Abstract

The pressure architecture of seventy five sedimentary basins was examined to determine spatial distribution of normal and abnormal pressure. Basins with like depositional histories have similar distribution patterns that are generally classified as either linear or tiered. Linear systems are common in dynamic basins and represent a systematic increase in pressure with increasing depth. Tiered systems occur in both dynamic and senile basins and contain distinct pressure domains or compartments whose distribution patterns are categorized as stepped, recessed, and ledged. Pressures in stepped basins increase with depth and form a staircase pattern of distinct pressure compartments. Recessed patterns are formed by a subnormally pressured interval, which is bounded both above and below by normal pressures. Ledged patterns consist of an overpressured section with subjacent and superjacent normally pressured intervals.

Stepped pressures are representative of basins containing thick sections of shale with intervening hydrocarbon-bearing sandstone reservoirs. Recessed patterns result when underpressured hydrocarbon-bearing carbonate or sandstone reservoirs are sealed from normally pressured reservoirs above and below. Ledged patterns have three distinct pressure domains: (1) a shallow, normal pressured sandstone-rich interval, (2) a shale-dominated interval that consists of overpressured mudrocks and sandstones, and (3) a deeper, normally pressured interval. This deeper normally pressured domain is dominated by carbonates or sandstones that are hydraulically connected to the surface, have active water drives, and contains gas that is buoyancy trapped above the water leg. Gas and oil accumulations in abnormally overpressured and underpressured intervals within tiered basins are dominantly stratigraphically trapped. In contrast, trapping of deep gas in sub-ledge, normally pressured intervals is facilitated by anticlinal folding or faulting.

In the Anadarko Basin, the overpressured Woodford shale can be superjacent to normally pressured Hunton Group carbonates. This juxtaposition creates the potential for fracturing fluid diversion during completion. Similar conditions exist in other basins where "frac barriers" needed to contain hydraulic stimulations are thin or absent and resource play intervals overlie lower pressured, water-charged permeable strata.
Selected References


Macauley, G., 1958, Late Paleozoic of Peace River area, Alberta, in Jurassic and Carboniferous of Western Canada: AAPG Special Publication 17, p. 289-308.


LITHOLOGIC CONTROLS of PRESSURE DISTRIBUTION in SEDIMENTARY BASINS

By

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Problem: Sedimentary Basins Exhibit a Variety of Pressure Distribution Patterns

Question: What Geologic Processes Influence Present Pressure Distribution

**Procedure and Summary of Results**

Examined Pressure Architecture of 75 Sedimentary Basins

Established Distribution of Normal and Abnormal Pressure (low and high)

Compared Pressure Architecture with Stratigraphy

Basins with Similar Depositional Histories can develop Pressure Architecture/Pressure Distribution Patterns that are Similar
Acknowledgements

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John Shelton
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Boone Pickens School of Geology

Dedication

David Powley
Amoco Production Company

For Recognizing and Systematically Documenting Reservoir Pressures in Sedimentary Basins
What are Normal and Abnormal Pressures?

Industry Standard = 0.465 psi/ft.

<table>
<thead>
<tr>
<th></th>
<th>Under</th>
<th>Normal (Hydrostatic)</th>
<th>Over</th>
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<tbody>
<tr>
<td>psi/ft</td>
<td>&lt; 0.433</td>
<td>0.433 – 0.51</td>
<td>&gt; 0.51</td>
</tr>
<tr>
<td>kPa/m</td>
<td>&lt; 9.71</td>
<td>9.71 – 11.4</td>
<td>&gt; 11.4</td>
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</table>

Swarbrick and Osborne, 1998
Pressure Distribution in Sedimentary Basins

Linear Pressure System

Linear Systematic Increase in Pressure with Depth in Dynamic and Senile Basins
Pressure Distribution in Sedimentary Basins

Stepped - Tiered Pressure System

Depth

Pressure

Normal Pressure

Overpressure

Seal
Pressure Distribution in Sedimentary Basins

Recessed - Tiered Pressure System

- Normal Pressure
- Underpressure
- Normal or Underpressure

Depth vs. Pressure Graph

Seal
Pressure Distribution in Sedimentary Basins

Ledged - Tiered Pressure System

Depth

Normal Pressure

Overpressure

Normal Pressure

Seal
The Study Area: Global Distribution of Sedimentary Basins Examined in this Study
Selected Basins to Illustrate Pressure Architecture
Abnormal Pressure Mechanisms

Overpressures

Stress Related
- Disequilibrium Compaction → poor fluid expulsion during compaction
- Tectonic Stress → reservoir compacted by compressive stress

Fluid Volume Changes
- Temperature Increase → fluids heated to increase volume
- Mineral Transformation → $\text{H}_2\text{O}$ released: smectite-illite transformation
- Hydrocarbon Generation → fluid HC generated from solid kerogen
- Cracking of Oil and Gas → gas generated from oil

Fluid Movement and Buoyancy
- Osmosis → fluid movement based on concentration
- Hydraulic Head → potential energy of recharge
- Buoyancy → density differences of gas, oil and water
- Transference → higher pressure communicates with lower pressure
Abnormal Pressure Mechanisms

**Underpressures**

**Stress Related**
- Rock Dilatancy $\rightarrow$ pore dilation from uplift & erosion

**Fluid Volume Changes**
- Thermal Effects $\rightarrow$ fluids cool and volume decreases

**Fluid Movement & Buoyancy**
- Osmosis $\rightarrow$ fluids react to concentration gradient
- Differential Gas Flow $\rightarrow$ gas expels faster than generated
- Groundwater Flow $\rightarrow$ groundwater discharges faster than recharge
- Leaking Reservoir $\rightarrow$ reservoir seal broken; pressure equilibrates with potentiometric head of reservoir fluid. If gas, pressure will be abnormally low.
Stepped Pressure System

• North Sea
• Sacramento
  – Thick sections of shale with intervening oil- and gas-bearing sandstones
  – Tiers represent increases in pressure with depth
  – Common in dynamic basins that continue to generate HC or transform oil to gas
adapted from Heritier et al., 1979

Frigg Field
Northern North Sea

North Sea Basin

Frigg Field
Northern North Sea

Stepped -Tiered Basin

United Kingdom

Aberdeen

Shetland Islands

180 Km

197 Km

Haugesund

390 Km

Netherlands

Germany

adapated from Heritier et al., 1979)
Generalized cross section (A-A’) of Frigg Field, Northern North Sea Basin, United Kingdom and Norway (adapted from Heritier et al., 1979 and Chiarelli and Duffaud, 1980).
Overpressure begins in Shale-rich K section North Sea Basin

Northern North Sea Basin
Frigg Field
United Kingdom & Norway
Stepped – Tiered Basin

Overpressure begins in Shale-rich K section

North Sea Basin

Adapted from:
D. Fowler,
Hettner et al., 1975,
& Lindberg et al., 1990
Generalized geologic map of the Sacramento Basin showing the location of the cross section. Map data from United States Geological Survey.
Geologic cross section (W-E) through Willows-Beehive Bend Gas Field, Sacramento Basin, California, USA (adapted from California Department of Oil, Gas, and Geothermal Resources, 1982).
Sacramento Basin

Shallow sandstone-rich interval is normally pressured.

Overpressures coincide with shale-rich formations beginning with Forbes Formation.

Stratigraphic column of the PDP for the Sacramento Basin, Willows-Beehive Bend area.
Recessed Pressure System

• Wind River Basin
• Big Horn Basin
• Alberta Basin
  – Subnormally pressured interval bounded above and usually below by normal pressures
  – Common in uplifted basins with breached reservoirs
Generalized geologic map of the Wind River Basin showing the location of the cross section. Map data adapted from the United States Geological Survey.
Shale dominated

Sandstone and carbonate dominated

Wind River Basin
Beaver Creek Field
Fremont County, Wyoming, USA
Recessed – Tiered Basin

Pressure, p.s.i.

Depth, Feet

Underpressured

Normal pressures

Adapted from D. Powley
Stratigraphic column of the PDP for the Wind River Basin, Beaver Creak area.

Underpressuring begins in the shale-dominated Cody interval and extends to the Chugwater. Sandstones and carbonates below Chugwater are normally pressured.

Generalized stratigraphic column of the Wind River Basin (adapted from Paape, 1968) Petroleum-producing formations are marked with a circle (Keefer and Johnson, 1993).
Generalized cross section (SW-NE) through the Beaver Creek Anticline, Wind River Basin, U.S.A. (adapted from Kewanee Oil Co, 1961).
Generalized geologic map of the Big Horn Basin showing the location of the cross section. Map data adapted from the United States Geological Survey.
Big Horn Basin

Normal pressures extend to the Chugwater. Underpressures on the Hamilton Dome extend from the Chugwater to the top of Precambrian.

Generalized geologic map of the Alberta Basin showing the location of the cross section. Map data from the Geological Survey of Canada and USGS.
Alberta Basin
Gold Creek Field
Alberta, Canada
Recessed – Tiered Basin

Depth, Feet

Pressure, p.s.i.

Cardium
Dunvegan
Spirit River
Jurassic
Triassic
Permian - Pennsylvanian
Mississippian
Devonian

Normal Pressures
.46 p.s.i./ft

Underpressures

Normal Pressures
.46 p.s.i./ft

Adapted from
D. Powley
Underpressure occurs in K rocks exposed to surface. Normal pressure returns in deeper shale-rich strata.

Geologic cross section (W-E) across central Alberta Basin, Alberta, Canada (adapted from Bachu, 1999).
Ledged Pressure Systems

- Maturin Basin
- Anadarko Basin
  - Shallow normal pressure in sandstone-rich interval
  - Shale-dominated overpressured interval with discontinuous sandstones or very low porosity carbonates or coarse siliciclastics (GW)
  - Deeper normally pressured interval with reservoirs in continuity with the outcrop
Generalized geologic map of the Maturin Basin showing the location of the cross section. Map data from the United States Geological Survey.
Geologic cross section (N-S) through the central portion of the Maturin Basin, Venezuela (adapted from Villaroel, 1993).

**Maturin Basin**

**Normal Pressure**

**Overpressured**

**Normal Pressure**

**Overpressure Confined to Shale-rich Members of the Oficina Formation**
## Maturin Basin

<table>
<thead>
<tr>
<th>Age</th>
<th>Formation</th>
<th>Lithology</th>
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<tbody>
<tr>
<td>Recent</td>
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</tr>
<tr>
<td>Pliocene</td>
<td>Mesa</td>
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<tr>
<td>Miocene</td>
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<td>Upper</td>
<td>Las Piedras</td>
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<tr>
<td>Middle</td>
<td>Freites</td>
<td></td>
</tr>
<tr>
<td>Lower</td>
<td>Oficina</td>
<td>Blanco</td>
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<td>Colorado</td>
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<tr>
<td>Oligocene</td>
<td>Merecure</td>
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</tr>
</tbody>
</table>

- **Normal pressure**
  - approx. 5,000 ft depth
- **Overpressured**
  - approx. 8,800 ft depth
- **Normal pressure**
Generalized geologic map of the Anadarko Basin showing the location of the cross section. Map data from the USGS.
Generalized stratigraphic column of the Anadarko Basin (adapted from Al-Shaieb et al., 1999) No scale is intended.

Anadarko Basin

Overpressure occurs in shale-rich intervals below 8,000 to 10,000 ft with discontinuous reservoirs.

Normal pressure returns in regionally continuous reservoirs of the Hunton Gp. and Arbuckle Gp. that are hydraulically linked to surface.

Generalized stratigraphic column of the Anadarko Basin (adapted from Al-Shaieb et al., 1999) No scale is intended.
Anadarko Basin
Reynold-Cheyenne Area
Oklahoma, USA
Ledged – Tiered Basin

Pressure, p.s.i.

Depth, Feet

Normal Pressures 0.465 p.s.i./ft

Virgilian
Missourian
“Skinner”
“Red Fork”
Upper Morrowan
Woodford Shale
Ordovician-Devonian “Hunton”

Overpressured MCC

Normally Pressured Hunton Group

Adapted from Al-Shaieb et al, 1994
Anadarko Basin

- Prior to recent drilling activity, Woodford pressure was only known from a few vertical wells and mud-weight-derived values
- Reservoir pressures in CANA area show Woodford to be slightly overpressured with pressures increasing to the west, with P-D values reaching (0.65+) in Dewey County
- Hunton Group carbonates below the Woodford are mostly normally pressured creating a potential for communication and flow from higher to lower pressure
- Hunton communicated with outcrop in Pennsylvanian; it continues today
Deep Normal Pressure

- Deep normally pressured interval is of interest to industry because of fluid-disposal potential.
- Arbuckle Group reservoirs are mostly normal to slightly subnormal across Oklahoma.
- Areas of slight overpressure exist where elevation of recharge creates potential energy.
- Overpressure in Wilburton field is likely increased as a result of buoyancy-related compression.
Anadarko Basin

Comparison of compartmentalized and overpressured Morrow reservoir pressures with normally pressured Arbuckle Group

Pressure-Depth Relationship:

Compartmentalized and Hydrostatic Reservoirs

Puckette, 1996
Arbuckle Group Potentiometric Surface Map
Reconstructed in NE OK

Puckette, 1996
Buoyancy and higher elevation of the recharge zone combine to generate overpressure in the Arbuckle Group reservoir, Wilburton Field. From Puckette (1996).
Conclusions

1. Combination of sealing and conduit lithologies create an environment where either normal or abnormal pressure is maintained.

2. Stepped-Tiered Basins with upper normal and deeper overpressure:
   - **Normal pressure** occurs mostly in coarser clastics
   - **Overpressure** occurs in intervals with seal-forming shales and chalks; it is result of disequilibrium compaction and HC generation.
Conclusions

3. Recessed-Tiered Basins with upper normal, middle underpressured and deep normal or upper normal and deeper underpressured.

Normal pressure occurs in shale with interbedded sandstones

Underpressure occurs in regionally deposited coarser-grained clastic material that has active water drive; or exposed at surface

Deeper normal pressure, if present, occurs in intervals dominated by carbonates that are continuous to the surface
Conclusions

4. Ledged-Tiered Basins: upper normal, middle overpressured and deep normal
   - **Normal pressure** occurs in intervals with sandstone, shale and carbonate
   - **Overpressured** interval is dominated by shale with laterally discontinuous reservoirs
   - **Deep normal pressure** occurs in laterally extensive sandstones and carbonates with reservoir continuity to the surface

5. Normally pressured intervals in all types usually require a structural component to trap oil and gas as these reservoirs have strong water drive
References


Kewanee Oil Company, 1961, A Stratigraphic Study of the Wind River Basin, Special Study Section, Kewanee Oil Company


Macauley, G., 1958, Late Paleozoic of Peace River Area, Alberta, *in* AAPG Special Publication 17: Jurassic and Carboniferous of Western Canada, pp. 289-308.


