Summary

Casing impairment leads to loss of pressure integrity, pinching of production tubing, or an inability to lower workover tools. Usually, impairment arises through shear owing to displacement of the rock strata along bedding planes or along more steeply inclined fault planes. These displacements are shear failures. They are triggered by stress concentrations generated by volume changes resulting from production or injection activity. Volume changes may arise from pressure changes, temperature changes, or solids movement (solids injection or production).

Dominant casing-deformation mechanisms are localized horizontal shear at weak lithology interfaces within the overburden; localized horizontal shear at the top of production and injection intervals; and casing buckling within the producing interval, primarily located near perforations.

Mitigating casing damage usually means reducing the amount of shear slip or finding a method of allowing slip or distortion to occur without immediately affecting the casing. Strengthening the casing-cement system seldom will eliminate shear, although in some circumstances it may retard it. Proper well location or inclination, underreaming, special completions approaches, reservoir management, and other methods exist to reduce the frequency or rate of casing shear.

Shearing Mechanisms

Casing shear is caused by rock shear. Rock shear is caused by changes in stress and pressure, induced by typical petroleum-recovery activities such as depletion, injection, and heating.

Rock Mechanics and Formation Shear. Because geomaterials are not homogeneous and isotropic, and because they display strain-weakening, rock-mass shear deformation tends to be concentrated in planes, rather than occurring as uniform shear distortion. Rock shear occurs as relative lateral displacement, often across a planar feature such as a bedding plane, joint, or fault. Even if there are no shear occurs as relative lateral displacement, often across a planar surface which previously has slipped on planes 45° from the principal-stress planes, and the maximum shear stress, $\tau_{\text{max}}$, is defined as $(\sigma_1-\sigma_2)/2$.

Thus, the larger the difference in the major and minor principal stresses, the greater the shear stress, and the closer a rock is to a state of failure or shear slip. However, a rock generally will not slip along the plane of maximum shear stress, but at an angle to it, as shown in the triaxial test schematic in Fig. 1c.

A common slip criterion for a geomaterial (or for a plane of weakness in the strata), called the Mohr-Coulomb (MC) criterion, is expressed in terms of effective stresses as shown in Fig. 2. The effective (or matrix) stress, $\sigma'$, is defined by Terzaghi's law, $\sigma'=\sigma-\rho$, often expressed tensorially as $\sigma'_{ij}=\sigma_{ij}-\rho \delta_{ij}$. Simply stated, the important factor in formation shear is the effective stress that is transferred by grain-to-grain (matrix) forces, and this is affected not only by the boundary loads and the depth of burial, but also by the fluid pressure, $p$. Higher fluid pressures mean lower effective stresses.

The slip criterion is referred to by many different terms: shear strength, failure criterion, yield criterion, or Coulomb criterion. It is expressed often as an equation that stipulates the maximum permissible shear stress along the slip surface being analyzed. The simplest linear form, the linear MC criterion, may be written as

$$\tau_{\text{max}}=c+\sigma_s \tan \phi. \quad \text{(1)}$$

Here, $\tau_{\text{max}}$ is the maximum shear stress that the plane can sustain before slip; $c$ is the cohesion of the rock; $\sigma_s$ is the normal effective stress across the slip plane; and $\phi$ is the internal friction angle. The material parameters $c$ and $\phi$ are determined empirically from testing and are defined in Fig. 2.

The normal effective stress across potential slip surfaces, $\sigma_s$, is determined by calculations, usually with a finite element numerical model that can account for different strata properties, boundary conditions, and changes in volume, temperature, pressure, and stresses. Often, nonlinear (curvilinear) MC criteria are used because a linear MC criterion is insufficient, but all MC criteria are nevertheless based on laboratory test results. Finally, one may note that many failure criteria of different forms have been published, but they all serve the same function: to relate the maximum permissible shear stress to the effective normal stress in a geomaterial.

Casing Shear. Loss of casing function occurs when the pressure integrity of the casing is impaired, or when the distortion of the particularly weak bed or slickensided zone in a shale sequence will shear before an interface because of the low intrinsic strength.
wellbore becomes so large that tools cannot be lowered down the hole, or the production tubing is impaired.

Pressure-integrity loss arises through two mechanisms. The casing collar threads become sufficiently distorted so that the seal is lost (thread popping), or a physical rupture of the casing develops (cracking or ripping). The former is probably more common, particularly if the casing collar is close to the slip plane.

Fig. 3 illustrates the general distortion of casing evidenced as a “dogleg,” a bend sharp enough that tools cannot be lowered or production device rods cannot operate. In this diagram, the shear-displacement zone is drawn as a dislocation spread out over a limited height; but in geomaterials, it is most common to have all relative slip occurring on a single thin plane, usually only a few millimeters in thickness.

Three critical forms of well damage involving shear have been observed.

- Localized horizontal shear at weak lithology interfaces within the overburden during reservoir compaction or heave.
- Localized horizontal shear at the top of a production or injection interval caused by volume changes in the interval that arise from pressure and temperature changes.
- Casing buckling and shear within the producing interval, primarily along perforations, and mainly because of axial buckling when lateral constraint is removed, but occasionally due to shearing at a lithological interface.

Compaction-Induced Shearing

Shearing that accompanies reservoir compaction or heave can induce casing shear; the larger the $\Delta V$ in the zone, the greater the casing impairment potential in the overburden.$^{3-9}$

Compaction is a volume diminution of the reservoir induced by a reduction in $p_o$, usually associated with depletion. The pressure decrease causes an increase in the grain-to-grain forces, and reservoir compaction occurs as these contacts compress or crush. If the reservoir behaves as a linear elastic material, a constant coefficient of compressibility, determined from testing, suffices to give a first-order estimate of the compaction. Because compressible reservoirs are granular and rarely behave in an elastic manner, calculations of compaction require experimental compressibility data. Fig. 4 shows an experimental compaction curve for a stratum in a high-porosity reservoir. Under conditions of drawdown $\Delta p_o$ (path A $\rightarrow$ B), a porosity reduction of $-5\%$ is evidenced. If the reservoir is thick (e.g., 100 m), this converts to 5 m compaction.

Because of the continuity of overlying rocks and the general lenticular cross-sectional shape of a reservoir, compaction is a downward and inward motion. This leads to the reactions in the overburden illustrated in Fig. 5. The crestal section experiences an increase in $\sigma_3$; the remote flanks experience a drop in $\sigma_3$; and the rocks above the shoulders experience an increase in the shear stress, $\tau$.

If the shear stress anywhere in the overburden exceeds the strength of the bedding planes, low-angle slip occurs. If there is a potential for reactivation of low-angle thrust faults in the crest region, a thrusting mechanism can develop as the horizontal stresses increase, leading to the condition $\sigma_4 = \sigma_1 > \sigma_3 = \sigma_5$. Finally, there is the potential for a high-angle normal fault mechanism to develop on the flanks, leading to the condition $\sigma_1 = \sigma_4 > \sigma_3 = \sigma_5$. We have identified all three cases in practice.

In general, casing shear is most common on the shoulders of the structure where the maximum shear stress is likely to be concentrated in a flat-lying, lenticular reservoir case. Whether crestal-thrust faults or flank-normal faults develop depends on the initial tectonic stress conditions.

The mechanism of bedding-plane slip can be demonstrated by placing two strips of wood together and bending them. In the center, there is no shear slip, but slip must occur on both sides away from the central portion. Bending a telephone directory and noting the distortion patterns and slip of pages is instructive, but note that strain-weakening geomaterials concentrate shear slip along a few planes, in contrast to the telephone book in which all pages slip by each other.

Overburden flexural shear is most intense near the reservoir. The intensity drops off with distance from the reservoir; thus, casing shear is more common near the reservoir.

Injection-Induced Shearing

Injection leads to shearing by two mechanisms: higher pressure reduces the effective normal stress (Eq. 1), making shear easier;
and reservoir expansion leads to shearing near bounding interfaces where stresses are concentrated.

High-pressure injection, as from waterfloods, steam fracturing, etc., reduces the effective stress, leading to a volumetric expansion, as illustrated by path A→C in Fig. 4. The bounding strata, being relatively impermeable seal rocks, do not experience a similar stress change; therefore, they have no tendency to expand. Fig. 6 demonstrates that as a pressured zone propagates from the injection point and the permeable rock tries to expand outward, a large shear stress is imposed on the interface between the reservoir and the bounding strata. If this shear stress exceeds the interface strength, slip ensues, and casings in offset wells can be impaired. In Fig. 6, the injection well may be a single well or a line of wells under injection; the latter case is more critical for shear slip.

Casing Shear in Thermal Processes

Steaming processes may involve ΔT values as large as 250°C; higher temperature changes are associated with firefloods. The thermal-expansion coefficient of a typical high-porosity sand is \( \approx 6 \times 10^{-6} \) °C⁻¹; therefore, an expansion of 0.2% by volume is a reasonable expectation. Because geomaterials in situ are stiff (\( E \approx 5 \times 10^6 \) GPa usually), even much smaller expansions can lead to large stress changes and shear slip.

Consider a case of massive advective heating of a zone in a sandstone reservoir as shown in Fig. 9. Rock expansion generates increased stresses in some directions, decreased stresses in others (overall stress equilibrium must be maintained). The outwardly directed stress, \( \sigma_r \), increases as the expanding zone is constrained by the surrounding rock. The condition \( \sigma_r > \sigma_h > \sigma_v \) is generated, and a thrust fault (low-angle) condition can be reached in the unheated rock in advance of the thermal front.
Furthermore, strain incompatibility and shearing develop at upper and lower interfaces. The reservoir is heated rapidly because of advective heat transfer, and bounding, low-permeability strata are heated very slowly through conduction. Shear-stress concentrations arise across the interfaces, and slip ensues when the material strength is exceeded. The shear/slip zone is most intense at the front of a steep thermal gradient, and in the case of a symmetric vertical well, the induced shear-stress concentration along the interface at the injection wellbore will be small (Fig. 9).

The worst case for shear of offset wells in a thermal project probably arises in line-drive steam injection, as all deformation is forced outward along the front. Cyclic steam stimulation in single wells leads to lower shear-stress concentrations at the leading edge and slower propagation because of the radial spreading effects.

If a thermal project also involves high-pressure injection, and with the exception of steam-assisted gravity drainage they usually do, there is a much greater chance for casing shear. The thermal-expansion effects generate large shear stresses, whereas the high pore pressures reduce the effective stresses across potential failure planes. Given that the differential thermal straining associated with advancing temperature fronts also tends to rupture grain-to-grain mineral cohesion, the potential for shear slip is even greater.

Steaming also involves high pressures that can migrate along the cement/rock interface of wells to higher elevations, helping trigger slip in shallower zones along planes of weakness (usually bedding planes). Casing rupture from combined thermal stresses and corrosion is common in thermal projects, making high-pressure leakage at higher elevations even more common.

Casing Shear in Slurry Fracture Injection Projects

Slurry fracture injection (SFI™) involves placing large volumes of solid wastes into permeable reservoirs through the cyclic injection of an aqueous slurry.10,11 The shape of the injection zone is complex, with components of vertical, horizontal, and inclined fractures. Because permeable reservoirs are used, pressures tend to dissipate after the injection cycles that last 8 to 12 hours daily; during active injection, pressures may migrate upward along the casing, leading to pressurization of overlying zones that may shear.

The major factor leading to shear in SFI™ projects is the large permanent volume change (15 to 50 000 m³) arising from solids placement. Upward flexure of the overburden, similar to but in the reverse sense of Fig. 5, leads to bedding-plane slip. In a manner similar to the effects of thermal expansion depicted in Fig. 9, shear of any weak interfaces just above the injection zone can occur, particularly if there is high-pressure leakage along casing.

Ekofisk and Valhall: Compaction Shearing

The Ekofisk and Valhall fields in the North Sea produce from relatively deep and compressible chalk formations. At Ekofisk, deformations have been measured in most of the wells in the field. Casing damage at the Valhall field occurs in both the overburden and reservoir, but overburden damage appears to be more uniformly distributed across the field, compared to the Ekofisk case.

The thick chalk reservoirs at Ekofisk and Valhall initially had zones with porosities as high as 50% near the top of the structures. The reservoirs were overpressured (~85% of $\sigma_1$), and production drawdown soon led to massive compaction and casing shear.12 As of 2000, Ekofisk has experienced more than 10 m of reservoir compaction, and most wells penetrating the reservoir have been impaired by shearing at least once, in some cases as many as four times. Each impairment requires well plugging followed by a new sidetrack.

Casing-shear zones are found in the overpressured shale caprock above the reservoir. Deformations are concentrated in the shoulders of the reservoir, with a large percentage occurring near the Balder shale interval about 160 m feet above the reservoir top. The specific slip planes generally are located at sand/shale interfaces, and they have been shown to emit microseismic bursts over time because of the episodic stick-slip behavior typical of geomechanics. Caliper logs show a distinct, localized shear pattern to these deformations. Operators at Ekofisk have used underreaming (Fig. 10) across the Balder formation to mitigate shear damage. This technique appears to be successful.

Deformations within the producing horizon most often appear as column buckling, are generally near perforated intervals, and usually are associated with solids production. Strictly speaking, this is not a shearing process, but more of a column buckling caused by axial loading and loss of lateral restraint resulting from solids production and reduction of lateral stress through depletion (Fig. 11). Mitigation strategies at Valhall to counteract buckling have included the use of concentric and heavy-wall casing within the producing formation.

Further compaction will continue to generate shear slip of zones, and the magnitude of compaction is so exceptionally large in these reservoirs that thrust faulting in the central portion or normal faulting at the flanks are definite possibilities.

Wilmington Earthquakes: Production Shearing

The Wilmington field in Long Beach, California is located near the southwestern edge of the Los Angeles sedimentary basin. The producing structure is a broad, asymmetrical anticline, broken in geological times.13 Massive reservoir compaction and production-stress changes induced severe casing damage to more than 500 wells, including compression damage within the producing interval and shear damage within the producing intervals and in the overburden. Casing-collar logs show that 15-m casing joints were shortened as much as 400 mm within producing intervals. Surface subsidence at the field eventually reached approximately 9.5 m and was eventually brought under control by overbalanced water injection ($V_{inj} > V_{max}$) in the late 1960’s. The graph in Fig. 12 shows that before subsidence was controlled completely, however, well damage at Wilmington was mitigated effectively using underreaming.
The vast majority of well damage at Wilmington was associated with subsidence-induced bedding plane slip and low angle faulting. During the period of maximum subsidence in the 1950’s, five or six small, shallow earthquakes of relatively low magnitude (M2 to M4) were recorded in the field. Hundreds of oilwell casings were sheared during the earthquakes, and much of the shear movement was confined to thin beds of clay shale, about 2 m thick, lying between much thicker beds of sandstone and siltstone. The maximum horizontal shearing movement measured in one thin bed was approximately 225 mm. The damage areas were located away from the center of the subsidence bowl, at the steepest gradient of the subsidence contours, in the shoulders of the reservoir (see Fig. 5). Fig. 13 presents an outline of the areas of well damage superimposed on the field subsidence contours. The lateral position of well damage corresponded with the developing shoulders of the subsidence bowl (maximum slip region), not with the regions of maximum subsidence.

Well damage was concentrated at weak horizontal bedding planes in the overburden. These planes slipped both seismically and aseismically during the period from 1945 to 1970. In addition to horizontal slip, there was some evidence of high-angle normal fault reactivation because of the stress changes in the reservoir; this was the likely mechanism associated with the seismic well losses in the mid-1950’s. Some minor additional well damage continued through the 1980’s, primarily located around aseismically slipping, steep normal fault within the producing interval (mechanism likely similar to that shown in Fig. 8).

**Athabasca Cyclic Steam Injection Shearing**

Fig. 14 depicts the Canadian Gregoire Lake thermal project located 50 km south of Fort McMurray. In the 1970’s, prolonged steam injection took place along a line of wells in an attempt to reduce the viscosity and generate oil flow to offset wells. Injection of steam took place at a depth of about 250 m near the bottom of a thick (45 m) oil-sand deposit. Injection was above fracture pressure throughout the steaming because the extremely low hydraulic conductivity of the heavy-oil sand (<10⁶ API) predicates against any matrix flow while the oil sand is cool.

The heavy-oil saturated (9.5 API) McMurray formation zone is mainly a coarse-grained un cemented quartzose sandstone of 30% porosity that has been geologically overcompacted by a cycle of deeper burial (>500 m) and subsequent erosion, leading to the stress condition \(\sigma_H > \sigma_v > \sigma_H\) at these depths in this region. The compaction potential of the reservoir is negligible, but there is a tendency to shear and dilate as steep temperature gradients propagate through the materials, exacerbating the effects of temperature-induced strain.

Fig. 15 illustrates the lithostratigraphy. The reservoir contains a few thin oil-free strata and is characterized overall by a decreasing grain size and increasing incidence of shaly partings higher in the formation. At the upper interface, near the top of the McMurray formation, is a stiff 0.3- to 0.5-m thick concretionary bed (siderite cement with a low porosity) that is probably 3 to 5 times stiffer than the surrounding strata. This bed is an ideal zone for high shear-stress concentrations.

After some period of injection above fracture pressure, casing impairment was observed in the middle of the oil zone in an offset well. Later, casing shears were observed at the bottom of the interface with the concretionary bed (Fig. 16), consistent with a shallow-angle rising-slip feature, causing the well-rupture sequence A→B→C. Eventually, the majority of the offset wells evidenced failures in shear, often related to collar thread popping or to an inability to lower tools. Commonly, casing-pressure-integrity impairment was noted without the presence of a thermal anomaly, indicating that the shearing mechanism was propagating far in advance of the thermal front.

The proposed mechanism is a low-angle thrust fault triggered by a combination of an increase in \(\sigma_H(\sigma_v)\) and a reduction in the effective stress across the plane because of the high injection pressures. Because the fracture plane was undoubtedly a plane of complete parting \(\left(p_w > \sigma_v\right)\), all natural-shear stresses had to be concentrated at the advancing tip of the parting plane, generating an in-line shear plane that propagated well in advance of the actual plane of parting (as sketched in Fig. 7).

Mitigation attempts, including double-walled high-strength casing with annular high-strength cement, generally were not effective. Later attempts included steam injection at the interface to soften the strata, but explicit data on the success of these measures is not available.

**Cold Lake Thermal Well Shearing**

Massive, heavy-oil (<10⁶ API) reserves are exploited in the Cold Lake oil sands area of eastern Alberta, Canada, using cyclic steam...
injection. The 30- to 50-m thick, 30 to 32% porosity arkosic Cold Lake oil sands are found in a single reservoir at a depth of approximately 450 m in the Clearwater formation of the Cretaceous Mannville group. Overlying the Clearwater formation is the sand-shale Grand Rapids formation, which is overlain by the smectitic marine shales of the Colorado group of Upper Cretaceous age. The lithostratigraphy is similar to that shown in Fig. 15, although thicknesses and depths are different.

In the cyclic-steam approach, the same wellbore is used for both steam injection and oil production. Downhole well spacing is 4 acres on a 1.7 aspect ratio (approximately 170×100 m per well), and wells are drilled from pads usually containing 20 wellsites. A typical well will go through 10 or more injection/production

Fig. 13—Subsidence contours and shear areas in Wilmington field, Long Beach, California.

Fig. 14—Location of Canadian well shear examples.

Fig. 15—Approximate stratigraphy, Gregoire Lake.
cycles, each lasting several months. The cased well is exposed cyclically to fracture-injection pressures up to 10 to 12 MPa and temperatures up to 325°C.

More than 250 wells have failed at the Cold Lake heavy-oil field. Well failures have occurred at the top of the producing interval, at a shallow shale interval in the overburden, and near the base of the Colorado shale. Inclinometer surveys indicate localized shear displacements on weak bedding planes on the order of 100 mm and in some cases larger than 200 mm near the top of the producing interval. These arise because of pressure and thermally induced expansion and contraction of the oil sands (Figs. 6 and 9). Failures higher in the overburden occur by slip along weak bedding planes because of cyclic reservoir heave and compaction (Fig. 5).

When the reservoir is steamed, it expands in all directions as fluids are injected into the sand matrix. Uplift or “heave” in excess of 500 mm is recorded at the surface, and the tendency for lateral movement is accommodated by bedding-plane slip.15 Well damage from formation shear occurs primarily in two zones: upheaval failures near the base of the Colorado shale layers, and downhole failures within the Clearwater oil sands and at the interface between the Clearwater and overlying Grand Rapids formations. As usual, slip occurs at interfaces where strain discontinuities develop, and along the weakest beds, again near interfaces, in upheaval regions.

Many of the early failures could be ascribed to thermal stresses exceeding connection strength (threads popping), combined with sulfate stress cracking, and most failures occurred at a coupling in the upper part of the wellbore. Once a leak occurred, bedding-plane slip was facilitated by high-pressure fluid leakage into the strata from nearby wells. In several instances, a primary well failure, perhaps caused by corrosion, would occur on a pad; some weeks later, when cyclic steam operations were initiated in the deeper Clearwater formation, other wells at the same pad would be sheared at the same depth as the first well leakage.

About 85 to 90% of the downhole failures at Cold Lake, more than 200 wells, occurred at the top of the producing interval at the interface with an overlying Grand Rapids shale stratum. These failures are a direct result of shear stresses generated by steam injection and production in the oil sands. The overlying strata are not pressurized or heated and resist the tendency of the injection zone to expand, resulting in shear at the interface. Shear slip is the opposite sense undoubtedly also occurs when the reservoir compacts during the production phase.

The wells at Cold Lake are fully cemented across the Clearwater/Grand Rapids interface and hence, cannot accommodate much shear displacement. Vertical deformations also can induce shear deformations on deviated wells. For the approximately 200 wells damaged at this interface, those oriented at angles greater than 30° from vertical have been observed to fail at twice the rate (normalized with respect to the number of wells at that deviation) as wells oriented at angles less than 30° from vertical.

The shearing damage to wells is localized, sometimes confined to only 50 to 100 mm of wellbore length. When a coupling is located within a meter of the shear zone, it acts as a weak link, and threads tend to pop.

Downhole integrity loss often can be repaired, but upheaval shear failures at Cold Lake are serious events that could result in the release of fluids to the surface. These cannot be repaired, and the wells must be abandoned. Multiple upheaval casing failures have caused the abandonment of an entire pad of wells resulting from destabilization of the shale zone where shear is concentrated.

**Belridge, California: Diatomite Compaction**

The Belridge field is located in the southwestern San Joaquin Valley, California, about 80 km west of Bakersfield. The field is about 18 km long and 2.5 km wide. There are two primary producing intervals in the field. The first is the shallow Tulare formation, comprised of unconsolidated to loosely consolidated sands about 100 to 180 m thick. Beneath these sands lies the Belridge diatomite at an average depth of 500 m with an average thickness of 300 m. The diatomite averages 52.8% porosity, is highly compressible, and is subject to fabric collapse; a consequence is massive reservoir compaction under pressure depletion, leading to compaction and surface subsidence.

Well damage in Belridge was first noted in 1983; since then, more than 900 wells have been damaged, peaking at more than 160 wells per year in 1988, and currently averaging about 20 wells per year. The majority of well damage occurs within two zones, one near the top of the diatomite and the other approximately 120 m higher, located in a 12-m-thick shale bed between the upper and lower Tulare sands. Thermal operations within the Tulare D sands at Belridge also probably are contributing to casing damage in those zones.

Water injection has reduced subsidence from −0.45 m/yr in 1987 to the current rate of about 0.03 to 0.05 m/yr. Although well damage has declined significantly, impairment continues at about 3% of active wells per year. Casing strategies have been implemented to mitigate well damage, including thick-walled casing, slip joints, underreaming, and reservoir pressure maintenance strategies.

The major improvements were associated with casing strategies that allowed more slip by increasing annular space between the casing and the production tubing, by underreaming the zone before casing placement, and by strengthening casing in regions where bending was observed. In the Belridge case, strengthening of casing is more likely to be successful in mitigating shear because the formation is extremely soft when remolded by shear, and the stronger casing allows plastic flow around the well.

Without presenting details, we note that casing shear has been common in other areas near the Belridge field, such as in the Lost Hills field diatomite, where there is also significant compaction and surface subsidence.

**Alberta SFI™ Activity: Injection Shearing**

Large-scale injection of waste oily sands, slops, and back-produced drilling muds through slurry injection at high pressures takes place in unconsolidated sandstones of 30% porosity in Alberta and Saskatchewan, Canada, (Fig. 14).10,11 In some cases, more than 20 000 m³ of sand have been injected as aqueous slurries of density 1.15 to 1.25 g/cm³ over periods of many months at rates of 600 to 800 m³/day (total slurry rates). Waste injection takes place at depths of 350 to 650 m in strata ranging from thick (40 m) quartzose sands to less thick (12 m), fine-grained arkosic sands with clay streaks. Despite generally trouble-free operations for many months, well integrity problems may develop occasionally.

The mechanism involved in loss of well integrity is apparently shear displacement, leading to loss of pressure integrity or to tubing pinching in the casing. The large volumes put into the sands causes the reservoir to settle in the wellbores, as in the case of compaction (Fig. 5), but in the opposite sense of motion. In the one case where the casing distortion was located precisely, it was apparent that the most “clayey” (and hence weakest) zone in the overburden, approximately 25 m above the target horizon, slipped laterally. The slip may have been helped by transmission of high pressures along the casing, reducing the strength in the zone that slipped, therefore the hydraulic seal of the well is an important issue.

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**Fig. 16—Sequential fracture-induced casing shear.**

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Other Cases of Formation Slip: Conditions
Casing shearing has been identified in many other cases, at various depths, and in reservoirs subjected to various extraction processes. It is possible to state a few generalities on the probability of formation slip leading to casing failure. We will differentiate between the two most important cases: shear at the top of the producing interval, and shear higher in the overburden. The latter is associated more generally with compaction, the former with thermal processes, although there is much overlap in the mechanisms, and there are other mechanisms and exacerbating conditions (pressure migration along casing, Euler buckling in the producing horizon, normal fault reactivation, etc.).

In general, overburden-formation slip leading to casing impairment is most likely to occur when the magnitude of compaction or heave is large; where there are large stiffness contrasts such as sandstone-shale interfaces; if the overburden has weak-shale bedding planes; and where the casing traverses the shoulders of the structure.

In the case of shearing at the upper interface of the reservoir, it appears that casing impairment in offset wells dominates and is more likely to occur when temperature changes are large in thermal projects; when pressure changes are large in injection or depletion projects; and if there is an impermeable barrier at the top retarding advective heat and pressure migration, leading to a shear-stress concentration along the interface.

In all cases, if the naturally occurring shear stresses are large (high $\sigma_\gamma -\sigma_\delta$ values), if there are high natural pressures in the shale zones, or if there is transmission of high injection pressures to the susceptible zone by some means, shearing probability and magnitude will increase.

Clearly, we have not identified specifically all cases where casing shear can arise. In many other circumstances casing shear can occur, and we note a few that are worthy of consideration.

- Geothermal reservoir exploitation (large $-\Delta p$ and $-\Delta T$ lead to large $-\Delta V$).
- Massive cold water injection into hot reservoirs ($-\Delta T$ and increased pore pressure to reduce strength).
- Large-scale solids production as in cases of chalk and heavy-oil sand exploitation through cold production with massive sand ingress.\(^{16}\)

Low-porosity cases or situations such as strongly cemented sandstone or carbonates tend not to evidence casing shear, despite the fact that numerical modeling shows that the magnitude of the shear stresses can be large. This is because there are strong cohesive forces that resist the tendency to slip and because the generally high stiffness tends to predominate against large volume changes under conditions of pressurization or depletion.

Cures for Casing Shear
Options for reducing the incidence of casing shear are limited to deliberate avoidance, strengthening of the casing, allowing more compliance between casing and formation, or reducing the magnitude of slip along planes. It is more realistic to apply several tactics simultaneously to reduce casing shear incidence and rate, rather than seeking to eliminate it.

Strengthening the Casing. Simulation results and field experience show that the strength of the casing-cement system is of little consequence in resisting shear displacement of strata. It is possible to make casings that have moments of inertia many times greater than conventional casing by using double-walled annuli filled with cement. In general, however, the size of the induced shear planes is so large (greater than thousands of square meters) that the presence of a “strong” casing cannot resist slip, only retard the process somewhat. The stiffer the casing-cement system, the more likely it is to focus (attract) stresses. Casing strengthening may be effective in cases where the slipping strata are highly porous, soft, and susceptible to plastic flow after fabric collapse, such as diatomite or chalk beds (Fig. 17). Note that if only a small plasticity zone is generated, casing collapse is inevitable. However, if the plastically flowing zone is large (or if the material porosity is very high), the well cross-section is less affected and the casing dogleg is distributed over a long section, allowing workovers and reducing casing thread popping.

Increasing System Compliance. If a stiff and resistant casing attracts stress and cannot resist the induced shear slip, it makes much more sense to increase the compliance of the wellbore-casing system so that it can distort over a greater length before collapsing or developing severe dogleg (Figs. 10 and 17). Options include the following.

- Avoiding cementing the susceptible zones or using an extremely ductile cementing agent that can “flow.”
- Underreaming across the zone and avoiding cement.
- Increasing the casing size to allow more distortion before the tubing is pinched.
- Weakening or remolding the formation in the susceptible zone to allow more plastic deformation.

In each case, a larger amount of shear slip can take place before well function is impaired, as is evident from examining Figs. 3 and 10.

Avoidance of Slip Planes. It is possible to place wellbores in regions where the magnitude of shear slip is likely to be lower than other areas (Fig. 18). Given a production strategy (spatio-temporal drawdown distribution) and reasonable material parameters (stiffness, strength, and stratigraphy), numerical geomechanical modeling can be used to indicate where the shear stresses and slip are likely to be the greatest. Some suggested tactics include the following.

- In simple cases such as a rectangular or lenticular reservoir (Fig. 5), drill wells in the center.
- In flat reservoirs with thermal or high-pressure processes as illustrated in Figs. 6 and 9, avoid inclined processes that may intersect high-shear zones.
• Avoid locations that will be intersected by steep thermal gradient fronts such as advective thermal fronts or boundaries between advective and conductive zones.
• In cases of strongly anisotropic horizontal-stress fields, adjust well spacing in the most optimum direction commensurate with the process being employed.
• Use short-radius or long-reach wells to avoid intersecting regions of greatest slip (Fig. 18).
• Orient horizontal wells parallel to the potential slip surfaces to increase chances of avoidance.

Three-dimensional geomechanical modeling will be necessary to optimize well locations, and it is recommended strongly that a microseismic monitoring program be implemented to confirm and further optimize the design during operations.

Reducing Formation Slip. In the case of compaction, slip magnitude is proportional to compaction magnitude, and any means of pressure maintenance that reduces compaction will lead to a reduction of shear slip along bedding planes in the overburden. Similar slip magnitude reduction efforts can be employed in other cases; some options include the following.
• Reduce the size of steam slugs in cyclic steam injection.
• Earlier implementation of pressure maintenance on all depletion-driven technologies.
• Use lower differences in pressure or temperature.
• Use more appropriate cements and better cementing approaches to reduce the incidence of leakage along casing.

Reservoir Stress Management. If a 3D geomechanical model can give realistic predictions of the shear stresses induced by a process, then the model can be used to investigate exploitation alternatives that may lead to lower shear stresses, as well as identify sites of least shear displacement. The model must be used in conjunction with a reservoir pressure evolution model and must be confirmed and calibrated with real data. Therefore, a few comments about monitoring are appropriate.17

Specific localization of shearing strata interfaces may be undertaken using microseismic monitoring, and this is strongly advised in cases where shear is likely to be an important factor. However, for microseismic emissions to occur, slip must occur; therefore, this is a tactic to use in ongoing reservoir stress management and cannot be an a priori avoidance method.

Precision permanent tiltmeters arrayed in shallow sites or deeper monitor wells will allow the deformation patterns to be analyzed quantitatively. In turn, this permits good calibration of the geomechanical model.

Casings penetrating zones that are known to be susceptible to shear should be surveyed periodically with multiple-arm calipers to obtain a 3D representation of the distortion. In turn, this gives insight into the direction of motion and the magnitude and rate of slip, allowing specific quantitative design decisions to be made for new wells or repairs.

Conclusion
Casing impairment through shear occurs whenever large induced stress changes occur in weak, stratified sediments. Thermal-stimulation cases and large compaction cases almost inevitably generate large numbers of casing-shear incidents. Casing shear may be linked also to reactivation of old faults, high-pressure injection, slurry-fracture injection, or massive solids production.

The lithostatigraphic conditions and initial stress state have a strong influence on the time of onset and magnitude of casing shear. Furthermore, combined with the reservoir geometry and the pressure history of the reservoir, these factors control which planes will shear, by how much, and when. The only way to quantify these factors is to make a commitment to 3D geomechanical modeling. Model results can be used to help decide drilling strategies and even timing of well placement in particular locations.

Reducing the incidence and rate of casing impairment through shear can be achieved through a number of tactics. Favorable ones include avoidance of the most troublesome regions, increasing the compliance of the casing-wellbore system through susceptible horizons, and altering the process to reduce the magnitude of shear slip. In some cases, stronger casing may help, but only in those cases where the strata are exceptionally weak and tend to deform by general plastic flow. Geomechanical modeling is necessary to quantify all of these approaches.

Finally, the vital role of monitoring in the design process and reservoir stress management strategy must be revisited. Monitoring of data allows location of slip zones as well as assessment of direction of movement, rate, and magnitude of slip.18 Deformation data allow models to be calibrated, increasing their utility as management tools.

Nomenclature

- $c'$ = cohesion of the rock
- $E$ = Young’s modulus
- $k$ = permeability
- $p$ = fluid pressure
- $\Delta p$ = change in pressure
- $p_{ij}$ = injection pressure
- $p_{0}$ = initial or in-situ fluid pressure
- $\Delta T$ = change in temperature
- $\nu$ = positive
- $V$ = volume
- $\Delta V$ = change in volume
- $V_{ij}$ = volume injected
- $V_{prod}$ = volume produced
- $\sigma'$ = effective stress
- $\Delta \sigma$ = change in stress
- $\sigma_{ij}$ = smaller horizontal stress
- $\sigma_{ii}$ = larger horizontal stress
- $\sigma_s$ = effective stress normal to a slip plane
- $\sigma_r$ = radial or outwardly directed stress
- $\sigma_t$ = vertical stress
- $\sigma_m$ = major principal stress
- $\sigma_o$ = intermediate principal stress
- $\sigma_m$ = minor principal stresses
- $\delta$ = Kroenecker delta
- $\tau$ = natural shear stresses
- $\phi'$ = internal friction angle

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