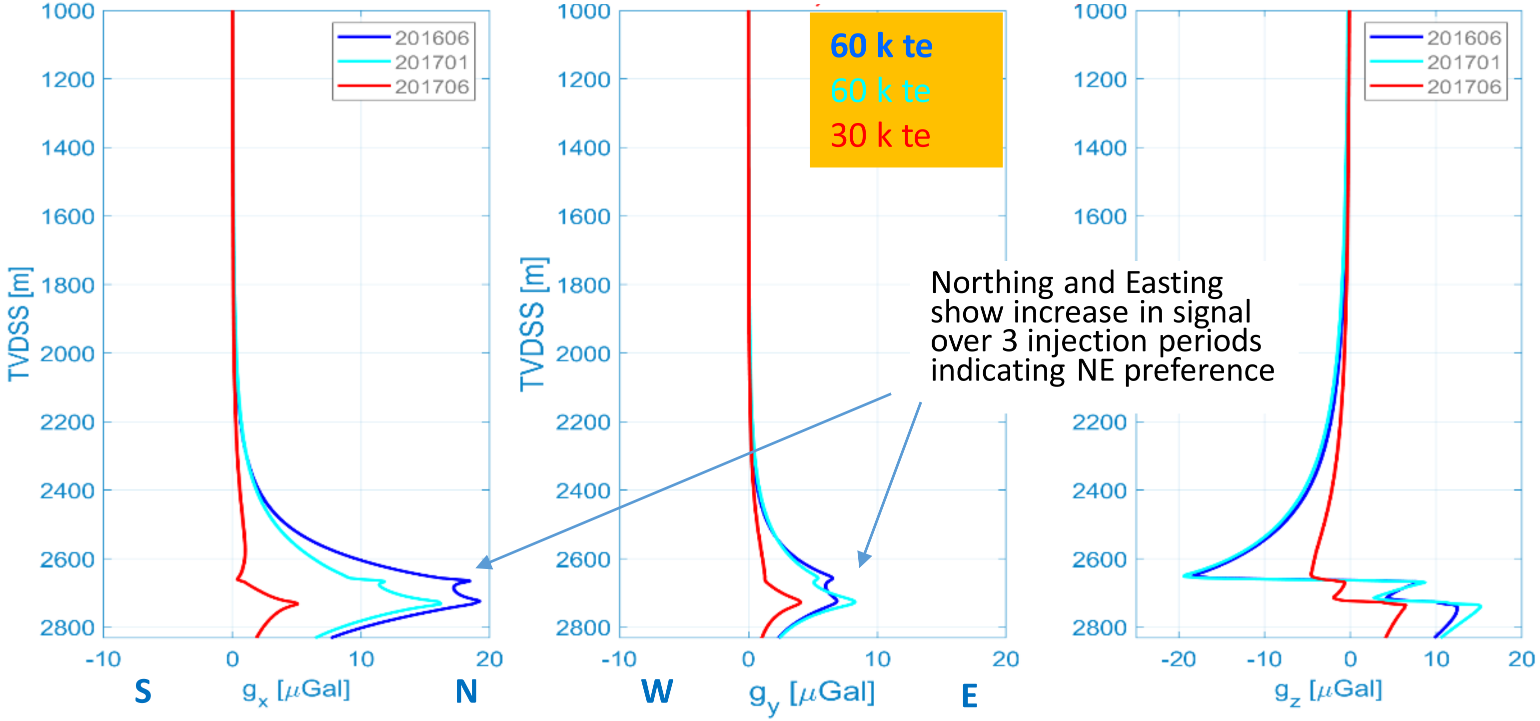


- Geophysically hard to define, sitting below the massive salt structures
- Conceptual Libra Field model built based on publicly available seismic imaging and well log data
- A clear gravity response (> 80 µGal) due to water replacing oil over 6 months of production (41 kb/d, ~7mmbbl)
- 3-axis measurement indicates direction of fluid movement 100's of metres from wellbore

4D gravity time-lapse, CO_2 Plume injection example
CCS monitoring Aquistore, Williston Basin, Canada

- Verify injection periods where sufficient injection taken place
- Feasibility model shows measurable response (~ 20 µGal) from CO_2 plume growth replacing water over appropriate time period (12 months)

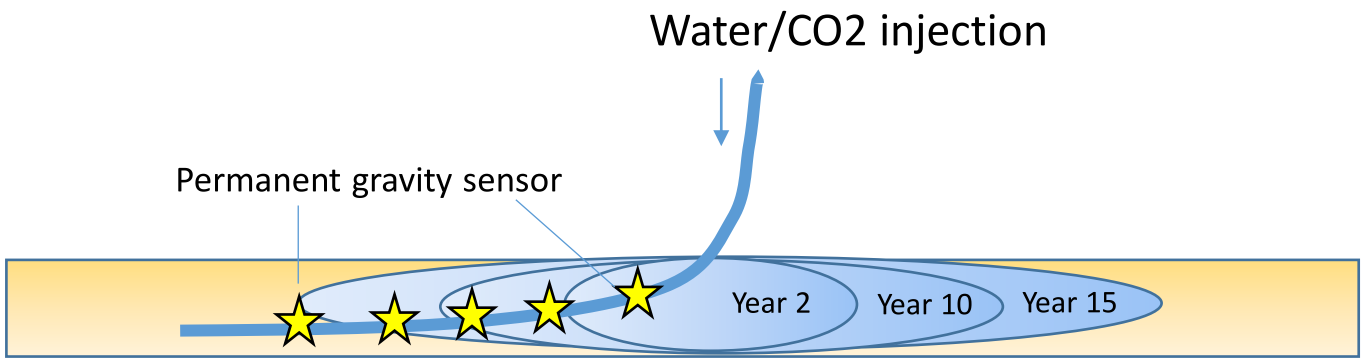


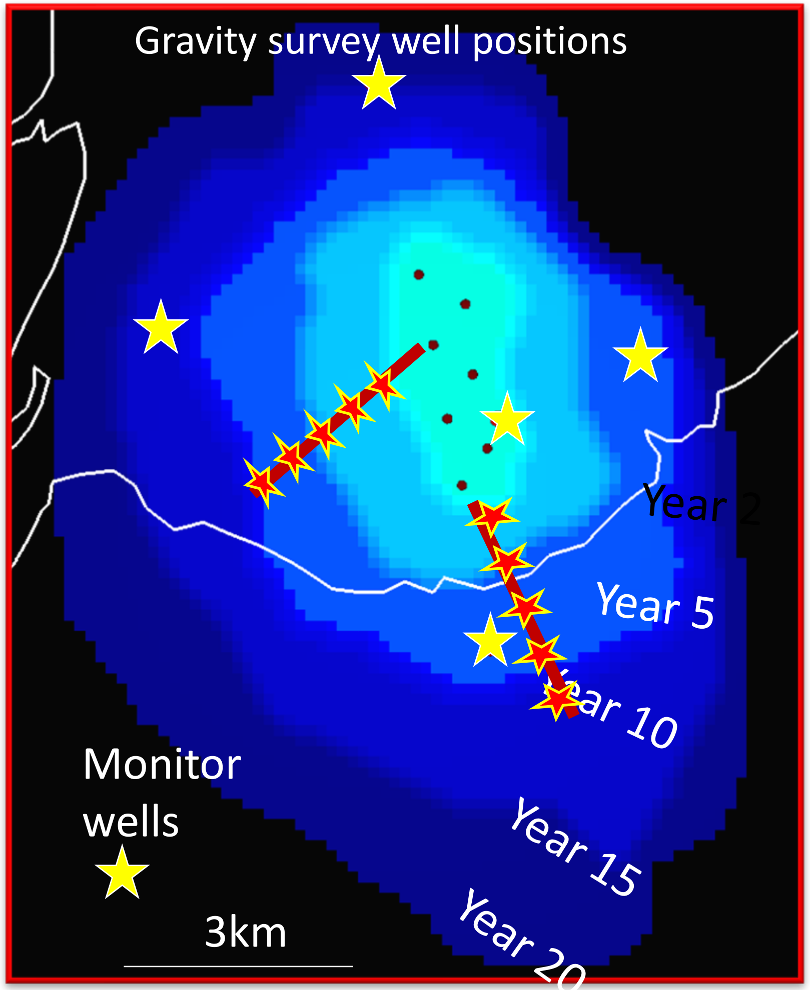


Source: Energias Market Research

Future Value of MEMS sensors in 4D gravity time-lapse permanent sensing

- Field Demonstration of permanent borehole microgravity
- Opportunity:
  - One or two wells could monitor an entire field like Prudhoe Bay
  - Life of well monitoring of movement of fluids 100’s m from the wellbore





Reitz, 2014

Summary: 4D time-lapse gravity for Reservoir Saturation monitoring with MEMS sensors, emerging and future

- 4D time lapse gravity: deep reading time-lapse measure of fluid substitution
- 2-1/8" wireline deployed, potential for permanent completion
- Wide range of uses in reservoir management to optimize sweep
- Fill gap between near-wellbore logs and 4D seismic, cost effectively
- Commercial trials ongoing, more required to achieve commerciality in 2021

Water/Gas
- CCS, Canada
- Gas field, Offshore

Water/Oil
- ME, US, Onshore
- Brazil, UKCS, Offshore

Commercial
- Expand tool-fleet
- Multiple operations

2020

Commercial field trials

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Why now? What about oil price today?

- Our technology does this…
  - Early detection of production problems through surveillance – water breakthrough, coning, cusping etc.
  - Can reduce future infill wells / identify attic or by-passed hydrocarbons
  - Optimize well intervention through zonal isolation, production sidetracks etc.

- Opportunity to optimise reservoir surveillance programme

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