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# Managing reservoirs with 4D seismic

By accelerating the identification and mapping of production-induced seismic changes, a new 4D feature can enable operators to increase the potential of finding hydrocarbons in poorly drained or overlooked sections of offshore reservoirs.

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Time-lapse seismic, often referred to as 4D seismic, is a method of repeating 3D seismic surveys over subsurface reservoirs to detect changes in rock and fluid properties. It has been most used in the sector to monitor production changes in oil and gas fields. However, its usage in monitoring underground storage of $CO_2$ is expected to grow, as the need for large-scale carbon sequestration increases.

Thanks to 4D seismic's rapid adoption, and as repeat survey frequency increases on newer fields, 4D seismic analysis is quickly becoming a big data challenge. Sharp Reflections is a leader in the use of high-performance computing to accelerate seismic analysis. Recently, we partnered with Equinor to find ways to improve 4D interpretation workflows. Our new solution, announced earlier this summer, is helping to build upon our strength in pre-stack computing. It will help interpretation teams efficiently analyze the growing flood of 4D data to make time-critical well placement decisions in fields with active drilling campaigns. As 4D usage increases in the sector, we believe we are in a strong position to support operators to take advantage of the opportunities presented.

Our PreStack Pro 6.2 software update allowed us to expand our 4D capabilities to the market. We strongly believe that by accelerating the identification and mapping of production-induced seismic changes, the new 4D features will enable operators to increase the potential of finding hydrocarbons in poorly drained or overlooked sections of offshore reservoirs, **Fig. 1.**

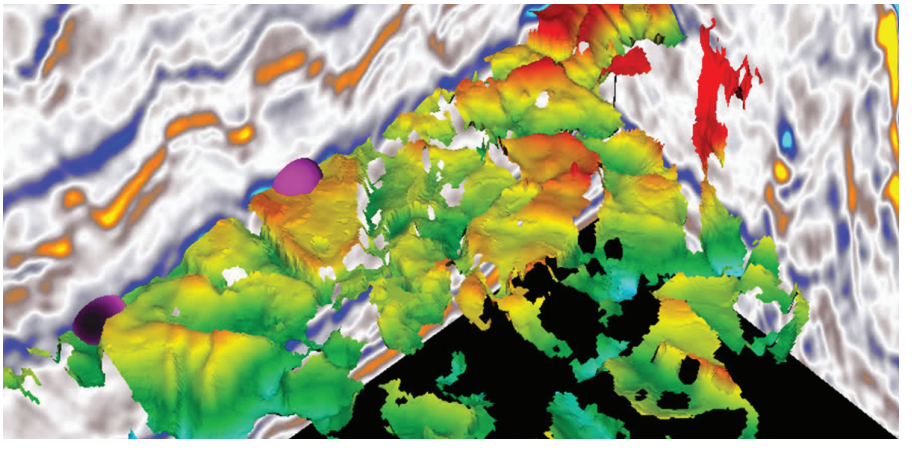
4D seismic will play an increasingly important role in ongoing reservoir management. This is true, now more than ever, due to a retraction in frontier exploration and the potential reduction in the opening of new fields. These latest updates to PreStack Pro provide operators with a fast and more interactive platform to analyze the changes in seismic vintages over time. This ultimately will provide them with the opportunity to optimize their field developments as new 4D information streams in.

**4D—basics and challenges to exploit AVO.** All 4D studies attempt to link seismic changes to changes in pressure, saturation and other reservoir properties. Analysis methods seek to quantify changes in both seismic amplitudes and travel time, or so-called time-shifts, between seismic traces recorded on different surveys. Typically, time-shifts between surveys are estimated by advanced geophysical algorithms. Time-shift corrections are then applied to calculate amplitude changes directly on the registered datasets. From there, 4D interpretation can be aided by seismic modelling of different production scenarios.

Amplitudes and time-shifts both vary as a function of offset (AVO and TVO, respectively). These effects may be observed by measuring the respective seismic changes on pre-stack gathers or partial angle stacks. However, 4D AVO and TVO analysis generates many more individual volumes, and an even larger number of difference volumes, **Fig. 2.** In practice, reservoir teams have a fixed time frame to integrate 4D results into their overall reservoir management decisions, making the speed of analysis of vital importance. New 4D acquisition methods, including repeat ocean bottom nodes and permanent reservoir monitoring (PRM) systems, are leading to much more frequent survey acquisition. Interpretation speed is quickly becoming a workflow bottleneck.

As a result, the majority of 4D seismic projects today continue to rely on post-stack analysis of 4D seismic differences, often with one single stack per vintage. While overall 4D changes are readily detected with this approach, it is difficult to attribute the observations to specific changes in fluid saturation changes, pressure, temperature, and possibly even seismic acquisition and processing artefacts.

**Fig. 1.** PreStack Pro 6.2 software enables operators to find hydrocarbons in poorly drained or overlooked sections of an offshore reservoir.



For this reason, we are now leveraging big data computing to help customers fully utilize pre-stack data for 4D interpretation. We aim to achieve more detailed results, with the same amount of effort, and in the same amount of time, as the traditional and less insightful post-stack methods.

Ultimately, our approach to 4D advancement is based on the ambition to reduce analysis cycle time while adding reservoir detail that improves decision-making. For 3D and 4D, this has seen us provide a solution for interpreters and processors to collaborate, helping to optimize data for specific targets to better delineate reservoirs and improve fluid detection.

**About PreStack Pro.** Our team originally developed the PreStack Pro software to meet industry demands for modern software that could efficiently view, process and analyze 3D pre-stack seismic datasets. By working with pre-stack data, it is possible for interpreters to condition the cleaned data before it is stacked, which will go a long way to provide the confidence required for successful decision-making. Data quality is no longer compromised, as the software integrates pre-stack data conditioning with rigorous QC directly into the analysis workflow, ensuring successful seismic reservoir characterization results. With an interactive high-performance cloud solution in place, users can calibrate the seismic to well data, create custom stacks and interpret 3D and 4D reservoir distribution, all in one modern software tool.

Pre-stack seismic is the full-fidelity output of seismic processing, which is later "stacked" to produce one or more final 3D volumes. As seismic data storage capacity continues to grow exponentially, pre-stack data are increasingly being mined directly, to discriminate reservoir fluids and predict reservoir quality away from well control.

Our solutions leverage cluster and cloud computing to make pre-stack seismic analysis interactive, and our in-memory software can analyze large regional 3D datasets. QC and data cleaning are integrated directly into the data analysis workflow, to give interpreters a better understanding of data quality and its impact on analytical results. With PreStack Pro, users can ensure that their data meets the high standards required for seismic AVO inversion or other advanced techniques, **Fig. 3.**

While originally developed to analyze marine seismic data, PreStack Pro is increasingly being used to analyze land and ocean bottom seismic datasets that provide wide or full azimuth coverage. Pre-stack data in these settings are even richer, as it records data as a function of azimuth and offset. In these surveys, each pre-stack gather comprises a 3D volume of traces, and datasets are almost always too large to analyze on a single scientific workstation. As a result, few seismic interpretation systems have been adapted for azimuthal data, which is now a common processing deliverable.

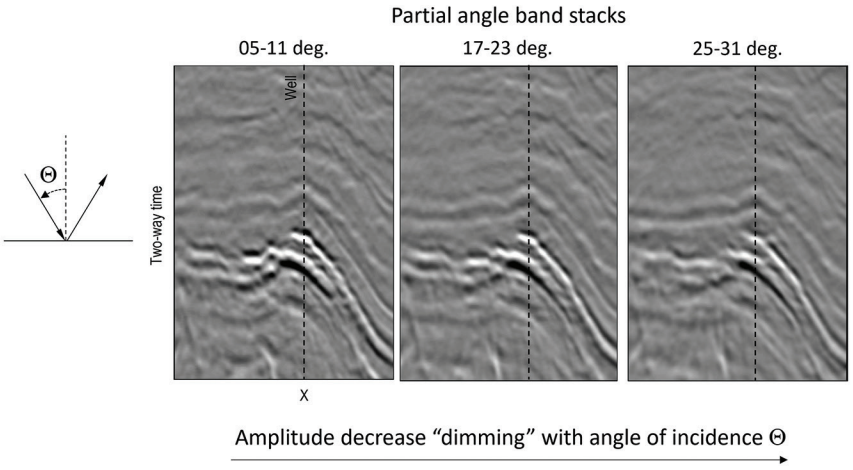
**4D analysis in PreStack Pro.** Geophysicists from Equinor began using PreStack Pro on 4D projects several years ago, with the software proving useful for visualizing time-lapse changes directly on pre-stack gathers. It was also used to apply identical pre-stack seismic conditioning workflows to each 4D survey. In certain cases, this helped to reduce noise, improve survey repeatability, and helped to identify more subtle seismic changes. Expert users soon discovered that with a few "smart hacks," they could use PreStack Pro's azimuthal data model to work with time-lapse data. This helped with the visual comparison of time-lapse volumes and made it possible to run equivalent gather conditioning workflows on all vintages. These early solutions were impactful but had limitations.

To start with, users had to establish naming conventions to label and track vintages. Common time-lapse QC and match filtering tools were also missing, and they still had to be applied in other software. In addition, some data conditioning modules were designed to operate on genuine azimuthal data and could not be used on these "pseudo-azimuthal" volumes (where each vintage was treated as an azimuth). As the number of volumes grew, it also became more cumbersome to compute and visualize differences between vintages, especially as more advanced attributes were utilized. It soon became clear that adding just a few additional capabilities could dramatically improve PreStack Pro's usefulness for time-lapse data. Sharp Reflections and Equinor embarked on a joint R&D effort that filled the obvious functionality gaps, delivering the new capabilities in less than a year.

We started by introducing "vintage" as a new seismic data class, to allow users to combine any number of vintages into a single dataset. Angle stacks, attributes, and maps are now treated as multi-vintage objects, helping to improve data organization and produce immediate benefits. We upgraded all viewers to display these multi-vintage datasets and to show changes between volumes without first computing difference volumes. Interpreters can now scroll through all vintages interactively, to pinpoint changes that are often difficult to detect on static displays.

For quantitative comparison of time-lapse data, we added a new suite of QC attributes that monitor survey repeatability, including NRMS difference between vintages, time-shift and phase rotation maps. New trace and survey matching options ensure that the amplitudes, phase and wavelets are consistent between vintages. We also extended PreStack Pro's data conditioning toolkit to recognize time-lapse inputs, to automatically apply identical processing to all vintages. Each vintage within a dataset is now processed

**Fig. 2.** 4D amplitude and time-shift analysis generates greater individual volumes and an even larger number of difference volumes increasing subsurface image quality.



independently, using the same parameters. We upgraded the interpretation and attribute tools in the same manner, such that calculations are automatically applied to every volume or map in the time-lapse collection.

Amplitude variation with angle (AVA) analysis, extended elastic impedance (EEI) inversion, horizon tracking, and amplitude mapping can now all be performed simultaneously on multi-vintage volumes. This advanced automation reduces repetitive work and cuts interpretation cycle time significantly. This initial phase of 4D development produced a powerful framework for efficient and fast 4D seismic analysis.

**Going further in 4D development.** The development of the 6.2 software update with Equinor was successful and well-received, and we were delighted to introduce it to the market in May 2021. The solution was tailor-made for Equinor, and we worked closely together on the project from inception to launch, ensuring that the final product worked as intended and would help support streamlined, successful operations.

Despite these advances, the new features, alone, did not produce a complete standalone 4D analysis solution. Once we announced the update to the market, we looked toward what we could do next. Sharp Reflections was built on the belief that more can always be done, with a constant ambition and willingness to go above and beyond, paired with scientific and technological innovation.

We began hosting webinars and seminars to introduce the new capabilities to our broader customer base. Immediately, we could see there was a real, tangible interest in pushing the boundaries of 4D seismic analysis by further extending the capabilities in PreStack Pro, **Fig. 4.**

We canvassed current and potential R&D partners to identify the missing components, which included direct time shift estimation algorithms and 4D AVO inversion capabilities. We also considered how to build on our strengths in multi-trace computing to propose new 4D analysis concepts which are not yet available in commercial software. With this analysis in mind, we plan to further develop quantitative tools for efficient 4D seismic analysis on the PreStack Pro software platform. There is much more to come, and we continue to work on changes to support the use of 4D seismic within the sector.

**R&D partnerships.** We want to support geoscientists to "dig deeper" into larger amounts of data with the same amount of effort, helping to create more insightful results in a shorter timeframe than previously possible. Time-lapse analysis remains a specialist task in many companies, and many advanced algorithms are accessed as research code designed for expert users. By harnessing PreStack Pro's powerful and unique 5-D data model, and pairing this with the implementation of existing methods and algorithms into a framework model, we can deliver these same high-end capabilities to a wider user base.

To this end, we are organizing a new joint-industry consortium to fund this ambitious set of developments. We are laying plans to work closely with two leading research organizations to build on our offering. Once sponsorship commitments are finalized, we plan to announce details of the program. Work is expected to commence by late 2021. The aim of these collaborations will be to combine best-in-class research algorithms with a best in-class software platform for prestack seismic data processing and analysis, with both partnerships serving to extend the capabilities and know-how of our own R&D team.

**Riding the digitalization wave.** Those operating in the oil and gas sector are embracing the current drive toward digitalization, and with good reason. The technological advancements that we have seen in the sector have been nothing short of revolutionary, with opportunities available to enhance most, if not all, of the oil and gas sectors' operations. Artificial intelligence and machine learning applications are gaining traction, and have the potential to simplify complex workflows. Training neural networks designed to run on 3D seismic volumes is proving to be a very compute-intensive task, and we see great potential to apply our big data solutions to accelerate these efforts.

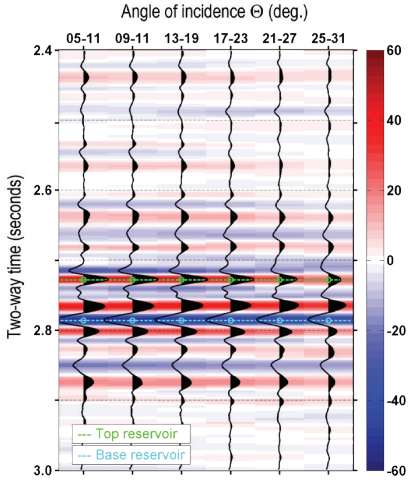
One facet of digitalization that is arguably overlooked is automation: the ability for new technological advancements to reduce time spent on analysis by reducing repetitive tasks. The core applications, processes, and analytics needed for quantitative seismic analysis within most companies are fragmented.

We are actively looking for ways to automate these workflows to accelerate results, to reduce the need for shortcuts and compromises. We want to help customers successfully leverage the full range of data that they have acquired. This requires better collaboration between processors and interpreters, so it is easier to understand how changes to gathers are reflected in volume attributes, final stacks and amplitude maps. Our ambition is to support clients to drill the best prospects and wells by using all their seismic data to make informed decisions.

**Looking to the future.** Seismic monitoring of subsurface changes has evolved continuously since its inception more than 30 years ago in the late 1980s. Seismic data quality has improved beyond recognition, enabled by improvements in recording equipment and acquisition methods. Increased channel counts, denser recording, and improved knowledge of source and receiver locations have fueled these trends.

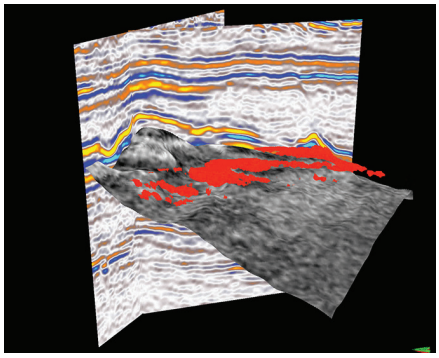
With these changes, the data volume increased by orders of magnitude, and we do not see this trend changing. With the realization that fiber-optic cables can be used as seismic sensors, the spatial sampling of the seismic wavefield, as well as the possibility to create and monitor surveys at ever closer intervals, will also continue. As such, the ability to handle ever-increasing amounts of 4D seismic data will become more important than ever.

**Fig. 3.** PreStack Pro solution leverages cluster and cloud computing to make prestack seismic analysis interactive, while in-memory software can analyze large regional 3D datasets.



Similarly, during the 30 years to date of 4D seismic analysis, the industry has continued to innovate regarding data analysis and interpretation. We have learned that we can monitor processes and readily detect signals that were previously not recognized or considered outside the limit of detection. For example, early seismic reservoir monitoring focused solely on changes within the reservoir. Any changes observed outside the reservoir were considered acquisition or seismic processing artefacts until it was realized that minute time-lapse time shifts above the reservoir could be conclusively linked to reservoir compaction and ensuing overburden stretching.

**Fig. 4.** Using scientific and technological innovation, the new 4D seismic methodology is delivering tangible results by enhancing analysis capabilities.



We can expect a continuous improvement of the ability to monitor geomechanical changes from time-lapse seismic data. To my mind, this will include inversion methods for tensor stress changes and localized subsurface deformations. This enables a range of geomechanical monitoring and prediction scenarios such as fault re-activation, cap-rock integrity assessment and localized well-failure diagnosis. Advanced software will be required to deliver these insights.

As the energy sector changes in line with the ongoing energy transition, the focus of reservoirs will shift to geothermal reservoirs and better monitoring of $CO_2$ sequestration sites. Monitoring reservoir processes and knowledge of the extent to which a reservoir is depleted or fully utilized will stay important, and 4D seismic must adjust to these new challenges. In the future, as in the present, the goal of reservoir engineering will be to drill the right number of wells to extract resources efficiently, while preventing hazardous situations from occurring.

**Value delivered.** Ongoing digitalization, paired with an increased focus on improved oil recovery from existing fields, has created the perfect backdrop for Sharp Reflections' new initiatives in 4D seismic analysis. Time-lapse activity will grow going forward, and multiple opportunities are available for companies that want to take advantage. Our strengths in pre-stack computing have provided an ideal launch pad for this new software toolbox, and we are excited about the future. We will continue to look beyond the horizon to find novel methods and analysis solutions to keep pace with the increasing flow of digital seismic data and help operators make good business decisions. WO

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