Bring geophysics closer to the reservoir – A new paradigm in reservoir characterization and monitoring

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Summary

Surface geophysics has good coverage, but is limited in vertical resolution and quality, especially in areas with complex overburden. To realize high-fidelity reservoir characterization and monitoring, we foresee the need to bring geophysics closer to the reservoir to transfer geophysical measurements more in line with the resolution obtainable by logs. Sensors, and probably sources, need to be deployed tens or hundreds of meters below the surface. We envision this happening for targeted applications in areas from 10 to 100 km^2.

Setting the stage

Reservoir engineers need geophysics to fill in the gap in information between the wells to help with reservoir management and improve recovery. This translates into a need for ultra-high vertical resolution for reliable reservoir properties, and monitoring. The realities of surface geophysics in the Middle East and many other areas with complex overburden are rather unappealing. Surface seismic on the Arabian peninsula can provide structural information with perhaps 50-100 ft vertical resolution. Mature areas are covered by multiple legacy surveys each escalating in cost, but from an engineer's perspective with little added value. Engineers build billion-cell reservoir simulation models with 25x25 m grids which are not routinely populated using seismic data. As a geophysicists, we never stop trying to improve data fidelity and quality and we have had some successes using higher channel counts and wide azimuth acquisition, but far too often what we extract is only incrementally better than legacy data. A revolution is needed in geophysical data acquisition to achieve our goals. As we discovered in 4D trials with buried receivers (Bakulin et al., 2012) we have the beginnings of a solution. All of us are familiar with the concept of resolution and associated trade-offs (Figure 1): to see big picture – one needs to be high above the target and to see details one needs to be close. We have largely concentrated on these two extremes for a very long time; we perfected our surface geophysics to image large volumes but at low resolution and we use logging to see incredible details but very locally. Yet developments in these two areas did not fulfill the engineers needs that we outlined earlier. We think this can be changed by bringing geophysics closer to the reservoir, i.e. by literally burying sensors and perhaps sources below near-surface complexities, in deeper boreholes and in producing boreholes. Then we stand a chance to greatly increase resolution and start using geophysics (seismic, EM and gravity) for development and reservoir applications.

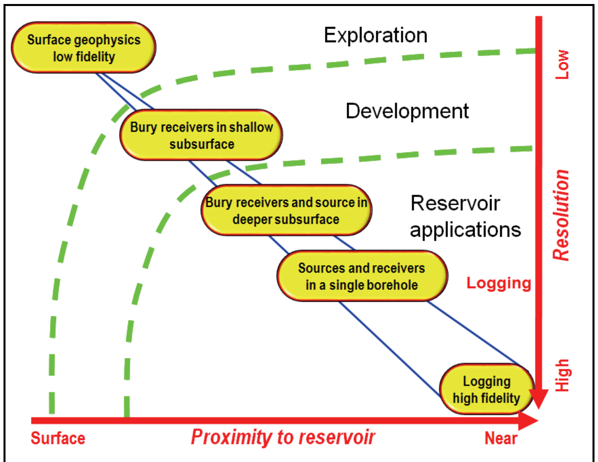

Figure 1. Proximity of geophysics impacts resolution and fidelity of geophysical products especially in the presence of complex near surface.

Complex overburden/near surface challenge

The complexity of the surface data is controlled by overburden or near surface heterogeneities. The near surface in the Middle East represents an extreme complexity in this spectrum. On the left in Figure 2 you see a synthetic surface seismic record for a realistic elastic 1D model from Saudi Arabia. About 99% of what you see is horizontally propagating noise. In real life this noise is greatly complicated by backscattering and diffractions from myriad surface and near-surface scatterers. We record tens of thousands of channels and thousands of sources to be able to process this noise out and uncover hidden signals. This is a game of diminishing returns. Recording systems are reaching 1,000,000+ channels. Yet, fundamentally recorded noise is not smaller nor is the signal bigger. Using brute force we incrementally improve the fidelity of recovered signals, but the resolution does not improve significantly (Figure 3). On the right in Figure 2 you see a record obtained with source and receiver buried below the near-surface layer. About 95% of the wave path is the same, but chopping that top 5% off makes a big difference. Reflections are now clearly visible. Such high fidelity should allow us to estimate reservoir properties, build better reservoir models, see subtle fracture systems, correctly illuminate stratigraphic targets, image low relief structures and better manage our reservoirs. We can get

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higher resolution images with a buried experiment using 100 or 1000 times less number of channels. This has been demonstrated for small areas using technologies such as Seismovie (Forgues et al., 2006). It may or may not be cheaper than a 1,000,000 channel surface system – but it can deliver a fundamentally different product with a much higher fidelity that satisfies the engineers demands. Increased resolution is achievable and we know that. Cross-well seismic gives 10 ft resolution, whereas sonic imaging from a single well can achieve <1 ft. Existing techniques only provide 2D sections and the challenge is to increase areal coverage and be able to image a 3D volume between wells.

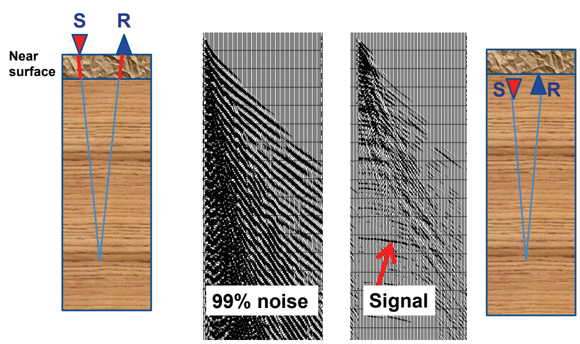

Figure 2. Near surface creates noise and kills signal, while buried acquisition can overcome that.

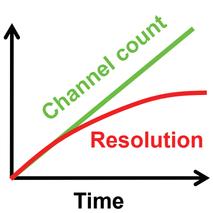

Figure 3. While "arms race" for surface seismic channel count (and costs) continues, resolution and fidelity of surface data has largely stagnated.

Challenges and integration

Most critical is to acknowledge that to implement this vision we have to address all components of such a system (Figure 5), including cheap drilling, smart sensors, slim and powerful sources and efficient sensor deployment. There are significant technical and commercial challenges since only fragments of each component is currently available, while things like drilling reside outside the geophysical service industry. It should be noted that the physics of what we want is well understood, the challenges are only engineering and economic in nature. A significant involvement of operators jointly with the service industry, is likely required to create the critical mass of investment needed to move this forward. Let us look more closely at some of these challenges.

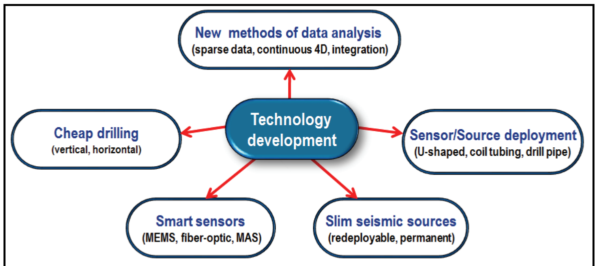

Figure 4. Components needed to bring geophysics closer to the reservoir.

Deploying sensors for in-situ seismic

While there are many ways to deploy sensors in the subsurface, remember the key is to maintain the areal coverage. Vertical holes (Figure 5) provide a simple and flexible design easily adaptable to a crowded oilfield environment with plenty of surface and underground obstructions. They also enable straightforward sensor deployment with variable sensor coupling media. This is the approach we are currently mastering at Saudi Aramco. It works well with shallow deployments. In the future we anticipate usage of horizontal wells (Bakulin et al., 2007; La Follett et al., 2014) for deploying cheap continuous sensors such as distributed fiber-optic sensors. The cost effectiveness and adaptation to our geology - with karsts and abundant lost circulation zones - needs to be evaluated. We are not talking about classical borehole geophysics here. Rather we think of it as buried seismic acquisition or in-situ seismic, which may look in its ultimate configuration as shown in Figure 6. Yes, it may be expensive, yes, it requires a lot of commitment in acquisition and subsurface engineering, but it can justify itself in places where producers routinely leave 50 % or more of the resources behind – which is the current situation in most of the world's fields. These are places where we already have most of the infrastructure. If we can obtain high-fidelity pictures of the reservoir and monitor how it is flowing at finer scales, we are certain to increase recovery and optimize reservoir management.

In the context of the Middle East, we envision to cover not one or two square kilometers but hundreds of square kilometers with such systems. We may need to go deeper, tens and hundreds of meters, into the subsurface because of our complex near surface. We want to instrument every inch of the relatively expensive real estate represented by observation boreholes and eventually go from vertical to horizontal holes. Middle Eastern fields represent significant global reserves with a long-term recovery goal. The near surface remains the biggest unknown with insufficient information gathered to date. Time-based processing with heavy emphasis on statistics and little physics does not provide a clear picture of the near surface. We still remain unsure of the vertical extent of the near surface complexity, 10 m, 50 m, or 500 m? Yet this knowledge is

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critical for success. Extrapolation of overseas experience (Forgues et al., 2006; Cotton et al., 2012) to Saudi Arabia was not helpful during our first 4D pilot with buried acquisition systems (Bakulin et al., 2012), so we have started our own development program.

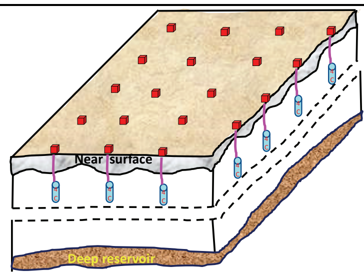

Figure 5. Vertical holes provide a simple and flexible design easily adaptable to a crowded oilfield environment with plenty of surface and underground obstructions.

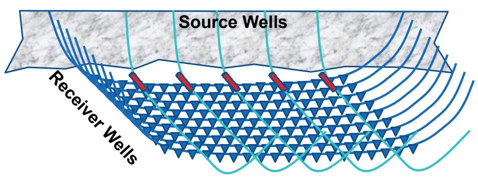

Figure 6. In-situ seismic in its ultimate form.

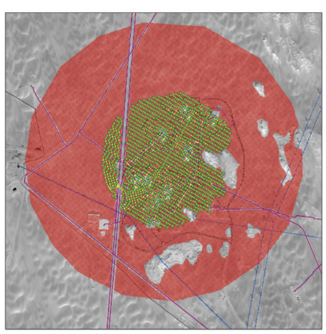

Figure 7. Saudi Aramco permanent installation for continuous monitoring with 1000 buried receivers (green) and surface vibrators (red).

Saudi Aramco permanent buried receiver installation

Our projects with buried seismic acquisition enabled us to learn much more about the near surface – we started to obtain hard data. In one field trial we have drilled more than 1000 shallow holes down to 70-80 m (Figure 7). They are equipped with four-component sensors, making a permanent installation for continuous 24/7 monitoring of CO_2 injection throughout the life of the project (Bakulin et al., 2012).

We have learned valuable lessons during deployment by optimizing our drilling with air and foam (Bakulin et al., 2013). We made land hydrophones and dual sensors work for up/down separation (Burnstad et al., 2012). We achieved seismic repeatability comparable to marine acquisition (Bakulin et al., 2012, 2014). Buried receivers allow a drastic improvement in repeatability: normalized NRMS is reduced from 53% (surface permanent sensors) to <15% for buried sensors, thus making it feasible to monitor CO_2 injection using continuous monitoring.

Lessons and next steps

Saudi Aramco's first field installation also highlighted areas for improvement – we have 70 m of real estate in each vertical hole and with current sensor technology we can only afford a single sensor placed at the bottom. We are keen to replace it with new generation sensors in the next installation that would allow a complete antenna in each hole. Distributed acoustic sensing will be one of the options (La Follett et al., 2014).

In terms of sources we currently use surface vibrators though it is clear that much better repeatability could be achieved with permanently installed buried sources. The challenge is that currently available piezoelectric sources have insufficient signal strength to illuminate the deep target zone in arid environment (Berron et al., 2012). So development of a stronger cost-effective permanent source is one of the challenges to meet.

We see that engineers are hungry for information not only in the area of monitoring but also in high-fidelity reservoir characterization to build accurate reservoir models. Because of surface seismic limitations even in the areas of shallow water, pilot holes are currently drilled to help map sand stringers not visible on seismic volumes, so that laterals can then target the required zones (Figure 8). We envisage that in-situ seismic can map the stringers with 5" resolution above and below the well, and greatly improve stringer penetration of sidetracks. The challenge is to adapt existing cross-well tools for surveys in single borehole and develop new processing techniques.

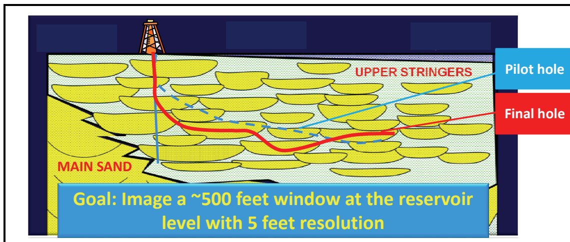

Figure 8. Single horizontal well seismic.

Electromagnetic applications

Electromagnetic (EM) technology is one of the most promising techniques that allows characterization of fluids in the reservoir, due to the large contrast in electrical properties between conductive brine and gas or oil fluids.

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The skin depth parameter (proportional to the square root of resistivity over frequency) controls the propagation of electromagnetic waves and is defined as the distance at which the amplitude of the field is reduced by 1/e of its original value (approx. 37%). This property governs the resolution achievable with EM-related techniques for which proximity to the target is an essential requirement for high-resolution imaging. Challenges in this field are related to high-power transmitters, design of sensors with low maintenance and high stability for permanent installation in wells. Repeatability of EM measurements and remedial actions is still a topic not well documented in the industry. Recent feasibility analysis of surface-to-borehole EM in a realistic Saudi Arabian reservoir model utilizing transmitters at the surface and arrays of receivers in the borehole (Colombo and McNeice, 2013) have also shown that the electric field is the only EM field showing sensitivity above an estimated noise floor, when considering waterflood time-lapse resistivity variations over two and five year periods (Figure 9). The vertical electric field E_z, in particular, shows the maximum spatial resolution and sensitivity to time-lapse fluid saturation changes in the reservoir. Maintenance of devices and the need of providing an effective low contact resistance with the rock formations have prevented, until now, the development of reliable borehole electric field sensors. We address this problem by the utilization of capacitive electric field sensors to be deployed as permanent installation on production tubing (Colombo et al., 2014). Sensors of this type can be completely isolated from the environment thus opening the opportunity of implementing permanent EM sensing technology for reservoir monitoring.

Discussion and conclusions

We are confident that resolution goals are achievable. We know that deeper formations are better behaved compared to the near surface. With single well imaging in Saudi Arabia we can see more than 100 ft away from a borehole with <1 ft resolution (Figure 9e). Deeper geological structures in the Middle East are relatively simple with logs correlating over many kilometers. So we have little doubt that at some depth acquired seismic and EM data would be of much higher fidelity than conventional surface data. It is possible that the near surface may be much thicker for Saudi Arabia than for other places in the world, but we are determined to explore this direction methodically and vigorously, and discover the economic and geophysical sweet spots for each particular application.

The Middle East is known for having among the most challenging geophysical data quality in the world. Significant reserves make additional improved recovery a worthy long-term goal. We have already embarked on the road for bringing geophysics closer to the reservoir to meet this goal. With many technical, economic and engineering challenges ahead, there is a clear need for collaboration with service providers and opportunities for other industry partners to participate.

Acknowledgments

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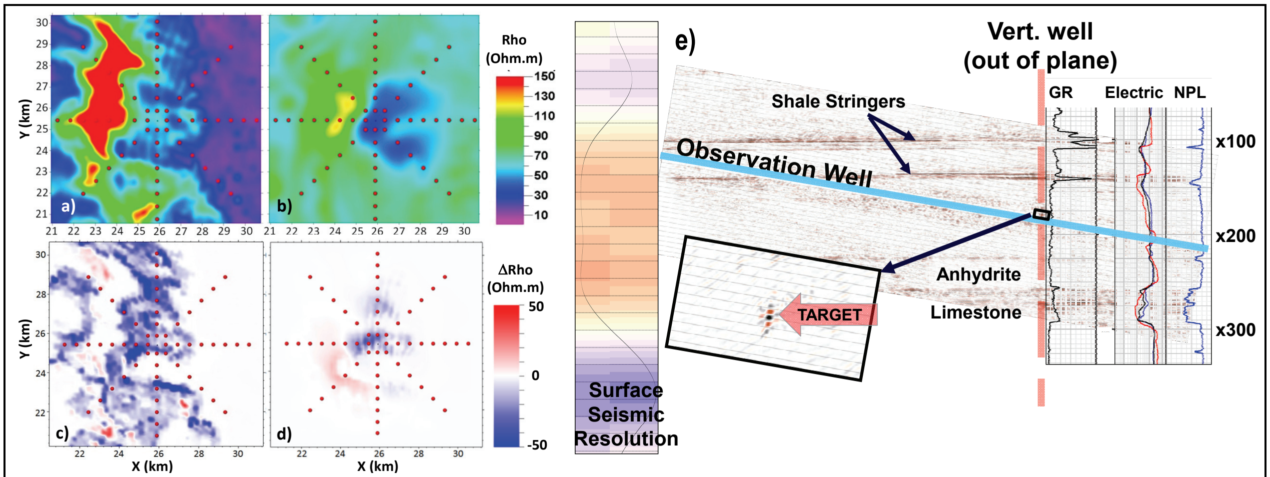

Figure 9. Surface-to-borehole EM modeling showing: a) distribution f resistive oil patches in an otherwise flooded reservoir from a black oil simulator; b) 3D inversion results of the E_z (vertical electric field) component as measured by the vertical borehole array; 3) two-year time-lapse distribution of resistivity as a result of flooding; d) recovery of the time-lapse anomalies from 3D inversion of E_z. Dots show the position of modeled electric bipoles on the surface transmitting a frequency of 10Hz. e) Field data image obtained with high-frequency sonic sources and receivers in a single well. In competent deep formations of Saudi Arabia, we can image more than hundred feet above and below the well with sub-foot resolution comparable to logs. We can also image smaller targets such as neighboring wells (Jervis et al., 2012).

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