

An Unconventional Future for Seismic?

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Introduction

From the perspective of a Geophysical Services company we see the current trends in the world economy as something of a “pause for breath” before growth is predicted to continue at a challenging pace for the limited hydrocarbon resources available.

Even though new conventional hydrocarbon plays may still be found in the few under-explored regions of the world such as the Arctic, competition will be fierce to secure acreage for Oil&Gas companies.

So at this time, more than ever, it is vital to maximise recovery from existing reserves while considering the merits of the vast potential of unconventional hydrocarbon resources such as shale gas.

A final point for consideration is the increasing interest in carbon capture and sequestration, the impact that this could have on the world economy and the contribution that our industry is positioned to provide. How can new seismic technologies help addressing those issues in the future?

Themes for Future Seismic

Given this global context we see major developments in geophysics and seismic applications around these themes:

- Better spatial sampling of the seismic wavefield with high-density wide-azimuth geometries
- Better understanding of and better utilisation of the full seismic wavefield
- Reduced turnaround in acquisition and processing
- Integration of active and passive seismic monitoring techniques; surface and borehole
- Quantitative seismic reservoir monitoring; integration with the dynamic model
- Integration of geomechanics i.e. the consideration of the effect of temperature, stress and strain in the reservoir.

High-Density Wide-Azimuth: Next Generation Seismic

In the evolution of seismic acquisition geometries, land has generally been the poor cousin to marine seismic. Due to economic and technical hurdles, 3D land has been sparsely sampled resulting in aliased surface wave noise and significant acquisition footprint noise.

However, during the shift to wide azimuth

acquisition, we have seen that economic compromises have been made which leaves marine wide-azimuth poorly sampled in the cross-line direction, (or other directions depending on the fundamental geometry of the acquisition template).

At the same time land seismic has undergone a revolution in channel count and vibroseis source productivity (Bianchi et al., 2008) which enable commercial high-density wide-azimuth surveys to be acquired onshore (Sambell, 2009), (Seeni et al., 2009) which put their marine counterparts to shame.

These next generation land surveys are producing a step change in image quality thanks to 3 main factors:

- Improved illumination and multiple attenuation from the wide-azimuth geometry
- The ability to record and therefore effectively remove un-aliased ground-roll and guided wave noise
- A new generation of true 3D wide-azimuth algorithms which respect the azimuthal variations present within the data

In areas such as the Gulf of Mexico we have managed so far with our coarse cross-line sampling looking at deep targets. However further gains are to be made by improving the spatial sampling, as we have recently done onshore. The obvious solution to this is to follow the trend of land seismic and improve source productivity by introducing more sources and simultaneous source techniques.

In terms of processing wide-azimuth data the industry has gone through a period of rapid learning and development. Initially a challenge and a daunting exercise in data management, a new generation of processing and imaging algorithms is being developed to take full advantage of the information. It includes existing techniques such as true 3D SRME, the extension of familiar transforms such as tau-p to tau-px-py (Hugonnet et al., 2008) and the development of higher dimensional algorithms such as 5D Interpolation (Tradd et al., 2008).

On the imaging side it quickly became apparent that azimuthal velocity variation and residual moveout was a major feature of wide-azimuth data, particularly in onshore areas. With high-density data these variations can be analysed and compensated for more easily in a true 3D fashion (Lecerf et al.) and azimuth-sectoring assumptions can be avoided.

We can now routinely perform true 3D velocity model building, by picking events and residual moveout on a 3D

surface in a 3D gather and inputting this to tomographic inversion (Huang et al.). The additional azimuthal information allows more accurate derivation of Tilted Transverse Isotropy (TTI) anisotropic parameters, vital in areas where dipping

sediments exhibit anisotropy, to create accurate velocity models for the latest TTI imaging algorithms. TTI reverse time migration (RTM) can be performed on WAZ data (Huang et al.) to provide well focused images beneath complex overburdens.

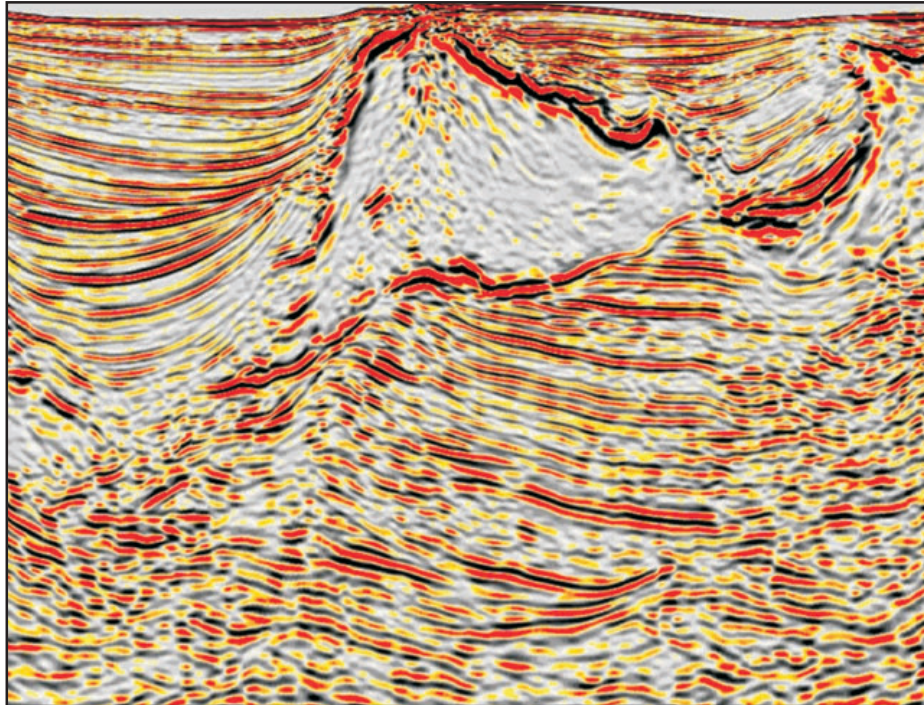


Fig.1 (a) VTI reverse time migration

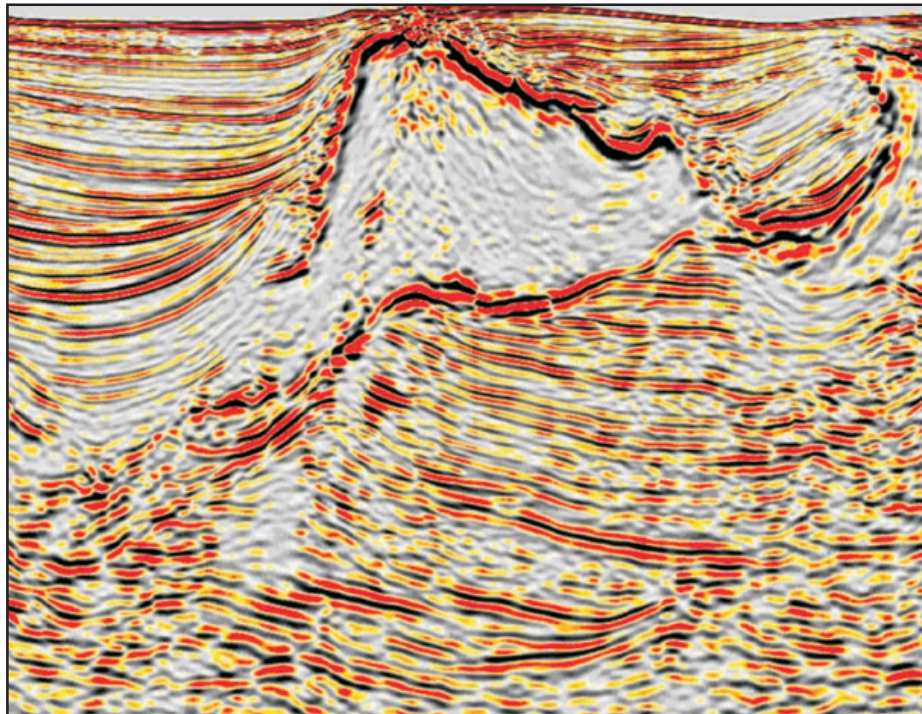


Fig.1 (b): TTI reverse time migration showing more focused imaging beneath and on flanks of salt

Reverse time propagation has also been applied in the development of a new way to perform full waveform inversion (FWI), (Zhang et al., 2008). FWI is widely anticipated to provide the next big advance in imaging as it provides a powerful tool to obtain a high resolution velocity model for imaging and interpretation. We have already seen exciting examples of FWI and expect this to become widely commercialised over the next few years.

As wide-azimuth data has proved to be invaluable in helping to constrain our anisotropy models for imaging, the question that now arises is how accurate these models are for the fractured, unconventional resources of the future. Research has already started into the derivation and application of higher-order models such as orthorhombic.

The elastic wavefield is still under-utilised in this industry. Multi-component surface and seabed seismic will play an increasingly important role in the characterization and monitoring of reservoirs. This is especially true for unconventional resources.

Applications of multicomponent data for lithology discrimination (to identify shale lenses and stringers) have already been demonstrated for Heavy Oil. For tight gas and shale gas reservoirs where stress and fractures dominate production, shear wave birefringence provides a useful independent measure of fracture intensity independent to the azimuthal anisotropy of P-wave velocity and attributes. As we see the increase in use of ocean bottom nodes and permanent ocean bottom cable (OBC) for the monitoring of producing fields, 4D multicomponent seismic is becoming a reality. Unfortunately we generally discard the 3C data as soon as we have performed PZ summation. However there are good case histories which demonstrate advances in PS statics, joint velocity model building with P-wave data, PS depth imaging (Ronholt et al.) and inversion which show us how we can extract the most value from the full elastic wavefield.

Apart from multicomponent there are other parts of the seismic wavefield that we are learning to make better use of: low frequencies and multiple.

Low frequencies are increasingly important in seismic data to provide deeper penetration for imaging beneath complex overburdens, especially sub-salt and sub-basalt. The availability of low frequencies for full waveform inversion provides better velocity models and wider bandwidths for seismic inversion. This has led to an increased drive to acquire the lowest possible frequencies.

Newer streamers have a reduced digital low cut filter, enabling data to be recorded down to 2Hz, compared with older streamers which had a hydrophone low cut around 5Hz. Solid streamers have proved to be the ideal low-noise platform for recording low frequencies. Low frequency data requires

as well work and optimisation on the source side.

Analysis of the frequencies of the recent TIDES data, recorded by CGGVeritas as part of the Tsunami prediction project offshore Sumatra, showed that useful data below 2.5 Hz was being recorded without excessive noise contamination. This data was recorded using Sentinel solid streamers at a depth of 22m and an 8.5m source depth. Recording at depth to avoid low frequency noise contamination does not necessarily mean that the high frequencies have to be sacrificed. New deghosting techniques allow significant signal to be recovered at frequencies around the cable ghost notch.

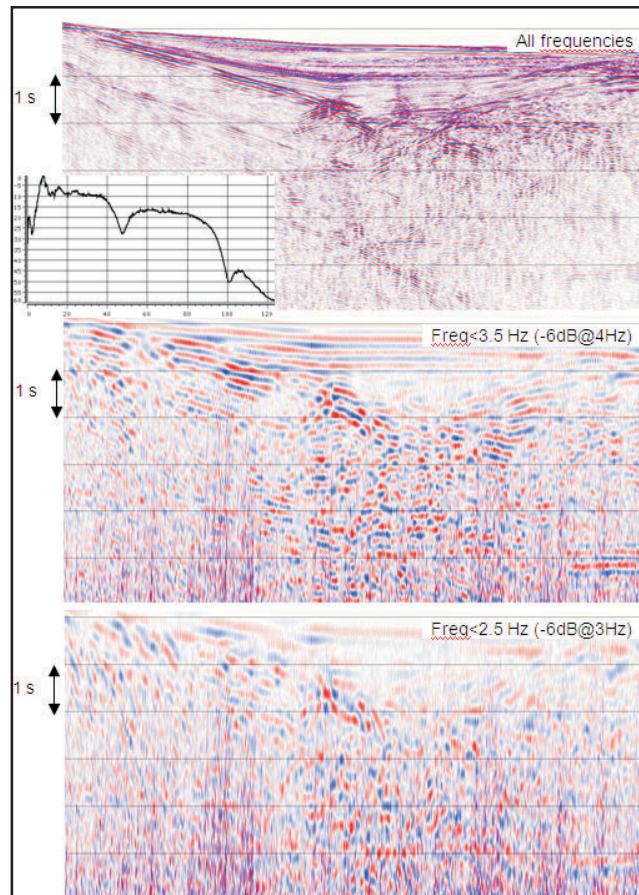


Fig.2 Data from the recent TIDES project, showing useful data below 2.5Hz

Multiples, once the arch-enemy of processing geophysicists and interpreters, are also enjoying a boost in popularity. In fact they are providing useful information where primaries are sparse or just not recorded.

Mirror migration using first order surface multiples has been developed (Grion et al.) for use where there is poor illumination of shallow targets. This is especially common for ocean bottom seismic (OBS) recording. Mirror migration generates better images than those produced conventionally from the primary up-going waves, particularly for the seabed itself which cannot be imaged at all with OBS primaries.

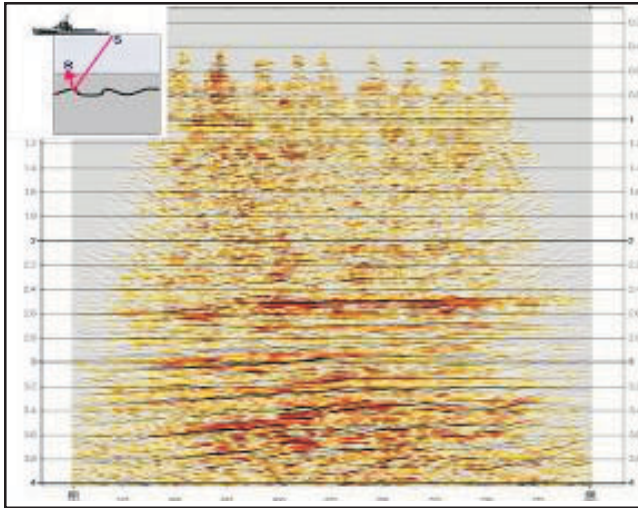


Fig.3a) Conventional imaging of the upgoing waves according to the geometry illustrated on the top left. Note the poor imaging of shallow reflectors.

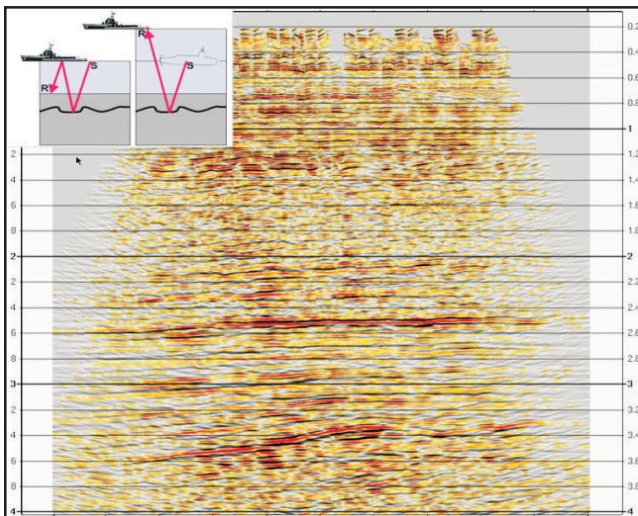


Fig.3b) Mirror migration produced from the ghost according to the geometry illustrated on the top left. Note the improvements in the shallow section and the reduced multiple content of the deep data.

Efficiencies reduce turnaround

The revolution in productivity achieved in land acquisition has led to a vast improvement in turnaround, in spite of acquiring denser data. Heliportable acquisition, stakeless surveying techniques, and wireless recording systems have all contributed to improvements in efficiency. The terabytes of data being acquired have required updates to be made to the QC systems. Automatic collection of statistics and flagging of anomalies allows even these vast quantities of data to be QC'd in real time.

Marine data is also being acquired faster, as there are more vessels available towing 12 or more streamers. Improvements in streamer steering mean that these cables can be controlled more easily, allowing faster line turns

and reducing the amount of infill required by over 50% in some cases.

Faster computers and more efficient algorithms and working practises have also reduced the processing time so that sophisticated sequences can now be performed in a reasonable timeframe. As with land acquisition, improvements in QC procedures have been critical, as these reduce the number of re-runs that are required. More sophisticated velocity analysis and model building techniques have also contributed to enhancement in imaging the subsurface.

The net result of these improvements in efficiency is a significant reduction in the overall timeline of the survey. Although these efficiencies do not involve "high end" seismic technologies they are becoming more and more important, and do require a strong technology market to produce the necessary tools for the job.

Integration of active and passive seismic monitoring techniques; surface and borehole

Borehole seismic data has been used for long but has been mainly limited to time-depth calibration. Recent advances in VSP tool technology have seen the introduction of a 100-level tool (the Sercel MaxiWave) capable of operating on a standard wireline. With this kind of borehole receiver array, interval "massive" 3D VSP's can be acquired very efficiently. Perhaps the most important opportunity these large borehole arrays afford is the simultaneous acquisition of 3D VSP data during a surface seismic survey (Seeni et al.). This completely changes the economics of 3D VSP and makes combined campaigns with surface seismic a very attractive proposition.

3D VSP can be used to calibrate and guide the surface seismic processing, identify interbed multiples, derive anisotropy parameters and provide a link with petrophysical borehole data. In addition 3D VSP's can deliver a more detailed picture of the reservoir through high-resolution imaging and reservoir characterisation.

Microseismic monitoring techniques have emerged as commercial applications over the last 10 years. Borehole receiver arrays are now regularly used to provide real-time monitoring of fracture stimulation operations in tight formations. The use of receiver arrays on the surface for microseismic monitoring is also becoming more widespread. With an areal surface array it is possible to not only locate microseismic events but to determine their focal plane mechanism which provides information on the nature of the event, its orientation and the stresses that caused it.

As with active borehole seismic and surface seismic there are synergies and efficiencies which can be gained by combining all these techniques. For example it is easy to

consider using a permanent down-hole receiver array or OBC life-of-field installation for microseismic monitoring of a field between repeat 4D monitor surveys. This could yield important information on stress effects in the reservoir and overburden due to production-induced compaction/extension.

A novel system which combines all these elements (areal surface receiver array, downhole receiver arrays, passive monitoring and active repeat 4D surveys) has been under testing for the monitoring of Heavy Oil production onshore. The SeisMovie system (Forgues et al.) uses buried receiver and source arrays to achieve excellent 4D repeatability and sub-millisecond accuracy in an environment sheltered from surface noise and the variations of the weathering layer. SeisMovie uses highly repeatable low-power piezoelectric sources deployed in boreholes to provide on-demand active seismic monitoring. With continuous multicomponent recording it is possible to interrogate the data for microseismic events even during active reflection seismic acquisition. Such permanent recording provides unprecedented details of subtle and rapid variations in the reservoir and could even provide early warning of scenarios such as cap-rock failure, activation of fractures and by-passing of portions of the reservoir.

Quantitative Seismic Monitoring

To maximise recovery from producing fields we must look to more accurate and better calibrated reservoir models, both static and dynamic.

Improvements in seismic acquisition and processing, and a better understanding of petrophysics (linking seismic to rock properties with petro-elastic models) is enabling us to move qualitative interpretation of seismic data to quantitative interpretation.

As 4D seismic has matured we are beginning to collect more monitor surveys over mature fields. For example in the North Sea we can have 7 vintages of seismic data available, and as Life-of-Field seismic monitoring becomes more widespread we can expect even more.

Recently developed multi-vintage processes find the global best fit of data and parameters for all the vintages simultaneously. This has been demonstrated for 4D Binning (Zahibi et al.), 4D matching through the analysis of time-shifts and even simultaneous elastic inversion.

To improve the volumetric accuracy of 4D, more projects are now being performed in the depth domain where the use of more sophisticated migration algorithms and anisotropy models allow the more accurate positioning of 4D signal and key features such as bounding faults.

Global 4D elastic inversion appears as a powerful

tool for the interpretation of time-lapse seismic data, especially when cascaded with 4D Bayesian Fluid Classification (Doyen et al.). Within its stratigraphic framework, geologically conformable layers and features such as pinch-outs can be properly represented and 4D time-shifts can be compensated for.

The most important feature of Global 4D Inversion, apart from the fact it finds the best-fit global solution for all the seismic vintages, is that it introduces coupling in the form of rock physics constraints. This reduces the inherent uncertainty in seismic inversion by using a-priori information and our knowledge of the production mechanism in a reservoir. The deterministic nature of most current 4D inversion algorithms means that the resulting models are band-limited and require up-scaling to match the reservoir model. However there are ways to deliver rock properties at the same fine scale as the reservoir model from seismic results.

The first is to use a stochastic inversion (Moyen et al.) which extends the bandwidth of the seismic using statistical variogram models based on available well data. The advantage of this approach is that it allows the uncertainty space of seismic inversion to be fully explored and quantified in terms of ranked net pay or sand body connectivity for example.

The other approach is to invert directly for petrophysical properties in a petrophysical inversion (Doyen et al.). A user-defined petro-elastic relationship controls the interaction between the reservoir model (expressed in rock properties) and the seismic data. The result is an accurate one-step workflow from seismic direct to the reservoir model in depth (or time).

Integration of Geomechanics

During the last decade or so, the geophysical industry has shown a growing interest for geomechanics. This will play an important role as the E&P industry focus on more difficult reservoirs, in frontiers areas and unconventional resources.

Geomechanics examines the engineering behavior of rocks under existing or imposed stress conditions (Collins, 2005). As such, it addresses all problems that have some component of rock and soil mechanics or fracture mechanics. The effects that stress, deformation and temperature have on seismic and their relation to fluid flow (Settari, 2007), has largely been ignored in the seismic industry up until now. The connection between geophysics and geomechanics becomes obvious when we realize how much the seismic impedances (both velocities and to a lesser degree, densities) depend on elastic properties and stress state of the reservoir and the surrounding rocks.

Furthermore, deformation may occur where subsidence and compaction are involved and affect the

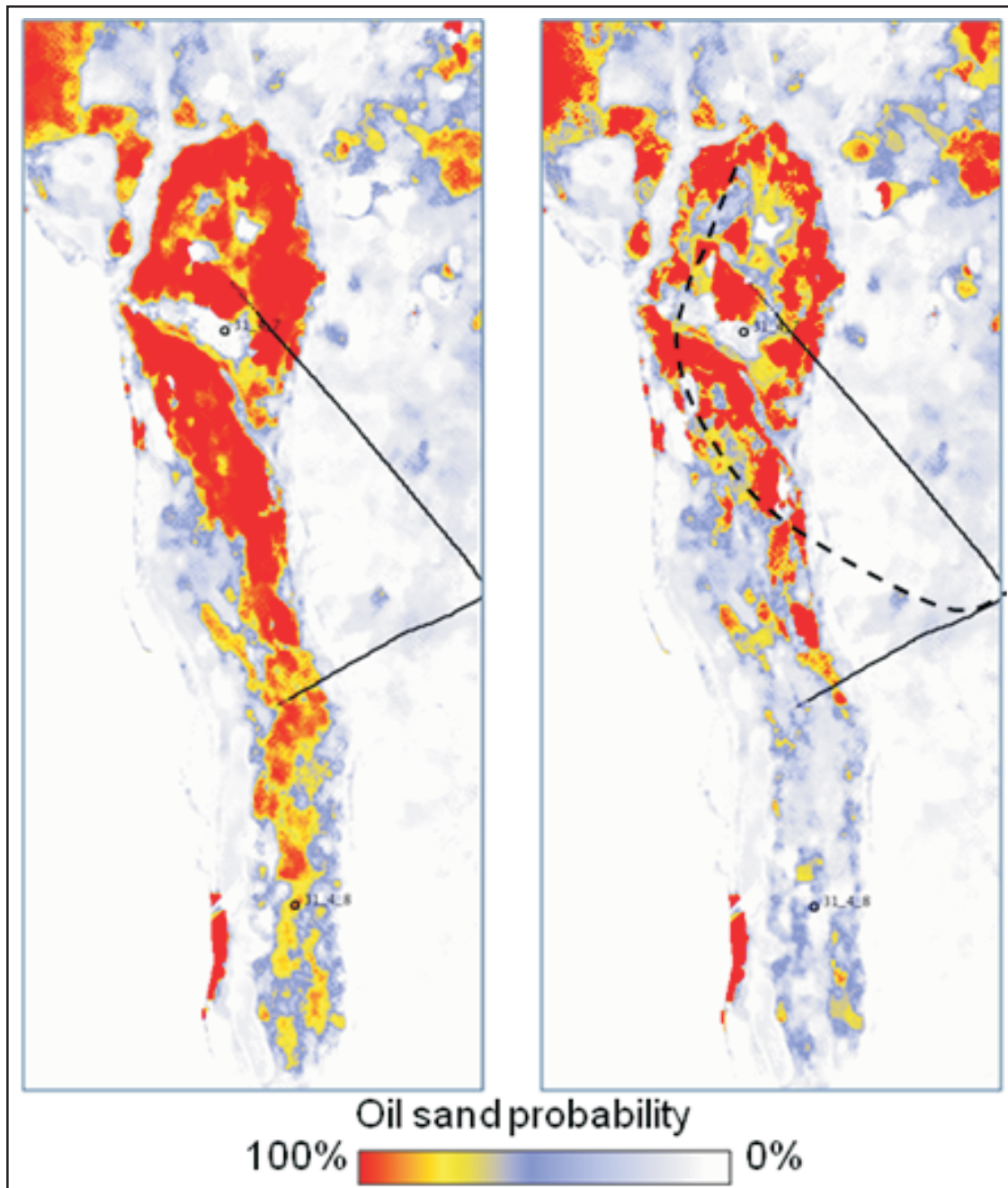


Fig.4 Oil-sand probability distribution maps close to the original oil-water contact from the combined 4D global inversion and 4D Bayesian lithology classification workflow. The dotted well path shows a well drilled in 2005 which provided Sw log data to compare to the results.

response of a seismic survey. 4D seismic which was initially meant to image fluid saturation changes in the reservoirs must now include the impact of stress changes and account for geomechanical components when interpreting the results. Hawkins et al.(2007) demonstrated the extension of geomechanical effects throughout much of the subsurface in and around the reservoirs in the North Sea High-Pressure High-Temperature Central Graben. Compaction of the reservoirs caused stretching or extensional stresses in the overburden/sideburden and underburden. This work involved the inversion for stresses from observed 4D time shifts.

Coupled geomechanical and fluid flow modeling capabilities and strategies exist today and research in these coupling techniques continues. Reservoir models should in the future encompass the over- and under-burden, particularly where production involves the injection of fluid such as steam in the case of heavy oil reservoirs.

P. Collins, in 2005, described how steam injection for enhancing heavy oil production, associated with increased pressures and temperatures, alter rock stresses to cause shear failure within and beyond the growing steam

chamber. O.Lerat et al. (2009) proposed the coupling of geomechanics and fluid flow models to predict the seismic response of the steam chamber and surrounding rock.

Fractured reservoirs are another area where geomechanics plays an important role. Their characterization is a key component to build flow models. Although fractures are assumed to be static, it is well known that permeability of fractures media is stress dependent. Wellbore core and image log data, microseismic monitoring, surface seismic and time lapse response to injection and depletion attributes can be combined to assess effective stress dependence of fractures rocks compliance, velocity and reflectivity.

Conclusions

Facing new challenges, seismic acquisition and processing continuously innovate at a high pace. With more accurate models of the sub-surface and fewer simplifying assumptions we are able to image new plays and targets which were not visible to us 5 years ago. As we progressively move from a qualitative to a quantitative approach, we also see the need for a multidisciplinary approach as seismic must embrace more and more geomechanics and reservoir engineering.

Besides all the technical challenges summarized, seismic industry faces also growing environmental concerns. Reducing operations footprint, ensuring protection of sea life and reducing carbon footprint are some key challenges that need also to be addressed in the coming years.

So it is fair to anticipate strong evolution and new improvements in our activities in the future. Commitment to research and development will certainly remain the main driver for the seismic business. This focus on innovation and new technologies deployment should continue to be fully shared by Geophysical Services Companies and Oil&Gas Companies for the benefit of all the industry.

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