Time-lapse (4D) effect and reservoir sand production pattern in a mature North Sea field

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Sand production is not uncommon in producing fields. Its severity, however, remains a growing concern in many mature fields and deepwater reservoirs often characterized by poor consolidation. Reservoir sand production is simultaneously a source of concern and benefit in conventional and heavy oil production. Porosity increase and changes in local stress magnitude, which often enhance permeability, have been associated with severe sanding. On the other hand, sand production has been linked to a large number of field incidences involving loss of well integrity, casing collapse, and corrosion of downhole systems. It also poses problems for separators and transport facilities. The poorly consolidated Gudao reservoir in Shengli oil field, China, provides a typical example of casing failure, resulting from severe reservoir sanding (Figure 1). Sand-production-induced casing problems can vary from complete shearing to contortion of well casing depending on the severity of the sand flow.

Prominent among the causes of reservoir sanding are (among others) reservoir consolidation, well deviation through the reservoir, perforation size, depth of penetration, grain size, perforation-induced damages, capillary forces associated with water cut, flow rate, and most importantly in Forties Field, (UK North Sea) reservoir time-lapse strain resulting from pore-pressure depletion. Substantial strains (>0.2%) can be induced by the effective and shear stress changes on the reservoir rock. This strain is sufficient to severely degrade the reservoir grain cohesion by breaking the small amount of brittle grain-grain mineral cements, thereby reducing the sand strength (Zhang and Dusseault, 2004).

Papamichos et al. (2001) demonstrated, using a hollow cylindrical specimen, that cumulative sand production increases linearly with fluid-flow rate and effective stress. Observing the mechanism and accounting for all possible factors of sand production in a producing reservoir is difficult in practice. The task becomes harder with poor availability of field records; most sand production records are typically incomplete, wherever they exist.

Reservoir monitoring for pressure, temperature, and fluid production has long been a critical element of field exploitation to optimize hydrocarbon recovery. Time-lapse (also called 4D) seismic has joined borehole and production-based techniques in providing a measure of changes in the reservoir between the producer and injector wells. The importance and relevance of 4D seismic varies from identifying reservoir compartmentalization, monitoring fluid fronts and identifying by-passed oil (Meadows, 2008). Other applications include pressure monitoring, strain analysis and perturbation of local stress in the vicinity of the well (Hatchell and Bourne, 2005). Time-lapse seismic requires consecutive seismic volumes to be conformable in data acquisition and processing. Most recent 3D seismic campaigns have repeatability in mind right from the acquisition design stage for use as a base survey for later acquisition. However, such foresight has not always been the case, such that the challenge remains how best to compare two seismic volumes that are not conformable in acquisition or processing in order to compute changes in reservoir properties induced by depletion.

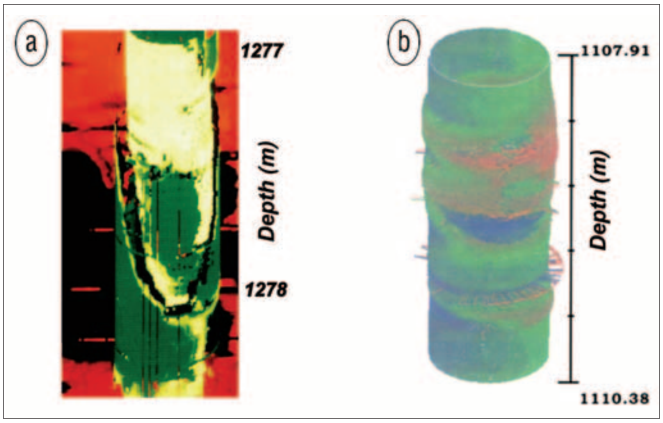

Figure 1. Examples of casing failure due to excessive sanding in the unconsolidated Gudao reservoir of the Shengli Field in China using ultrasonic televiewer. (a) Three-dimensional view of shear failure and (b) casing enlargement. Red patches in (b) show enlarged wellbore. (After Peng et al., 2007).

In this paper, we investigate sand-production patterns in several high-sand-producing wells in Forties Field. We search for contributing factors as well as a possible link between time-lapse effect and sand production/well failures. Forties Field, which lies in the UK sector of the North Sea, is approximately 180 km northeast of Aberdeen, Scotland. We observe that the magnitude of the production-induced strain, part of which is propagated to the base of the reservoir, is of the order of 0.2%, which is significant enough to induce the weakening of grain cohesion, thereby impacting the geomechanical properties of the reservoir. Our analysis of sand production in the field shows that, in addition to the well known causes of sanding (e.g., poor reservoir consolidation, high well angle of deviation through the reservoir and high flow rate), reservoir strain, resulting from pore-pressure depletion, also contributes significantly to reservoir sand production in Forties Field.

Production/pressure history and well failures

The reservoir of Forties Field comprises Late Paleocene submarine fan sands as well as mud and channel complexes. The Forties sandstone, (thickness of 100–200 m) can be divided into three units of roughly equal thickness. The initial fan advance is represented by the lowest unit, the Lower Main Sand, with the overlying Upper Main Sand being deposited as a fairly broad channel complex. Both units extend across the entire field and have not been further subdivided. The topmost unit, the Channel complex, which lies beneath a thick, monotonous section of gray-to-brown variably calcareous and carbonaceous mudstones ranging from upper Paleocene to Holocene (Thomas et al., 1974), consists of three major sandy channel systems (Delta/Echo, Bravo, and Alpha in order of decreasing age) and areas of interchannel mudstone. The youngest, Charlie Sand, is considered a distinct unit separated from the older sands by the Charlie Shale.

The Forties fans and channel complexes are generally friable. Porosity runs as high as 35% and permeability is in the range of a few darcies. The high recovery factor, which is in excess of 45%, bears testimony to the excellent reservoir porosity and permeability of the reservoir. A more comprehensive description of field geology and stratigraphy is given by Thomas et al. (1974) and Hill and Wood (1980).

Significant targets in the deeper section of the field have been identified and are currently being evaluated. The field remains productive and still commands a significant investment from the operator. More than 350 wells have been drilled in the field since the commencement of exploration and field development in the 1970s. While a good number of these wells have been abandoned, some have continued to produce for more than 15 years.

Forties Field cumulative production, which is supported by water injection, is in excess of 2.5 billion barrels. Reservoir pressure has been generally well maintained field-wide, though steep decreases have been recorded in the Charlie Sands, causing a depletion-induced stress in the production zone, especially within the time interval being studied in this paper. Figure 2 shows pressure measurements for the Charlie reservoir from 1975 to 2009. The marked interval (1988–2000) represents the time interval between the seismic surveys.

Forties Field continues to produce through a comprehensive reservoir monitoring program. This concerted effort to keep the "giant" alive has faced a series of difficult drilling, well completion, and sand-production problems. These problems result in lost production and corrosion of materials. Where possible, remedial activities cost millions of dollars per annum and often lead to the loss of wells. These losses ultimately add to production cost. The unpredictable and strongly varying fabrics of shale types in the overburden also pose a major challenge during drilling in Forties Field; over 65% of wells drilled between 2002 and 2007 have experienced some form of instability problem (McIntyre et. al, 2009).

Forties time-lapse (4D) surveys: Data balancing and quality control

Various reservoir monitoring studies on Forties Field have been targeted at identifying and developing by-passed potentials. Ribeiro et al. (2007) reported the time-lapse (4D) effect between the 2000 and 2005 surveys. No previous studies, however, have reported on production-induced changes in reservoir geomechanics and how such changes, when coupled with well parameters, have contributed to sanding and multiple well failures in the field. This lack of comparison is in part due to the nonconformable seismic volumes available for that period. The first 3D seismic survey was acquired in 1988, using 25 × 25-m bins, after production of about 1.8 billion barrels of oil. A further 600 million barrels of oil production separates the 1988 survey and the next 3D survey in 2000, which was acquired on a smaller 12.5 × 12.5-m bins, rotated 22° from the initial 1988 grid.

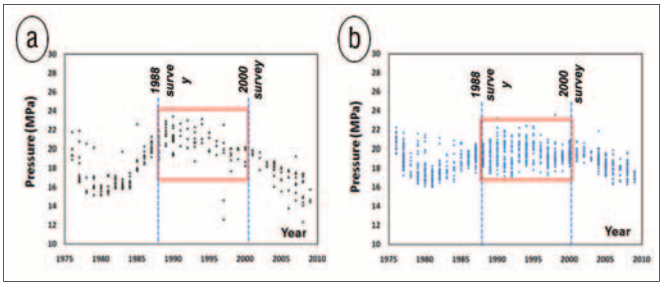

Figure 2. Historical pressure profile of (a) Charlie and (b) non-Charlie wells. The interval of interpretation in this paper is marked by the red rectangle. Observe that, within the interval of study, reservoir pore pressure has been fairly steady in non-Charlie wells as opposed to a steady decrease of pressure in the Charlie wells, producing the observed higher strain around the Charlie complex. A significant increase in water injection accounts for the increase in pore pressure between 1985 and 1988.

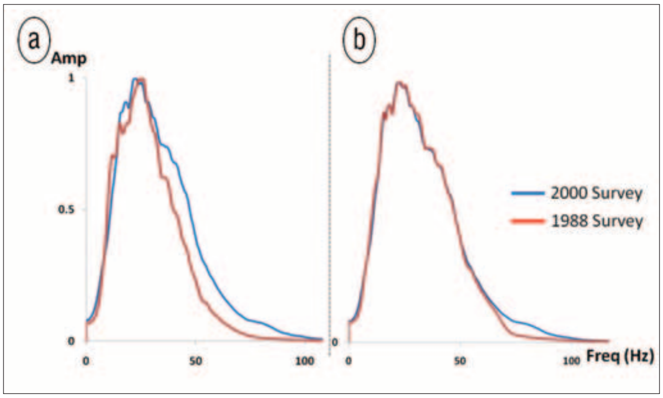

Figure 3. Frequency spectra (a) before and (b) after 4D balancing.

To achieve conformity between the 1988 and 2000 surveys, we employ a workflow that includes regridding, denoising, and frequency/amplitude spectral balancing. Extensive quality control is necessary to avoid signal distortion from the use of shaping filters. A comparison of the spectra before and after the application of a shaping filter is shown in Figure 3.

The normalized root mean square (nrms) serves an index of repeatability between any two traces $b(t)$ and $a(t)$ within a time interval t_1 and t_2; it is defined as

$$nrms = \frac{2*\sqrt{[\sum_{t1}^{t2}\{(b(t)-a(t)\}^2]}}{\sqrt{[\sum_{t1}^{t2}(b(t))^2]}+\sqrt{[\sum_{t1}^{t2}(a(t))^2]}} \qquad (1)$$

Although lower values of nrms are desirable, the nrms at 200 ms above the regional seal (the Sele Formation) was of the order of 0.30 (Figure 4), well within the typical threshold for more modern 4D surveys (Helgerud et al., 2009). A perfectly repeated survey should have an nrms value of 0.0 for regions devoid of production effects. Factors including weather and other random noise, differences in processing artifacts due to differences in spatial sampling, acquisition footprint, and physical obstructions such as drilling rigs and production platforms, contribute to higher values of nrms.

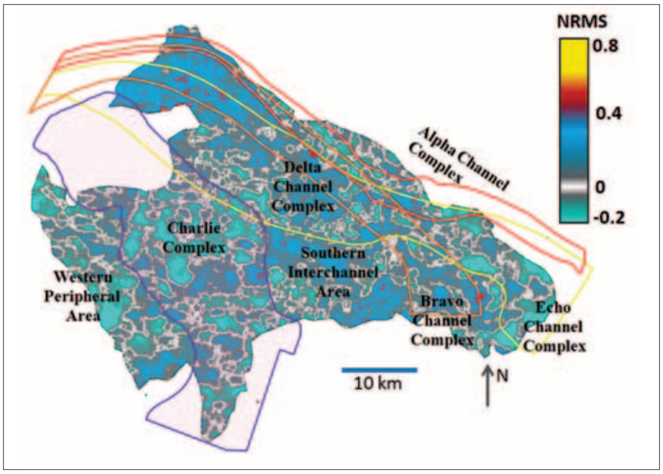

Figure 4. *The nrms index of repeatability 200 ms above reservoir top.*

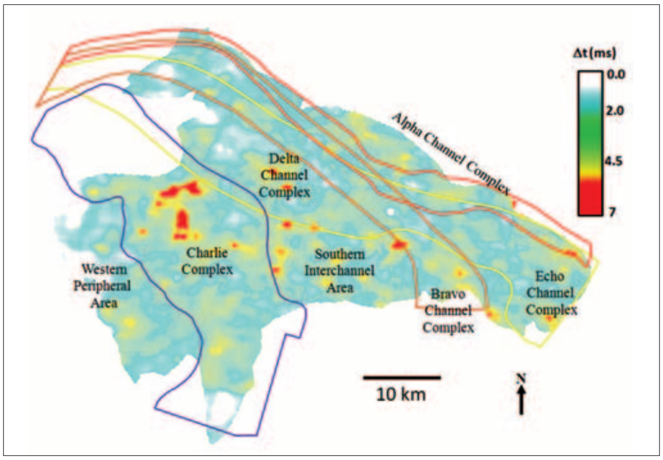

Figure 5. *Time lag, Δt, at the top of regional Sele seal. The high traveltime lag around the Charlie complex, due to a steady decrease in reservoir pore pressure, is an indication of compaction in the Charlie complex.*

Time-lapse effects and reservoir geomechanics

Time-lapse seismic has also become an important tool for monitoring reservoir stress changes and the accompanying strain. Time-lapse effects include changes in amplitude (reflectivity) as well as time lags between two surveys (Δt), which in turn can be due to changes in velocity (due to pressure, saturation and porosity changes), and reservoir strain, ε_{zz}, (due to stress increase and compaction).

We cross-correlated the 1988 and 2000 surveys (after estimating and removing the background time shift) to compute the time lag between them. The background time lag was estimated at a region immediately above the regional Sele shale, which we assumed to be the seal, that was devoid of production effects.

The time lag, Δt = T2000 – T1988, at the top of the regional Sele seal ranges from about +7.0 ms above the Charlie sandstone to near 0.0 ms above other complexes, conforming to the production and pressure depletion profiles. The field's pressure history shows that pressure-depletion is higher in the Charlie sandstone, giving rise to the high time lag shown in Figure 5. A decrease in pore pressure leads to an increase in stress carried by

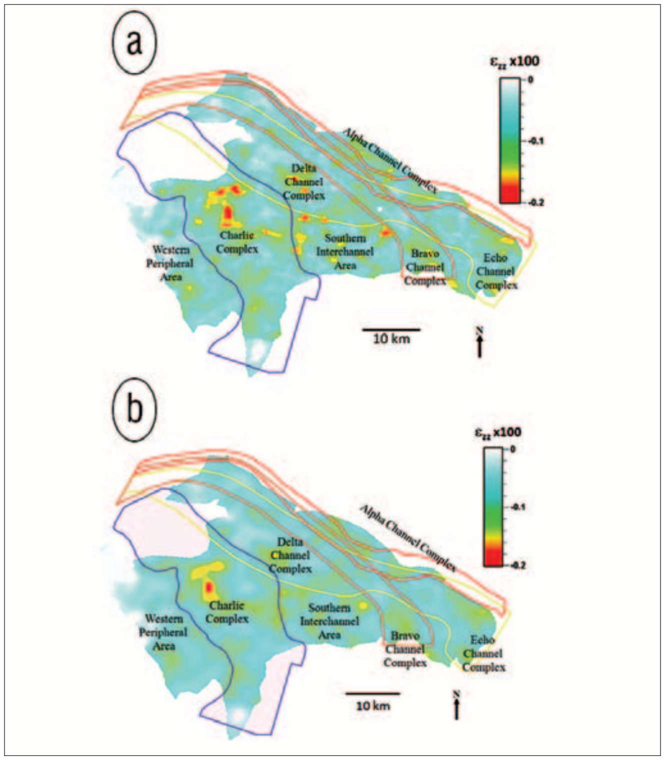

Figure 6. *Computed strain, ε_{zz}, at the (a) top of the Sele regional seal and (b) base of the reservoir. The significant pore pressure decline in Charlie wells accounts for the high strain (> 0.2%) seen around the complex.*

the load-bearing rock frame of the reservoir, inducing compaction within the reservoir. This compaction may be accompanied by microscale deformation mechanisms such as cement breakage at grain contacts, grain sliding, and rotation. While the reservoir compacts and subsides, the overburden shale dilates in order to maintain stability. This compaction in the reservoir and dilation in the overburden, when significant, can give rise to geomechanical problems such as wellbore instability, severe sanding, subsidence, roof cracks, and ultimately the failure of the overburden.

Hatchell and Bourne showed that fractional changes in velocity occur in proportion to fractional changes in path length, T. Thus, the time strain for normal incidence P-waves can be written as:

$$\tau = \partial T / T = (1 + R)\varepsilon_{zz}, \qquad (2)$$

where R defines the ratio of 4D fractional velocity changes to fractional thickness changes and ε_{zz} is the uniaxial strain. Hatchell and Bourne found that R lies in the range $4 < R < 8$ for rocks undergoing extension and in the range $0 < R < 2$ for rocks undergoing compaction (Sayers, 2010). In Forties Field, R = 0.75 within the reservoir while R = 0.70 in the overburden. This range of values lies outside most reported figures. Such anomalous values could be due to the high porosity and the extremely weak frame characterizing the Forties reservoir and overburden shale, suggesting a good potential for grain-on-grain contact squeezing and dilation within the reservoir and overburden, respectively. The Charlie sands and southern interchannel area have high strain associated with increased stress, while the other areas have

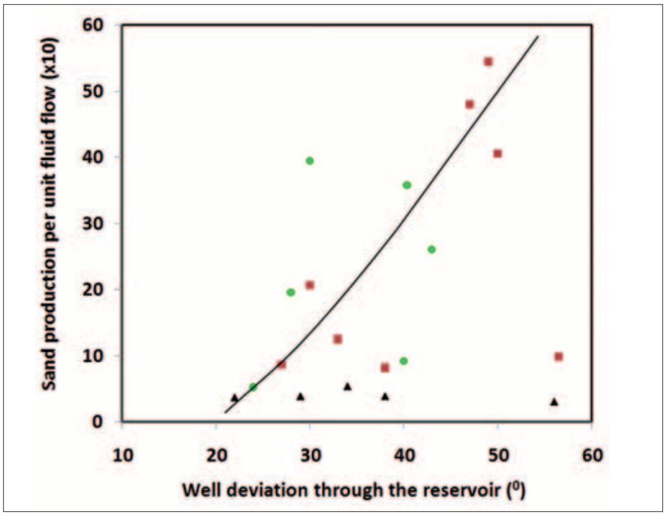

Figure 7. *Sand production per unit flow as a function of well deviation angle through the reservoir. Colors represent wells from different complexes.*

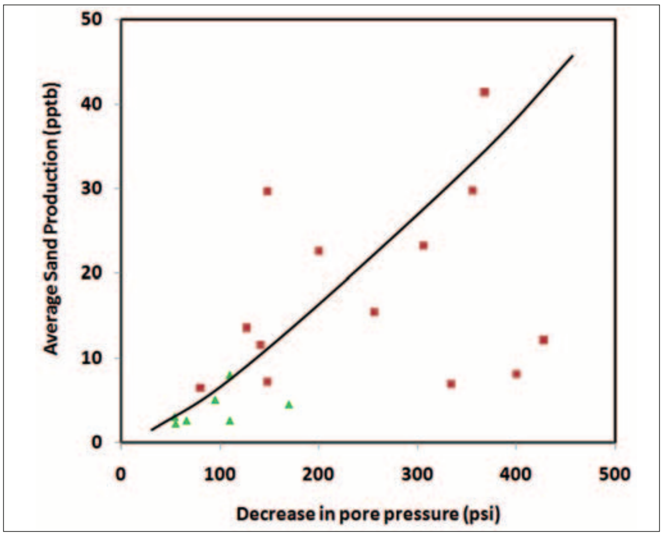

Figure 8. *Crossplots showing average sand-production increases with decrease in pore pressure. Colors represent wells from different complexes.*

experienced minimal strain, conformable with the field's pressure history. The analysis also shows that stress increase is not confined to the top and within the reservoir but is also propagated to the reservoir base inducing significant velocity change and potential instability (Figure 6).

Sand-production pattern

Forties Field has been plagued by severe sand production and an array of drilling and completion problems. Severe sanding in this mature UK North Sea field often leads to loss of a well, reduced production, increased cost of production (associated with clean up, drilling of sidetrack wells, and corrosion prevention). Understanding the field-specific sand production mechanism(s) and sanding pattern in Forties Field will go a long way in identifying vulnerable wells and guiding remedial actions. Incomplete sand-production records and difficulty in eliminating transitional sanding due to extraneous factors such as workovers limit the amount of available data and reliability of sand production analysis.

While poor consolidation has contributed largely to sand production in the field, we observe that other factors such as multiple completion, high well deviation angle, flow rate, and increase in effective stress have contributed significantly to sanding. Specifically, we observe a gradual increase in sanding as the well deviation angle through the reservoir increases (Figure 7). The observed correlation is not unexpected. This is because of the higher perturbation of particle cohesion as the deviation angle increases, coupled with a potential for higher exposure areas. Furthermore, a good correlation is observed between pore-pressure decrease and sand production (Figure 8). The increase in the matrix-supported load resulting from a decrease in pore pressure can lead to a displacement of grain particles within the sand matrix and thus trigger a re-alignment of grains with more sand being produced in the process. While these observations and correlation may be true, each element cannot fully account for the pattern of sanding individually. In other words, sand production is a combined effect of the aforementioned factors, with some factors playing more prominent roles than others.

Figure 9 shows a typical failed well due to excessive sanding in Forties Field. While increase in effective stress around the well and well deviation are less significant, the well failure can be linked directly to high fluid-flow rate and the weakening of grain cohesion resulting from multiple and repeated perforations over the years. In some cases, the failures are not due primarily to fluid-flow rate and repeated perforations, but to significant reservoir strain arising from pore-pressure depletion. In other cases, severe sanding has been recorded due to a combination of all these factors. Figure 10 is a typical case of high deviation angle, significant strain development around the well, and high flow rate.

Conclusion

Sand production remains a source of concern in both conventional and heavy oil production. Factors such as reservoir consolidation, well deviation angle through the reservoir, perforation size, depth of penetration of perforation, grain size, capillary forces associated with water cut, flow rate, and more importantly reservoir strain resulting from pore-pressure depletion contribute to reservoir sanding. Understanding field-specific sand production patterns in mature fields and poorly consolidated reservoirs is vital in guiding remedial activities and identifying sand-prone wells.

The Forties Field time-lapse seismic study using the 1988 and 2000 seismic surveys reveals an increased stress associated with pore-pressure changes in the Charlie complex. The high time lag in the overburden shale above the Charlie sandstone suggests a significant increase in the reservoir stress. Reservoir strain analysis shows that the magnitude of the production-induced strain, part of which is propagated to the base of the reservoir, is of the order of 0.2%, which is significant enough to impact the geomechanical properties of the reservoir. We observe a correlation between sand production and the time-lapse effect. Results of sand production analysis in Forties Field show

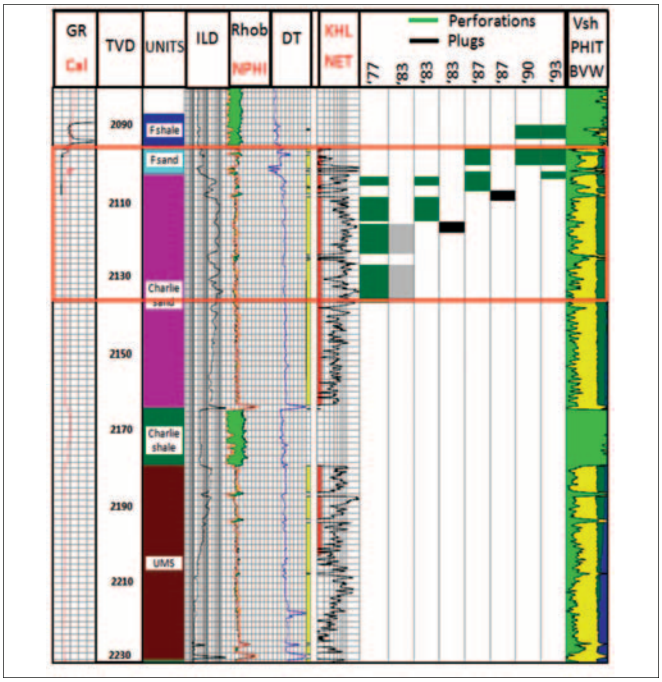

Figure 9. Logs from a well in Forties Field with high sand production. Multiple and repeated perforation coupled with high fluid-flow rate contributed significantly to the high sand production and the subsequent failure of the well. The red rectangle marks the sand-producing interval.

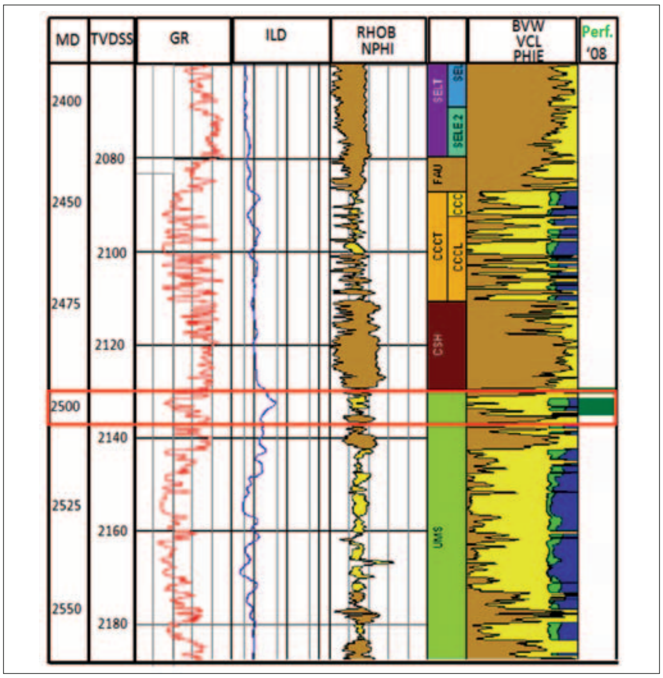

Figure 10. *An example of high well sanding not attributable to only one factor but the combined effects of strain development, high flow rate, and steep deviation angle through the reservoir. The red rectangle marks the sand-producing interval.*

that, in addition to poor reservoir consolidation, high well angle of deviation through the reservoir and high flow rate (the well known factors), reservoir strain due to pore pressure depletion is observed to contribute significantly to sand production. For poorly consolidated reservoirs, maintaining reservoir pressure at or close to the initial condition not only helps sustain hydrocarbon production, but it also serves as a sand production management tool. TLE

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