Abstract

Mud gas logging provides an initial insight into reservoir fluids while drilling. Despite providing information only on the light end of petroleum fluids (methane to pentanes), its strength lies in its good depth resolution and continuity along the borehole. Developments in the last decade have equipped traditional mud gas logging with advanced degassing systems and geochemical analyzers known as advanced mud gas logging (AMGL) tools. Geochemistry-wise, critical new measurements developed included key C₆-C₈ isomers and a game-changing continuous high-resolution carbon stable isotope composition of methane (expressed as δ¹³C-C₁).

The AMGL has opened novel avenues of interpretation of mud gas data. One of the added values is the while-drilling quantification of gaseous alkanes per unit volume of rock in conventional reservoirs and the recognition of common petroleum-alteration processes. These processes include mixing thermogenic and biogenic fluids, biodegradation of petroleum, and phase separation and leakage via cap rocks, among others. Identifying fluid alterations prevents the mistyping of petroleum fluids based solely on classical gas ratios.

In-house AMGL methodology involves novel interpretative fluid-typing and alteration-flagging tools. The C₁ isotope logging can indicate direct maturity proxy with some limitations. The combination of δ¹³C-C₁ log with advanced mud gas molecular data while drilling, has enhanced the traditional Schoell diagram with six thermogenic fluid types along vitrinite reflectance equivalent (VRE) maturity isolines, and a level of mixing with biogenic C₁. Additionally, there are workflows with advanced interpretation diagrams: spider plot, modified Bernard, gas wetness versus character, C₂/iC₄ versus C₂/C₃, parent fluid fingerprinting iC₄/nC₄ versus δ¹³C-C₁, and diffusion-leakage versus migration-mixing δ¹³C-C₁ versus C₂/C₁.

This toolkit enabled the development of new interpretation decision-trees for higher confidence of fluid-typing and fluid-alterations flagging. As such, this AMGL methodology (molecular composition coupled with C₁ isotope signature) provides early information on petroleum systems, especially charge history, enabling targeting of specific mobile fluids for further analyses, leading eventually to their production.
Charge History *Clues* from Advanced Geochemical Mud-Gas Logging

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Real-time LWD

Real-time Mud-gas logging

Spot Mud-gas sampling,

LWD memory data and reporting (DFA and sampling while pulling out)

Mud-gas logging Reporting

Wireline data acquisition and fluid downhole sampling

Downhole Fluid Analysis (DFA), pressures reports

Rushed spot-sample isotopes results

Downhole samples analysis, All spot-sample isotope results & reports

Number of days

0

X

X+1

X+2

X+10

X+30+
Agenda

- Introduction to mud-gas logging and interpretation
- Advancements on mud-gas logging
- Light-end fluid composition logging
  - Real-time clues from light-end fractions
- Conclusions
Mud-gas Logging

- Formation fluids are released from the pore space by the crushing action of the bit

- Fluids released into the mud are expected to be either
  - Dissolved in mud phase (OBM or WBM)
  - Adsorbed on solids
  - Free phase

- Analysis of light hydrocarbons by vaporization in gas extractors at specific locations
Fluid Characterization – Mud-gas Ratios


**Single plots:**
- Triangular diagram \((C2/CT, nC4/CT, C3/CT)\)
- Pixler plots \(C1/C2, C1/C3, C1/C4, C1/C5\)
- Spider diagram (multiple ratios)
- Cross plots \(C1/C2, C1/C3, etc.\)

**Continuous plots:**
- Wetness (Wh) \(\frac{(C2+C3+C4+C5)}{(C1+C2+C3+C4+C5)} \times 100\)
- Balance (Bh) \(\frac{(C1+C2)}{(C3+C4+C5)}\)
- Character (Ch) \(\frac{(C4+C5)}{(C3)}\)
- Binary ratios - \(C1/C2, etc.\)

- Reliability highly depends on geographical area and petroleum context
- Plots need modification as they are very old and not updated
Advancement in mud-gas logging…

- Advancement in mud-gas extractor and gas analyzers enables quantitative gas analysis

- Specific processes and evaluation of the adsorbed and dissolved hydrocarbons allow quantitative measurement of hydrocarbons in mud

**Controlled thermodynamics**
1) Constant volume
2) Constant temperature
3) Constant pressure
4) Controlled agitation

**GCMS**
1) Higher resolution of peaks
2) Detection of more species of hydrocarbon and non-hydrocarbon
3) Quick cycle time
4) Analysis under vacuum conditions

**CRDS (Cavity Ring Down Spectroscopy) for isotopes**
1) Quantitative isotopic composition analysis on methane and ethane (future)
2) Specific QC equipment to remove contaminants
3) Cycle time is very short (below one minute)

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**GCMS**: Gas Chromatography Mass Spectrometer

**CRDS**: Cavity Ring Down Spectroscopy
## Standard vs Advanced Mud-gas (AMG)

<table>
<thead>
<tr>
<th>Process</th>
<th>Conventional System</th>
<th>Advanced System</th>
</tr>
</thead>
<tbody>
<tr>
<td>Extraction process</td>
<td>Extraction process not controlled</td>
<td>Smaller mud volume, higher agitation speed and constant high temperature for high efficiency</td>
</tr>
<tr>
<td>Extraction efficiency</td>
<td>Cannot be determined</td>
<td>Extraction efficiency determination for fluid compositional analysis</td>
</tr>
<tr>
<td>Analyzer</td>
<td>Flame Ionization detector, Output: C1-C5</td>
<td>GC separation and mass spectrometer, Output: Alkanes C1-C8, Cyclo Alkanes (MCC6), Aromatics (C6H6, C7H8) and Inorganics (CO2, He, H2)</td>
</tr>
<tr>
<td>Quality control</td>
<td>No means to verify quality of acquisition</td>
<td>Sensors to record operational integrity of equipment</td>
</tr>
</tbody>
</table>

**Effect of extraction conditions on measurement.**
- Advanced mud-gas = PVT sample composition
- Conventional system gives lighter fluid
Cross-well Correlations ➤ Vertical and horizontal connectivity

Complex Reservoirs ➤ Multilayered system with variable porosity

Thin Beds / LRP ➤ Hydrocarbon presence in thin beds (low-resistivity pay)

Support to Geosteering ➤ Remain within target

HPHT ➤ De-risk and optimize formation testing and sampling in HPHT well
Additional information from C6+ logging

- C6+ hydrocarbons are always part of the liquid phase
- Allows enhanced characterization of formation fluids
- Enables identification of contacts and transition zones
  - differentiation between gas-oil and oil-water contacts

Additional information from C6+ logging

Source rock characterization (W. Odden et al., 1998)

C6-C7 fluid fingerprinting (W. D. Masterson et al., 2001)

Alteration processes (Thompson, 1983)

Currently a qualitative approach by advanced mud-gas logging

Fig. 11: Concentrations from whole-core gas chromatography of selected compounds in the West Sak field oils and in the 1E-11 oil from the Kuparuk field. The relatively high concentrations of methylcyclohexane (MCH), cyclohexane, and methylcyclopentane (MCP) in the West Sak zone A oils are also evident in the underlying Kuparuk field oil.
**C6-C7 Isomers Applications**

<table>
<thead>
<tr>
<th>Name</th>
<th>Ratio</th>
<th>Process</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Ben/nC6</td>
<td>• Fractionation</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Water washing</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• TSR</td>
</tr>
<tr>
<td>B</td>
<td>Tol/nC7</td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>nC6 + nC7/CC6 + MCC6</td>
<td>• Maturation</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Biodegradation</td>
</tr>
<tr>
<td>X</td>
<td>mXylene + p-xylene/nC8</td>
<td></td>
</tr>
<tr>
<td>I</td>
<td>2- + 3-MC6 + ΣDMC5s</td>
<td>• Maturation</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Biodegradation</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Source</td>
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<tr>
<td>F</td>
<td>nC7/MCC6</td>
<td>• Maturation</td>
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<tr>
<td></td>
<td></td>
<td>• Biodegradation</td>
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<tr>
<td>H</td>
<td>100 x nC7/ΣCC6 + C2HCs</td>
<td>• Maturation</td>
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<tr>
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<td>• Biodegradation</td>
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<tr>
<td>S</td>
<td>nC6/2,2-DMC4</td>
<td>• Maturation</td>
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<tr>
<td></td>
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<td>• Biodegradation</td>
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<td>• Source</td>
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<td>R</td>
<td>nC7/2-MC6</td>
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<tr>
<td>U</td>
<td>CC6/MCC6</td>
<td>• Maturation</td>
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<tr>
<td></td>
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<td>• Source</td>
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</tbody>
</table>

**Thompson Star Plot**
The abundance and distribution of diamondoids in biodegraded oils from the San Joaquin Valley: Implications for biodegradation of diamondoids in petroleum reservoirs, Zhibin Wei et al., 2007

Propane goes first. Ethane last.
Workflows: AMG – molecular composition

Is it HC-rich zone? (Relatively high NORM.TOT.GAS.)

Are indications of liquid OIL or GAS consistent?

NO

Biogenic C1 present. OR

Mature gas re-charged into oil reservoir?

Use: • CI+ presence • MCC6 presence • MATURITY (FLAIR)*

Possible single charge unaltered fluid

Use:
• All OIL vs GAS tracks
• CI+ presence
• MATURITY (FLAIR)
• I/n ratios*

OR

NO (mix with primary biogenic C1). Use:
• CI+ presence • MCC6 presence • MATURITY (FLAIR)*

Mix of biogenic C1 and mature thermogenic gas

Note: All ratios may consistently indicate gas, yet CI-containing Wil/Eh might be the most red. Likely no CI+. Near cutoff I/n.

* I/n ratios can increase if kerogen III in source Rock of fluid
* In heavy biodegradation cases, even CI+ and I/C in CI will be biodegraded, and CI/C4 ratio affected
* CI-C6 n-alkanes affected already at low level of biodegradation, methylcyclohexane as more resistant might still indicative of initial charge of liquid fraction.

* Higher I/n can be due to kerogen III contribution to the source rock of the fluid. If no base from kerogen III, I/n can serve as an additional rough maturity proxy: for oils typically I/C4/I/C4 < 0.6 and I/C5/I/C5 < 1.0
$\delta^{13}\text{C-C1}$ as a proxy for fluid maturity

Variation of $\delta^{13}\text{C-C1}$ along pathways of the carbon cycle

Typical variation of $\delta^{13}\text{C-C1}$ during the burial process

Modified after Schimmelmann et al. 2006
Methane isotope logging trends
Modified Bernard Plot

Basic Bernard plot
- Delineate biogenic and thermogenic gas
- Indication of mixing
- Indication of maturity

Modified Bernard plot:
- Providing basic fluid association of methane and isotope trends using quantitative C1-C3
Schoell plot:
- Delineate biogenic and thermogenic gas
- Indication of mixing, maturity and gas association with fluids

Modified Schoell plot:
- Developed internally by SLB
- Fluid association of methane and isotope trends using Quantitative C1-C5
- Vitrinite reflectance equivalence scale for non-altered fluids
Mixing trend – active hydrocarbon system detection: simple mixing trend between the two end-members

Bernard diagram

Schoell diagram
Workflows: C1 isotope log + AMGL

- HC-rich zone
- Biogenic C1 Contribution?
- Thermogenic component biodegraded?
- C6+ presence*
  * In severe cases (biodegradation level >4 PM – Peters-Moldovan scale, even C2 and C4 will be biodegraded, and C2/C4 ratio affected)
- n-alkanes will be likely affected too; still methylcyclohexane as more resistant might be indicative

- OIL/GAS tracks
  - iC4/nC4
  - Character
  - LH_Q
  - C2/C3 vs C2/iC4
  - C6+ presence

- OIL/GAS tracks#
  - iC4/nC4
  - Wh vs Bh
  - Character
  - LH_Q
  - C2/C3 vs C2/iC4
  - C6+ presence
  - MATURITY (δ^{13}C-C1)
  - Schoell-FT co-genetic fluid typing
- * Check consistency of Oils vs Gas
  Indications: Higher iC4 and δ13C-C3 can be also due to kerogen III contribution to the source rock of this fluid – kerogen III present in SR
Key Message

Conclusions

- Mud-gas composition represents reservoir rock-contained fluid composition
  - Appropriate correction make mud-gas immune to drilling and rig conditions

- Interpretation
  - Addition of critical parameters: mud-gas isotopes and C6+ isomers
  - Continuity of data helps understand seals, contacts and transition zones

- Delivering key information on time
  - Fluid abundance, fluid types, fluid alterations
  - High-frequency distribution of the above

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