Normal pressures have gradients are in the range 9.8 to 11.0 kPa/m. If gradients are outside this narrow range the reservoir is exhibiting abnormal pressures.

Overpressure is indicated by gradients in excess of 11.0 kPa/m. Underpressure is indicated pressures less than 9.8 kPa/m.
<table>
<thead>
<tr>
<th>FLUID TYPE</th>
<th>DENSITY Mg/m³</th>
<th>API Degrees</th>
<th>SALINITY g/L</th>
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API gravity is a dimensionless measure of density used in the petroleum industry. The units are called API degrees.

The scale is very sensitive to specific gravity in the range 0.6 to 1.0 for liquid hydrocarbons.

Heavy oils have API gravities from $10^\circ$ to $20^\circ$. Light oils span the range $20^\circ$ to $50^\circ$ API.

The relationship between API and SG is:

$\circ\text{API} = \frac{141.5}{\text{SG}} - 131.5$

For example, for a 0.800 SG light oil the API gravity is $176.9 - 131.5 = 45.4^\circ\text{API}$

$\text{SG} = \frac{141.5}{(131.5 + \circ\text{API})}$

For example, for a $12^\circ\text{API}$ heavy oil the SG is $141.5 / 143.5 = 0.986$. 
Static pressure gradients show breaks at points corresponding to the gas-oil (GOC) and oil-water (OWC) contacts.

- **GAS**: 1.5 kPa/m
- **OIL**: 8.5 kPa/m
- **BRINE**: 11.6 kPa/m
Abnormal pressures are created and maintained by the restriction of pore fluid movement.

Several kinds of stress changes can lead to abnormal pore fluid pressures:

- rapid geologic loading (deposition) or unloading (erosion) creating compaction (consolidation) disequilibrium
- thermal expansion of fluids
- regional compressive (squeezing) or tensile (stretching) tectonic stresses
- generation of oil and gas from organic matter.

Abnormal pressures are created when external stress changes take place too quickly for fluid flow to dissipate the excess pore-pressures generated.
PROCESSES

1. **Epeirogenic Movements:**
   Uplift and subsidence associated with erosion and deposition.

2. **Aquathermal Pressures:**
   Thermal expansion and contraction of porous media and reservoir fluids.

3. **Osmotic Pressures:**
   Membrane filtration by shales and clays. Water flow to equalize brine concentrations.

4. **Chemical Diagenesis:**
   Precipitation from trapped pore waters and other chemical processes.

5. **Hydrocarbon Generation:**
   Carbonization of trapped organic matter.

6. **Buoyancy Forces:**
   Density differences between reservoir fluids.

7. **Tectonic Stresses:**
   Compressive and dilational regional stresses.

8. **Clay conversion:**
   Volume change reactions involving clay minerals.
Overpressure in shales is a common feature of "young" (<50 Ma) sedimentary sequences. There has been insufficient time for the porepressures generated by burial to dissipate.
All abnormal pressures are examples of disequilibrium. Given time the pressures will return to normal hydrostatic gradients.

Individual intervals in the geologic section may be either underpressured or overpressured depending on their recent geologic history.

Abnormal pressures are maintained because many geological materials (evaporites, ductile shales etc) have very low permeabilities and the time required to dissipate pressure differences can be thousands or even millions of years.
UNDERPRESSURED RESERVOIRS

Underpressured reservoirs are common in rocks that have been subjected to recent uplift and erosion. Many fields in the western USA and the Alberta Basin are underpressured for this reason.

The Keyes field in Oklahoma produces gas from a depth of 1460 m. Two evaporite seals are present, the Blaine Anhydrite at 305 m depth and the Wellington Salt at 853 m depth. The extent of the underpressure in the Keyes sandstone gas reservoir at 1460 m is 9,000 kPa.
At depths of 3 km or more, overpressure in reservoirs is common for three main reasons:

- Compaction Disequilibrium
- Thermal Expansion
- Oil Generation

Abnormal pressures due to compaction imply rapid burial. **Oil window** P-T conditions are usually 2.5 to 6.5 km depth and 60 to 160°C.

Seals may be broken by very high pressure gradients leading to tertiary migration.

Overpressures are common in the Gulf Coast and North Sea.
LOCAL OVERPRESSURE

Regional overpressured reservoirs are common in rocks that have been subjected to rapid burial and oil generation. Many fields in the US Gulf Coast, Iran, North Sea are overpressured in this way.

The Antelope Field, ND, in the Bakken of the Williston Basin, is a typical example of a locally overpressured oil reservoir.

The dense organic Bakken Shale source rock has a central silty-sand interval that forms a reservoir. Local oil generation is the reason for the large overpressure of almost 18,000 kPa.
The magnitude of pressure abnormalities created by oil and gas generation can be calculated.

The precise position of the oil window depends on geothermal gradients and rates of burial but at depths of 3.5 to 5.5 km, when oil
cracks to gas at 50% oil saturation, an excess pressure of about 150,000 kPa is generated.
FORMATION EVALUATION

*Formation evaluation* can be defined as the practice of determining the physical and chemical properties of rocks and their contained fluids.

Four main tools are available:

1. Mud logging
2. Wireline logging
3. Core analysis
4. Drillstem testing

*Well logging* is the process of creating a record (or log) of some engineering or geological property as a function of depth or time.

This includes many kinds of data:

1. Mud logs
2. Wireline logs
3. Core analysis plots
4. Stratigraphic core logs
5. Drillstem test parameter logs
WELL LOGGING

For simplicity, we will use well logging to mean *mud logging* and *well logging* only.

Since the first 10 electrical logs completed in 1927 the number of wireline logs conducted per year has risen to over 500,000 in 1997. The adoption of wireline logs as a commercial services dates back to 1950.

Over half (53%) of all wireline logs conducted are *radiation logs* of some kind. About 35% are *electrical logs* and the remaining 12% are *acoustic logs*.

Mud logging was first introduced as a commercial service in 1939. The first mud logs involved only the detection of combustible gases. By the 1970's, mud logging had developed into a computerized procedure providing continuous records of a large number of physical and chemical parameters.
MUD LOGGING

In the process of drilling, cuttings are mixed with the drilling fluid (mud) and carried to the surface where they are subjected to some or all of the following:

- gas-in-mud analysis
- oil-in-mud analysis
- gas-in-cuttings analysis
- oil-in-cuttings analysis
- cuttings description
- non-hydrocarbon gas identification
- cuttings density determination
- drilling-fluid property analysis

The hydrocarbon analyses, drill penetration rate, cuttings description and other properties plotted as a function of depth constitute a mud log.

The mud log is the important first stage in the formation evaluation cycle ahead of coring, wireline logging and drillstem testing.
MUD LOGGING SENSORS

Sensors *on the surface* monitor:

- in and out mud weight, flow and temperature
- in and out mud salinity and resistivity
- mud pit level and volume
- standpipe pressure
- hook load (weight on bit)
- drillpipe rotary torque and revolution rate
- mud pump rate and pressure
- total bit revolutions
- depth penetration and rate of penetration

Sensors *on the drillstring* (near the bit) monitor:

- direction and inclination of the hole
- resistivity of the formation
- natural gamma radiation
- mud temperature and resistivity
- weight and torque on the bit
- mud column pressure
IMPORTANCE OF MUD LOGGING

Comprehensive data on drilling performance and mud conditions are essential to safe and cost-effective drilling operations.

Formation evaluation, drilling optimization and rig-site safety are all served by mud logging information.

Continuous monitoring of drilling fluid properties, pressures and volumes provides early warning of potential hazards including:

• abnormal formation pressures
• sour gas (hydrogen sulphide)
• salt-section penetration

Weight on bit and rotary torque relationships provide insight on:

• formation properties including fracturing
• optimizing bit performance
DRILLING FLUID

Drilling fluid (mud) is formulated to control formation fluid pressure. Because mud pressure normally exceeds formation pressure (overbalanced drilling), mud filtrate invades newly drilled formation and flushes hydrocarbon ahead of the bit.

Flushing tendencies increase as the pressure overbalance is increased. The desire to avoid "blow-outs" often leads to drilling with mud pressures significantly in excess of formation pressures.

For logging purposes, an optimum drilling fluid involves:

- straight in-gauge holes
- minimum overbalance
- effective cutting carrying capacity
- no hydrocarbon contamination
In a typical drilling circulation system, mud passes down the drillpipe and exits through the annulus.
DRILLING FLUID CIRCULATION

Drilling fluid is pumped to the bottom of the hole through the drillpipe and collars and arrives after a time that depends on the drillstring volume. Contamination from joint lubricants can be a problem and chemical reactions can occur between drillstring and muds generating H₂, which may be falsely detected as hydrocarbon.

At the drill bit, flow ports designed to increase pressure and velocity at the bit-formation interface can increase the tendency for flushing and effect hydrocarbon logging. The design of the bit teeth controls the size and shape of cuttings.

The annulus between the drillpipe and the borehole face is the conduit for mud and cuttings returning to the surface. This exposes the cuttings to contamination by caving from previously drilled formations and/or produced fluids.
DRILLING RETURNS

Drilling returns are moved from the **wellhead** to the surface processing equipment through a **mud return flowline** or ditch. It is important to minimize or avoid gas escape in this section.

Losses can be minimized by:

- maintaining the flowline full
- avoiding turbulence
- minimizing the length of open flowline
- ensuring the flowline entry is below mud level
The returns next pass through a feed tank and over a vibrating screen called a **shale shaker** to remove coarse cuttings from the mud.

The mud slurry passes to a tank compartment or **settling pit** where coarse particles can gravity settle.
MUD CONDITIONING

Subsequent tank compartments pass the mud through a *degasser*, to minimize hydrocarbon contamination in the recirculated fluids, and on through *desanders* and *desilters*, to remove finer particles.

The objective of this part of the circulation system is to maintain mud quality and minimize contamination and degradation of the mud.

The final tank compartment is the *suction pit* from which the mud pump draws. Here additional material is added to the mud to maintain its density and viscosity before it is pumped into the drillstring and down to the bit.

Suction pit additives include:
- mud (bentonite, etc)
- lubricants (diesel etc)
- densifiers (barite etc)
- fluid (brine etc)
Finally, the mud arrives in the active *suction pit* where it is conditioned to the required density and viscosity before it passes through the mud pump and back to the hole.

Because drilling advances in the time interval it takes for mud and cuttings to flow up the hole, there is a *lag* between the driller's depth when the sample is cut and the driller's depth when the sample arrives at the surface.

Mud pump displacement measurement is critical to the assignment of accurate depths to cuttings samples. Differences are measured in the number of pump strokes, which are readily converted to depth increments.

This lag is measured by using both gas (acetylene generated from addition of calcium carbide) and solid tracers (crushed brick etc) because buoyancy causes gases and cuttings to travel at different rates in the annulus.
Penetration rate is measured by recording the movement of the kelly relative to the kelly bushing. It is recorded as distance for a fixed time (m/hr) or time for a fixed distance (hr/m).

A **drilling break** occurs at the onset of a faster rate of penetration. Drilling rate logs show a **dulling trend** as the bit is worn down and breaks when a new bit is used.

A **drill-off trend** indicates increasing formation pressure as the cuttings are removed more efficiently as the overbalance is reduced. Hydraulic jetting is used to flush the cuttings in strongly overbalanced drilling.
DRILLING RATE DATA

Drilling rate data can be used in three ways:
1. identification lithology changes.
2. making well-to-well correlations.
3. detection of abnormal pressures.

Lithology: A drilling break is the first indication of a porosity in a prospective lithology. Rate of penetration is expected to correlate with SP, gamma ray, density and acoustic wireline logs.

Correlation: A penetration rate log is useful for making stratigraphic correlations before a wireline log has been run.

Pressure Detection: Drilling rate is found to be approximated by: \( R = a \cdot f \cdot (W/d_b)^d \) where \( a \) is a lithology-dependent constant, \( f \) is the rotary speed, \( W \) is the weight on the bit, \( d_b \) is the bit diameter and \( d \) is the drillability or d-exponent. The d-exponent normally increases with depth.
but is observed to fall with depth when overpressure is encountered.
LOGGING HYDROCARBONS

Hydrocarbon sensing is a critical component of mud logging.

Logging cuttings lithologies, and penetration rates are important for reducing ambiguities in the origin of entrained oil and gas but the ultimate success or failure of a mud logging operation depends on the sensitivity and reliability of hydrocarbon monitoring.

Identification of the sources of oil and gas in drilling returns is a prerequisite to successful formation evaluation.

Oil and gas enter the drilling fluid from several sources:

1. cuttings and fluids from the current interval,
2. production from previously drilled intervals,
3. thermocatalytic generation during drilling,
4. contamination
LIBERATED AND EXPELLED FLUIDS

As a new hole is drilled, a cylindrical volume of formation is broken up and mixed with the drilling fluid. This process *liberates* formation fluids into the drilling fluid.

Cuttings from a newly drilled interval retain a portion of their formation fluids in the chips. The cuttings and fluids enter the mud column under *bottom hole pressure* (bhp).

As the cuttings travel to the surface the pressure reduces. The retained fluids in the chips expand and are *expelled* into the drilling returns.

There is no practical method to distinguish between liberated and expelled fluids since these component are mixed in the mud column.

The combined liberated, expelled and retained fluids constitute a *show*. 
PRODUCED FLUIDS

While drilling proceeds with underbalanced pressures or while the hole is swabbed during trips, oil and gas can be produced into the hole from previously drilled formations.

RECYCLED FLUIDS

Produced formation fluids (oil and gas) may be recirculated as drilling continues. Recycled oil and gas represent those hydrocarbons not removed by the surface conditioning of the mud.

Good drilling practice avoids significant recirculation since recycled hydrocarbons can obscure new shows.
Contamination gas or oil is defined as hydrocarbon artificially introduced into the drilling fluid from sources other than the penetrated formations.

There are many potential sources of contaminants. Most are readily distinguished from their fluorescence characteristics.
CONTAMINANT SOURCES

A common contaminant is **diesel fuel**, which may either: contribute small amounts of gas or scavenge gas and deplete the mud returns. Diesel contamination is either a minor nuisance as a source of gas or a serious problem as a scavenger. These problems are minimized by using Grade 1 or Grade 2 refined diesel products rather than bunker fuel.

Hydrocarbon gases can also originate from organic additives (such as lubricant greases and pipe dope), which may generate $\text{H}_2\text{S}$ or $\text{CO}_2$ and interfere with some gas-in-mud measurements.

THERMOCATALYTIC GENERATION

Conversion of organic content by thermal processes associated with drilling has been postulated as a source of false shows. The phenomenon is most likely to occur during the slow drilling of organic-rich shales.