Chapter 1

The Challenge of Lost Circulation

Drilling a well is the most common way to access oil and gas resources and geothermal reservoirs. During drilling, a fluid is circulated in the well. This fluid (the *drilling fluid*) cools the drillstring, transports rock cuttings out of the well, and prevents the surrounding formation from collapse. The bottomhole pressure of the drilling fluid is kept within a certain “window.” The lower bound of the wellbore pressure is usually dictated by the formation pore pressure or the minimum pressure obtained from the borehole stability analysis, whichever is greater. If the bottomhole pressure drops below the pore pressure, an influx of formation fluids into the well may occur. If the bottomhole pressure drops below the minimum value obtained from borehole stability analysis, the formation may cave in.

The upper operational bound of the bottomhole pressure is chosen so as to avoid lost circulation. *Lost circulation* is a situation where less fluid is returned from the wellbore than is pumped into it. When lost circulation occurs, some drilling fluid is lost into the formation. Lost circulation gives rise to nonproductive time spent on regaining circulation. According to Ref. [1], lost circulation was responsible for more than 10% of nonproductive time spent when drilling in the Gulf of Mexico between 1993 and 2003. The inability to cure losses and resume drilling may, in the worst case, necessitate sidetracking or abandoning the well.

The economic impact of lost circulation includes, in addition, the costs of the lost drilling fluid and of the treatment used to cure the problem. According to one estimate, the cost of drilling fluids amounts to 25%—40% of total drilling costs [2]. Given that both regular drilling fluids and lost circulation materials are often quite expensive, the direct economic impact of losing these substances into the formation may be substantial. The cost issue is especially relevant for oil-based muds that are usually more costly than water-based fluids.

In addition to the direct economic impact (cost of expensive drilling fluid and nonproductive time), lost circulation may cause additional drilling problems. In particular, the reduced rate of returns may impair cuttings transport out of the well. This leads to poor hole cleaning, especially in deviated and horizontal wells [3]. Poor hole cleaning may eventually result in pack-offs and stuck pipe.

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Losing drilling fluid into the formation in the pay zone increases formation damage as pores and fractures in the reservoir rock become plugged with particles present in the drilling mud (barite, bentonite, cuttings, solids used as lost circulation material, etc.). The formation damage created by lost circulation needs to be removed before production can start, which leads to additional costs.

Severe cases of lost circulation may lead to well control problems. In particular, the mud column disappearing into the formation may reduce the fluid pressure in the well, which will enable the influx of formation fluids, in particular gas, into the well. This may eventually lead to a kick or borehole collapse. Lost circulation in tophole sections may lead to shallow water flow events.

Given the scope of its negative consequences, lost circulation has been identified as “one of the drilling industry’s most singular problems” [4]. According to some estimates, the annual cost of lost circulation problems, including the cost of materials and the rig time, is around one billion dollars globally [5,6].

Lost circulation in the overburden can be equally as bad as in the reservoir, even though formation damage is of no concern there. If losses are not treated properly and drilling proceeds without first sealing the thief zone, subsequent cement jobs can be compromised. The quality of well cementing depends crucially on placing the cement column all the way up to the target height. If an unplugged thief zone exists against the annulus to be cemented, cement slurry may escape into this zone during the cement job, and the cemented length of the annulus will be shorter than planned. Remedial cementing can be employed to cure the problem, but this will increase nonproductive time and incur extra costs.

Lost circulation is common in geothermal drilling (Boxes 1.1 and 1.2) [7,8]. Large fracture apertures (on the order of cm) often cause severe or total losses while drilling the overburden or the reservoir. According to Ref. [9], lost circulation problems are responsible for 10% of well costs in mature geothermal fields and often more than 20% of well costs in exploration wells in the United States. In Iceland, an analysis revealed that lost circulation or hole collapse was the primary cause of drilling troubles in 18 out of 24 wells in the Hengill Geothermal Area [10]. These problems may further lead to cement losses into the formation during subsequent well cementing.

Wells drilled in fields with elevated geothermal gradient are often prone to losses caused by cooling. When the relatively cold drilling fluid coming from the surface contacts the much hotter formation, the rock contracts and the hoop stress around the hole becomes smaller—ie, less compressive. The rock is then easier to fracture because of this effect. Ballooning and losses observed in some Gulf of Mexico wells are attributed to this effect [11].

Lost circulation is common in naturally fractured formations. Severe or total losses are common in carbonate rocks in the Middle East [12].
In a naturally fractured carbonate field in Iran, mud losses were reported in 35% of drilled wells [3]. In Saudi Arabia, 32% of wells in the naturally fractured carbonate Khuff Formation experience ballooning, while 10% experience lost circulation [13].

The best way to deal with lost circulation is to prevent it from happening altogether in the first place. In practice, however, this may be difficult to achieve. Nevertheless, technological improvements in formation characterization and drilling fluid design enable the prevention of losses in many wells. Preventing lost circulation requires that the mechanics and physics of this drilling problem are fully understood.

The most obvious way to prevent lost circulation is to keep the downhole pressure sufficiently low—ie, below the upper operational pressure bound. In practice, however, it is not quite obvious how this upper bound should be chosen. In competent intact formations, the upper bound of the operational

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**BOX 1.1 Lost Circulation in a Geothermal Well in Iceland**

Lost circulation is a common problem in geothermal drilling, where it is exacerbated by high temperatures and hard rocks. A sequence of lost circulation events while drilling a geothermal well in the Krafla field in Iceland in 2008–09 was described by Pállsson et al. in their paper “Drilling of the well IDDP-1” (Geothermics, 2014, 49, 23–30).

The well, IDDP-1, was part of the Iceland Deep Drilling Project and was originally designed to reach a 4500-m depth. Severe problems were encountered during drilling, and the well had to be sidetracked every time it approached magma at 2100 m. Mud losses were experienced often, becoming worse as the depth increased. Also, the well became increasingly more unstable and washed out with depth, which affected the hole cleaning and reduced the rate of penetration that already was low due to the hard rock.

Minor mud losses occurred in the first 1000 m while drilling for the intermediate 18-5/8” casing. The losses were cured with lost circulation material.

Losses of 20 L/s were then experienced at 1432 m. The problem was cured by cementing the thief zone.

Losses in excess of 60 L/s were experienced at 2043 m. The losses could not be cured. The weighted drilling fluid was replaced with water, and drilling continued.

At 2101 m, the bottomhole assembly broke. After unsuccessful fishing, a cement plug was placed, and the well was sidetracked.

Upon the sidetrack, total losses occurred at 2054 m. A cement plug was placed in the well, and the drilling continued from 2060 m. Losses resumed at 2067 m, and total loss of circulation occurred at 2076 m.

Continued problems with stuck pipe and unsuccessful fishing attempts at 2103 m forced a second sidetrack. Mud losses continued after the sidetrack, and total loss of circulation occurred at 2071 m. Drilling was terminated upon reaching magma at 2100 m. The well was then tested and completed.
bottomhole pressure is often set equal to the minimum in situ stress (minus some safety margin). The upper pressure bound is often called fracture pressure (We shall prefer the term “fracturing pressure” rather than “fracture pressure” in this book to avoid possible confusion with the fluid pressure inside a fracture. Fracture gradient, routinely used in drilling practice, is the fracturing pressure divided by the height of the mud column (psi/ft or kPa/m). The fracture gradient, in general, increases with depth since the bulk density of rocks, in general, increases with depth. Deviations from this trend, however, are possible. In particular, depleted formations may exhibit significantly lower pore pressure gradient and fracture gradient.) in this case, since an induced fracture will not propagate if the wellbore pressure stays below the minimum in situ stress. However, as we shall see, mud can be lost not only into induced fractures, but also into high-permeability zones (gravel, unconsolidated sand, etc.), large cavities, and natural fractures. The minimum in situ stress plays only a minor role in those scenarios. Also, induced fractures do not always cause lost circulation. As long as the induced fracture is short and narrow, losses might be acceptable or not noticeable at all.

**BOX 1.2 Losses in Geothermal Well WK204 in New Zealand**

A dramatic sequence of lost circulation events, culminating in a blowout, occurred during drilling of an investigation well at Wairakei Geothermal Field in New Zealand in 1960. The case history was described by Bolton et al. in their paper “Dramatic incidents during drilling at Wairakei Geothermal Field, New Zealand” (Geothermics, 2009, 38, 40–47).

The well was drilled near a fault. The initial design was as follows:

- 406-mm casing to 27 m (surface casing);
- 298-mm casing to 122 m (anchor casing);
- 219-mm casing to 305 m or deeper, if the conditions allow.

Major losses were experienced while drilling for the 298-mm casing. Cementing the casing required six times the annular volume, indicating that cement went into thief zones.

While drilling for the 219-mm casing, a thief zone was encountered at 134 m. The zone was sealed, and drilling continued to the target depth of 305 m with full returns. The decision was made to continue drilling deeper than 305 m.

Major losses started at 350 m. Attempts to cure the losses with increasingly coarser lost circulation materials were unsuccessful. The drill bit dropped by 1.5 m at 373 m. Further developments eventually resulted in stopping the pumps.

In the aftermath of the events, the lost circulation experienced at 350–373 m was attributed to the well penetrating a high-pressure high-temperature (HPHT) zone near the fault. Buildup of temperature and pressure in the hole after the pumps were stopped eventually led to breakdown of the seal set at 134 m, and a blowout.
Therefore, it would be more appropriate to call the upper operational pressure bound “lost-circulation pressure” rather than “fracturing pressure.” Lost-circulation pressure means simply the bottomhole pressure above which lost circulation will occur, without reference to any specific (and often unknown) mechanism.

The lost-circulation pressure is a major uncertainty, even in competent rocks. This uncertainty is increased in depleted or complex reservoirs where pore pressure and stress distributions are rarely known. In naturally fractured rocks, the lost-circulation pressure depends on both the orientation and the aperture of natural fractures. Apertures of natural fractures may indeed be so small that the drilling fluid will not be able to enter them. Different fracture orientations mean that different fractures will open and cause losses at different wellbore pressures. Since there is usually a great variety in both apertures and orientations of natural fractures, it makes sense to consider a spectrum of lost-circulation pressures, rather than a single value, in such formations. This shift of paradigm may help in situations where the upper pressure bound estimated from formation integrity and leakoff tests performed on a short openhole section below the casing shoe is later found to be misleading. Indeed, a short open hole pressurized in such tests provides only a sample of the natural fractures that may be encountered by the drill bit during subsequent drilling. The results of the tests are therefore not always representative of what lies ahead.

The profiles of pore pressure and fracturing pressure (or, alternatively, pore pressure gradient and fracture gradient) versus depth determine the maximum length of the interval that can be drilled with the same mud weight. Thus, they determine the location of casing points along the well. This is illustrated for a fictitious vertical onshore well in Fig. 1.1 by plotting the upper and lower operational pressure profiles. The static bottomhole pressure is shown with the dotted line. Inclined parts of the dotted line must pass through zero pressure at the surface since the annular pressure is zero at the surface (This is true for conventional drilling where the circulation system is opened to the atmosphere. In managed pressure drilling, a backpressure may be applied.). Jumps in the dotted line signify changes in the mud weight. The largest possible lengths of the intervals are shown by asterisks. Indeed, moving the casing point located at $D_1$ deeper along the hole would bring the static bottomhole pressure below the pore pressure in the lower part of the interval. Increasing the mud weight to remedy this problem would increase the slope of the dotted line, which would violate the upper pressure bound in the upper part of the interval. This example shows that the lost-circulation pressure and the pore pressure (or the borehole stability limit) play crucial roles in setting up the casing program.

An alternative representation of the problem is possible in terms of the pore pressure gradient and lost-circulation pressure gradient. This is illustrated for
a fictitious vertical onshore well in Fig. 1.2. The result—ie, the locations of the casing points—is, of course, the same as in Fig. 1.1.

The ability to predict the lost-circulation pressure is therefore crucial for optimizing the casing program. Figs. 1.1 and 1.2 also suggest that if the lost-circulation pressure could be increased, longer intervals could be drilled with the same mud weight. It would reduce the number of casing points and increase the well diameter at the target depth. This is the motivation for applying special treatments to increase the lost-circulation pressure in the open hole (“wellbore strengthening”), discussed in chapter “Preventing Lost Circulation.”

Even if the bottomhole pressure stays below the lost-circulation pressure during normal drilling, pressure surges during trips and connections may exceed this upper bound and cause lost circulation. When a connection is made, circulation is suspended. During connection, the drilling fluid starts developing gel strength. When circulation is resumed after connection, the pressure needs to be increased sufficiently to break the gel. This may lead to
substantial pressure changes during connections. If the operational pressure window is narrow—eg. in a deepwater well—the reduction of pressure before connection may lead to a formation fluid influx, and the pressure surge after connection may lead to lost circulation.

Trips may cause formation fluid influx when pulling out of the hole, and lost circulation when running in hole. Preventing influxes and lost circulation during trips can be achieved, for example, by optimizing the drilling fluid rheology.

Drilling through depleted formations is often required in order to access deeper reservoirs. Depleted formations are prone to mud losses. In some wells drilled in depleted formations, losses on the order of thousands of barrels have been reported [14]. The minimum horizontal stress is usually reduced in depleted reservoirs (chapter: Stresses in Rocks). This reduction affects the operational pressure window by reducing the fracturing pressure and thereby increasing the risk of mud losses.
Deviated or horizontal wells are prone to lost circulation. The operational pressure window is narrow in such wells. In some cases, the window may close altogether as the inclination increases. In extended reach wells, the problem is additionally aggravated by increasing annular pressure losses along the horizontal section. Since the fracturing pressure remains approximately the same at the same depth, the bottomhole pressure will eventually exceed it.

A considerable share of mud losses occur when running casing or pumping cement. Running the casing pipe generates an excessive bottomhole pressure that can lead to formation breakdown. During cementing, high density and rheology of cement result in an elevated bottomhole pressure, likely to be the highest pressure the formation is ever exposed to during well construction. This may lead to lost circulation during a cement job.

Another example of formation where losses are common is subsalt rubble zones [15]. Such formations are often represented by relatively weak and/or fractured shale. It has been argued that fractures in these shales are caused by deformation in the adjacent salt throughout geological history [15]. Pore pressure in the subsalt shale can be either lower or higher than the pore pressure in the salt. The former scenario is the case, for example, in the Hassi Messaoud field, where severe losses were experienced [16]; the latter scenario is the case, for example, in the Gulf of Mexico, with pore pressure vs. depth schematically shown in Fig. 1.3. High pore pressure in shale below the salt is

![Figure 1.3](image-url)
caused by the salt “trapping” the pore pressure. It results in a narrow margin between the pore pressure and the lost-circulation pressure in shale. As with other fractured rocks, filling fractures in the subsalt shale with cement or lost circulation material is not an easy task. According to one report from 1999, “the cost of drilling formations approximately 1500 ft above the salt to approximately 1500 ft below the salt have reached several million dollars” [15]. The nonproductive time associated with such intervals can be weeks. As an example, more than half of the wells drilled in the Hassi Messaoud field experienced total losses in subsalt shale [16].

Lost circulation is exacerbated in deepwater drilling. The fracture gradient is often quite low in deepwater wells [17] (Fig. 1.4). This results in a narrow operational pressure window in such wells. Exceeding the fracture gradient can lead to mud losses.

Lost circulation is a multidisciplinary challenge. Combatting lost circulation requires a complex approach that includes rock mechanical analysis, careful well trajectory planning, optimization of drilling fluid rheology and composition, optimization of loss prevention and lost circulation materials, and optimization of drilling hydraulics [18].

Considerable advances in petroleum-related rock mechanics, including hydraulic fracture mechanics, over the past decades have improved our understanding of lost circulation. Better methods of mud loss prediction and more effective treatments make it possible to drill wells that would be impossible to drill a few decades ago. At the same time, increasingly more difficult drilling conditions are encountered as ever deeper reserves are involved in exploration and production. This results in persistence of the lost-circulation challenge to this day.

FIGURE 1.4 Fracture gradient as a function of vertical depth in deepwater drilling: water depth in case A is greater than in case B.
Lost-circulation incidents happen regularly all over the world. In the future, the incidence of lost circulation is likely to increase. Five types of challenging wells are becoming increasingly common in oil and gas industry and will continue to be so in future:

- deepwater wells;
- wells in depleted reservoirs;
- deviated, horizontal, and extended-reach wells;
- HPHT wells;
- combinations of the above.

As we will see in subsequent chapters, the risk of lost circulation is increased in all five of these types of wells.

The aim of this book is to prepare the reader for the lost-circulation challenges of tomorrow. This is done by providing an up-to-date explanation of lost-circulation mechanisms and of current industrial practices. We start our journey into the realm of lost circulation by reviewing some basic concepts of rock mechanics in the next chapter.

REFERENCES


