Origin and Distribution of Overpressure in the Northern Malay Basin*

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Search and Discovery Article #41103 (2012)**
Posted December 31, 2012

*Adapted from oral presentation at AAPG International Conference and Exhibition, Singapore, September 16-19, 2012
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Abstract

Pore pressure data and sonic velocity-vertical effective stress plots from 31 wells reveal that overpressures in the northern Malay Basin are primarily generated by fluid expansion and located basin-wide within the 2A, 2B and 2C source rock formations. Overpressure magnitude increases towards the basin-centre, with maximum pore pressure gradients of >19.0 MPa/km observed in the southeast part of the study area. The overpressures are predominately associated with gas, with gas sampled in over 83% of overpressure measurements. The association of overpressures with gas, combined with a regional geology that largely precludes other fluid expansion overpressure mechanisms, provides the first convincing in-situ evidence for basin-wide gas generation overpressure.

Overpressure magnitude analysis indicates that gas generation accounts for approximately 46-67% of the measured excess pore pressure in the region, with the remaining 33-54% being generated by coincident disequilibrium compaction. Thus, the data herein suggests that gas generation, if acting in isolation, produces a maximum pressure gradient of 15.2 MPa/km (0.672 psi/ft), and not lithostatic magnitudes as is often hypothesized. The gas generation overpressures in this study are not associated with a significant porosity anomaly and thus represent a major drilling hazard, with traditional pore pressure prediction techniques underestimating pressure gradients by 2.3 ±1.5 MPa/km (0.102 ±0.066 psi/ft). However, pore pressure prediction is possible using a modified approach after careful smoothing and picking of velocity data.
References


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Paper in press – AAPG Bulletin
Importance of Overpressure Origin

- Pore pressure estimated from the **porosity** anomaly often associated with overpressure.

- ‘Undercompaction’ only associated with disequilibrium compaction.

- **Other overpressure mechanisms** have no/little porosity anomaly – pore pressure underestimated.

DIFFERENT OVERPRESSURE ORIGINS REQUIRE DIFFERENT PREDICTION STRATEGIES

Example of undercompaction associated with overpressures, offshore Brunei.
Overpressure Origins?

- Disequilibrium compaction (most common).
- Smectite-Illite (and other diagenetic processes), gas maturation, aquathermal expansion, lateral transfer, load transfer, vertical transfer.
- Gas maturation often hypothesized to generate high magnitude pressures – rarely shown in-situ or regionally.

Overpressure mechanisms affect rocks in different ways – we need to first understand overpressure generation mechanism to reliably predict pore pressure (and avoid potential disastrous consequences).
South China Sea

Philippine Sea plate

Study Area
# Geological Overview

## Depositional Environment

<table>
<thead>
<tr>
<th>Depositional Environment</th>
<th>Unit</th>
<th>Net to Gross</th>
</tr>
</thead>
<tbody>
<tr>
<td>Marine</td>
<td>Fm3</td>
<td>Low</td>
</tr>
<tr>
<td>Fluvio-Deltaic</td>
<td>2E</td>
<td>High</td>
</tr>
<tr>
<td>Upper to Lower Delta Plain</td>
<td>2D</td>
<td>Medium</td>
</tr>
<tr>
<td>Offshore to Delta Front</td>
<td>2C</td>
<td>Low</td>
</tr>
<tr>
<td>Upper Delta Plain</td>
<td>2B</td>
<td>Low to Medium</td>
</tr>
<tr>
<td>Delta Plain to Delta Front</td>
<td>2A</td>
<td>Low</td>
</tr>
<tr>
<td>Alluvial Plain</td>
<td>Fm1</td>
<td>Low to Medium</td>
</tr>
</tbody>
</table>

- **Delta plain to delta front**: Dark grey
- **Channel sand**: White
- **Fluvial to delta plain**: Light grey
- **Bar sand**: Medium grey
- **Marine shales with minor fine sand**: Light grey
- **Major coal seam**: Thin black line
Origin and Distribution of Overpressure in the Northern Malay Basin

• INTRODUCTION AND AIMS

• OVERPRESSURE DISTRIBUTION

• OVERPRESSURE ORIGIN

• IMPLICATIONS & CONCLUSIONS
Data Summary

- 990 WFTs, 20 DSTs, mud weights, formations, petrophysical log and pore fluid data provided for 35 wells throughout Northern Malay Basin (Thailand section).

- Overpressures (WFT/DST >11.5 MPa/km or >0.51 psi/ft) in 27 wells (in southeast of study area).

- Moderate-high magnitude overpressures (>14.0 MPa/km or > 0.62 psi/ft) observed in 14 wells.

- Overpressures observed in formations 2C, 2B and 2A.
Overpressure Distribution and Magnitude

- Overpressures (red) in southeast of study area
- Overpressures not observed in northwest (blue)
- Pressures greater in magnitude towards southeast
Typical Overpressured Well Profiles

(a) Well A Pressure (MPa)
- LOP
- FIT
- RFT/MDT
- Mud Weight
- Lithostat
- Hydrostat
- Gas
- Poss Gas

(b) Well B Pressure (MPa)
- RFT/MDT
- Mud Weight
- DST
- Lithostat
- Hydrostat

Depth (TVD, mSS)

Top 2E
Top 2D
Top 2C
Top 2B
Top 2A
Top FM1

T.D.

12 MPa/km

14 16 18 20 22

3500

3000

2500

2000

1500

1000

500

0
Typical Overpressure Profile

• Whilst magnitude varies, pressures tend to follow the same profile with depth:
  - top overpressure at/near top of 2C Fm;
  - approximately constant gradient through 2C, 2B, upper 2A formations;
  - return to hydrostatic near base 2A Fm.

• Some minor overpressures in base 2D and top fm 1 (vertical transfer?).

• Overpressure magnitude appears inversely proportional to net-to-gross.

Schematic of typical pore pressure trend with depth and formation.
Origin and Distribution of Overpressure in the Northern Malay Basin

- INTRODUCTION AND AIMS
- OVERPRESSURE DISTRIBUTION
- OVERPRESSURE ORIGIN
- IMPLICATIONS & CONCLUSIONS
Determining Overpressure Origin: Porosity-Effective Stress Plots

- **Porosity**
  - Fluid isolation depth
  - Normal compaction
  - Porosity path for disequilibrium compaction overpressure
  - Porosity path for fluid expansion overpressure

- **Pressure**
  - Lithostat
  - Lithostat-parallel disequilibrium compaction overpressure
  - Fluid expansion overpressure

- **Depth**

- **Vertical Effective Stress**
  - Unloading curve
  - Loading curve
  - Porosity⁻¹ or sonic velocity at depth of maximum burial

- **Points**
  - Unloading curve
  - Loading curve
  - DC

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**Legend**

- FE curve
- Hydrostat
- Vertical Effective Stress

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Overpressured RFTs (285)

Normally pressurized RFTs (loading curve)

Disequilibrium Compaction Overpressure

Fluid Expansion Overpressure

Velocity at Maximum Burial Depth

Loading Curve

Unloading Curve

Sonic Velocity – Vertical Effective Stress: All Data
FM 2C, 2B, 2A Summary:

- Overpressures in 2C, 2B and 2A formations plot mostly ‘off’ of the loading curve.

- Indicates that some of overpressure generated by a fluid expansion or transfer mechanism.
Sonic Velocity-Vertical Effective Stress: by Magnitude

• Higher magnitude overpressures lie further off of the loading curve.

• Further indication that significant component of overpressure is generated by a fluid expansion mechanism.
Overpressure Origin
Summary:

• Significant component generated by fluid expansion – but which mechanism?

• Low smectite content, stratigraphically confined to low net-to-gross sequences: smectite-to-illite and load, vertical or lateral transfer unlikely.
Sonic Velocity-Density Cross Plots

Adapted from Hoesni, 2004 and O’Conner et al., 2011

Disequilibrium compaction overpressures plot on loading curve

Clay diagenesis or chemical compaction mechanisms

Load transfer or combined mechanisms

Fluid expansion (e.g. gas generation)

Loading curve (normally pressured)

Adapted from Hoesni, 2004 and O’Conner et al., 2011

Density (g/cm³)

Sonic Velocity (km/s)
Sonic Velocity-Density Cross Plots

- Classic gas generation signature with increasing and decreasing pressure gradient
- Sediments still compacting with increasing depth
Sonic Velocity-Vertical Effective Stress – Fluid Type

- 84% of all overpressured RFT measurements sampled gas (c.f. 60% normally pressured).

- Fm 2 A-C is source rock for most produced hydrocarbons.

- Suggests kerogen-to-gas maturation as likely dominant overpressure cause in 2A-C.

- Some other overpressure, likely disequilibrium compaction (on loading curve).
Evidence for Disequilibrium Compaction?

- All overpressure requires a good seal – but if seal exists during burial or loading, disequilibrium compaction should also occur!

- Evidence of undercompaction, especially towards basin centre
How Much Gas Generation Overpressure?

- ‘Distance’ from loading curve less than amount of overpressure
- Magnitude of gas overpressure increases towards basin centre.
- Proportion of gas overpressure decreases towards basin centre.
Approximate magnitude of overpressure generated by disequilibrium compaction

Approximate magnitude of overpressure generated by kerogen-to-gas maturation

Total maximum overpressure

<table>
<thead>
<tr>
<th>Unit</th>
<th>Net to Gross</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fm3</td>
<td>Low</td>
</tr>
<tr>
<td>2E</td>
<td>High</td>
</tr>
<tr>
<td>2D</td>
<td>Medium</td>
</tr>
<tr>
<td>2C</td>
<td>Low</td>
</tr>
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<td>2B</td>
<td>Low to Medium</td>
</tr>
<tr>
<td>2A</td>
<td>Low</td>
</tr>
<tr>
<td>Fm1</td>
<td>Low to Medium</td>
</tr>
</tbody>
</table>

Some minor vertical transfer

OP into base of Fm2D

Hydrostatic

Mild OP

(60-85% gas generation)

Moderate OP

(50-65% gas generation)

High OP

(35-55% gas generation)

Some minor vertical transfer OP into top of Fm1
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Implications for Pore Pressure Prediction

- Overpressures often do not have a significant porosity anomaly and difficult to predict!

- Typical pore pressure prediction methods all underestimate pore pressure gradient.

- Underestimation significant - generally by 1.0 to 4.0 MPa/km (0.04 to 0.17 psi/ft or 0.8 to 3.3 ppg).

- Worse in high pressure areas – numerous drilling problems observed.
New Play Type?

<table>
<thead>
<tr>
<th>Unit</th>
<th>Net to Gross</th>
<th>NW</th>
<th>SE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fm3</td>
<td>Low</td>
<td>90 km</td>
<td></td>
</tr>
<tr>
<td>2E</td>
<td>High</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2D</td>
<td>Medium</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2C</td>
<td>Low</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2B</td>
<td>Low to Medium</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2A</td>
<td>Low</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fm1</td>
<td>Low to Medium</td>
<td></td>
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</tr>
</tbody>
</table>

Approximate magnitude of overpressure generated by disequilibrium compaction.

Approximate magnitude of overpressure generated by kerogen-to-gas maturation.

- Total maximum overpressure
- Some minor vertical transfer OP into base of Fm2D
- Hydrostatic
- Mild OP (60-85% gas generation)
- Moderate OP (50-65% gas generation)
- High OP (35-55% gas generation)
- Some minor vertical transfer OP into top of Fm1
Summary

• Overpressures primarily occur in the 2C, 2B and 2A formations in the SE part of the North Malay Basin.

• Overpressures lie significantly off loading curve, suggesting component of overpressure generated by fluid expansion.

• Stratigraphic confinement to source rocks and association with gas suggests probable kerogen-to-gas maturation overpressure.

• Disequilibrium compaction also occurs, particularly in deeper, rapidly deposited regions towards basin centre (into Malaysia?).

• Overpressures in formations 2A-C are NOT associated with large porosity or sonic velocity anomaly – potential dangerous underprediction using usual methods!

• Potential for HP/HT stratigraphic gas plays towards basin centre.
ACKNOWLEDGEMENTS

• The authors wish to thank PTT Exploration and Production and BG for permission to publish this research.

• This research was partly funded through an Australian Research Council Discovery Project Grant (DP0878258).