Compaction and Subsidence

Pressure drawdown in a producing field can lead to reservoir compaction, movement of the overburden and subsidence of the surface above the reservoir. This compaction and subsidence can prove costly, both for production and surface facilities.

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Venice, the Italian city known for the romance of its canals, is slowly sinking into its surrounding lagoon, mostly due to natural causes. This is an improvement over the recent past: for several decades of the 20th century, Venice was rapidly sinking into the lagoon. From the 1940s until the 1970s, extraction of water and natural gas from below the city radically increased the subsidence rate.[1]

Subsidence is a sinking of a surface, such as ground level, relative to a stable reference point. It occurs naturally as a result of plate-tectonic activity, above active faults and in places where fluid is expelled from underlying sediments. Fluid expulsion is common at river deltas, such as the Po River delta around Venice. This effect, which amounts to a subsidence rate of a few centimeters per century in Venice, is distinct from eustasy, or a change in sea level, which accounts for a rise of about 13 cm [5 in.] per century in Venice.

After World War II, two practices increased the subsidence rate of Venice. First, the amount of water withdrawn from aquifers underlying the city increased dramatically to accommodate a growing population. As a result, the water levels in these aquifers dropped significantly. Secondly, natural gas was extracted from an industrial zone on the mainland just across the lagoon. The subsidence rate measured between 1968 and 1969 had increased from its low historic rate to 1.7 cm/yr [0.7 in./yr] in the industrial area and 1.4 cm/yr [0.6 in./yr] in the city center.[2]

This dramatically higher rate of subsidence was caused by compaction, which is a decrease in volume of a reservoir resulting from pressure reduction and production of fluids, in this case, water and gas. The terms compaction and subsidence describe two distinct processes. Compaction is a volumetric change in a reservoir, while subsidence is a change of level of a surface. That surface could be a formation top, the mudline in a submarine area or a section of the Earth's surface above the compacting formation, as is the case with Venice.

A record 2-m [6.6-ft] flood submerged Venice in November 1966.[3] After the flood, extraction of both natural gas and water was essentially halted around the city to control subsidence. Aquifer levels rose again, and the ground rebounded a few centimeters. However, the rebound was only a fraction of the ground-level change that had occurred over the period of water and gas extraction. Today, the slow natural subsidence continues.

In the oil and gas industry, some cases of subsidence have become well-known. Goose Creek field south of Houston was one of the first that received intense study. Subsidence over that field was first noticed in 1918, eventually reaching more than 3 ft [0.9 m] and submerging the Gaillard Peninsula, which lay over the center of the field.[4] The Wilmington field in California, USA, several fields at Lake Maracaibo in Venezuela, and the Groningen field in The Netherlands all had noticeable subsidence that required remediation because the surface above the reservoirs was at or near sea level.[5] The chalk fields in the Norwegian North Sea, notably Ekofisk, Eldfisk and Valhall fields, have compacted, and the resulting subsidence at the mudline generated concern for platform safety. Low-strength carbonate reservoirs in Northwest Java field, Indonesia, and fields offshore Sarawak, Malaysia, have also experienced significant subsidence.[6] The Belridge field in California and neighboring diatomite fields subsided and had numerous well failures.[7]

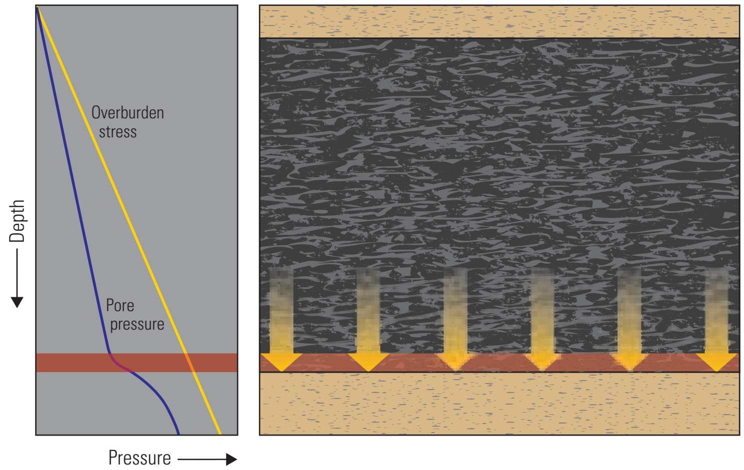
The economic consequences of compaction and subsidence can be huge, but not all of them are negative. Compaction may be beneficial, as it provides a potentially strong production-drive mechanism. In this article, we examine the issues relating to compaction and subsidence, illustrated by reservoir-management approaches in the North Sea, The Netherlands and the Gulf of Mexico.

Compaction Physics

A porous medium, such as a hydrocarbon-producing formation, contains fluid within its solid structure. This simple observation has profound implications when the material is placed under stress. For example, sediment deposited under water may have high porosity immediately after deposition, and it may behave more like a liquid with solid material in suspension, rather than a solid material containing liquid. As more sediment accumulates, the original layer must support the weight of the new material. As long as fluid pathways exist, some of the liquid will be expelled, and porosity will decline.

1. For more on subsidence in Venice: Brighenti G, Borgia GC and Mesini E: "Subsidence Studies in Italy," in Chilingarian GV, Donaldson EC and Yen TF (eds): *Subsidence Due to Fluid Withdrawal, Developments in Petroleum Science 41.* Amsterdam: Elsevier Science (1995): 248–253.
2. Brighenti et al, reference 1.
3. See http://www-geology.ucdavis.edu/~cowen/~GEL115/115CHXXsubsidence.html (accessed October 17, 2006).
4. Pratt WE and Johnson DW: "Local Subsidence of the Goose Creek Oil Field," *Journal of Geology* 34, no. 7–part 1 (October–November 1926): 577–590.
5. For more on subsidence in Wilmington field and Lake Maracaibo fields: Poland JF and Davis GH: "Land Subsidence Due to Withdrawal of Fluids," in Varnes DJ: *Reviews in Engineering Geology II*. Boulder, Colorado, USA: Geological Society of America (1969): 187–268.
6. For more on subsidence in Northwest Java field: Susilo Y, Rahamanda Z, Wibowo W, Tjahyadi R and Silitonga FJ: "Stimulation Efforts in Carbonate Gas Reservoir Experiencing Subsidence in Offshore North West Java Field—Indonesia," paper SPE 82264, presented at the SPE European Formation Damage Conference, The Hague, May 13–14, 2003.

   For more on subsidence in fields offshore Sarawak: Mah K-G and Draup A: "Managing Subsidence Risk in Gas Carbonate Fields Offshore Sarawak," paper SPE 88573, presented at the SPE Asia Pacific Oil and Gas Conference, Perth, Australia, October 18–20, 2004.
7. Fredrich JT, Arguello JG, Thorne BJ, Wawersik WR, Deitrick GL, de Rouffignac EP, Myer LR and Bruno MS: "Three-Dimensional Geomechanical Simulation of Reservoir Compaction and Implications for Well Failures in the Belridge Diatomite," paper SPE 36698, presented at the SPE Annual Technical Conference and Exhibition, Denver, October 6–9, 1996.



^ Overburden stress and pore pressure. The overburden stress (yellow arrows, *right*) on a formation increases with depth because of the added weight of overburden. The overburden stress (yellow line, *left*) is determined by integrating the density of the overburden. The pore pressure (blue) also increases with depth, with a gradient determined by the brine density. Beneath an impermeable stratum (red), the pore fluid becomes overpressured as the formation compacts under additional weight without being able to release pore fluid.

As burial depth of a sediment layer increases, the weight of the overlying sediments increases, tending to squeeze fluid out of the layer and reduce its porosity (above). The fluid pressure also increases with depth. If the overlying strata become impermeable to flow and the fluid cannot escape laterally, then as additional burial compacts the sediment, the fluid pressure increases beyond hydrostatic.[8] This fluid overpressure can also occur when rapid sedimentation rates outpace the expulsion rate of excess fluid from the formation.[9]

The result of having a pressurized fluid in a solid framework is that both the fluid and the solid support stresses on the material. This concept is the effective-stress principle, which states that the stress affecting the behavior of a solid material is the applied stress minus the support from the pore-fluid pressure.[10] When fluid is produced from a reservoir, the weight of the overburden does not decrease, but the pore pressure does, increasing the vertical effective stress acting on the solid matrix. The degree of resulting compaction depends on the compressibility of the rock and the boundary conditions.

Compressibility relates changes in volume to changes in applied stress. There are several ways of expressing the compressibility of a porous medium, but two are commonly used.[11] Pore-volume compressibility, C_{pv}, is a measure of the change in pore volume caused by a change in applied stress. Bulk compressibility, C_{bv}, is a measure of the change in bulk volume due to a change in applied stress; it is the inverse of the bulk modulus. Under an assumption that the grains are incompressible, C_{bv} is the product of porosity and C_{pv}. The compressibility value depends on the rock composition and depositional history, and can vary with changing pore-fluid composition.

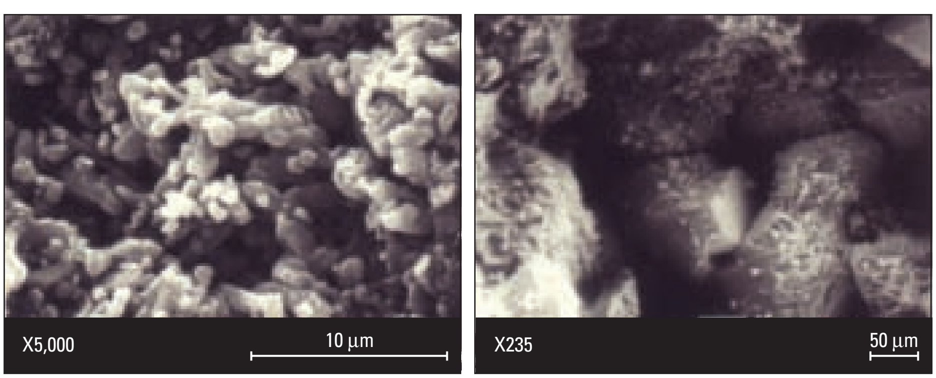
A competent, granular sandstone typically has a C_{pv} value of about 5 x 10^{-4}/MPa [3 x 10^{-6}/psi], but it can exceed 15 x 10^{-4}/MPa [100 x 10^{-6}/psi] for highly compressible North Sea chalks (below). Grain-bonding cement tends to increase rock stiffness, decreasing its compressibility.

Depositional history is important because compaction tends to cause irreversible changes in the rock fabric. Grains shift; clay particles deform; cemented bonds break; and even grains can break under loading. Since these changes are irreversible, the rock displays hysteresis. When stress on the rock decreases, which would occur if some of the overburden weight were eroded away or if formation pressure increased without additional deposition, the unloading material is less compressible than when it was loaded over the same stress interval. Also, the unloaded material is less compressible on reloading until the original stress condition is reached again (next page).[12]

Several mathematical formulations have been developed to model the behavior of rocks under stress, but to date there is no single formulation that the industry has accepted above the others. The best of these models have mechanisms for elastic and plastic deformations, thermal effects and time-dependent, or creep, effects.[13] Some rocks are weaker when at least partly saturated with water rather than oil. Although the physical mechanism for that effect is not completely understood, some models include algorithms to account for the water-weakening effect.

Subsidence Physics

It is difficult to observe compaction of a hydrocarbon reservoir, but subsidence at the surface is often easy to see. Water encroaches upon previously dry land; an offshore platform loses its air gap between high waves and the bottom deck; wellheads and casing may protrude above the surface; or surface structures sink. Subsidence has been a primary indicator of compaction over oil fields since it was first noticed at Goose Creek field in 1918.[14]



^ Chalk and sandstone structures. Scanning electron micrographs of outcrop samples show chalk from Stevns Klint, Denmark (*left*) and sandstone from Berea, Ohio, USA (*right*). The chalk is a weak jumble of uncemented fragments of coccoliths, while the sandstone is a more competent arrangement of cemented grains. This structural difference helps explain the extreme difference in compressibility between these materials. Note the much higher magnification of the chalk image.

The original engineering report about subsidence at Goose Creek field included a detailed discussion of other suspected causes of the local subsidence. However, the report showed that the effect was not due to the general subsidence of the Gulf coast; it was not due to a change in mean sea level; it was not erosion; and it was not a sinkhole caused by dissolution of limestone, salt or some other soluble formation. Maps of subsidence showed that a depression followed the general outline of the field. By the authors' rough calculation, the subsidence bowl accounted for only 20% of the oil, gas, water and sand that had been removed from the field. However, in the conclusion of the paper, they imply that the compaction occurred in the overlying clays, rather than in the producing formation itself.

Over the decades since the Goose Creek study, the understanding of subsidence resulting from fluid withdrawal has progressed significantly. Subsidence studies today involve detailed reservoir flow and geomechanical analysis, but the general principles can be explained without resorting to a complex model.

The formations involved are divided into four parts: the compacting volume, the overburden, the sideburden and the underburden. These last two terms are not generally used except in geomechanics, but refer to materials laterally connected to the compacting formation and those beneath it and the sideburden, respectively.

The compacting volume may include more than the hydrocarbon-bearing formation. Aquifers beside or below may also compact as they drain, and should be modeled as part of the compacting formation, albeit with different properties in many cases.

The decrease in volume caused by compacting a buried formation is usually transmitted to the surface. The subsidence bowl is generally wider than the compacted area. The amount that it spreads depends on the material properties of the overburden and the depth of the compacting formation. In addition, if the overburden does not expand, the volume of the bowl at surface is equal to the compaction volume at depth.

A subsidence bowl tends to be approximately symmetric, even if the compaction in the underlying volume is not. Because the bowl is a superposition of subsidence resulting from each compacting element, it tends to average out the variation. Overburden anisotropy from faults or material anisotropy can restrict or change the shape of the bowl; faults can allow slippage, preventing the spread of subsidence.

The overburden can also expand, although this is a minor effect for most overburden rocks. However, this volume change can result in a time-dependent effect as the overlying rock slowly creeps, first in expansion and later in compaction.

When a formation compacts, the sideburden often does not, either because it is impermeable, separated from the compacting formation by a sealing fault and therefore not experiencing an increase in effective stress, or simply because it is a stronger material. The overburden weight that had been supported by the compacting formation can now be supported partially by the sideburden. This creates what is termed a stress arch over the compacting formation. The extent and effectiveness of the stress arch in supporting overburden are functions of the material parameters of the over- and sideburden, the lateral extent of the compacting zone and the amount of compaction.

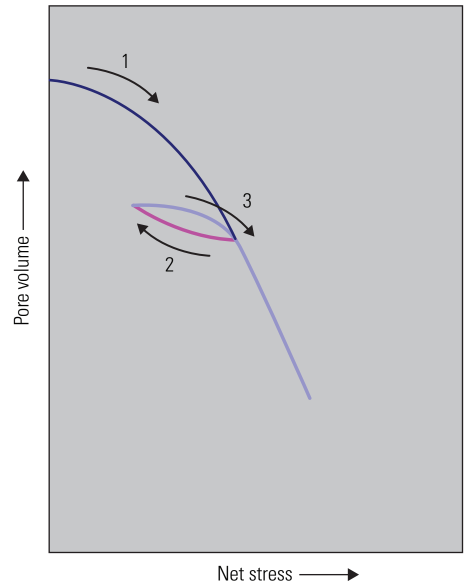
Although the predominant motion in a subsidence bowl is vertical, horizontal movements also occur. The horizontal movement is zero in the middle and at the outer boundary of the bowl and reaches a maximum, inward displacement in between. Large horizontal movements can have devastating effects on pipelines and other extensive surface structures unless they are designed to accommodate the strain.

Measuring Compaction and Subsidence

Subsidence-monitoring methods differ for onshore and offshore areas. Onshore, benchmarks are common tools of civil engineers. A benchmark is a survey mark at a known position and a measured elevation that is used to determine changes in elevation with respect to other benchmarks. Benchmarks outside of the subsidence bowl provide fixed reference points.

The most accurate way to determine an elevation difference between benchmarks is to connect two locations with a liquid-filled tube. The hydrostatic level will be the same at both ends of the tube, so changes in relative elevation can be determined with great accuracy. However, performing this type of survey over large areas can be prohibitively expensive. Most benchmark surveys compare elevation by sighting though a transit or using a laser, after careful leveling of the instrument. This method can also be used to obtain relative elevation changes between platforms within a complex.

Tiltmeters—devices that are sensitive to the change of angle on the surface or in wells—can provide subsidence data for onshore locations. These devices are also used to monitor the advance of an induced fracture.[15]



^ Compaction hysteresis. Increasing the net stress on a material that is in a plastic state causes a rapid decline in volume (1). If the material is unloaded, the volume rebound is not as large as the collapse was, and it is often close to the elastic response (2). Reloading the material initially causes a quasi-elastic response, until the previous high net-stress state is reached (3). At that point, the material again follows the plastic-failure line.

8. Hydrostatic pressure is the magnitude of pressure caused by the weight of the overlying column of brine, often obtained by integrating the brine density from surface to the depth datum.
9. Other geologic processes can also generate overpressure or underpressure situations; examples include chemical diagenesis, regional uplift or downthrust, and hydrocarbon migration.
10. The relationship is also called the net-stress principle: $\sigma = S - \alpha P$, where σ is the net or effective stress on the solid material, S is the stress applied to the body, P is the pore pressure and, in isotropic elastic solids, $\alpha = 1 - K_b/K_s$. Here, K is the bulk modulus, and this last term is the ratio of the bulk moduli of the rock (b) and the mineral grains in the rock (s). In highly porous and weak materials, the grain modulus is much greater than the rock modulus, so α is approximately 1, and $\sigma \approx S - P$. Both σ and S are tensors, so this equation applies in all three principal directions.
11. For a complete definition of the types of compressibilities: Zimmerman R: *Compressibility of Sandstones, Developments in Petroleum Science 29*. Amsterdam: Elsevier Scientific Publishing Company, 1991.
12. For a study of field stresses with pressure cycling: Santarelli FJ, Tronvoll JT, Svennekjaer M, Skeie H, Henriksen R and Bratli RK: "Reservoir Stress Path: The Depletion and the Rebound," paper SPE/ISRM 47350, presented at the SPE/ISRM Eurock '98 Symposium, Trondheim, Norway, July 8–10, 1998.
13. A deformation is elastic if, after a stress change, a material returns to its initial shape when the stresses return to the initial condition. Deformations that result in a permanent change in shape after such a stress cycle are termed plastic, or inelastic. Creep describes a deformation that continues after the stress change stops.
14. Pratt and Johnson, reference 4.
15. Bennett L, Le Calvez J, Sarver DR, Tanner K, Birk W, Waters G, Drew J, Michaud G, Primiero P, Eisner L, Jones R, Leslie D, Williams MJ, Govenlock J, Klem RC and Tezuka K: "The Source for Hydraulic Fracture Characterization," *Oilfield Review* 17, no. 4 (Winter 2005/2006): 42–57.

Global positioning system (GPS) stations can be used for fixed positions either onshore or offshore. Under ideal conditions, GPS techniques can detect elevation changes of about 2 mm.

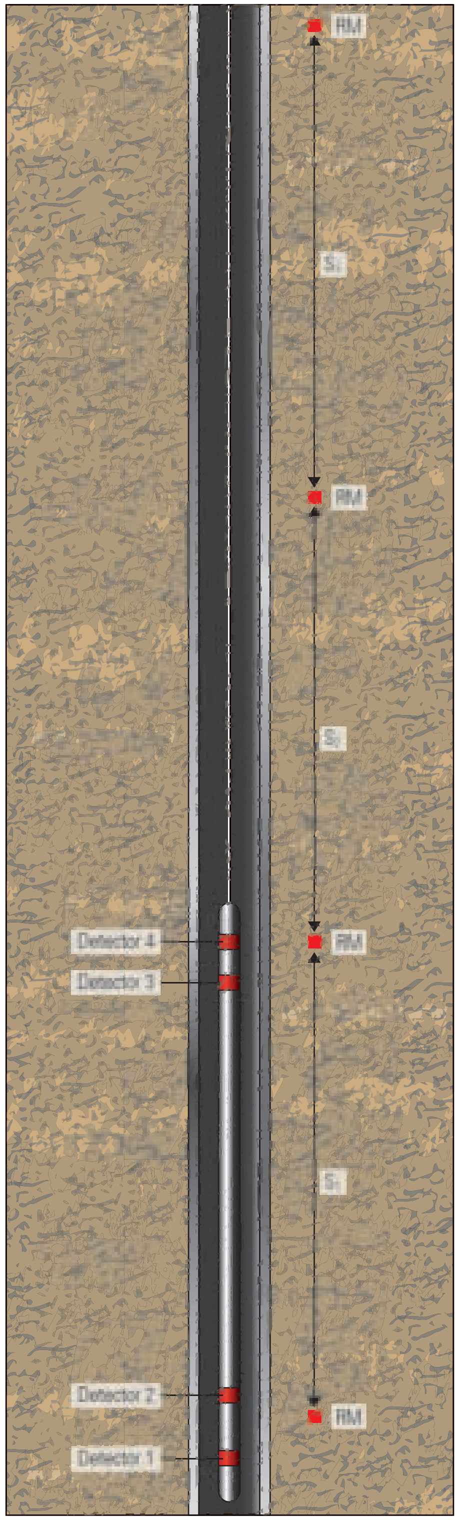
Another method that is under evaluation by several companies uses satellites for subsidence monitoring. Interferometric synthetic aperture radar (InSAR) relies on repeated imaging of a given geographic location by air- or space-borne radar platforms. With complex measurements—including magnitude and phase—of radar images of the same area, one can construct an interferogram from the difference in phase of the return from each point. The phase differences are sensitive to topography and any intrinsic change in position of a given ground reflector.

The change in distance is along the line of sight to the satellite, preventing it from directly distinguishing vertical and horizontal movement. However, over a compacting reservoir in a location without other tectonic movement, the change is assumed to be due to subsidence, and primarily vertical.

Benchmark reflectors can be established for InSAR, but a more widespread set of measurements can be obtained by using existing objects that scatter the radiation, such as road intersections or rooftops pointing in the appropriate direction. Any movement of these permanent or persistent scatterers that is unrelated to subsidence is generally not known, but the sheer quantity of reflectors compensates for that deficiency.

The InSAR method has limitations. Growth of vegetation between satellite passes can cause interpretation problems over open fields. Rapid changes in elevation, such as occur near active faults, are easier to measure than slow subsidence. Distance measurements can be made when the satellite is ascending or when it is descending. Since the angle of reflection is different, the two measures generally involve different sets of scatterers. The ascending and descending measurements of subsidence may not agree completely.[16]

Offshore, the subsidence bowl is not so easily accessed. Most commonly, subsidence is monitored at platforms. This is not merely a convenience, but a necessity. The air gap, or distance between mean sea level and the lowest structure of the platform, has to remain greater than the wave height. Companies use a statistically derived wave height, often the maximum wave height expected over a 100-year period.



^ Monitoring radioactive bullets. A sonde with four gamma ray detectors minimizes the effect of unintentional tool movement by detecting two radioactive markers (RM) almost simultaneously. The bullet separation, S_1, S_2 and S_3, should be approximately equal to the mean separation between the top and bottom pairs of detectors.

The air gap can be measured by several methods, all of which rely on a known benchmark on the platform. Continuous measurement of distance to the water can be obtained acoustically; alternatively, an underwater pressure transducer mounted on the leg of the platform can indicate the height of the water column above it. Interpretation of these two methods requires knowledge of sea level at the time of the measurement, which means tides and wind-driven waves have to be considered.

Today, the most common method for determining platform subsidence is by using GPS, as is done onshore. Some interpretation methods require a nearby platform that is not subsiding, but the methodology is improving, and some companies that provide this service to the industry now claim their interpretation does not require a near, fixed benchmark.

Subsidence affects pipelines and other structures on the seabed. Bathymetry surveys are the most direct way to map the extent of an undersea subsidence bowl. The survey indicates water depth with respect to sea level. This is generally obtained by bouncing an acoustic signal off the mudline and back to a receiver. The traveltime measurement must be corrected for the effects of water salinity and temperature. Repeat surveys can monitor the development of a subsidence bowl.

Formation compaction is usually more difficult to measure than subsidence. Shallow compaction that results in subsidence on land can sometimes be seen directly, when wellheads of shallow wells protrude farther and farther from the surface. This is the case in Mexico City, where the shallow aquifers have compacted and some well casings are around 5 m [16 ft] higher than when installed.[17]

The most common method for measuring compaction in deep formations is through use of radioactive bullets, or markers (left). With a special perforating gun, the bullets are fired into a formation at known intervals, such as 10 m [32.8 ft]. Each marker contains a low-strength, long-lived radioactive source, generally cesium. Specialized wireline logging tools, such as the Schlumberger Formation Subsidence Monitoring Tool (FSMT), Baker Atlas CMI Compaction Monitoring Instrument or Halliburton FCMT Formation Compaction Monitoring Tool, measure the relative positions of the radioactive marker accurately. Compaction-monitoring tools contain three or four detectors: two at the top of the sonde and one or two at the bottom. The mean spacing between the top and bottom detectors is roughly the same as the spacing between the markers. This minimizes distance errors due to any tool movement from the wireline cable stretching and contracting. Repeat surveys indicate the change in separation of the markers.

The best place to put markers is in a vertical monitor well. Deviated wells introduce an error in the position of the marker, depending on the orientation of the gun when the bullets are fired. Producing wells may also flow formation solids, introducing uncertainty about the cause of the marker movement—either compaction or solids production.

In the past, other methods were used for compaction monitoring, but most of them have been discontinued as insufficiently accurate. These include time-lapse logging for casing collar location and for petrophysical markers. Time-lapse seismic studies can also be used as tools for monitoring subsidence of subsurface formation tops. Although the method is generally too imprecise for accurate compaction monitoring, the extensive coverage of reservoirs provided by seismic surveys makes them useful for reservoir management. Subsurface movement can also be indicated by using microseismic arrays that detect and locate noise generated by compacting and yielding rock.

Vital input for compaction studies also comes from core measurements. A load frame stresses or strains a core sample and measures its response, including pore-volume changes, pore-pressure changes, length and diameter. These tests can also examine the effect of changing fluids or temperature on rock deformation and strength. Stress or strain boundary conditions similar to those expected in the field can be applied.

Two common laboratory conditions are hydrostatic-stress and uniaxial-strain boundary conditions. In the hydrostatic-stress condition, all three principal stresses are equal. This is the simplest of the compressibility conditions to apply, but is not representative of actual field conditions. The uniaxial-strain condition maintains a constant sample cross-sectional area, while the axial stress changes either through axial loading or reduction of pore pressure in the sample. Although this condition is felt to be closer to the boundary conditions in some fields, studies of changes in horizontal stresses caused by depletion in both the Ekofisk and Valhall chalk fields indicate some other boundary condition applies.[18]

The Impact of Compacting Formations

Despite a necessary focus on damage to wells and facilities caused by compaction and subsidence, the positive effect on production cannot be ignored. In the weak chalks of the North Sea and the diatomites of California, the so-called rock drive can be many times greater than fluid-expansion drive. Formation permeability can either increase or decrease, because open fractures can close or new fractures can be generated. Matrix permeability generally decreases as the pore spaces collapse or grains break.

The weakened material can flow into a wellbore. This happened most notably early in the history of the Norwegian chalk fields, where the chalk flowed like toothpaste.[19] A better understanding of chalk failure led to improved production methods that mitigated this behavior. In sandstone formations, sanding can be a common response of a mechanically weak material during production. Fracturing and borehole breakouts can also occur.

Casing collapse has been an ongoing problem in fields with large amounts of compaction. A compacting formation pulls the cemented casing along with it, compressing the axial dimension of the casing. However, above the formation, the overlying material typically elongates, and the casing there stretches. In either situation, the stress on the casing can exceed its mechanical strength and cause collapse within the compacting zone or fail in tension in the overburden. Shear failure and casing crushing can occur. Faults in the overburden also can reactivate because of differential movement, and bedding planes may have differential slippage. Both types of events may shear a wellbore that lies within an area of differential movement.

On the surface, remediation can also be costly. Since 1987, about US$ 3 billion has been spent to counter the effects of subsidence over the Ekofisk field, first raising the platforms 6 m [19.7 ft] and later replacing the platform complex.

The bowl formed by subsidence affects pipelines, roads and other structures. Lateral movement within the bowl can generate damage. Some of this damage can be mitigated by construction design, such as strain-relief loops in pipelines. However, a fault extending to the surface can generate step-offsets resulting in damage to structures crossing the fault.

Surface effects of subsidence can be extensive, particularly in low-lying areas near large bodies of water. For example, dike systems were constructed and repeatedly extended as the depression over the fields at Lake Maracaibo grew.[20] The Netherlands has an extensive dike and canal system; over the subsiding Groningen field, the ground level is monitored and the dike system enhanced as needed. Wilmington, California, took a different approach, mandating a waterflood in the field underlying the city, which successfully stopped the subsidence.

In the subsurface, drilling and completion practices must account for the effects of compaction. Field experience can indicate areas that should be avoided in well paths, such as faults. This may be as simple as changing the wellbore trajectory somewhat or as complex and expensive as adding platforms to reach remote parts of a field. Heavy-walled tubulars can sustain additional strain, but often require a cost-benefit analysis to compare their use against accepting a shorter well life.

In new developments, many of these decisions must be made in advance of designing facilities. Information from exploratory drilling and offset wells are used to develop models to help in these decisions.

Simulating a Compacting Reservoir

The behavior of a mechanically dynamic reservoir requires more sophisticated modeling than the pressure-dependent pore volume that is included in most flow simulators. Volume units can compact or stretch and can also change shape.

Historically, reservoir flow simulation and geomechanical simulation were done separately.[21] However, the physical parameters, particularly pore pressures, are affected by both flow dynamics and mechanical deformation. As a first approximation, one model is run first and its results are used as input for the other model. The first model typically is a flow simulation, because it runs more quickly. With no feedback to the first model, this approach is considered to be uncoupled, and the resulting output of the same value—such as pore pressure—of the two models can be divergent.

16. InSAR has also been used to measure uplift. For information on satellite measurements of ground deformation around the volcanic caldera of Yellowstone National Park, Wyoming, USA: http://volcanoes.usgs.gov/yvo/2006/uplift.html (accessed September 29, 2006).
17. Poland and Davis, reference 5.
18. Goulty NR: "Reservoir Stress Path During Depletion of Norwegian Chalk Oilfields," *Petroleum Geoscience* 9, no. 3 (2003): 233–241.
19. Simon DE, Coulter GR, King G and Holman G: "North Sea Chalk Completions—A Laboratory Study," *Journal of Petroleum Technology* 34, no. 11 (November 1982): 2531–2536.
20. Poland and Davis, reference 5: 214–216.
21. Here, to distinguish between conventional reservoir simulation, which includes complex flow dynamics and simple geomechanics, and geomechanical simulation, which has an opposite emphasis, the conventional simulation is referred to as a flow simulation.

The next level of modeling typically uses a flow simulator to solve a time-step first—again, because it runs faster—and feeds those results into a geomechanical simulator. If the comparable values from the two models do not agree within a given tolerance at the end of the time-step, parameters are adjusted and the time-step is rerun until they do agree. These iterations continue through subsequent time-steps of the simulation run. This method is termed loosely coupled. It requires more computer time but also produces results that are in closer agreement between the two simulators.

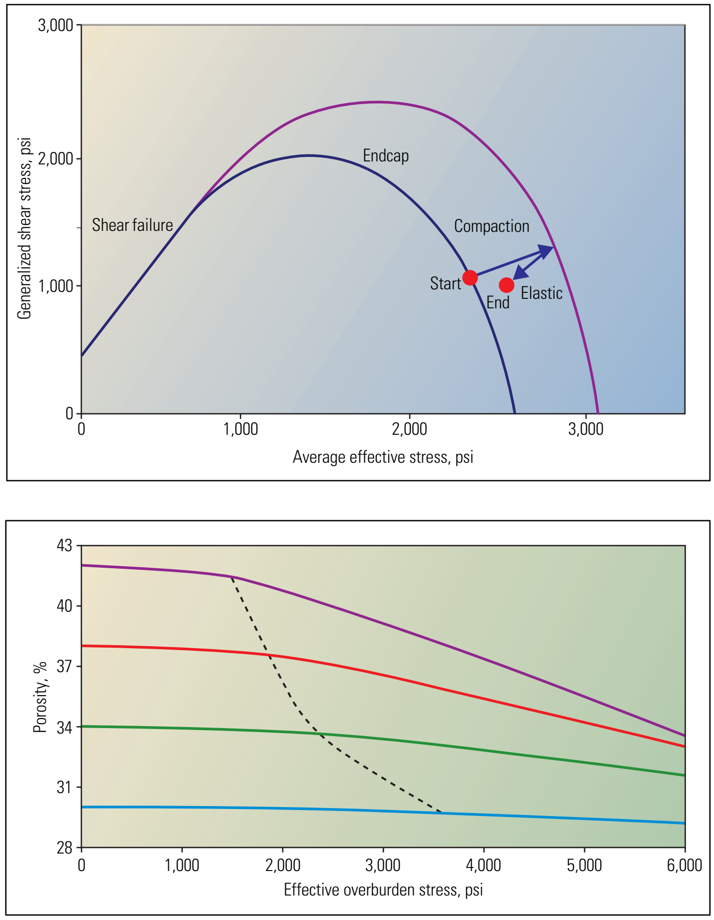
Both flow and mechanical modeling are mathematically complex, and combining the two into one simulator was difficult to achieve. Today, some simulators can carry out simultaneous flow and geomechanics solutions, including Schlumberger ECLIPSE Geomechanics reservoir simulation software, V.I.P.S. VISAGE multiphase stress dependent reservoir simulator and a few that oil companies, such as ConocoPhillips, or universities have developed in-house. This type of simulation is often referred to as fully coupled. These models are still not run as a standard, because they are considerably slower than uncoupled and loosely coupled models.

Waterflooding to Repressurize a Chalk Field

Waterflooding has been a recovery method in the E&P business for many years, either to displace hydrocarbons or to maintain the pressure needed to keep oil or gas in single phase. It has also been used to mitigate subsidence, such as in the Wilmington field, which sits under the harbor area of Long Beach, California. Severe subsidence at this economically important location led to a massive waterflooding program in the field that resulted in about a foot of rebound.[22]

Waterflooding has also been successful in the Ekofisk field, a huge chalk structure draped over a salt dome, with approximately 6.7 billion bbl [1 billion m^3] of original oil in place. In 1969, Phillips Petroleum, now ConocoPhillips, made the first discovery in the Norwegian sector of the North Sea for the Ekofisk partnership. The field still produces more than 300,000 bbl/d [47,700 m^3/d] of oil and more than 250 MMcf/d [7 million m^3/d] of gas.

The crest is approximately 2,900 m [9,500 ft] below sea level, in 78-m [256-ft] deep water. Field production comes from both the Ekofisk formation, which contains two-thirds of the reserves, and the underlying Tor formation. A thin, impermeable chalk, called the Tight Zone, separates the two formations.



^ Ekofisk chalk model. The chalk model is depicted on a plot of generalized shear stress against average effective stress (*top*). The material cannot go above the shear-failure line because it will fail in shear. The endcap represents the boundary between elastic (inside) and plastic (outside) behavior. If the stress condition is on the endcap (at *Start*), increasing it moves the endcap outward. Decreasing the stress (to *End*) moves the condition back into the expanded elastic zone. The behavior at the endcap can be seen in the chalk type curves for the field, showing the decrease in porosity with increasing effective overburden stress (*bottom*). The chalk initially behaves quasi-elastically, with a small porosity decrease. When the material crosses the endcap, the porosity declines more rapidly. The initial endcap location is porosity-dependent (dashed line), with lower-porosity chalks having a larger initial elastic region.

Porosity in both formations ranges from 25% to greater than 40% in producing areas of the field, and the productive zone can be as thick as 150 m [490 ft] within the crest of the field. Chalk up to about 50% porosity has been encountered in the field. Preservation of such high porosity at the depth of the reservoir is attributed to significant overpressuring and the early emplacement of hydrocarbons.

By 1984, platforms in Ekofisk field had subsided several meters, and many wells had failed. The operator began monitoring platform subsidence and obtained new bathymetry surveys of the mudline. Company scientists performed detailed geomechanical studies of core samples and created field models. They discovered that chalk compaction is extreme in this field: a decrease in formation pressure from the discovery value of 7,200 psi [49.6 MPa] to a potential abandonment condition at 3,200 psi [22 MPa] would result, for example, in a decrease in porosity from 38% to about 33% (above).

Chalk behavior depends on its stress state. At low confining and shear stresses, chalk is elastic, and a small decrease in formation pressure induces only a small elastic strain. However, a large decrease in formation pressure causes inelastic deformation and substantial strain. The onset of inelastic behavior occurs at the endcap, a surface in stress space that connects to the shear-failure line at high shear stresses. However, inelastic compaction alters the chalk, moving the endcap location to the higher effective-stress condition.

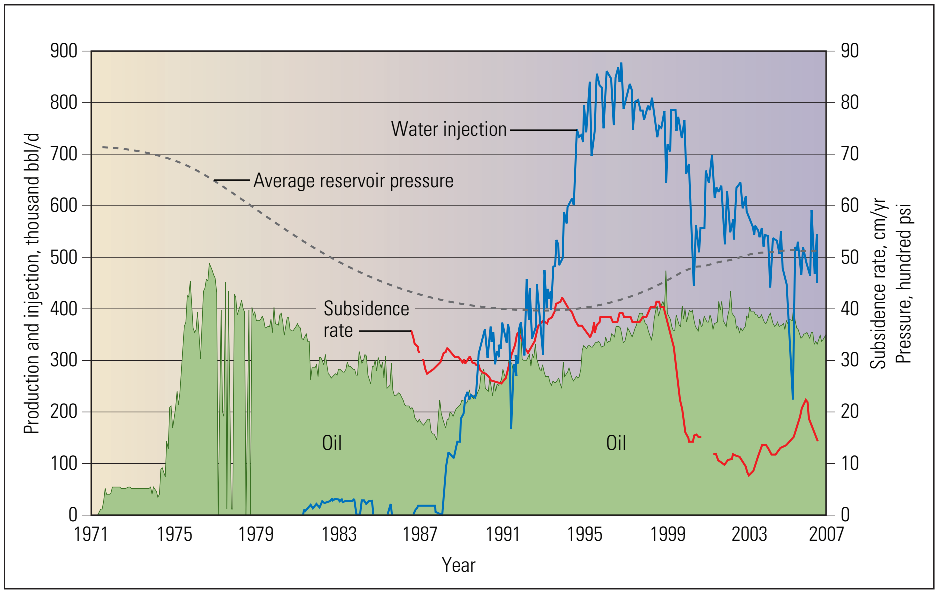
As a result of compaction, the subsidence rate in the mid- and late-1980s was about 30 cm/yr [1 ft/yr]. The resulting loss of air gap and potential impacts on platform safety became a major concern. The 6-m increase in platform height in 1987 was performed to increase the air gap between the lower decks and the expected maximum wave height.

In 1980, waterflooding was not initially considered a viable option in the Ekofisk field because tests indicated that the chalk was at best intermediate-wet and at worst oil-wet, reducing the water imbibition that aids waterflood efficiency. Nonetheless, the Ekofisk partnership felt the potential production gains warranted a small waterflood pilot, which was initiated in 1981.[23] The results from the pilot waterflood suggested good oil displacement and limited early water breakthrough.

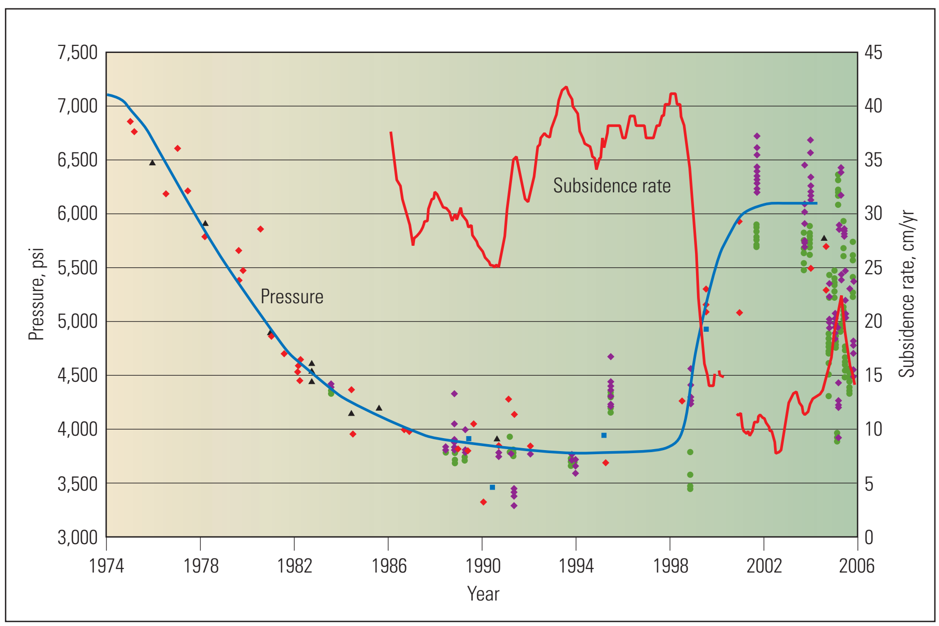
Operator Phillips, now ConocoPhillips, began staging a full-field waterflood in 1987. It was designed as a production enhancement mechanism, with voidage balance achieved in 1994. Despite this, the subsidence rate remained nearly constant as waterflooding continued under voidage balancing, reaching a maximum rate of 42 cm/yr [16.5 in./yr] in 1998 (above right).

A new complex of platforms was installed, both to withstand the continuing subsidence and to provide more facilities for an expansion of field activities.[24] During the changeover from the old platform complex to the new Ekofisk II complex in late 1998, water injection continued while production was halted for several weeks. During this period, and continuing since then, the subsidence rate decreased dramatically to a current rate of 15 cm/yr [5.9 in./yr] (right). While a reduction in subsidence rate such as this had been considered by the operator as a possibility, its magnitude was unexpected, based on the field subsidence history.

The voidage balancing condition achieved during the mid-1990s should have slowed the mechanical compaction, because the effective stress was no longer increasing. With voidage balancing, and later repressurization, company scientists expected the formations to stop compacting in that time period, and perhaps rebound slightly, but this did not happen. Although creep in the overburden can cause a delayed reaction between compaction and subsidence, the time delay would not be years, as seen with the subsidence-rate decrease that finally began in 1998.

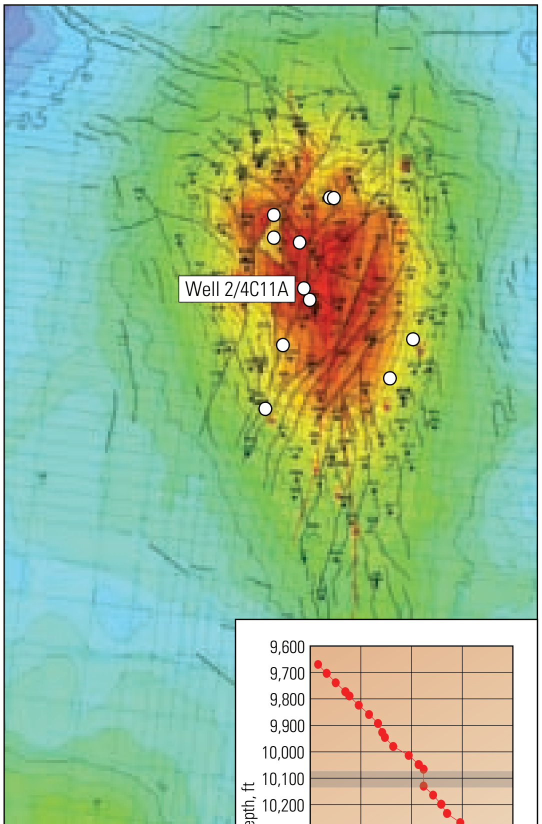


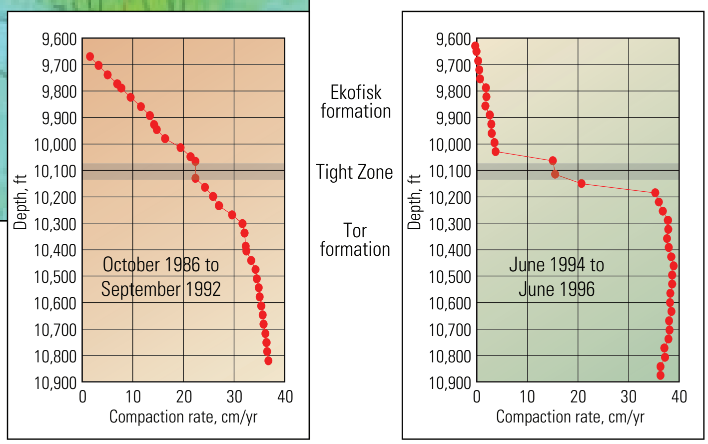
^ Ekofisk field production history. The oil rate (green) declined until large-scale water injection (blue) began in the late 1980s. The average reservoir pressure (dashed curve) also decreased until the water-injection rate increased in 1995. However, the subsidence rate (red) at the hotel, or quarters, platform did not decrease until production was shut in during the transition to the Ekofisk II complex in 1998.



^ Subsidence and pressures in the Ekofisk field crestal area. Pressure measurements in wells in the crestal area follow a trend (blue) with a rapid increase in mid-1998 that corresponds closely to the slowing of the subsidence rate (red).

22. Colazas XC and Strehle RW: "Subsidence in the Wilmington Oil Field, Long Beach, California, USA," in Chilingarian GV, Donaldson EC and Yen TF (eds): *Subsidence Due to Fluid Withdrawal, Developments in Petroleum Science 41*. Amsterdam: Elsevier Science (1995): 285–335.
23. Thomas LK, Dixon TN, Evans CE and Vienot ME: "Ekofisk Waterflood Pilot," *Journal of Petroleum Technology* 39, no. 2 (February 1987): 221–232. Originally paper SPE 13120, presented at the SPE Annual Technical Conference and Exhibition, Houston, September 16–19, 1984.
24. For more on the Ekofisk platform complex upgrade: "Ekofisk Phase II Looks to the Future," *Journal of Offshore Technology* 5, no. 4 (November 1997): 27–29.





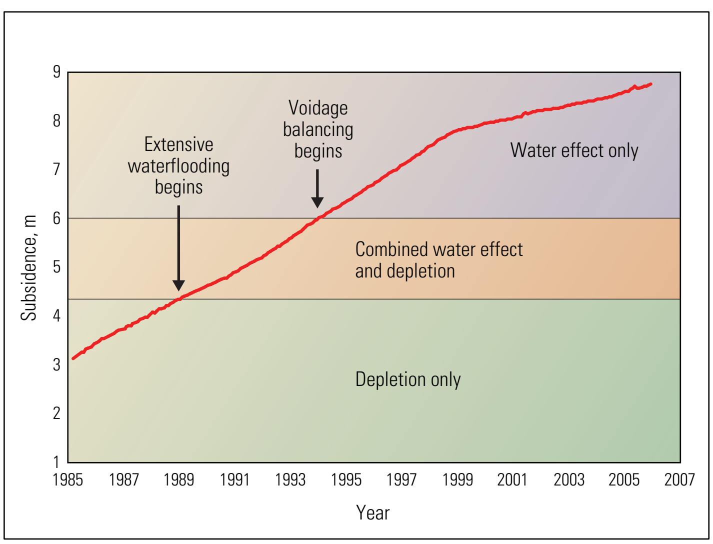
< Dedicated compaction monitoring in Well 2/4C11A. This crestal well (*field map*) was designed as a monitor well equipped with radioactive markers and had no production. Compaction is measured from the top of the markers and converted to an annual rate (*bottom left and right*). Since these numbers are cumulative, a vertical slope—such as in the Tight Zone near 10,100 ft—indicates no compaction. Between 1986 and 1992, both the Ekofisk and the Tor formations compacted significantly (*left*). When the waterflood front passed the well, in the period from 1994 to 1996 (*right*), most of compaction occurred within about 100 ft [30 m] of the Tight Zone, while the Ekofisk and Tor formations compacted slowly, or even stretched slightly as indicated by the leftward slope with depth below 10,500 ft.

The answer to the timing of the subsidence-rate decrease lay in a chalk-water interaction. Rapid compaction was seen in a dedicated Ekofisk compaction-monitoring well when the water front moved through the area (left). In laboratory tests, chalk compacts more when saturated with water than when saturated with oil.[25] An even more dramatic effect occurs when a stressed chalk sample with virtually no initial water saturation is flushed with seawater. The sample compacts immediately upon contact with the flood front, and a compaction front follows the flood front through the core.[26]

Water changes the constitutive properties of the chalk and mechanically weakens it. The chalk-water effect is modeled as a movement of the endcap that divides noncompacting, elastic behavior from compacting, plastic behavior. The effect of increasing water saturation is to move the endcap toward a lower stress state, decreasing the size of the elastic region with a minimal change in the stress condition. This is an unstable condition, so the chalk compacts as the endcap moves to accommodate the current stress condition. An equilibrium condition is achieved when the stress condition lies along the endcap (next page, top). Although the physical mechanism for this behavior is not completely understood, it appears to be related to ion exchange at intergranular contacts, leading to decreased cohesion of the chalk.[27]

This explanation applies to the Ekofisk field during the waterflood voidage-balancing period. The balance between water-induced compaction and a slow increase in support from pressure favored compaction, so the subsidence rate remained high. The period of injection without fluid withdrawal during the Ekofisk II installation in 1998 allowed sufficient pressure buildup—and effective stress decrease—to move the formation condition far enough inside the endcap that the balance shifted, and the subsidence rate declined. The continuing reservoir compaction after a several thousand-psi pressure increase is attributed to the ongoing balance between chalk weakening due to contact with seawater and the decreasing effective stress associated with reservoir repressurization (left).

ConocoPhillips compares field measurements of compaction and subsidence to results from loosely coupled geomechanical and flow models developed in-house. The current lower subsidence rate means concern for the loss of air gap and its impact on platform safety has been relieved somewhat. In addition, the emphasis in modeling has turned to optimizing field

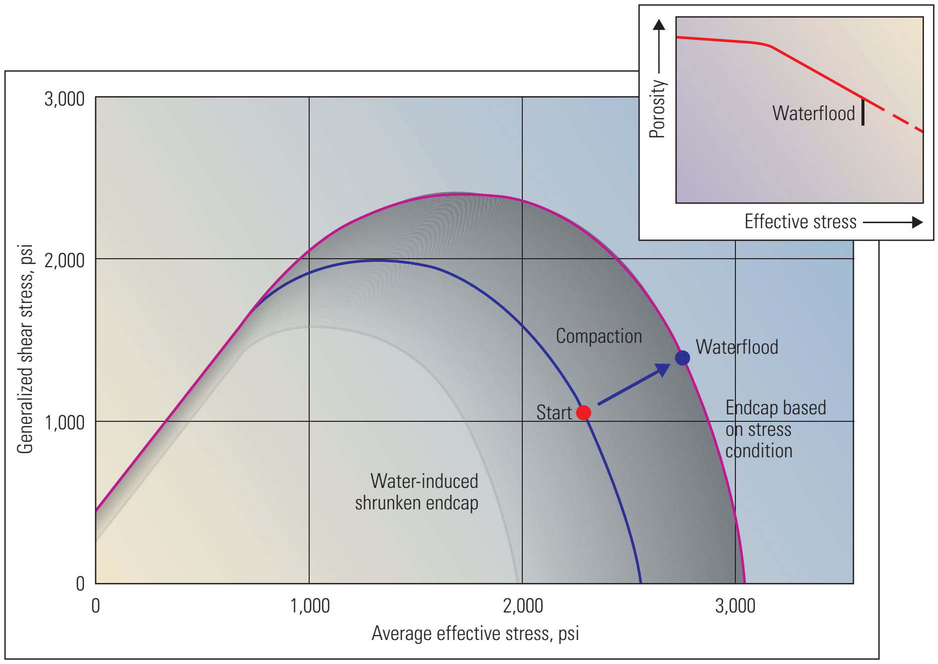


^ Subsidence from depletion and from water effect. Until 1989, all subsidence at the hotel complex was due to pressure depletion. After the injection rate balanced the voidage rate in 1994, the subsidence was all due to water-induced compaction. Both effects were in play in the period between these events.

management, for example, using the models to help place new wells. Some of these new well locations are determined through time-lapse seismic studies that track the waterflood front.

The dynamic nature of field management means that a deterministic subsidence model should be used with care. For example, the addition of new well slots in the Ekofisk II complex allows additional drainage of the field, invalidating older subsidence models that assumed fewer wells. On a smaller scale, well failures lead to lost production, and a replacement well may be relocated to another part of the field, both of which affect subsidence predictions.

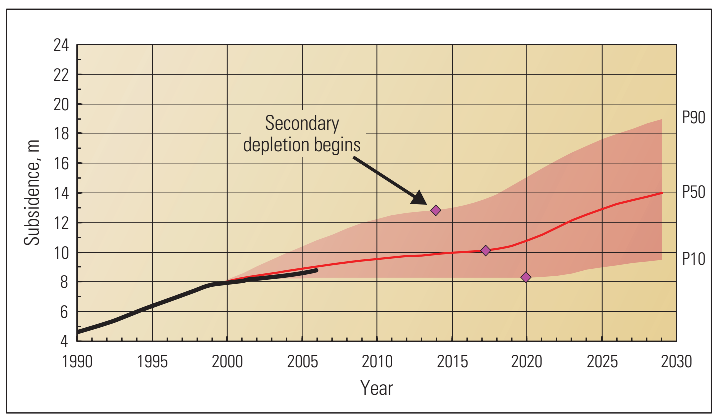
ConocoPhillips runs a number of models based on different scenarios to obtain a probabilistic view of reservoir performance, highlighting the 10%, 50% and 90% likelihood scenarios, termed P10, P50 and P90, respectively (below right). One of the main variables in the simulations is reservoir-management scenarios, such as the timing of secondary depletion, or blowdown—when waterflooding stops and pressure is allowed to decline again. In addition to the influence of well failures and changes in the number of producing wells already mentioned, the potential uses of CO_2 or air injection also potentially affect subsidence predictions. With this in mind, the subsidence model has to be updated regularly to reflect ongoing changes in reservoir management.



^ Water-induced chalk compaction. Producing from the chalk increases the average effective stress (from red circle at *Start*) and moves the elastic envelope outward. Waterflooding alters the material state; if the stress condition were allowed to change, the endcap would shrink (gray shading). However, the imposed stress condition (blue circle) has not changed, so the material deforms by compacting rapidly, essentially keeping the endcap in its original position. In a porosity-stress type curve (*inset*), this waterflood-induced behavior appears as a volume loss at constant stress, which is a departure from the behavior without waterflood (dashed curve). The volume change might occur over an extended time period, particularly in low-permeability chalk.

Time-Lapse Monitoring of Compaction

The Valhall field is a large chalk field about 21 km [13 mi] south of Ekofisk field in the Norwegian sector of the North Sea. It also has experienced significant reservoir compaction and seabed subsidence. The upper producing formation, the Tor formation, has original porosity exceeding 50% in places, and the more competent Hod formation has porosity as high as 40%. Production by operator Amoco, now BP, began in 1982, and seafloor subsidence at the platform complex in the center of the field now exceeds 5.6 m [18.4 ft]. The current subsidence rate is about 20 cm/yr [7.8 in./yr]. Production to date has been in excess of 550 million bbl [87 million m^3], with almost an equal amount of producible reserves remaining in place.[28]



^ Probability models for Ekofisk field. Subsidence results depend on the field-management plan for the field, so multiple subsidence models have been run. Results of the 10%, 50% and 90% likelihood models (P10, P50 and P90, respectively) are shown, with other results represented by the shaded area. The primary parameter causing difference in these models is the date to begin secondary depletion, or blowdown (diamonds).

25. Sylte JE, Thomas LK, Rhett DW, Bruning DD and Nagel NB: "Water Induced Compaction in the Ekofisk Field," paper SPE 56426, presented at the SPE Annual Technical Conference and Exhibition, Houston, October 3–6, 1999.

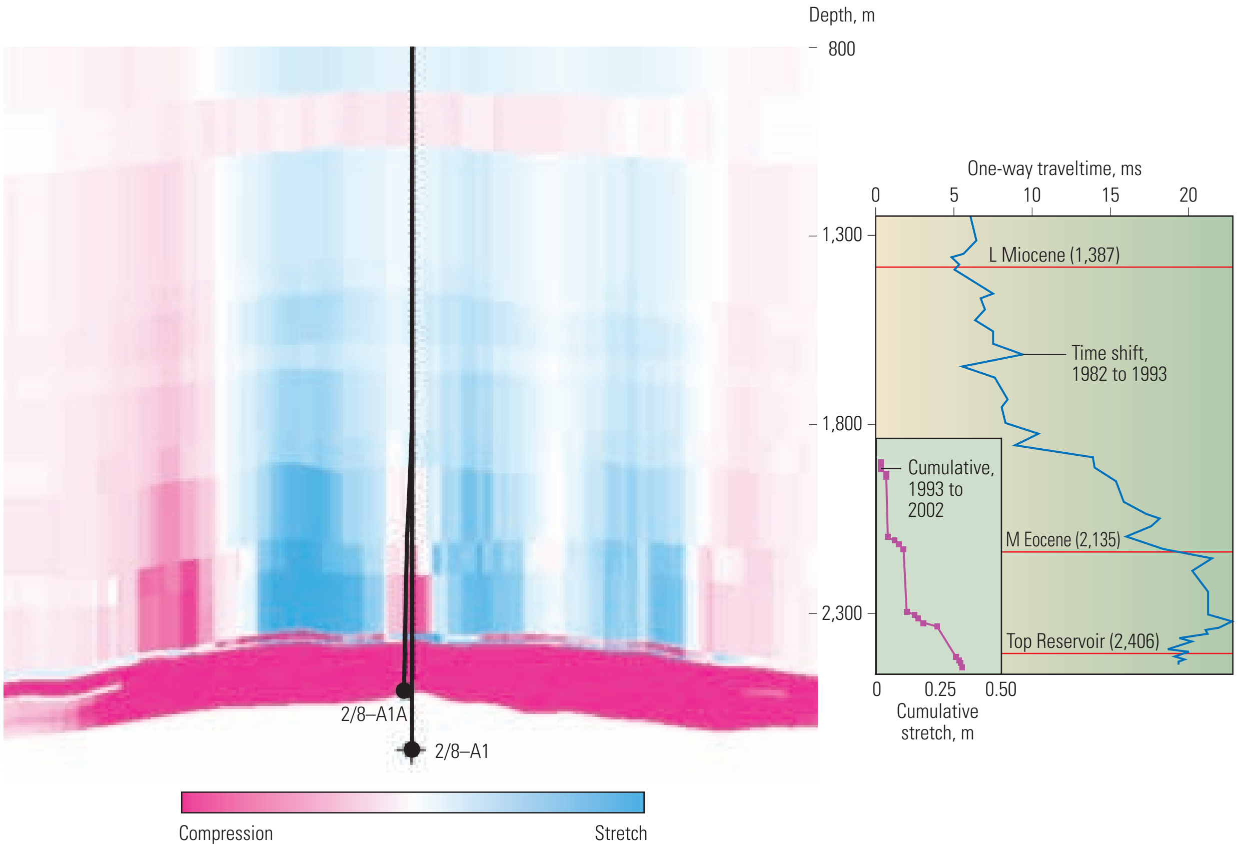
    For a detailed discussion of early work on water-induced compaction: Andersen MA: *Petroleum Research in North Sea Chalk*, Joint Chalk Research Monograph, RF-Rogaland Research, Stavanger, 1995.

26. Andersen MA: "Enhanced Compaction of Stressed North Sea Chalk During Waterflooding," presented at the Third European Core Analysts Symposium, Paris, September 14–16, 1992.

27. Korsnes RI, Strand S, Hoff Ø, Pedersen T, Madland MV and Austad T: "Does the Chemical Interaction Between Seawater and Chalk Affect the Mechanical Properties of Chalk?," presented at Eurock 2006, Liège, Belgium, May 9–12, 2006.

28. Barkved OI and Kristiansen T: "Seismic Time-Lapse Effects and Stress Changes: Examples from a Compacting Reservoir," *The Leading Edge* 24, no. 12 (December 2005): 1244–1248.

    For an overview of Valhall field: Barkved O, Heavey P, Kjelstadli R, Kleppan T and Kristiansen TG: "Valhall Field—Still on Plateau After 20 Years of Production," paper SPE 83957, presented at the SPE Offshore Europe 2003, Aberdeen, September 2–5, 2003.



^ Overburden stretch in the Valhall field. One-way traveltimes from a vertical seismic profile (VSP) in Well 2/8-A1 obtained in 1982 were subtracted from similar measurements in 2/8-A1A, obtained 60 m away in 1993 (*right*). The increasing traveltime is thought to be caused by a stretching in the overburden. Radioactive markers in the 2/8-A1A well show that stretching continues from 1993 through the most recent CMI survey in 2002 (*inset, right*). A loosely coupled geomechanical model over the period from 1992 through 2002 confirms this behavior (*left*). In this model, shades of red represent compression, and shades of blue are extension. The section between the middle Eocene and the top of the reservoir may be showing a local stress arch, with the traveltime change stopping and then reversing, and the geomechanical model result showing compaction.

Well failures were a serious problem, particularly in the 1980s. They were linked to formation compaction and subsidence in the overburden. The operator has used several methods of time-lapse evaluations to understand field behavior.

In 1982, the first development well, 2/8-A1, was drilled directly beneath the platform complex. In 1993, the well failed and was replaced by another vertical well, the 2/8-A1A, approximately 60 m [200 ft] away. The operator obtained a vertical seismic profile (VSP) when drilling each of the wells. The 60-m separation is close enough that the results can be compared (above).[29] The difference in the traveltime between the 1982 and 1993 surveys indicates a decrease in velocity that increases with depth, down to the middle Eocene. This change in traveltime is consistent with stretching of the shale formations.

Both the A1 and A1A wells were equipped with radioactive markers to monitor formation strain; the A1A well has markers in several intervals in the overburden shale. Results in the overburden from CMI Compaction Monitoring Instrument measurements are consistent with extensional strain that is greater just above the producing chalk and declines upward.

The crestal area of the field is highly productive. Both the geomechanical model and the VSP results indicate the same anomaly in this area. Just above the reservoir around Well A1A there is some overburden compaction and traveltime speedup where one would expect extension and traveltime slowdown. This could be the result of drainage from the overburden or

29. Kristiansen TG, Barkved OI, Buer K and Bakke R: "Production Induced Deformations Outside the Reservoir and Their Impact on 4D Seismic," paper IPTC 10818, presented at the International Petroleum Technology Conference, Doha, Qatar, November 21–23, 2005.

30. Graben are fault blocks that are downthrown relative to their surroundings, and horsts are the adjacent upthrown blocks. A horst and graben structure is typically formed by normal faulting in areas of rifting or extension.

31. Kristiansen TG, Barkved O and Pattillo PD: "Use of Passive Seismic Monitoring in Well and Casing Design in the Compacting and Subsiding Valhall Field, North Sea," paper SPE 65134, presented at the 2000 SPE European Petroleum Conference, Paris, October 24–25, 2000.

32. Kristiansen TG: "Drilling Wellbore Stability in the Compacting and Subsiding Valhall Field," paper IADC/SPE 87221, presented at the 2004 IADC/SPE Drilling Conference, Dallas, March 2–4, 2004.

33. Sayers CM: "Sensitivity of Time-Lapse Seismic to Reservoir Stress Path," *Geophysical Prospecting* 56, no. 3 (May 2006): 369–380.

Sayers CM: "Stress-Dependent Seismic Anisotropy of Shales," *Geophysics* 64, no. 1 (January–February 1999): 93–98.

Holt RM, Bakk A, Fjær E and Stenebråten JF: "Stress Sensitivity of Wave Velocities in Shale," *Expanded Abstracts*, Society of Exploration Geophysicists International Exposition and 75th Annual Meeting, Houston, November 6–11, 2005: 1593–1596.

a stiffer lithology that does not stretch as easily, but most likely results from a local stress-arch effect.

The Valhall field is a patchwork of horsts and graben, with chalk thin above the horsts and thick over the graben.[30] The amount of compaction in any area is related to the chalk thickness, among other factors, so the degree of compaction across the field is also a patchwork. There is a similarly complex response in the overburden model results, including local stress arches (right).

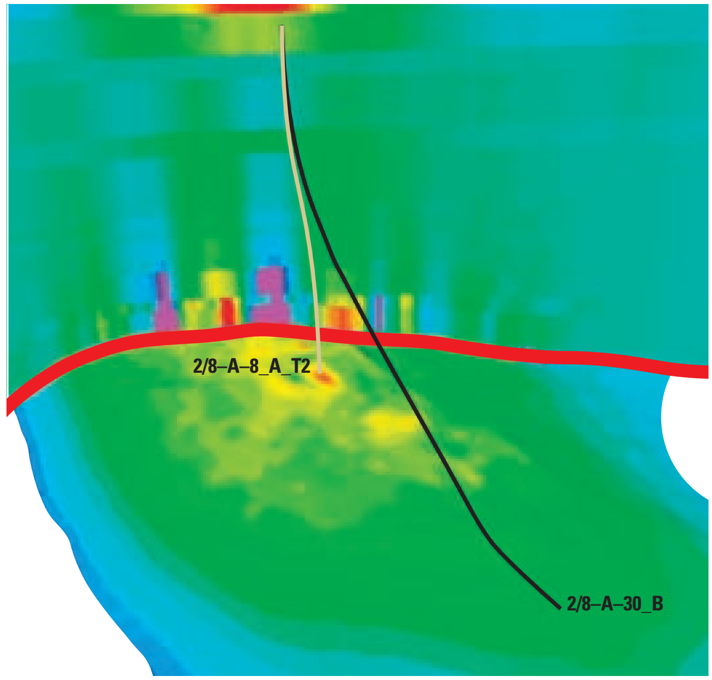
Differential movement in the overburden can reactivate existing faults, potentially causing well failure. Measured microseismic events correlate with locations of these faults.[31] An extensive study of overburden well failures led operator BP to abandon an extended-reach drilling program based at platforms in the center of the field in favor of unmanned satellite platforms in the north and south flanks of the field.[32] Wells from these platforms could avoid major faults in the highly compacting central portion of the field.

BP developed complex rock physics models for Valhall in the chalk and in the overburden. The overburden geomechanical model includes failure criteria specific to the shales and parameter values that depend on distance from the compacting formation. Anisotropy parameters, which vary as a function of stress path, change because of localized unloading in the shale when a stress arch forms.[33]

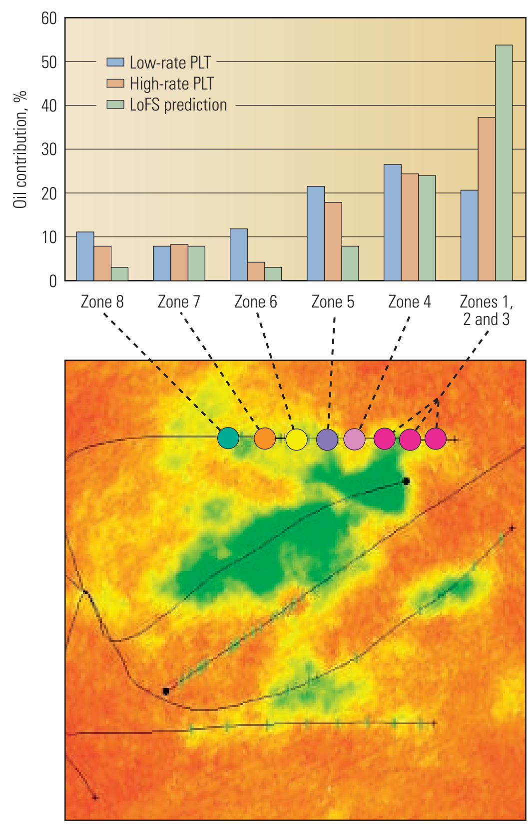
The dynamic response of the Valhall field to production and the large volume of remaining oil in place led BP to install a permanent array of seismic receivers in the seabed over the field in 2003. This life of field seismic (LoFS) project allows BP to repeat seismic surveys several times a year. The company can follow compaction changes in and around the reservoir every few months.

The LoFS response can also be used to monitor production around specific horizontal wells. For example, a horizontal well was added in an area that had several existing and abandoned producers. After a period of 12 months, the time-lapse seismic results showed an expanded compaction zone around the well. The production estimated from producing zones in that well compared reasonably well with a production-logging tool response (right).

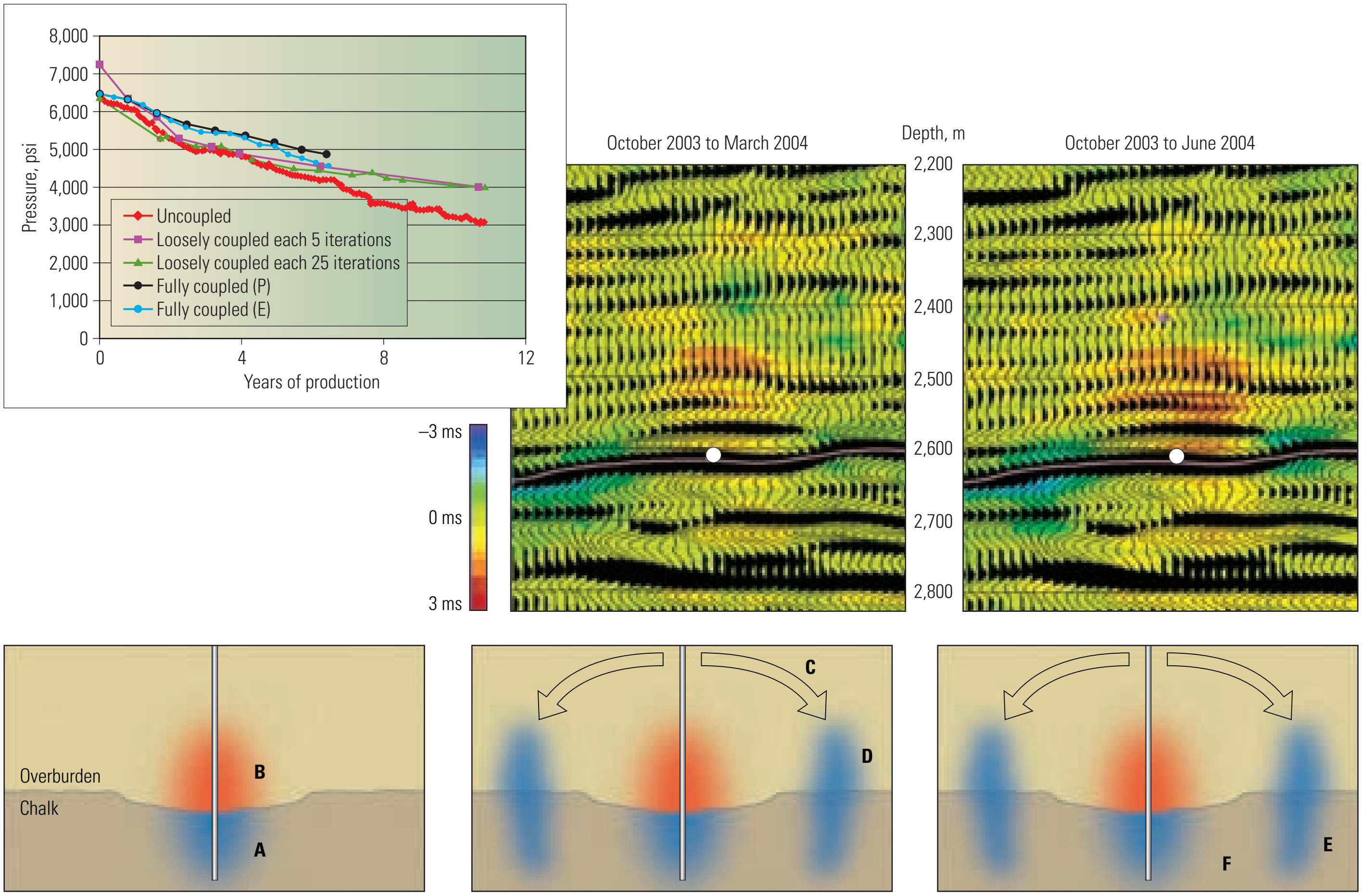
These time-lapse seismic studies also showed possible stress arching near a horizontal well. The compression and extension seen in these cross sections echoed similar results BP obtained from



^ Horsts and graben. The Valhall field contains horst and graben structures that affect the geomechanical model results. This composite image has a vertical section above the red line and a near-horizontal view following the top chalk below the red line. The model output is shown as velocity changes; increase is shown in red and yellow, and decrease is shown in blue. These colors also correspond to compaction (yellow and red) and extension (blue). The horst and graben structure of the field results in alternating areas of compaction and extension in the vertical section due to differential formation compaction and formation of arches in the overburden.



> Comparing time-lapse seismic surveys and production logging. The 18-month time-lapse seismic survey (*bottom*) locates several horizontal wells in this part of the field with depletion indicated by acoustic impedance difference, which relates to compaction (increasing from orange to yellow to green). The horizontal well near the top of this image had several perforated zones (filled circles). The majority of the production comes from the toe of the well, as determined by a production logging tool (PLT) at low (blue) and high (red) flow rates (*bar chart*). An estimate based on the change in acoustic impedance also yields a reasonable prediction of flow rate (green).



^ Stress arching and pressure effects in the Valhall field. Reservoir engineers have had difficulty matching the pressure decline using conventional modeling. An uncoupled model using an ECLIPSE flow model with a VISAGE mechanical model had a pressure decline that was more rapid than that experienced in the field (*top left*). Loosely coupling these models resulted in a slower pressure decline. Two versions were run, using either 5 or 25 flow-model iterations between each geomechanical-model step. With the VISAGE VIRAGE fully coupled model, the pressure decline was even slower and more in line with field experience, using both an elastic (*E*) and a plastic (*P*) geomechanical formulation. This fully coupled model allowed BP to understand the process (*bottom*). Production drawdown compacts the near-well chalk (A), stretching the overburden above (B). A stress arch forms, shifting support for the weight of shallower overburden laterally (C), resulting in a compression of the overburden and formation far from the wellbore (D). The coupled model shows that the compressed chalk (E) cannot drain to the wellbore quickly because of low chalk permeability (F). As a result, the overpressure in the pore fluid supports part of the stress-arch load. Uncoupled models do not treat these events as simultaneous, and so miss the interaction of stress arching and pore-pressure transfer. Stress arching like this has been seen in the field. Seismic images from the field show differences between a life of field seismic (LoFS) survey taken before production began and four months (*top center*) and six months (*top right*) after it began in a horizontal well (white circle) within the productive formation (bounded by dark reflectors). The well trajectory goes into the plane of these images. Extension, associated with traveltime increase (orange), appears to develop within certain layers above the well. On either side of the well, a traveltime decrease (blue and dark green) above and below the formation may indicate compression of the side supports of a stress arch. Behavior within the formation cannot be seen in the time-lapse seismic images.

a fully coupled flow and geomechanical model of Valhall field (above).[34]

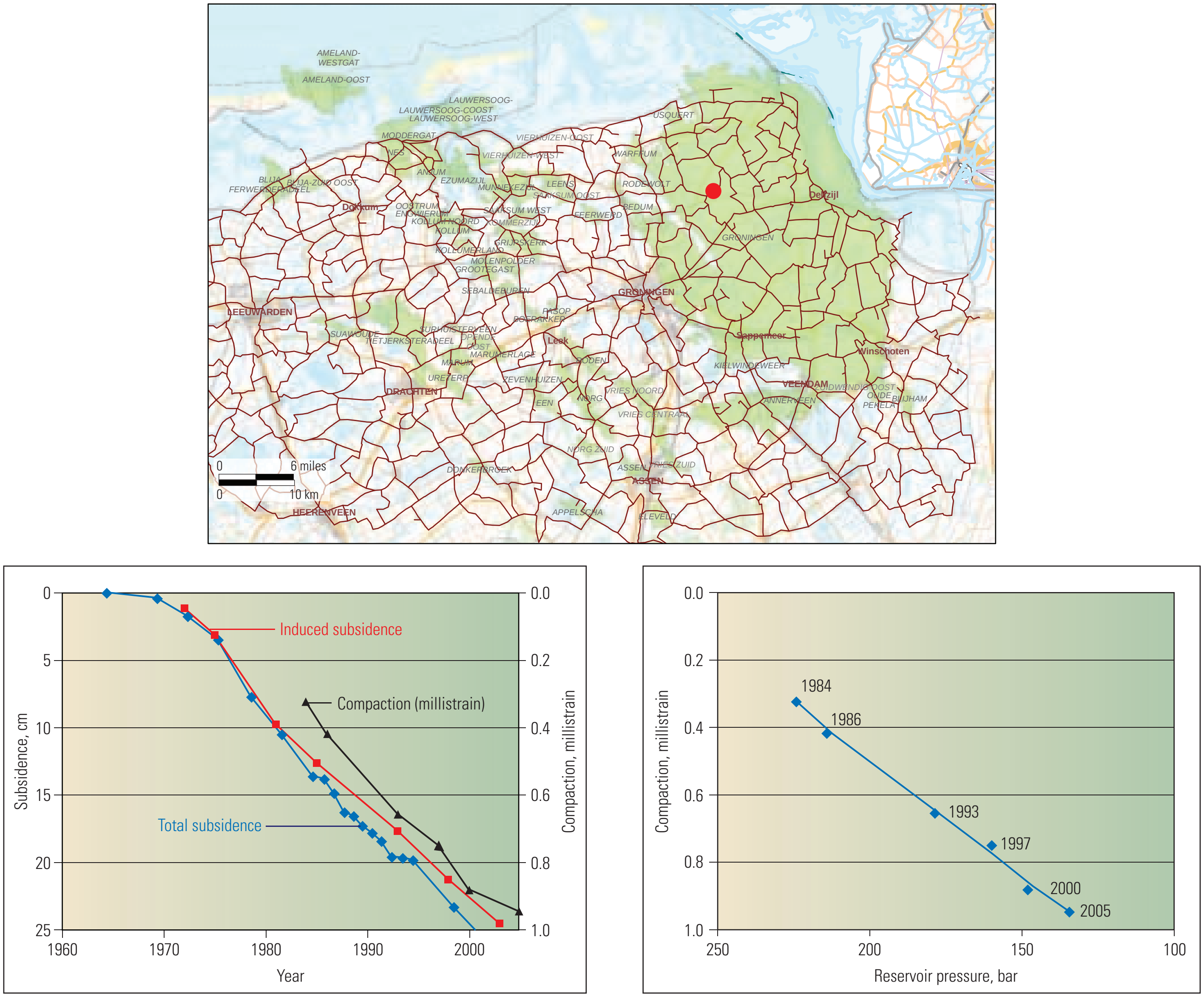
Models of Valhall field have predicted a quicker pressure decline than that typically seen in the field. However, the formation pressure of the fully coupled model was closer to the slow falloff seen in the field. BP saw more local arching in the fully coupled model, which helps to explain the difference between coupled and uncoupled models.

The slower pressure decline results from the slow drainage in this chalk formation with low matrix permeability. Above compacting chalk, as that near a producing well, the overburden stretches and a stress arch forms, redistributing stresses laterally to chalk at a distance from the well. This added load deforms that distant chalk and increases its pore pressure, but the tight chalk acts as a choke that is only partially open, preventing rapid drainage to the wellbore. This simultaneous determination of pressure, volume change and permeability requires full coupling to occur in the simulation. BP engineers found that this mechanism occurs at smaller scales—down to sets of pores—and at larger scales between horst and graben structures. The company is seeking ways to incorporate this behavior in the simpler models.

These examples show the importance that BP places on the LoFS results. The operator believes that multidisciplinary integration of seismic results with other subsurface data is needed to capture the value of these frequent time-lapse seismic results.[35]

34. Kristiansen TG and Pattillo PD: "Examples From 20 Years of Coupled Geomechanics and Fluid Flow Simulation at Valhall," paper P06, presented at the 12th SPE Bergen One-Day Seminar, Bergen, Norway, April 20, 2005.

35. Barkved OI, Kommedal JH, Kristiansen TG, Buer K, Kjelstadli RM, Haller N, Ackers M, Sund G and Bakke R: "Integrating Continuous 4D Seismic Data into Subsurface Workflows," paper C001, presented at the 67th EAGE Conference and Exhibition, Madrid, Spain, June 13–16, 2005.



^ Compaction and subsidence measurements, and the network of monitoring stations over the Groningen field. An extensive network of surface monitoring stations (*top*) covers several fields (green shading), including the large Groningen field in the northeast portion of this area. A benchmark near the center of the field (red circle) is also near a well used for compaction monitoring. Total measured subsidence (*bottom left*, blue) encompasses all effects, including gas production. Geodetic deformation analysis using data from all stations is required to derive subsidence induced only by gas production (red). Compaction in a nearby monitoring well (black) follows the same trend (note that the units are different). Replotting the Groningen data indicates that compaction increases linearly with pressure decline (*bottom right*).

Monitoring Ground Level

The Groningen gas field lies beneath the coastal plain of The Netherlands. It has been operated by Nederlandse Aardolie Maatschappij B.V. (NAM), a joint venture between Shell and ExxonMobil, since its discovery in 1959. The sandstone formation has porosity of 10% to 20% and is competent, meaning that it does not experience the type of pore collapse that occurs in the Ekofisk and Valhall fields. However, the formation is about 100 to 200 m [328 to 656 ft] thick, so even though its elastic strain is small, the total displacement of the reservoir boundaries is not. The formation is about 3 km [9,840 ft] deep. This depth, in combination with the reservoir's areal extent—a diameter of about 30 km [18.6 mi]—means that subsidence over the center of the field is about the same as the reduction in formation thickness.

In the low-lying areas of The Netherlands, water management is a primary concern. Protection against water encroachment may require embankment and reinforcement of levees, building water-control structures or installing pump stations. NAM provides funds when additional measures are required to combat the consequences of gas-production-induced subsidence. Knowing the amount of subsidence and its eventual extent is critical for this effort.

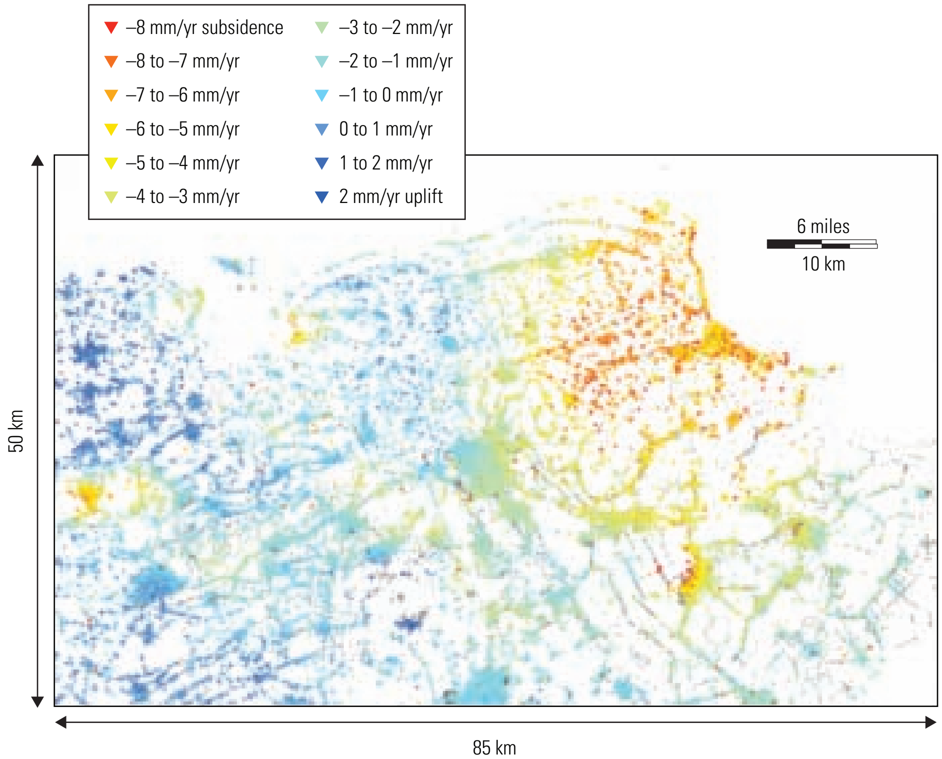
NAM operates several fields in this area, all of which are covered by a subsidence-monitoring program. In addition to subsidence from these fields, the adjoining aquifers also deplete and compact. A series of elevation surveys has monitored subsidence over this area, starting in 1963 (above). A contractor carries out the surveys in accordance with Dutch government guidelines. The leveling surveys measure the total subsidence, and geodetic deformation analysis using data from all stations is required to determine the subsidence induced by gas production.

Other monitoring takes place in wells in the fields. Radioactive bullets indicate formation compaction in several wells, and there are also several locations for monitoring the compaction of surface sediments. The radioactive bullet locations are monitored every five years using the Formation Subsidence Monitoring Tool (FSMT). Since monitoring began in 1983, formation compaction has increased linearly with pressure decline.

Shallow compaction is monitored in wells about 400 m [1,312 ft] deep, by accurately measuring the change in distance from surface to the bottom of the well. Measurements over Groningen field were made from 1970 through 2003 in 14 shallow wells. These observations have resulted in reliable trends, but those trends are location-specific and cannot be extrapolated areally. The shallow compaction-monitoring program over Groningen has been discontinued, but it is continuing over some outlying fields where monitoring began only in 1992.

The results of surface-subsidence and formation-compaction measurements are incorporated into a geomechanical model that is loosely coupled to a reservoir flow model. Results indicate that the maximum subsidence over Groningen in 2003 was about 24.5 cm [9.65 in.].

NAM also forecasts subsidence to the year 2050 and, at a 95% reliability interval, predicts a subsidence bowl with a maximum depth between 38 and 48 cm [15 and 19 in.], and a most probable value of 42 cm [16.5 in.]. The prediction completed in December 2005 is not very different from the 2000 prediction, with discrepancies mostly in the aquifer areas where well control is not available.



^ PS-InSAR measurement of the Groningen field. The extent of the Groningen field—yellow and red colors in the upper right of this map—is apparent in the measurement of permanent scatterers (PS) from a satellite InSAR measurement (in descent). The maximum subsidence rate over the center of the Groningen field is about 8 mm/yr [0.3 in./yr] averaged over the period from 1993 to 2003.

Prior to production of hydrocarbons from these fields, this part of The Netherlands had had no recorded seismic activity. Since 1986, there have been several light tremors, some causing minor damage to property. NAM began monitoring seismicity and settled claims with property owners. The Netherlands established a new mining law in 2004 that outlined a formal claims procedure.

Looking to the future, NAM has investigated the use of InSAR with permanent scatterers (PS) over Groningen field. In close cooperation with Delft University of Technology, NAM investigated the PS-InSAR technique for the Groningen field with a total of 104 interferograms obtained in the period 1993 to 2003 from the satellites ERS1 and ERS2. About two-thirds of those measurements were obtained while the satellite was descending toward the horizon. The PS density over the field is lower than in an urban environment, but there are enough scatterers to provide sufficient spatial coverage of the subsidence bowl (above).[36]

Although the PS-InSAR results reflect the approximate shape and degree of subsidence as determined by the leveling survey, there were discrepancies between the ascending and descending measurements. NAM continues to evaluate this technology, but more analytical understanding is needed before relying on this method for the Groningen field. Other companies are studying its use elsewhere, such as over diatomite fields in California.

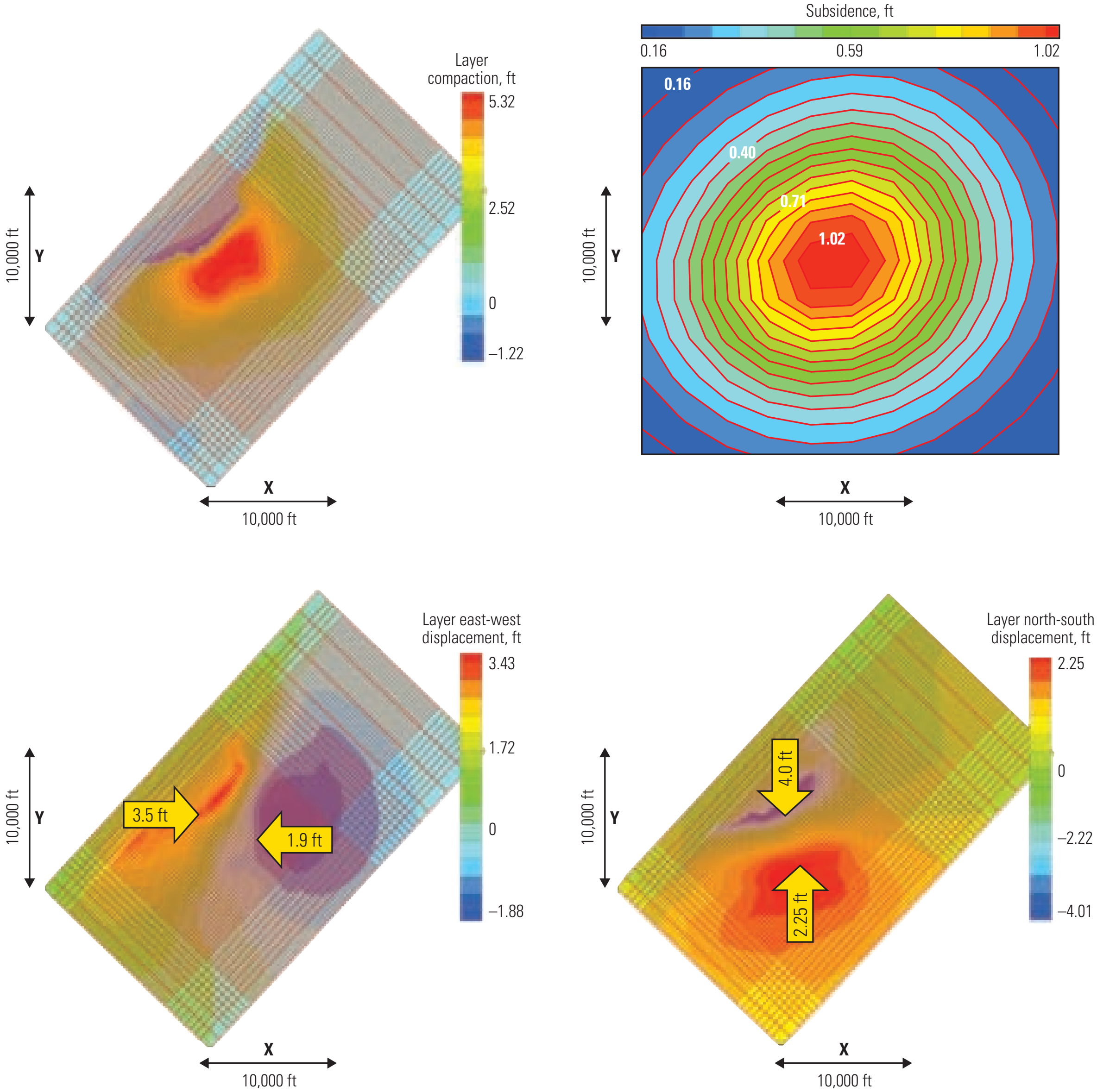
Some fields in the extended Groningen area are not yet in production, pending approval of a production plan that incorporates subsidence monitoring and control. As an example of the extent of these plans, some small fields underlie environmentally sensitive tidal flats. The proposed plan calls for tempering production to a rate that matches the natural rate of sedimentation in the tidal areas. Thus, although the producing formation will compact, the bird feeding grounds in the tidal flats will remain at the same level. Clearly, this is an example of a company working to minimize the impact of compaction and subsidence on the environment.

36. Ketelaar G, van Leijen F, Marinkovic P and Hanssen R: "On the Use of Point Target Characteristics in the Estimation of Low Subsidence Rates Due to Gas Extraction in Groningen, The Netherlands," presented at FRINGE05, the Fourth International Workshop on ERS/Envisat SAR Interferometry, Frascati, Italy, November 28–December 2, 2005.

37. Li X, Mitchum FL, Bruno M, Pattillo PD and Willson SM: "Compaction, Subsidence, and Associated Casing Damage and Well Failure Assessment for the Gulf of Mexico Shelf Matagorda Island 623 Field," paper SPE 84553, presented at the SPE Annual Technical Conference and Exhibition, Denver, October 5–8, 2003.

38. For more on sustained casing pressure: Abbas R, Cunningham E, Munk T, Bjelland B, Chukwueke V, Ferri A, Garrison G, Hollies D, Labat C and Moussa O: "Solutions for Long-Term Zonal Isolation," *Oilfield Review* 14, no. 3 (Autumn 2002): 16–29.

Brufatto C, Cochran J, Conn L, Power D, El-Zeghaty SZAA, Fraboulet B, Griffin T, James S, Munk T, Justus F, Levine JR, Montgomery C, Murphy D, Pfeiffer J, Pornpoch T and Rishmani L: "From Mud to Cement—Building Gas Wells," *Oilfield Review* 15, no. 3 (Autumn 2003): 62–76.



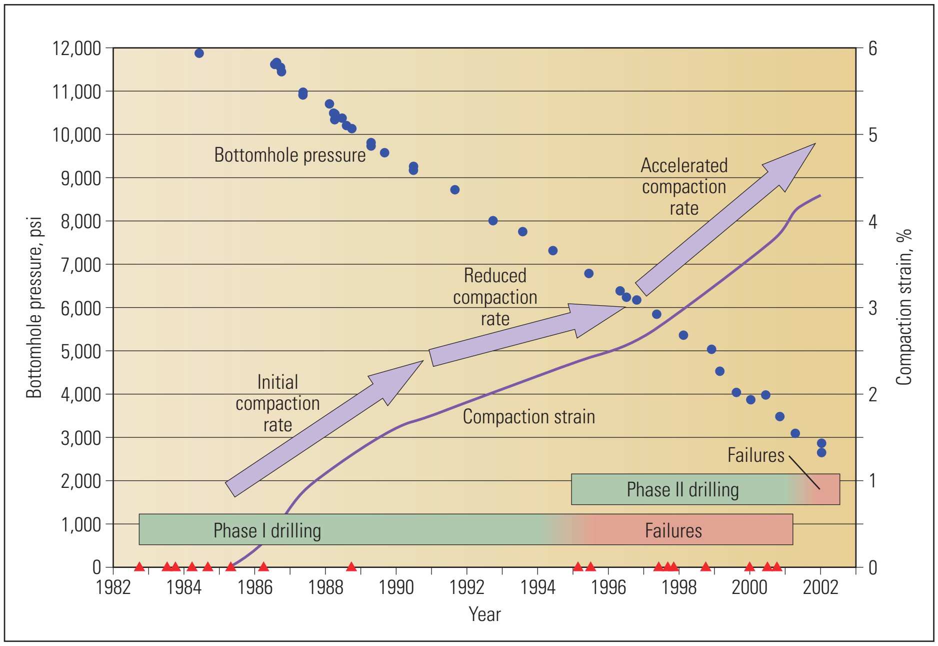
^ Compaction and subsidence in the Matagorda Island Block 623 field. The maximum formation compaction for the Siph (D) 120/122 reservoir is about 5.32 ft [1.62 m] (*top left*), with lateral movement toward the center of the field (*bottom left and right*). The mudline subsidence, centered over the field, has a maximum of 1 ft [0.3 m] (*top right*).

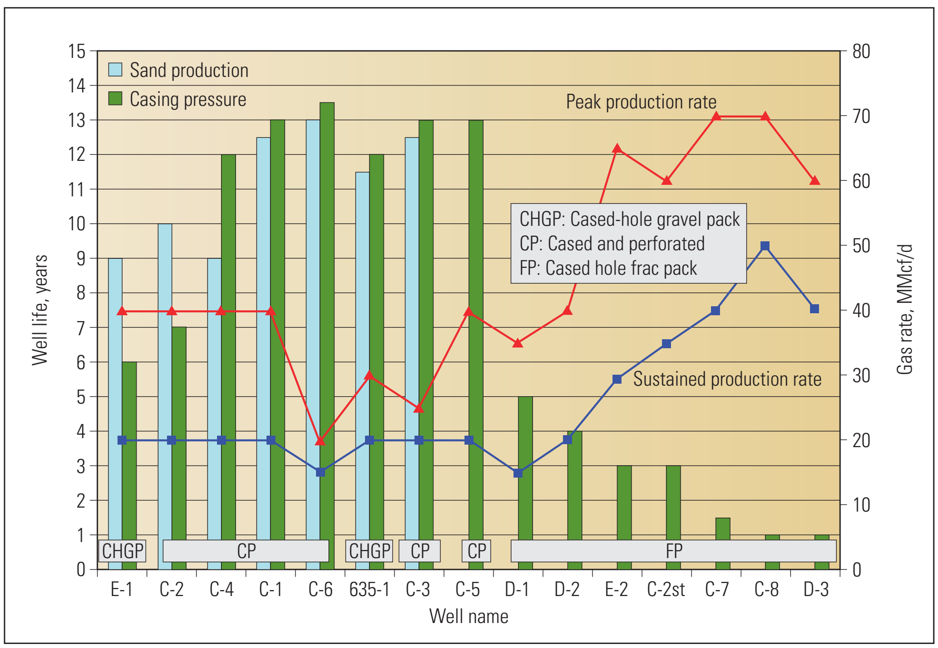
Mitigating Compaction-Induced Damage in the Gulf of Mexico

Problems with compaction have also occurred in the Gulf of Mexico. The Matagorda Island Block 623 field on the continental shelf experienced well failure or casing damage in all 17 development wells producing from the main reservoir during the past 16 years of production.[37] The well failures involved sand production and sustained casing pressure, and the casing damage in both reservoir and overburden sections included casing offset, tight spots and parted or collapsed casing.[38] Operator BP, formerly Amoco, performed a comprehensive analysis to determine the root cause and provide practical advice to apply to replacement wells.

This gas field with 3 Tcf [85 billion m^3] of reserves comprises a stacked series of highly overpressured sands and sits at depths between 9,000 and 13,500 ft [2,743 and 4,115 m] subsea. The overburden is also highly overpressured up to a depth of about 8,500 ft [2,590 m] subsea. The main reservoir, the Siph (D) 120/122 with a gross-pay thickness of 500 ft [152 m], had an initial formation pressure of 12,000 psi [82.7 MPa] at 13,100 ft [3,993 m] subsea.

The formation rock is poorly consolidated to well-cemented, fine-grained sandstone, with porosity ranging from 20 to 32%, and permeability from 10 to 2,843 mD. The pore-volume compressibility is a function of rock type and stage of depletion and varies from 4 x 10^{-6} to 17 x 10^{-6}/psi [6 x 10^{-4} to 25 x 10^{-4}/kPa]. As of April 2006, the reservoir had been depleted to a level of 1,417 psi [9.77 MPa]. From 1986 to 2000, the maximum reservoir compaction was 5.32 ft [1.62 m], with a subsidence bowl 1 ft [0.3 m] deep (above).





^ Well-failure history in the Siph (D) 120/122 formation. Phase I drilling occurred between 1982 and 1989, and Phase II drilling lasted from 1995 until 2001 (red triangles on axis, *top*). The first Phase I well failed in 1994, and the last one failed in 2001. Phase II wells failed more quickly. The pressure decline (points) was roughly linear with time. The formation had a high compaction rate (purple) early and late in field life, with a reduced rate in between. An analysis (*bottom*) showed that Phase I wells suffered sand production (light blue) before experiencing sustained casing pressure (green). The height of the bar is the length of well life before onset of the problem. The Phase II wells had shorter lives and no sand production. The peak (red) and constant (blue) well rates were significantly higher for Phase II wells.

Development occurred in three phases. Phase I wells were drilled between 1982 and 1989. Phase II wells were drilled between 1995 and 2001 (left). Failure in both phases occurred at about 2 to 3% compaction strain. Phase III wells were drilled after the root-cause study of the earlier well failures.

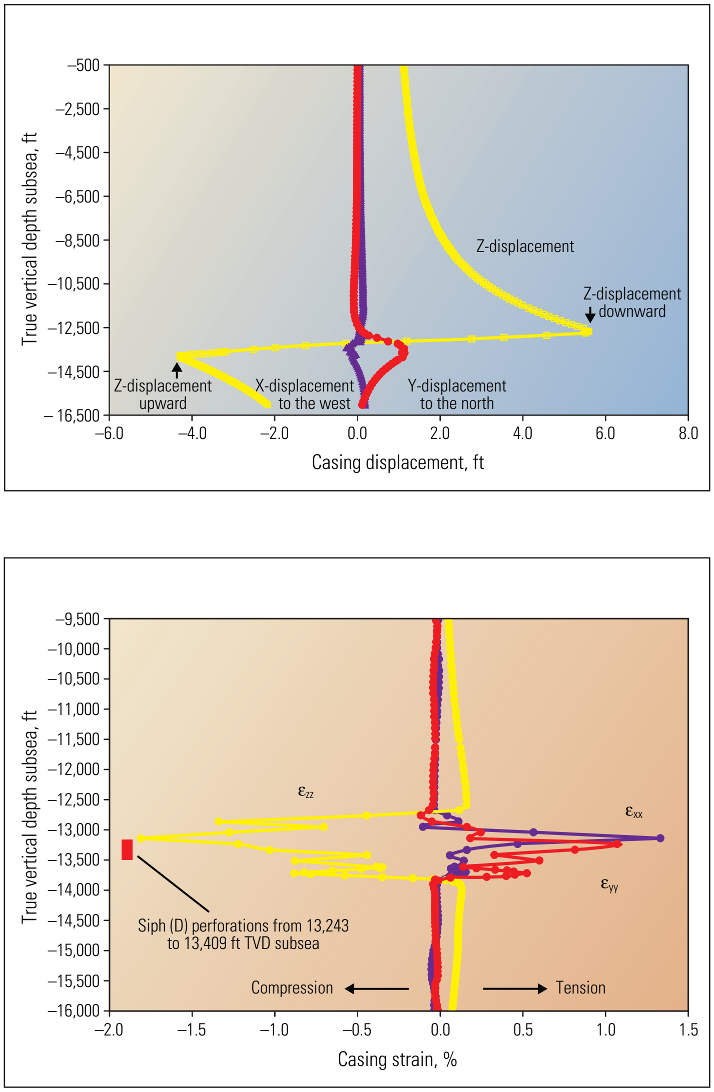
Sustained casing pressure in Phase I wells typically occurred about six months after a significant increase in sand production. Most of the Phase I failures in the overburden occurred near the top of the reservoir; none were associated with known faults. Wells failed after 10 to 13 years of production.

Casing damage in Phase II began much earlier in well life, after one to five years of production, and had a high correlation with major fault location. No sand production had been observed up to the time of the evaluation in 2001, but all wells developed sustained casing pressure. In addition to a much higher rate of production in Phase II wells, they were all completed as frac packs; Phase I wells had a variety of completion techniques, but none were frac packed.[39]

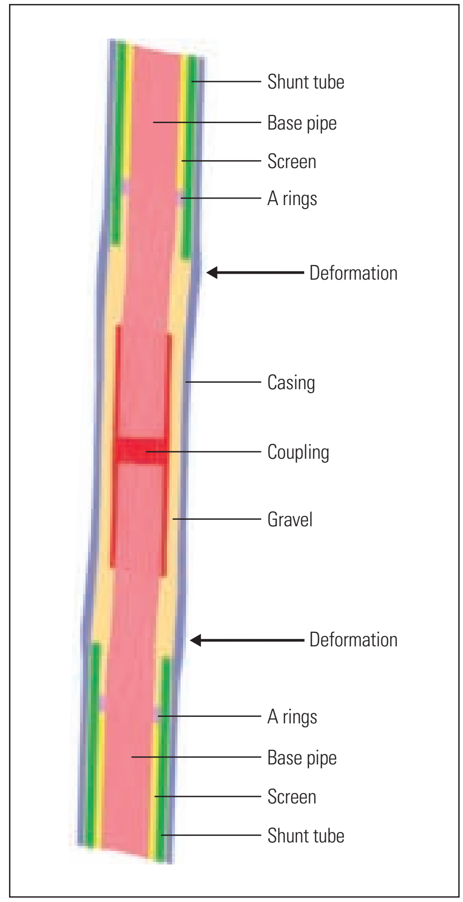
Operator BP conducted an evaluation of the failure modes using reservoir and well models and the geomechanical behavior of the formation and overburden. In the center of the field, formation compaction resulted in enough casing strain to cause failure (next page, left). Another geomechanical model examined fault and bedding-plane movement. It indicated that the faults would not become reactivated until depletion had reached about 9,000 psi [62 MPa], which occurred about one year after the completion of the Phase II drilling program. This result explains why no Phase I well failures were attributable to fault movement.[40]

Two completion methods used in this field were also modeled. Well orientation ranged from vertical to horizontal. A connection typical of casing and liner overlap in the overburden in Phase II wells was modeled, and it indicated that a vertically oriented well can accommodate only about 2% compaction in the surrounding formation before reaching a 10% plastic strain, the design limit for the casing. In contrast, the model showed that a horizontal well can accommodate almost 8% formation compaction before reaching the design limit.[41]

The second completion model examined a frac-pack assembly, also typical of Phase II wells. Again, a horizontal wellbore can accommodate more strain, 12% as opposed to 3% for a vertical orientation, before reaching the 10% design limit (next page, right).



^ Casing displacement and strain in a vertical well. Formation compaction led to significant casing displacement within the Siph (D) formation (*top*). The compressive strain, ε, reached about 1.8%, with tensile lateral strains (*bottom*).



^ Finite-element grid of a frac-pack under compaction. Formation compaction led to localized buckling at the casing (blue) between the screen (yellow) and the coupling (red).

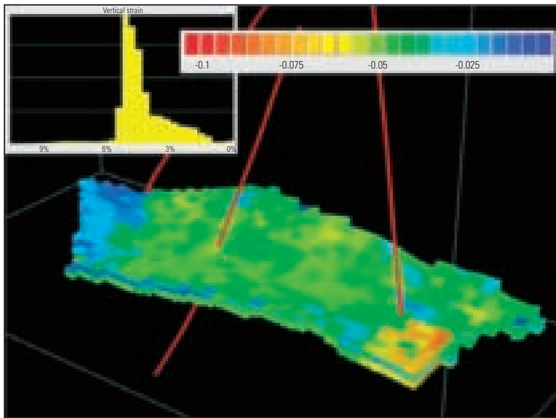
The evaluation indicated that three of five key Phase II wells would experience the 2 to 3% compaction strain before the end of the field life, so replacement wells would be necessary. A third phase of drilling has begun, but only about 1,800 psi [12.4 MPa] of depletion is left before abandonment, resulting in less than 1.5% additional compaction strain. This is insufficient to cause the completion to fail in the formation. However, the reactivated faults in the overburden will continue to move and potentially shear the casing.

Phase III wells were designed to counteract the fault-slip problem and to strengthen the pressure-seal capability of the wells; three wells have been drilled using the improved design. In the overpressured overburden, the annulus was back reamed to 15 in. [38 cm] and left uncemented to avoid the potential of shearing at reactivated faults. The 7⅝-in. liner was tied back to the 11⅞-in. casing shoe and cemented inside the 9⅝-in. casing, strengthening the well both structurally and hydraulically.

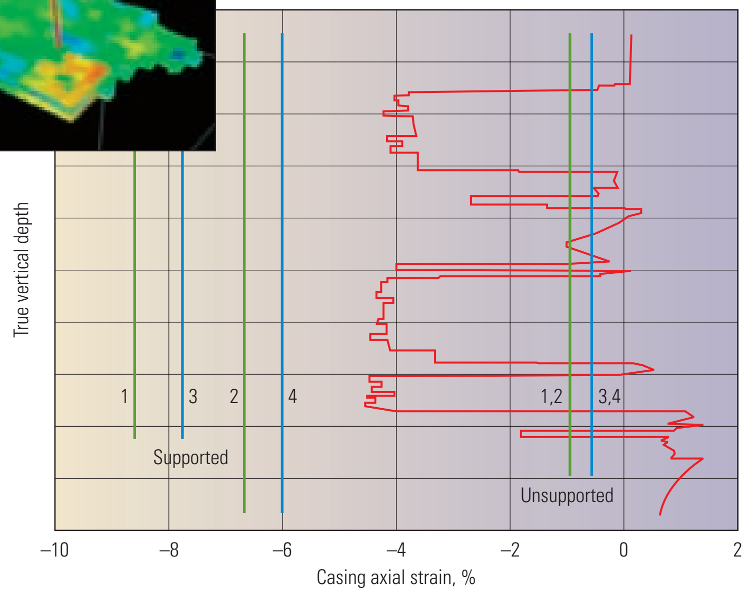
The Phase III wells are producing at high, stable rates, about 15 MMcf/d [425,000 m^3/d] for each well. The Matagorda Island study has provided BP with a methodology for other Gulf of Mexico fields. For example, the King West field, which had a much greater compressibility than the Matagorda Island field, was judged to be a low to moderate risk, because the expected pressure depletion is less.[42]

In another Gulf of Mexico field, a 3D mechanical earth model was developed to aid drilling and to assess the impact of compaction on well stability and subsidence. This deepwater turbidite reservoir, operated by Murphy Oil, comprises interbedded sand and shale.[43] The model showed that vertical strain could reach about 8% in a high-porosity section of the field. Even in an area of the field with lower strain, the well could experience casing buckling if it were

39. For more on frac packs: Gadiyar B, Meese C, Stimatz G, Morales H, Piedras J, Profinet J and Watson G: "Optimizing Frac Packs," *Oilfield Review* 16, no. 3 (Autumn 2004): 18–29.
40. Li et al, reference 37.
41. Li et al, reference 37.
42. Li X, Tinker SJ, Bruno M and Willson SM: "Compaction Considerations for the Gulf of Mexico Deepwater King West Field Completion Design," paper SPE/IADC 92652, presented at the SPE/IADC Drilling Conference, Amsterdam, February 23–25, 2005.
43. Sayers C, den Boer L, Lee D, Hooyman P and Lawrence R: "Predicting Reservoir Compaction and Casing Deformation in Deepwater Turbidites Using a 3D Mechanical Earth Model," paper SPE 103926, presented at the First International Oil Conference and Exhibition in Mexico, Cancun, Mexico, August 31–September 2, 2006.



Case	Casing diameter and weight	Young's modulus of formation, psi
1	9 ⅞-in. 62.8 lbm/ft	147,000
2	9 ⅞-in. 62.8 lbm/ft	88,300
3	7 ¾-in. 46.1 lbm/ft	147,000
4	7 ¾-in. 46.1 lbm/ft	88,300



^ Formation and casing strain in a Gulf of Mexico turbidite field. The mechanical earth model indicates that the vertical strain in the formation may reach 8% (yellow and orange shades) in the part of the field that has the highest porosity (*top left*). Along a proposed well path near that high-porosity area, the compressive strain on casing exceeds 4% in the sand formations, with a tensile strain up to 1% in the interbedded shales (*graph*). These values are lower than the vertical formation strain because the well is deviated, but that deviation also introduces shear stresses to the casing. Four cases are identified in the table: two types of casing were analyzed, each for two values of formation Young's modulus. For the four cases, unsupported casing buckles when casing strain is less than 1% (*right* on graph). However, if it is supported by cement and formation, the casing can withstand compressive strain of 6% or more before buckling (*left* on graph), which indicates the predicted strains on casing are within acceptable limits if the casing is supported.

unsupported by cement and formation (above). This showed the importance of drilling an in-gauge borehole with casing centralized, having a good-quality cement job and producing in a way that avoids sand production.

Overcoming That Sinking Feeling

The struggle to control subsidence will go on. As the case studies illustrate, engineers and geoscientists continue to develop and employ new tools to understand and mitigate its effects.

Coupled flow and geomechanical simulators may become powerful weapons in the struggle, but at this time they are still considered too slow for day-to-day reservoir management. Application of time-lapse seismic studies to monitor compaction across large portions of reservoirs has made great strides over the past couple of years; satellite measurements have potential to provide equally large coverage for subsidence. Waterflooding has been used to combat subsidence for many years, but combining it with new methods of modeling and monitoring promises to make it a more precise and effective management practice.

Mitigating wellbore damage is at least partly an economic issue. With enough steel in the borehole, many more wells can be protected from compacting, stretching, or minor movement of faults. But that protection comes at a high cost. Advances in modeling are also helping to make intelligent completion choices.

New problems will foster new tools. The Sonic Scanner acoustic scanning platform provides information about conditions around a wellbore.[44] The tool measures shear-wave anisotropy as low as 2%. Its multiple depths of investigation can provide a radial profile of compressional and shear behavior several feet into a formation. Application of this tool in a dynamic, compacting environment may hold promise for new discoveries, and perhaps new ways to determine geomechanical parameters in situ.

Even though the city of Venice continues to subside today, by understanding the effects of water and gas extraction and shutting in those wells, planners brought the effects of man-made subsidence under control, dramatically slowing the rate at which the city sinks. Modeling, monitoring and logging reduce uncertainties relating to compaction of a reservoir, allowing companies to mitigate its effect in oil and gas fields. However, as in Venice, the struggle between nature and technology continues. —MAA

44. Arroyo Franco JL, Mercado Ortiz MA, De GS, Renlie L and Williams S: "Sonic Investigations In and Around the Borehole," *Oilfield Review* 18, no. 1 (Spring 2006): 14–33.