The application of GOCE gravity data for basin and petroleum system analysis
A case-study from the Arabian Peninsula

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The use of GOCE gravity data for hydrocarbon exploration

GOCE+ GeoExplore

GOCE gravity data may provide improved models of the crust and lithosphere

Better understanding of the evolution of the thermal system in the basin

Prospectivity of the basin: areas where hydrocarbons are likely to be generated
- Generation of hydrocarbons
- Generation of hydrocarbons
- Generation of hydrocarbons

- Organic-rich source rocks in the basin need heat to get mature “cooked” and produce hydrocarbon (oil and gas)

- The heat needed for cooking the source rock:
  - *Energy from the mantel*
  - *Energy from radiogenic elements in the basement*
  - *Energy from radiogenic elements in the sediments*

The amount of heat within the basin is controlled (defined) by the heat flow [mW/m²]
Heat flow: Important parameter in hydrocarbon exploration

Heat flow is usually considered a “user input”

- Present-day heat flow (measured in wells or assumed for the basin) is applied:
  - Temporal extrapolation
    Apply present-day heat flow as “flat heat flow” for the whole basin history
  - Spatial extrapolation
    Apply present-day heat flow as “flat heat flow” for whole basin

\[
\frac{dT}{dz} = \frac{q}{k}
\]
Heat flow: Important parameter in hydrocarbon exploration

*Tectonic modelling of heat flow*

- Based on basin subsidence history (sedimentation, erosion, PWD, .. etc)
  
  *(heat flow variations though time and space)*

- Effect of sedimentation infill and heat production in the crust
  
  *(Improved McKenzie model)*

- Conducts calibration with measured
  
  *(Model calibration and verification)*

**Main inputs:**

*Lithosphere and Crust thickness*
Gravity data and heat flow modelling

• Heat flow can be determined from crustal and lithospheric models

• Gravity data can help constrain the crust the lithosphere underlying the basin
GOCE data and heat flow modelling

• Suitable for crust and lithosphere studies (can help “mapping” the Moho transition; essential for heat flow modeling).

• GOCE gradient data: higher horizontal resolution for crustal structure discrimination

• Suitable resolution for regional studies

Test case:
The Rub al’ Khali basin
(Arabian Peninsula)
GOCE + GeoExplore: Geophysical exploration and basin modeling

Arabian Peninsula (*The Rub al' Khali area*)

- Large, remote area
- Under-explored with high potential (frontier basin)
- Heterogeneous basement (Arabian shield), possible Impact on heat flow in the basin.

(Pollastro, 2003)
Geophysical exploration and basin modeling

Arabian Peninsula (*The Rub al’ Khali area*)

**Approach**

1. GOCE Gravity models
2. New Crust and Lithosphere models (thickness, composition)
3. New heat flow model (lateral variations)
4. Improved Maturity maps

Calibration
Workflow

- Building a geologic model of the area.
  - Layer thicknesses, litho-stratigraphy, paleo water depth, tectonic evolution.

- GOCE gravity model (gravity gradients, gravity anomaly)
  - Required correction and processing
  - Integration of different data (land, satellite ..etc)

- Inversion and forward modeling of gravity data
  - Crust model (thickness variations)

- Geologic model and crust model used for heat flow calculation
  - Stretching factor (β) for initial crust thickness
  - Heat flow maps through time

- Maturity of source rock units
Work progress

- Geological model
- Gravity models preparation and analysis
- Preliminary heat flow analysis
Work progress: Geologic model

Used for:

- Gravity modeling
- Heat flow modeling
- Maturity modeling
Work progress: GOCE gravity models / data

- Gravity anomaly data
- GOCE gradient data
- Combined gravity models

Used for:
- **Crust model**
- **Lithospheric thickness**

Bouguer anomaly map of KSA

GOCE gravity gradient components derived from gravity models over the region
Work progress: Gravity data analysis

- Preliminary analyses
  - Gravity anomaly forward modelling
  - Topographic reduction

- Sensitivity analysis
  - North-East Atlantic margins

Comparison between preliminary GOCE gravity gradients ($V_{ij}$) and gravity gradients from lithospheric density model ($U_{ij}$).
Work progress: Preliminary heat flow analysis

Effect of crust and lithosphere thickness on heat flow

Difference: HF (45) – HF(30)

Heat flow: crust 45 Km

Heat flow: crust 30 Km
Work progress: Preliminary heat flow analysis

Effect of crust and lithosphere thickness on heat flow

Heat flow:
- Litho 125 Km
- Litho 110 Km

Difference: HF(110) – HF(125)
Work progress: Preliminary heat flow analysis

Reconstructing crustal thickness in geologic time. Based on:

1. Present day crust thickness (obtained from GOCE for example)
2. Crustal stretching (obtained from basin subsidence analysis)

Important for heat flow variations through geologic times and therefore maturity and hydrocarbon generation though time.
Work progress: Preliminary heat flow analysis

Heat flow and maturity based on varying crustal thickness

Basal heat flow derived from a crustal model based on literature

Modelled present day maturity of Paleozoic source rock
Initial modelling of heat flow: preliminary conclusions

• Heat flow is sensitive to crustal thickness (radiogenic heat generation) and lithospheric thickness.

• Possible to link present day crustal thickness to paleo crustal thickness (important for tectonic heat flow modeling).

• Variations in crust thickness (provided by GOCE ?) will result in variations in heat flow and therefore hydrocarbon generation.
Future plans

• GOCE gravity data will be interpreted to update the crust and lithosphere models.
  
  • Hopefully a better resolution is provided by the gradient data (different crustal structures might be detected).
  
  • Sensitivity of GOCE to deep structures?

• New crust and lithosphere thickness model which can fit GOCE data, will be used to model the heat flow.

• The results will be calibrated to seismic stations, temperature, vitrinite reflectance and surface heat flow measurements.
Thank you for your attention
• Generation of hydrocarbons

• Organic-rich source rocks in the basin need heat to get mature “cooked” and produce hydrocarbon (oil and gas)

• The heat needed for cooking the source rock comes from the crust
  - Energy from the mantel
  - Energy from radiogenic elements in the basement
  - Energy from radiogenic elements in the sediments

• The amount of heat within the basin is controlled (defined) by the heat flow [mW/m²] within the basin
Work progress: Gravity data analysis

• Preliminary analyses
  • Gravity anomaly forward modelling
  • Topographic reduction
• Sensitivity analysis
  • North-East Atlantic margins

Comparison between preliminary GOCE gravity gradients (Vij) and gravity gradients from lithospheric density model (Uij).

Ebbing et al (2011)
Data: Basement model, Calibration data (Maturity modeling)

(Stern and Johnson, 2010)

(Al-Damegh et al., 2005)
Heat flow and Maturity (PetroProb):

- Subsidence Inversion - tectonic heat flow
  - Tectonic Subsidence curve
  - Lithosphere Parameters
    - Uncertainty Tectonic Subsidence (PWD/erosion)
    - Uncertainty Lithosphere Parameters (crust/lith)
    - Experimental design alternative
      - Inverted Tectonic model
      - End-members
        - MC sampling
      - Default "tectonic" Bsmt heat flow
        - MC sampling
      - Uncertainty "tectonic" bsmt heat flow
      - Uncertainty Maturation
        - Sensitivity Analysis - Calibration

- Heat flow Uncertainty
  - Uncertainty Tectonic Subsidence (PWE/erosion)
  - Uncertainty Sedimentary Thermal properties
    - Uncertainty "tectonic" bsmt heat flow

- Maturation Uncertainty
  - Sensitivity Analysis - Calibration
Heat flow modeling:
Probabilistic tectonic heat flow modeling (PetroProb)

- A multi-1D tectonic heat flow modelling approach
  *(Temporal and spatial variations)*
- Based on inversion of basin subsidence data
  (sedimentation, erosion, PWD, .. etc)
  *(Modelled tectonic heat flow)*
- Incorporates the effect of sedimentation infill and heat production in the crust
  *(Improved McKenzie model)*
- Includes uncertainty in the input parameters
  *(Probabilistic approach)*
- Conducts calibration with measured data and sensitivity analysis
  *(Model calibration and verification)*

Main inputs:
*Lithosphere and Crust thicknesses and properties*
The GOCE satellite mission

- Gravity Field and Steady-State Ocean Circulation Explorer (GOCE)
- ESA satellite launched in 2009
- Measures gravity gradient (gradiometer)

Objectives:
- Gravity field with high accuracy
- Spatial resolution of ~ 75 km
- Model of the Geoid (1-2 cm)

Solid Earth
Sea-level Change
Geodesy
Ocean Circulation
Basal heat flow and maturity in the basin

- **Heat flow** influences the maturity of the source rock
- Basement heat flow is influenced by the crust properties (composition) within the crust
- Variations in basal heat flow
- Variations (heterogeneity) within the basin

**Rub al’khali?**

- Heterogeneous basement (Arabian shield) shows maturity anomalies within the Arabian Platform

(Pillastro, 2003)