

Origins of Abnormal Pressure

In most geological settings, a "normal " set of parameters can be used to predict what formation pressures might be encountered while drilling. If these conditions always prevailed there would hardly ever be any problems in tailoring a drilling fluid system to control the well.

Unfortunately, various geological and mechanical variables conspire to produce pore pressures that are higher (or lower) than the "normal".

What information does the well planner have at their disposal to predict formation pressures for upcoming wells? The geological history of the area to be drilled is usually known. This, combined with a knowledge of how abnormal pressures develop in different geological settings, can enable the well planner to anticipate the location, extent and potential magnitude of possible pressure problems.

The fundamental difference between normally and abnormally pressured rocks is that in abnormally pressured zones the pore fluids no longer communicate 100% efficiently with the water-table (surface communication). Some mechanism is providing a seal or cap to interfere with the fluid column and preventing it from achieving normal hydrostatic equilibrium .

Once the continuity of the fluid column has been broken, the pore fluids can be acted upon in a number of ways. For example, if we picture the area of abnormal pressure as a compartment, it can be present in three different conditions; 1) it may be perfectly sealed like a balloon, 2) it may slowly leak like a punctured tyre, or 3) it may be so leaky that it holds pressure for a short period of time (these very leaky seals are not often knowingly drilled but have other geologically important roles, such as being the cause of major landslips and slope failures).

The criteria that determine the efficiency of the seal are

- its permeability,
- its thickness,
- the magnitude of the differential pressure
- the length of time over which the pressure changes have occurred.

The best seal would be a perfectly impermeable, plastic rock, capable of retaining its integrity and encapsulating a fluid-filled porous rock. An example of such a lithology is salt. As a result, salt can be the cause of many severe pressure problems. The most common seals that are drilled are claystones and shales. Not all claystone/shale sequences are impermeable, even the thickest ones, but a favourable combination of low permeability and sufficient thickness can sustain quite substantial overpressures, especially if the rock still has sufficient tensile strength.

Quite often, owing to slight permeability, there can be a pressure halo around the abnormally pressured zone which stretches as far as the next change in vertical permeability. This gradual leakage of pressure means that overpressures are very transient (in geologic terms), unless the pressure is constantly replenished by some other charging mechanism.

Bradley, in his 1975 paper, showed that there only needs to be a leakage of one "drop" of water per square centimeter every year for 300 years to bleed off a

differential pressure of 1000 psi. This is well within the permeability range of many shales.

For this reason, larger abnormal pressures are more likely to be encountered where the processes that formed them are recent or still active and seal efficiency is still very high.

How Does Abnormal Pressure Develop?

In order to describe the various pressure developing mechanisms (some proven and some only postulated) some simple analogies are required. The simplest is a tin full of water. The tin has a finite volume, a certain tensile strength and a sealing efficiency dependent on how firmly the lid is fixed on. To change the internal pressure in the tin we can do one of two things: 1) change the volume of the tin or 2) change the volume of the liquid. It is also important to consider the liquid in the absence of any gas cap (like a half empty cola bottle) since gas has a high compressibility and a low hydrostatic effect, which can lead to very different pressures at the top of the compartment from those that would have been encountered in the absence of gas.

First, let's look at systems where the compartment size changes, but not in equilibrium with the fluid (i.e. no fluid enters or escapes), then compare them with systems where the compartment size remains fixed, although these are not easy distinctions to make.

As we look at these mechanisms and the geological environment in which they occur, we will see that a knowledge of how pressure anomalies develop really can help the well planner to anticipate troublesome zones.

Lower Pressure Environments

Changing Compartment Size

If the confining pressure on a compartment is reduced, the compartment (if flexible) will relax and expand. If no fluid can enter the system those already inside it are required to fill a larger space. Thus the pressure drops.

Geological Settings

In areas where erosion has removed a significant thickness of the overburden, the more elastic sediments (like shales and claystones) may relax sufficiently to undergo an increase in pore volume. Also, this volume increase may draw in fluids from interbedded and surrounding porous rocks (i.e. lenticular sands) resulting in depletion of pressure in those sands. If the fluid available for the entire area is insufficient, the whole system, including clays, will be underpressured. Temperature is a complicating factor, but generally "decompressed expansion" in areas of uplift and erosion will lead to subnormal pressure. Nearly 60% of the rocks in the USA are subnormally pressured. In an underpressured compartment the seal is entirely matrix supported.

Changing Fluid Volume

The simplest form of fluid change, and the most common cause of lower-than-normal pressure, is depletion of reservoirs and aquifers through production. As such, in mature fields it is not uncommon to encounter underpressured sands. In the absence of a matrix supported seal, the consequence will be compaction of the reservoir and surface subsidence as the matrix takes on the full load. The

subsidence of the sea bed above the Ekofisk field in the North Sea is a good example. As mentioned above, temperature has an effect on the "decompressional expansion", and an increase in temperature gradient at the same time as the erosion may compensate for (or even over-compensate for) the loss of the imposed pressure. For this reason the areas most likely to be underpressured are those that were originally hot and undercompacted. This kind of situation can prevail in interior basins with high heat flows, but which don't become subsequently filled during the later sag phase.

Things That Look Like Underpressure

A low water table, or an aquifer with an outcrop below the water table, will show a pressure that is (for drilling purposes) subnormal. Subnormal pressure is not as dramatic as overpressure, but the resulting loss of circulation and consequent loss of hydrostatic pressure control in the well can be even more catastrophic than a "simple" kick from overpressure, and can be far more difficult to control.

Compaction Disequilibrium

As can be seen, compaction disequilibrium is a common cause of abnormal pressure. This is especially true in rapidly filling (Tertiary) sedimentary basins. Passive plate margins, with one or more large deltas (i.e. Gulf of Mexico, Niger Delta, etc.) are common areas for this type of geopressure. Under "normal" circumstances the sediments deposited at the delta front will dewater as the matrix material reshuffles itself (See Figure 1) under the influence of gravity and the overburden created by the deposition of even more overlying sediment. The dewatering process relies on slow, continuous permeability that ultimately connects with the surface/water table, allowing the pore fluid pressure to remain hydrostatic.

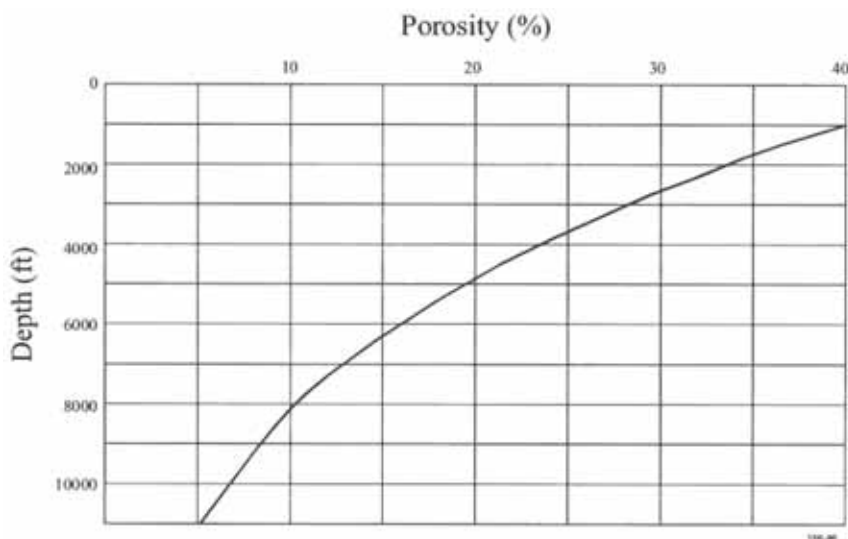


Figure 1: Porosity/Depth relationship for a typical compacting clay sequence

If seasonal changes in load (the switching of a channel) or a change in sediment source occurs, the quantity and/or type of sediment can change abruptly. A change from a clay/silt/sand mixture to clay alone can easily restrict the dewatering process to those clays/silts adjacent to a sand layer. Rapid loading by a huge thickness of the same clay/silt sediment may tip the dewatering balance

temporarily in favour of overpressure. In fact the dewatering process is rarely perfectly "normal".

This lack of dewatering conspires to cause the matrix stress between the grains to become "locked" as burial continues, and causes the pore fluids to be responsible for carrying the remaining overburden. The process will continue until the fluid pressure finds relief by rupturing the seal. This rupture can occur at pressures below the overburden if the rock is brittle or even as much as 40% above the overburden if the rocks have enough tensile strength. Since compaction disequilibrium is common in younger clays, a frequent result of this effect is a suite of mud diapirs, mud lumps, and sand volcanoes.

In the Mississippi River delta, these lumps (where the high pressures have reached the surface) are seen as small islands. Similar islands of mud have erupted in Indonesia. The pressures can sometimes be relieved by systems of sub-vertical faults above the diapir or by growth fault systems. The high pressures in these shale masses are a major contributing factor in the formation of massive "growth faults" that cut across the delta, trapping the rollover anticlines (which often form traps for oil and gas in the hanging-wall). The faults may also trap oil on the foot-wall side where the movement has brought sands against shales to seal them.

Fault movement and the presence of sand also helps to both segregate and redistribute pressures. Pressure anomalies are often laterally sealed by a clay smeared fault-plane, which can also have zones of mineralization associated with it. For this reason when drilling through growth faults it may be necessary to increase the mud density .

When normal faults move, the fault plane separates slightly or "dilates" (because of the high injected fluid pressure) and as it does, it allows the high pressure to communicate with any lower pressure potential along the fault plane. This can be the surface or a sand body adjacent to the fault. If the fault closes, any sands so charged are often resealed against shales and lay in wait for unsuspecting drillers. The problem is theoretically more acute in the distal part of the delta, where sands are thin and for any given throw are more likely to reseat against shales, instead of ending up next to another sand which would allow the pressure to dissipate.

A further complication is that any clay overpressured by compaction disequilibrium will tend to charge any adjacent sands which are at lower pressures, with the risk of creating an overpressured permeable zone. If the bed thickness is sufficient, the edges of the clay will bleed down first, compact, and seal the original overpressured area in the middle by virtue of the reduced permeability at the edge.

Tectonics

The process of overthrusting in the earth's crust is itself dependent upon overpressure, without the lubrication of overpressured fluids at the base of the thrust, the huge rock masses could not move in the way that they do. The almost total lack of deformation along many thrusts shows the efficiency of the fluids in the faulting process. It is possible to drill into a thrust which is still at high pressure, but generally their significance is two-fold.

1. It may load the underlying sediments and, if seals are present, impose an extra pressure on the contained pore fluids. This may also change the geothermal gradient seriously enough to alter the pressure.

2. It can lift compartments to higher levels without rupturing.

The phase before thrusting can also induce pressure. In the foreland basins of active mountain building thrust belts the horizontal stresses can reach twice the overburden before faulting occurs, any of that stress which acts directly on the pore fluids must necessarily cause excess pressure. The Qum oilfield in Iran is one of the best examples of pressure in the base of a thrust. The limestone below the thrust remains overpressured.

The physical/chemical transformation of one rock or mineral into another is often cited as a cause of overpressures. Many minerals will undergo a chemical metamorphoses at relatively low temperatures, long before true metamorphism occurs. A classic example is the transition of gypsum to anhydrite ($\text{CaSO}_4 \times 2\text{H}_2\text{O}$ to CaSO_4) in which there is a total volume change of about 50% with the expulsion of water. Normally this change occurs at about 40°C, at relatively shallow depths.

Conversely, pressures may be generated by the change from a high density porous rock to a lower density, less porous rock. A good example of this is dedolomitization. Under the right conditions dolomite (CaMgCO_3) will turn into calcite (CaCO_3). Since calcite crystals occupy more space than dolomite, with the absence of fractures, they will tend to squeeze out any remaining pore fluids.

Such a condition should only occur when the connate water is replaced by a fresher fluid (which can also rehydrate gypsum). This process is probably restricted to near surface sediments.

Clay Diagenesis

The diagenetic changes that occur in some types of clays are widely held to be the cause, either directly or indirectly, of overpressure. The precise nature of this mechanism has been hotly debated over the last twenty years.

The basic premise of this mechanism is that the surficial, younger argillaceous sediments are often rich in a smectite clay called montmorillonite (See Figure 2). A significant feature of the smectite group is its very high surface area. These clay platelets are held together by a weak electromagnetic force (Van der Waal's bonds), and there is a considerable amount of area to which up to ten layers of water can bond. The result is a low density "swelling clay", much like bentonite (a smectite clay), the major component of drilling fluids.

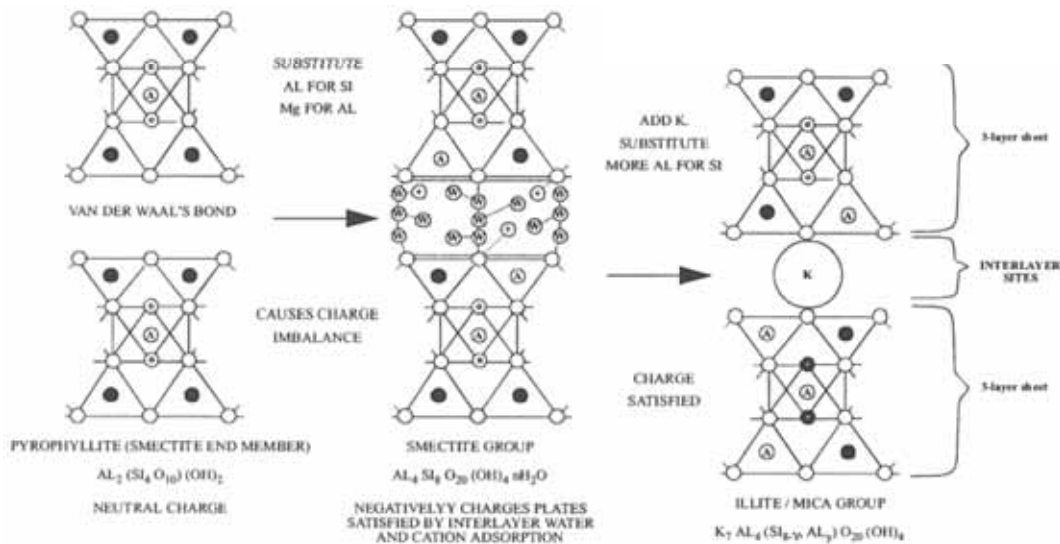


Figure 2: Changes in ionic substitution in three-layered sheets

Smectite clays go through a number of changes with burial. Initially, increasing pressure will drive out the loosely bound water (a process similar to normal compaction), but as the number of layers is reduced, the pressure required to release the remaining water increases. Ultimately, only high temperature and chemical processes will release the last layer, which can be bound with metallic cations.

Virginia Colton-Bradley (1987) studied the purely physical dewatering of smectites and its potential role in the development of overpressure. She concluded that smectites in the pore spaces of sand, under hydraulic pressure, lose their last two water layers with great difficulty. When smectites within a shale are subjected to lithostatic pressure and a temperature of $67^\circ - 81^\circ C$ the penultimate layer will be displaced. A further rise in temperature to $172^\circ - 192^\circ C$ is required to drive off the last layer, which is very closely bound between the clay plates.

These critical temperatures are raised under the influence of local overburden and although the initial dewatering may actually cause some overpressures, the resulting extra hydraulic pressure will also tend to inhibit further dewatering. Therefore, under most conditions the simple dewatering process will not lead to excessive overpressure, since there is a negative feedback loop at work. However, there is also the chemical diagenesis to consider.

The threshold temperature for the loss of the penultimate water layer is roughly the same at which hydrocarbons are generated. At this point the smectites can turn into illite clays. Depending upon the type of smectite (K or Na smectites react more quickly than Ca or Mg smectites), the presence of available cations like K^+ will satisfy the surface charges in place of water and collapse the clay into the more compact illite-type.

The remaining water is released into the new porosity created by the reduction in clay volume. Theories that this last water is super dense and "fluffed up" on its release have recently been backed up by theoretical studies. Monte Carlo simulation suggest a density of up to 1.3 g/cc (in a magnesium smectite). Total volume change is in the order of 6 percent.

Colton-Bradley also suggested that the bound water acidity (in Bronsted acidity) increases as the water layers are gradually lost. These factors also tend to drive the smectite clay into illite.

Other workers have found large variations in the temperature required to initiate simple, physical smectite dehydration. Bruce (1984) found a threshold temperature of 71 ° C in the Mississippi River and over 150° C in the Niger delta. He suggests that cation availability may partly control it.

The real links between overpressure and smectite/illite transformation appear to be more closely related to the higher density of the illite packets and the consequent loss of vertical permeability through the zone. In this way the clay is not always the direct source of the pressure but rather a mechanism for capping pressure, especially if hydrocarbons are beginning to form, or water is being driven upward by other processes.

Freed and Peacor (1989) studied the exact relationship between pressure and percentage of illite packets. They found that normal pressures stopped when the transformation began, and continued to rise through the zone of increasing illite. From this, it appears that 40% to 50% illite is sufficient to retard vertical permeability. This ties in well with the classic shale transition zone and throws new light on its possible development.

Recent work also helps to understand the "illite free" overpressure that was normally ascribed to compaction disequilibrium. It may be inferred that the hydrostatic pressure and "frozen" matrix stress have prevented simple dewatering, which are seen at shallower depths. At greater depths, the permeability effects of illite probably dominate.

In any clay-type pressure interpretation, we must consider the following:

Was there any original smectite? Some basins contain very little. As an example of this variability, smectite comprises 40% of the clay in the Northern Atlantic but only 20% in the Southern Atlantic. In the south western part of the Indian Ocean it reaches concentrations as high as 80% (Biscayne 1964- cited in Reike + Chilingeran).

Is there any sand present, which can act as a conduit to leak fluid away from the simple dehydration (or any other) mechanisms? The old "sand-count" as a means of assessing overall vertical permeability now has a more practical use.

At what depth, below the surface, does the combination of temperature and pore-water chemistry in the basin lead to the formation of illite rich zones?

What has happened geologically since the zone formed? Has the basin subsided or been elevated? Has the local heat flow changed?

Aquathermal Pressuring

Nobody can be in any doubt that if a tin of water was placed over a fire it will ultimately pop its lid. This analogy is important as an origin of overpressure. It was mentioned previously that the change in temperature, associated with cooling can cause a reduction in pressure. On the other hand, how much of a risk is temperature to drilling?

To heat a rock it must move to a higher geothermal gradient (i.e. bury it). The gradient itself, however, is regionally variable; some interior basins are cool, some active continental margins are hot. The actual rate of expansion in aqueous

brines and the resulting increases in pressure was documented by Barker in 1972, and criticized by Daines in 1980. The point of contention is not so much "does water expand" or "does the expansion cause pressure" but "can the seal really hold the pressure?"

The volume increase required to produce pressure is in the order of 0.05%, well within the leakage or tensile capabilities of all but the stiffest, toughest, and most impermeable seals. It is, on balance, more likely that aquathermal pressuring is an extra drive that ruptures seals, moves fluids and pressures, generally keeping the systems dynamic. Temperature also drives the convection of fluids in the upper parts of many basins, redistributing ions that can affect diagenesis.

Osmosis

Osmosis is the movement ions in water down a water concentration gradient (i.e. from fresh to saline). The ions will continue to move until the salinities balance or pressure prevents further movement. That pressure is postulated to be as much as 4000 psi in the subsurface, where shales can act as the semipermeable membranes.

Imposed Pressure

In some cases a system may exist with no pressure anomaly but with a reasonable seal. The previous pressures may have leaked away, leaving behind a compartment ready to receive pressure from an external source. Formations like this can be recharged from a number of sources, from faults (as already discussed) and even by drilling.

The most obvious man-made charging comes about during production, when fluids are pumped into a reservoir to replace the extracted hydrocarbons. As an example, in the Unita basin the Rangely field waterflooding has raised the pressure from abnormally low to a 0.6 psi/ft (1.39 bar/m) high, causing earthquakes on a nearby strike-slip fault. (Raleigh 1972).

Faults

As discussed earlier, normal faults and thrust faults are the result of various stress imbalances in the crust and superficial sediments. They are often caused by, helped by, or linked to overpressure. When moving and dilating, pressures can easily be transferred. This can result in moving fluids to a previously lower potential or bleeding pressure off, returning it back to hydrostatic. Faults are also good lateral seals.

Seismic Or Fault Pumping

A model for generating overpressure which attracted increasing interest through the 1980's was "seismic" or "fault" pumping. Rocks under stress tend to act like a heart, and pump fluid from one location to another. Based on studies of rock dilatancy during earthquakes, this theory proposes that the rock stresses which can cause wrench faulting and earthquakes can affect the pore volume of rocks.

Examination of vein mineralization by Sibson (1975) indicated that the zoning of the minerals was caused by discontinuous, episodic, passage of fluid through the veins. Further work by Burley, et al (1989), invokes this seismic pumping

mechanism and links it to pore water salinity changes inferred from the cementation history of the Tartan reservoir in the UK North Sea. These episodic influxes of hot mineralized fluids show up as distinct phases in quartz and carbonate veins.

More diagenetic evidence for the expulsion of fluids from deep pressure compartments is cited in Jansa and Urrea 1990. The dissolution of carbonates is linked to the highly acidic fluids developed when CO₂ dissolves under pressure in the presence of organic acids. Both are linked to kerogen maturation.

When pores expand, they will do so in the direction of least stress (σ_3), before the "valve" contracts. The vertical distance over which the pushed fluids will travel is reckoned (by Burley) to be as much as 2000 meters. The source pushing the hot fluids can come from various mechanisms; tectonic forces or "thermobaric" drives working on the fluids caused by diagenetic mechanisms (like hydrocarbon maturation or smectite dehydration).

In any event, the hot fluids are injected, in a slow rhythmic fashion to higher levels. The incidental evidence for this rhythmic flow is also recorded in the work of researchers like Hunt (1990), who identified cycles of fluid "breakout" followed by resealing at intervals of thousands of years. Hunt's fluid pumps are principally of thermobaric origin and are also responsible for hydrocarbon migration into zones of lower pressure as the basin sinks, his ideas follow closely the work of Powley .

Tigert, in his thesis "*Pressure Seals and Their Diagenetic Zebra Structure Patterns*", found alternating cemented and porous bands in transition zones, while other workers have found slightly fractured pressure seals infilled with calcite and silica. These bands are on the scale of one inch of cement to each foot of clean sand (Powley). In nearly all cases it appears that the faults along which the fluids flow and the "valve" area become so mineralized and sclerotic that they eventually seal up completely.

General Basin Structure

Most deep basins appear to be divided into two zones. From the surface to 10,000 feet, the systems are widespread, convective and hydrostatic, with combinations of the various in situ mechanisms causing overpressure. This normally shows up as forms of simple compaction disequilibrium.

Below 10,000 ft. the basins are layered cells or compartments with boundaries that cut through lithological and stratigraphic boundaries. It is in this deep basin setting, at high temperatures and pressures, that the real seismic pumping operates (rather than simple fault charging).

As the basin subsides hydrocarbons mature, collect and are expelled with hot fluids repeatedly pumped upwards to create the zoned seals, areas of abnormally hot fluid and lateral seals. Some hydrocarbon occurrences have been linked to breaches in the lateral seals (since hydrocarbons do not tend to accumulate in areas of high pressure potential). When a compartment breaches, it tends to be the hydrocarbons that leave and not the water. This link to the location of hydrocarbons was the main impetus for the work by several oil companies on pressure compartments. It should be stressed that the work is best applied on its home territory (i.e. North America) and is exportable only with care.

Gas Hydrates and Pingos

In deep, cold oceans and in the polar regions a variety of situations exist where dangerous overpressures can develop.

Gas hydrates are frozen mixtures of methane contained in crystalline water. Because of the arrangement of the methane within the ice, it can store > 160 times more gas per unit volume than free gas. When drilled, they can release massive amounts of gas. Biogenic and seeping gas can also collect below permafrost.

A well known symptom of water overpressure caused by ice is the "pingo", a form of mud-lump in the tundra, these anticlinal-looking mounds grow in the winter due to the freezing of shoaling lakes, trapping the water and compressing it.

Paleopressures, Uplift and the Effects of Structure

"Paleopressure" is old pressure in a new place. The relationship between depth, pressure and fluid density clearly shows how an enclosed but normally pressured compartment at great depth can be turned into an "overpressured" one by lifting it to a shallower depth. If the pressure is maintained at half the previous depth, twice the drilling fluid density is required to balance it. This phenomenon is relatively rare but in some areas, locally common.

Since the combination of circumstances required to lift a pressured compartment without breaching it are so special in a particularly favourable setting it may happen more than once. Classic settings for this are: (a) In mountain building zones where thrusts and isostatic adjustments can cause the rocks to rise. In the South American Andes some very high pressures have been caused like this; (b) In areas of wrench tectonics where blocks may be "popped-up" or inverted having previously been in low basins. If the cover is young and flexible high pressure may be preserved. Some areas around the British Isles exhibit this and are rendered virtually undrillable; (c) Inside salt domes.

Halokinesis causes the formation of overpressure in a variety of ways, one of which is to trap porous rocks and carry them to shallower depths. Salt is plastic, light and has no porosity so it is the ideal medium to seal porous rocks. When it flows as a wall, stock or diapir it can develop internal vortices like a billowing cloud of smoke, which can trap, encapsulate and lift the surrounding country rock. These fragments, usually dolomite or anhydrite, are referred to as "rafts" although they are not floating they are being swept upwards on a very slow plume. They can contain gas (including H₂S), oil or water and may appear quite unexpectedly. They may be solitary or in clusters. Either way, they are a significant hazard to drilling and are difficult to control. One common practice is to bleed them down, since they usually have limited extent. At the well site the observed rate of depletion should give some idea of how long the process may take. In the worst cases one raft will "blow-out" into another leaving the rig operator to wait until equilibrium is established. Generally, no transitions into the raft are observed.

Within a completely sealed compartment Pascal's law states that any pressure imposed internally is distributed equally around the compartment, regardless of, and in addition to, hydrostatic pressures.

In this way an equally pressured compartment with any structural elevation will demonstrate higher pressures at the highest (shallowest) point and from thereon down through the compartment the pressures encountered will equal the overpressure of the fluid within the compartment. This can occur on the flanks of diapirs or in small lenses of sand on anticlines.

Further complications arise if gas is present, since the overpressure experienced at the top of the structure is supplemented by the lack of hydrostatic control by the gas and the buoyancy of the water below. This additional pressure is a function of the difference between the density gradients of water and gas, multiplied by the vertical height. At the base of the gas column the pressure is the highest overpressure plus the (minimal) gas hydrostatic. At the base of the system it is the top overpressure value plus the continued hydrostatic, (i.e. water or oil plus gas).

Evaporite Deposits

Evaporite deposits can play a significant role in the generation of geopressures, generally by one of three ways:

Sealing Role - Since evaporites are totally impermeable, they become an almost perfect seal to fluid movement. This barrier to the vertical expulsion of fluids from underlying sediments, together with restricted lateral drainage can produce overpressured zones in formations underlying evaporite sequences. The mobility of these formations, such as halite, also means that any fractures that develop can be quickly repaired, maintaining the salt's effectiveness as a seal. This mobility can have the opposite effect by creating "holes" in the formation where the salt used to be and allowing some fluid drainage.

Tectonism

Movement of salt domes can affect pore pressure in a number of ways:

1. Previously deep lying sediments may be pushed closer to the surface while maintaining their original pore pressure. They are no longer "normal" when compared to surrounding formations.
2. Isolated rafts of permeable rock may become trapped within the salt dome and also be transported to higher levels, while maintaining their original pore pressures.
3. Pierced formations may become isolated and lateral drainage may become restricted.
4. Osmosis may become important if sediments containing different pore fluid salinities are brought closer together, separated by a semi-permeable clay membrane.

Sulphate Diagenesis

Sulphate diagenesis can assist in the generation of geopressured zones in manner similar to that of montmorillonite dehydration. Gypsum is the precipitated form of Calcium Sulphate. Transformation to anhydrite occurs fairly early on in the burial process, generally above 40°C (The presence of salt will lower this temperature to around 25°C, with pressure an important factor). The change from gypsum to anhydrite involves the production of free water into pore spaces.

If this is limited, and lateral drainage is restricted, then increases in pore pressure could result. Water amounting to up to 38% of the original volume may be released, but since the change often occurs at shallow depths, it is usually possible for most of the expelled water to escape.

Hydrocarbon Generation and Migration

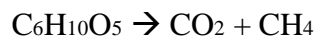
The breakdown products of organic molecules are among the most significant agents in producing overpressure, particularly in very shallow and very deep settings. The pressures they create are largely unrelated to compaction, and because of this the methods used to detect geopressures caused by compaction disequilibrium will not work well. The combination of this, along with the growing number of deep wells, requiring on-site pressure monitoring, is one of the greatest challenges for the "pressure engineer" today.

Biogenic Methane

Any organic material trapped within sediments, without previously being oxidized, is a prime target for bacterial decay and slow cooking. This decay produces pockets of shallow gas since, much like the generation of marsh-gas, the temperatures are generally too low to produce any oils, and the organic matter tends to be of terrestrial origin (lignites, peat, etc.). The bacteria present in the ground water acts to produce this methane gas

Some shallow gas may have originated at greater depths and has seeped as a plume into the surface sediments, where it becomes trapped under the surface clays or permafrost.

Cellulose can be broken down into both methane and carbon dioxide



The methane and carbon dioxide, if they escape to the surface, can be the origin of calcareous nodules on the seabed and may form mounds or diapirs where the gas has displaced the fluid from the recently deposited clays. This will cause the clays to have extra buoyancy relative to their surroundings. Any further gas leakage will cause gas plumes into the sea. Where the gas seepage does not change the clays, the result may be deep craters and pock-marks in the seabed.

Shallow gas can create significant drilling hazards.

Due to the low fracture gradients within the sediments, diverter lines or dynamic kill methods are generally used. A avoidance of shallow gas by close attention to high resolution seismic, or other offset data is important. The drilling of small diameter pilot holes and the use of MWD resistivity tools can enhance detection and prevent problems from developing.

Thermochemical Generation

The majority of hydrocarbons in the subsurface are formed by the deep burial and thermal maturation of kerogens. This process generally occurs within a specific "window" of temperatures, and the particular local combination of time, temperature and type of organic matter (e.g. is it algal or terrestrial plant debris) will produce oils (heavy or light), gases (dry or wet) or condensates plus some other very significant non-hydrocarbon compounds.

In this last category, the most important to overpressure and well safety are carbon dioxide, hydrogen sulphide and other acid gases. These can all lead to quite dramatic changes in pore fluid chemistry, which can radically affect diagenesis in the surrounding rocks.

The temperature range associated with the normal "oil window" begins at 65°C and proceeds to 150°C. Gas occurs as the increasingly smaller "dryer" molecules are produced, since the temperature continues to increase. Ultimately, beyond about 230°C, metamorphic processes take over and any remaining carbon is reduced to graphite. The depths that correspond to the various windows will vary from basin to basin, and with time, but it is not unreasonable to say that the oil window starts at about 7000 ft (2000m), peaks at about 14,000 ft and ends about 17,000 ft. This assumes an average geothermal gradient.

The type of hydrocarbon present has the most dramatic effect on any overpressure produced. Although oil is lighter than water and will rise through water because of its buoyancy during secondary migration, it is the production of gas that has the most serious consequences. Gas expands much more than oil or water, and whenever it is trapped, it reduces the hydrostatic control.

The production of hydrocarbons from organic matter, and light hydrocarbons from heavies, also increases the total number of molecules and therefore increases the space they occupy. If there is adequate drainage then no pressure increases will occur. Where drainage is restricted, pore pressures can increase and with continued compaction, since less water is expelled, the remaining pore water may become saturated with gas. If the free gas is unable to escape, then the pore pressure will rise. This increase in pore pressure may assist in causing small cracks and fissures to form which may help in migration of hydrocarbons to reservoir rocks (and results in reduction of pore pressures).

If the hydrocarbons move into permeable rocks that have restricted drainage then they could be subject to increased pore pressure by external charging (imposed pressures). Some undercompacted claystones show high gas values, which may help to confirm this mechanism as an origin of geopressured zones. Where hydrocarbon generation has occurred there are often high residual levels of CO₂ as a result of the original high organic content of the formation.

Hydrocarbon Gradient

The presence of hydrocarbons in the pore fluid column will cause variations in the pore fluid gradients, and therefore in the magnitude of the pore pressure. Both oil and gas have lower fluid densities than water and their presence will create lower than expected pore pressure gradients. Where gas is present as a free gas cap, overlain by impermeable rocks, its compressibility can result in a higher than expected pore pressure gradient, until the oil or water column is reached. Then the pore pressures would return to normal.

In producing fields, reservoir depletion may cause reductions in pore pressure (below normal for the area) which could result in drilling problems such as lost circulation or stuck pipe.

Alternatively fluid injection for enhanced recovery may produce higher than expected pore pressures over limited areas.

References

Barker, Colin, *Aquathermal Pressuring-Role of Temperature in Development of Abnormal Pressure Zones*; AAPG, 1972, vol. 56/10, p. 2068-2071

Berderhoeft, J.D., et al, *Possible Mechanism for Concentration of Brines in Subsurface Formations*, AAPG, 1963, vol.47/2

Biscayne, P .E., *Mineralogy and Sedimentation of the Deepsea Sediment Fine Fraction in the Atlantic Ocean and Adjacent Seas and Oceans*; Yale University, Department of Geology and Geochemistry Technical Report 8, 1964, 86 pp

Bradley, J.S., *Abnormal Formation Pressure*, AAPG, 1975, vol. 59/6, p. 957-973

Bradley-Colten, Virginia A., *Role of Pressure in Smectite Dehydration- Effects on Geopressure and Smectite-to-Illite Transformation*; AAPG, 1987, vol. 71/11, p. 1414-1427

Bruce, Oemont, H., *Smectite Dehydration-Its Relation to Structural Development and Hydrocarbon Accumulation in Northern Gulf of Mexico Basin*; AAPG, 1984, vol. 68/6, p. 673-683

Burst, J.F., *Diagenesis of GulfCoast Clayey Sediments and Its Possible Relation to Petroleum Migration*, AAPG, 1969, vol. 53/1

Daines, Stephen R., *Aquathermal Pressuring and Geopressure Evaluation*; AAPG, 1982, vol. 66/7, p. 931-939

Deer, W .A., et al, *An Introduction to Rock Forming Minerals*, Longmans Press. 1967

Fertl, W .H., *Abnormal Formation Pressures*, Elsevier Press, 1973

Freed, Robert L. and Peacor, Donald R., *Geopressured Shale and Sealing Effect of Smectite to Illite Transition*; AAPG, 1989, vol. 73/10, p. 1223- 1232

Fritz, Mary, *Geologists Seek "Seals of Approval"*, AAPG Explorer, 1989, May, pp 1-5

Fyfe, W.S., et al, *Fluids in the Earth's Crust*, Eisevier Scientific Pub. Co.

Greener, P .E., *Pore Pressure: Fundamentals, General Ramifications and Implications for Structural Geology*, AAPG Course Notes #4, 1978

Hanshaw, B.B., et al, *Osmotic Equilibrium and Overthrust Faulting*, GSA Bulletin, 1965, vol. 76/12

Hinch, H.H., *The Nature of Shales and the Dynamics of Hydrocarbon Expulsion in the Gulf Coast Tertiary Section*, AAPG Course Notes #8,1978

Iain Hillier

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