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DRILLING IN OVERPRESSURED FORMATIONS IN AUSTRALIA

INTRODUCTION

Abnormally pressured formations occur more frequently than is generally realised in Australia's sedimentary basins (Figure 1 & 2). The Artesian water flows common in this country are just one indication of abnormal pressures. However, the zones which create the major drilling problems are generally deeper and are generally those containing gaseous hydrocarbons. When these pressures occur in conjunction with a highly permeable gas-filled reservoir, a blowout will result unless preventive action has been taken.

More frequently, abnormal pressures occur in shale, siltstone, claystone, or mudstone formations which have limited effective porosity. In these rock types the gas may occur in fractures or in thin porous beds and will reveal itself by invasion or "cutting" of the mud in circulation by gas without causing a blowout. The problem of sloughing shale is well known to any experienced driller and is often caused by abnormal pressures.

A formation is considered to be overpressured when the fluid contained within the reservoir is at a pressure greater than that exerted by the pressure of the natural formation water if that water extended to surface. Fresh water (specific gravity 1.00) has a pressure gradient of 0.433 psi/ft, sea water 0.445 psi/ft and saturated salt water 0.465 psi/ft. Formations with a pressure gradient greater than 0.47 psi/ft are therefore considered over-pressured. This corresponds to a well filled to surface with mud of 1.07 specific gravity (8.9 lb/gallon). These fluid gradients are not to be confused with overburden pressures caused by the weight of the solid material. The commonest sedimentary rocks have a specific gravity between 2.0 and 3.0, with an average of around 2.30, so that the overburden pressure gradient is approximately 1.0 psi/ft depending on formation specific gravity. The overburden pressure may be regarded as the upper limit of possible formation pressures, and fluid pressure gradients as high as 1.04 psi/ft have been recorded. Obviously in those rare instances where the fluid pressure exceeds the overburden pressure a natural blowout occurs. These have been reported in various parts of the world and normally follow major earth movements such as earthquakes.

General Causes of Overpressure

There are many possible causes of overpressure, the most frequently encountered being:

1. Fossilised pressures - A normally pressured structure may be subject to erosion, with perhaps several thousand feet of cover being removed. In certain conditions, the formation pressure may remain unchanged and the formation then becomes overpressured.

2. Compaction - When newly deposited, a sediment may contain around 50% of water. As additional layers of sediment are laid down, their weight tends to squeeze out the water, reducing the water content of the sediment and increasing the contact pressure between the matrix grains. If easy access to the free surface of the sediment is provided, then the water is expelled easily and the pressure of the water at any point is very close to the normal hydrostatic gradient. However, if for any reason the water cannot freely escape, then the formation water will tend to be pressured by the overburden and part of the load will be taken by the water and part by the formation grains. Fine-grained sediments such as clays and shales can prevent free escape of water and these may therefore be overpressured. A sand lens within such a shale body will likewise be overpressured.

3. Hydrocarbon column - A thick reservoir section containing hydrocarbons can exhibit all the signs of being overpressured. The underlying water in the reservoir may be completely normal in pressure, but since hydrocarbons, especially gas, generally have a much lower density than water the pressure gradient from top to bottom of the reservoir may be much less than would be the case if it were full of water. This means that on entering a thick hydrocarbon-bearing reservoir, an abnormally high pressure may be encountered.

4. In situ generation of hydrocarbons - An organic shale being laid down under anaerobic conditions can produce hydrocarbons. If these hydrocarbons are prevented from escaping into the atmosphere or into an adjoining reservoir, then pressure may be built up, only to be relieved when a hole is drilled into it.

5. Reservoir inter-communication - If two separate reservoirs are brought into communication with each other, then fluid may be transferred from one to the other until pressures are equalised. This communication can be brought about by natural causes (faulting) or by man-made causes (subsurface blow-out).

6. Diapirism - Certain rock units such as salt, shale, and volcanic ash may behave as fluids and may flow to adapt themselves to a minimum energy condition. This means a flow from a high-pressure environment to a lower-pressure one where the intrusion of this formation may increase pressures locally. Salt domes are a typical example of this mechanism.

7. Artesian flow - A reservoir rock which is penetrated by a drilling well and which outcrops at a higher elevation may contain water at a pressure greater than the normal hydrostatic pressure. This phenomenon is widespread and may be encountered in many of Australia's sedimentary basins.

Precautions for Wells in Overpressured Areas

Every well should be planned by a competent engineer. The drilling rig, including blow-out preventor (BOP) equipment, must be selected with a view to the depths and pressures expected. The casing depths should be matched with the rating of the blowout preventors. The majority of wells will be normally pressured near surface but may encounter several changes in the fluid pressure gradient as drilling proceeds. Ideally a string of casing will be set at each change in pressure gradient and maximum protection can be assured by changing the specific gravity of the mud in circulation to suit the new pressure gradient. It must be rememembered that the casing and BOP's together act as a seal on the well and a pressure greater than the theoretical formation fracture pressure must not be allowed to accumulate at the shoe of the last casing string. The choke assembly and mud specific gravity can be manipulated to prevent such excess accumulations.

Vital precautions when drilling into prospective formations at depth are:

(a) Use a low water-loss mud of the optimum specific gravity. Low water-loss is necessary to prevent undue invasion of hydrocarbon reservoirs. The lower the mud specific gravity, the faster the penetration rate. Ideally the mud specific gravity should be sufficient to overbalance the formation fluid pressures by 200 to 300 psi. Some operators regularly pressure-test the open hole to determine the breakdown pressure. This is good practice unless a potential reservoir has been encountered.

(b) Keep the hole full of fluid at all times. This is particularly important when pulling out of the hole with the drill string as mud must be added to replace the volume of pipe withdrawn from the hole.

(c) Maintain regular blow-out drills. This is normally done by the supervisor simulating a mud gain without informing the drill crew. The time taken by the crew to implement kick control procedures is taken and recorded on the drill reports.

(d) As a minimum safeguard, maintain a record of shale density and penetration rate as a means of detecting entry into overpressured formations.

In summary it should be apparent that every well must be planned in advance by a competent drilling engineer and the drilling performed by trained crews under suitable supervision.

Means of Detecting Abnormal Pressure

All sedimentary rocks have some porosity and permeability. Explorationists speak in terms of effective porosity and permeability, which basically means that these characteristics are of sufficient magnitude to be measured by ordinary techniques. All hydrocarbon reservoirs, apart from those containing very viscous or fixed hydrocarbons, must be contained by a cap rock over the reservoir. It follows therefore that if the reservoir is at abnormal pressure, a considerable thickness of the cap rock will also be overpressured. These abnormal pressures affect the drillability, electrical resistivity, and density of the shale or other cap rock. Thus if the cap rock is of considerable thickness and is reasonably homogeneous a change in any of the above characteristics is an indication of abnormal pressures. Means of detection include:

1. Penetration rate - It has been found that there is a recognizable relationship between differential pressure and penetration rate. Differential pressure is the difference between the pressure of the mud column and the formation fluid pressure and it may be positive or negative. When the differential pressure is negative, that is when the formation pressure exceeds the mud pressure at bottom, the penetration rate is high. This may be visualized as the chips exploding into the hole as they are broken off by the bit in contrast to the usual situation where they are held down by a positive differential pressure. A continuous plot penetration rate recorder is of value when all drilling parameters including mud weight are held constant. Such a recorder gives best results when an automatic driller is used to maintain constant weight on bit and rotary speed is kept constant by the driller. Under these conditions a gradual decrease in penetration rate would be noticed under normal conditions principally due to dulling of the bit and increasing differential pressure.

It is often impracticable to maintain constant drilling parameters and a so-called "d" exponent may be calculated and plotted to adjust for bit size, weight on bit, and rotary speed.

$$"d" = \frac{\text{Log}\left(\frac{R}{60N}\right)}{\text{Log}\left(\frac{12W}{10^6 D}\right)}$$

R = penetration rate (ft/hr)
N = rotary speed RPM
W = weight on bit (lb)
D. = Bit diameter (inches)

In any case, the possibility of a formation change must be considered and supplemental means of detection employed. The accompanying figure 3 represents the bit drilling trends that need to be established in order that this method should be workable. Note that the sandy intervals may be disregarded.

2. Torque, drag, and hole fill - Abnormally pressured shales tend to move into the well bore and may be regarded as plastic. This results in a diminished hole diameter and increased torque on the bit. This torque increase is readily observed at surface and may be used to confirm the other indications of overpressures. Drag and hole fill up on trips are related occurrences with the same root cause.

3. Mud pump pressure and pit level indicators - entry of less dense fluid into the annulus will normally decrease the pump pressure owing to the U-tube effect between the drill pipe and annulus. However, should the volume of the entry be large the pump pressure may increase with a simultaneous volume gain in the mud pits. In either case blowout procedures should be implemented and the drilling break circulated before drilling ahead.

4. Mud logging and cuttings volume - A mud logging unit continuously monitors the amount of gas suspended in the mud. When a shale contains gas and is under a negative pressure differential, the amount of sloughing will be severe and the amount of cuttings returned over the shaker will increase to a noticeable extent. Increases in gas influx normally occur during connections and trips due to the decreased bottom-hole pressure when the pump is shutdown. An increasing amount of gas with each connection is a certain indication of increasing pore pressure.

5. Shale densities - A fairly new technique of pressure detection that has gained wide acceptance is surface measurement of shale density. Shale cuttings are placed in a reference tube or bathed in pans of reference

fluid to determine the density of the shale. The readings are plotted and show a compaction trend in a thick homogeneous section. Departures from this trend are indicative of an increase in pressure gradient. The presence of montmorillonite will tend to give a lower than normal density, but as this mineral is usually found in beds formed under deep marine conditions and therefore particularly subject to overpressuring, this characteristic is not harmful.

6. Wireline logging - When a combination of the preceding factors suggests that the bit has entered an abnormally pressured zone, confirmation can be obtained from wireline logs. As it may also be necessary to run a casing string at about this time to protect the upper part of the hole from the increase in weight of the mud column, the logging run is timely. The types of logs suitable for this purpose are electrical (either conductivity or resistivity), sonic, and density. As indicated previously, porosity of shale is decreased as overburden pressure increases, because of the greater compaction pressure. Thus as depth increases a normally pressured shale will have a decreasing porosity. If the shale is under-compacted, i.e. if not all the fluid has been allowed to escape, then the shale will have a greater porosity relative to depth. This increase in porosity would affect both the sonic and the density logs. Similarly, the relative increase in formation water, due to increased pore space, could affect the electrical log, and resistivity would accordingly decrease over the overpressured zone. Other reasons for these changes in log response are possible and the results of the full logging suite must be considered before concluding that overpressure is the problem. The obvious disadvantage of downhole logs is that it is impracticable to run logs every few hundred feet as drilling proceeds. Tools designed to log the hole continuously as drilling proceeds have been developed, but have not so far gained acceptance by the industry.

Surface indications should therefore be the first approach and extra logging runs are often a wise precaution in new areas.

Occurrences of Overpressure in Australia

The occurrences of overpressure are very widespread around Australia, both onshore and offshore, and in formations of many different geological ages.

In Queensland, several wells have demonstrated high pressures; in fact two wells, Arcturus No. 1 and Rolleston No. 1, blew out at relatively shallow depths. In contrast, Leopardwood No. 1 encountered a pressure of more than 7500 psi at a depth of 12,849 feet. This was recorded during a drillstem test and showed the presence of a high pressure but comparatively tight water sand.

Victoria's first (and indeed Australia's first) offshore well Barracouta - 1 (originally known as Esso Gippsland Shelf No. 1) blew out for a short time when at a depth of 4351 feet and it is calculated that for this to happen, the formation pressure must have been in excess of 2195 psi. A later production test also confirmed overpressuring at the top of the relatively thick gas sand encountered in this well.

Over in the west many wells have had problems from high pressures, perhaps the most notable being Madeleine No. 1; this well kicked when at a depth of 13,254 feet with a mud specific gravity of 1.55 (12.9 lb/gallon), which showed that the pressure at that depth exceeded 8891 psi. This well kick occurred while drilling in a siltstone. At Dampier No. 1, while drilling at 12,483 feet, the mud (specific gravity 1.25) became gas cut, once again indicating high formation fluid pressures. One of the highest overpressures on the mainland of Australia was encountered at Yulleroo No. 1. A drillstem test at 11,100 feet gave a built-up pressure of 6900 psi. This compares with a normal hydrostatic pressure of 5160 psi.

A large proportion of wells drilled in the Northern Territory have had pressure problems. In the Amadeus Basin, Palm Valley No. 1 demonstrated this during a production test at 6000 feet, while offshore Petrel No. 1 showed this quite conclusively by blowing out at 13,054 feet while drilling with a mud specific gravity of 1.26 (10.5 lb/gallon). Heron No. 1 showed an even higher pressure gradient when it kicked at a depth of 12,115 feet while drilling with 14.0 lb/gallon mud (specific gravity 1.68).

Papua New Guinea

Papua New Guinea has an abundance of deep sediments of Tertiary and Mesozoic ages. They have also been found to be severely faulted in many areas. Both of these conditions are conducive to the development of abnormal pressure conditions.

The Pliocene-Miocene mudstones of the Aure Trough have been known for their high-pressure gas content since pre-war days. Later exploration proved that the Aptian Mudstone of Lower Cretaceous age was similarly affected.

The Australasian Petroleum Company as operator for the Oil Search group of companies encountered high pressures at depth while exploring in the early 1950's. Mud with a specific gravity as high as 2.2 was required to keep the hole open and the consumption of barytes on wells to 13,000 feet and deeper was phenomenal. The increase in transportation costs, which were already high because of terrain and climate, caused the company to attempt back-pressure drilling. This technique requires a rotating type BOP and a separator and choke installation on the return line. By maintaining a back-pressure on the well head at all times a reduction in mud weight is feasible. The method was not very successful, largely because the proper equipment had not at that time been developed.

The Rarako Creek No. 1 well drilled by Nakoro Petroleum in 1967 was plagued by the same problem from 3500 feet to total depth of 10,100 feet. Muds as high as 2.28 specific gravity were required to complete the hole. Some saving in transportation was effected by reclaiming barytes after it had settled out in the mud pits. The gas detector was saturated from 2150 feet, but logging did not indicate any reservoirs worthy of testing. The formation was Pliocene and a thrust fault was present, resulting in a repeated section of 1850 feet.

The Tovala No. 1 well encountered incipient blowout conditions from 4500 feet. At 4650 feet the well blew out with 2.41 specific gravity mud in the well. This indicates a pressure gradient of 1.04 psi/ft, which may be assumed to be nearly equal to the overburden pressure at that depth. At a depth of 9518 feet the well blew again with a 2.16 mud. In both cases the well was brought under control without a significant increase in mud specific gravity. In fact the practical limits of mud density had been reached as it is difficult to keep barytes in suspension in greater concentration. Testing proved that the gas and salt water reservoirs were of limited extent and it appears that partial pressure depletion enabled drilling to continue.

Offshore in the Aure Trough, Phillips Petroleum Company and partners encountered abnormal conditions at several wells. The Iokea No. 1 well tested a salt water zone at 5131 feet which recorded a formation pressure of 4687 psi (gradients 0.91 psi/ft). A second test at 5553 feet recorded 4894 psi, giving a gradient of 0.49 psi/ft between the test intervals. This is very close to a saturated salt-water gradient and demonstrates that although a reservoir may be at abnormal pressure when first encountered, the fluid pressure gradient within the reservoir will correspond to that of normal reservoirs.

This fact created a special problem at the Pasca No. 1 gas discovery. Tests of the reef encountered at 7216 feet had a formation pressure of 4446 psi (0.616 psi/ft gradient). A later test recorded a pressure of 4640 psi at 8000 feet. The gradient between tests was therefore $\frac{194}{784} = 0.247$ psi/ft. It is obvious that mud cannot be suitably weighted to control pressures at both depths as the pressure gradient produced by the mud in use was 0.58 psi/ft. The reservoir was a high permeability reefal limestone, so that circulation was lost when the mud density became excessive. The operator was able to drill the section successfully by means of the floating mud cap technique. This resulted in the loss of cuttings samples, but the nature of the reef was reasonably well established from logs. Figure 4 shows the calculated pressure gradients in three Papuan wells. The effect of the gas reservoir encountered in the Pasca well is apparent.

Means of combating overpressure

1. Bleed off - In the case of gas-bearing overpressured shales or thin discrete sand bodies containing gas, a normal weight mud may be used for drilling the hole and the pressure relieved by allowing gas to enter the mud, to be subsequently removed at the surface by a degasser before the mud is pumped back down the hole. This method can only be used where experience has shown that it can be adopted safely. The dangers are obvious, in that if a major sand body were to be encountered a blowout could ensure or hole sloughing in an incompetent shale could lead to sticking of the drill string. However, within these limitations, the method can be used efficiently and can produce high drilling rates at economical cost.

2. Weighting of mud - The normal course of action to combat overpressure is to weight the mud with barytes or with lead ores. Specific gravities in excess of 3.0 can be achieved by this method, but at relatively high cost. As drilling progresses mud weight is carefully checked and adjusted to cope with existing conditions down the hole, and where conditions are known in advance the mud can be weighted before entering an abnormally pressured formation.

3. Floating mud cap - In Papua, Phillips Petroleum on severals wells used a technique of a heavy annulus mud which remained between the drill pipe and the wall of the hole; drilling was achieved by pumping sea-water down the drill pipe while maintaining this floating mud cap in the annulus. This method has the disadvantage that the well is in a very critical balance and also leads to a high mud consumption and loss of drill cuttings for geological examination; however, at the time it was the only method available to combat the problems in this area and enabled them to successfully drill wells which would otherwise have presented insurmountable difficulties.

4. Back Pressure Drilling - Pressure can be applied in excess of the normal mud column by choking back the return of mud to the mud pumps. The rotating head, which is in effect a type of blowout preventor, is used above the normal BOP's, with a choke controlling the pressure of mud in the annulus at the surface. Varying the choke opening can change the pressure as required at the bottom of the hole to allow drilling to continue.

Conclusion

While it can be seen that overpressured formations are by no means uncommon in Australia and Papua New Guinea, methods are now available to overcome the drilling problems associated with this condition.

As more information is gained regarding pressure conditions in each of our many sedimentary basins, drilling conditions, including formation pressures, can be more accurately predicted to enable an optimum drilling program to be designed, enabling exploration to be carried out with safety and at minimum cost.

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