By Andrew Long (Andrew.Long@pgs.com)

EAGE 2021: Decarbonization the Catalyst for a New Geoscience Era?

Held in Amsterdam on October 17-22, the annual EAGE conference provided a particularly interesting industry forum as the world moves into a lower carbon future. Carbon Capture and Storage (CCS) featured strongly in the program, and the proportional CCS content of future conferences is expected to grow substantially. I comment on short-term applications of surface seismic methods and geological paradigms to CCS and note that much R&D into both geophysical and geochemical aspects is necessary to support the likely scale of CCS for global net-zero goals.

Synergies between towed streamer and ocean bottom node (OBN) acquisition had a high profile—with particular emphasis upon wide-tow multi-source developments, low-frequency seismic considerations, and various continuous wavefield source concepts. For seismic imaging, Full Waveform Inversion (FWI) has progressed beyond a velocity model building tool to now yield seismic interpretation deliverables of various sophistication. The most complete realization combines model building and full-wavefield least-squares migration into an abbreviated workflow for rapid project turnaround. Overall, it is evident that greater seismic acquisition and imaging effort, combined with better integration of geoscience and engineering methods, is necessary to solve long-standing conventional hydrocarbon discovery and recovery challenges, and to meet the unique subsurface resolution and characterization requirements for the transition to a net-zero carbon emissions. This may seem familiar, but a clear urgency exists to accelerate access to better data—augmented of course by machine learning and other automation platforms—and to throw everything at previously unassailable problems on quite grand scales.

An elephant in the room is whether the challenge of decarbonizing the planet with sustainable, affordable and accessible energy sources can motivate a new generation and boost recruitment to the geosciences and engineering – and on what timescale. Several forum discussions attempted to address these challenges.

Last Minute Covid Changes

The 2021 EAGE technical program contained about 200 oral sessions, ePoster sessions, workshop events, short courses and special forums distributed over the days of October 17-22 in a hybrid mixture of live and pre-recorded content. Total combined registrations on the first day were about 1,500 in-person and 1,00 virtual participants.

As was the case at the recent IMAGE21 conference in Denver, a clear message arising at EAGE 2021 was the need to embrace virtual participation for all future events. Only part of the overall program was available online, and did not include workshops, short courses, or ePoster presentations. Even if the pandemic disappears, there have always been so many geoscientists unable to physically travel for financial and logistical reasons—particularly the younger generation who will be employed by the ‘new energy’ industry as it develops. Time for the major professional societies to get their act together and make virtual platforms accessible and highly functional for everyone.

Now a highlight of the overall program, several Dedicated Session themes include Induced Seismicity, Innovations and Game Changers, Energy Transition; topics related to Reservoir Management, Petroleum Systems of NW

Europe, Depositional Processes; and two sessions dedicated to Low Frequency Seismic Data Acquisition and its Impact on Imaging and Inversion.

Preparing for Energy Transition

Although the overall EAGE 2021 program contained several sessions dedicated to energy transition / net-zero carbon topics such as CO2 storage, geothermal energy and mining, the technical content remained overwhelmingly focused upon the characterization and recovery of convenventional hydrocarbons. There were, however, a series of Forum Sessions in the opening sessiion and in the main program break each day that addressed "Energy Transition – Will great expectations be realized?", "How the Oil Industry is Addressing the Energy mix to Meet the Goals of the Transition Era", "Role of Geoscience and Engineering in Meeting Decarbonization Goals", and "Great Career Challenge – the Changing Education and Opportunities for Tomorrow's Energy Professionals". Such topics will expectably be increasingly represented in future EAGE event technical programs. You can find posts where I highlighted the fact that the EAGE has prioritized three themes that will benefit its members; including "The Energy Transition", "Digitalization", and "Career Development & Talent Acquisition" (with sub-categories of student activities, mentoring, and lifelong learning). In the first post I suggested that that "Career Development & Talent Acquisition" is the most critical, and in the second post I observed that the forum session on education and career opportunities probed quite deeply into myriad challenges confronting our profession, and the forum session devoted to decarbonization offered hope that solutions are already being found. One of the greatest challenges to the recruitment of a new generation of geoscientists and engineers is the disconnect between public perception of the oil and gas industry as a 'sunset industry' and our own views. On one hand, we need to be proactively engaged in transparent dialogue with opponents to our industry so that we better understand each other, but our industry still also needs to wake up to the true scale of its challenges. Arguments can be made that oil companies are not doing enough to develop the attraction of what our profession will be like in the future, and universities are not able to find answers to modern challenges without external assistance. The solutions are clearly broad collaboration between industry, academia, and community.

As has traditionally been the case, a large component of the EAGE 2021 program was dedicated to reservoir management, with session themes such as Reservoir Engineering, Integrated Subsurface, Mining & Civil Engineering, SPE and Joint EAGE – SPE. 4D (time-lapse 3D) technical content had a heavy component related to CCS (carbon capture and storage), as well as applications to geothermal and energy storage in the subsurface. I summarize several CCS contributions below.

Carbon Capture and Storage (CCS): The Growth Story

Net-zero ambitions are driving the extremely high interest in CCS for a variety of scenarios—all of which will necessitate intensive geophysical and geochemical monitoring. Consensus from CCS advocates seems to be that current CCS efforts must increase by approximately 100-fold within the next 20 years, and be about 50 GT per year by 2050. New global arenas for both geosciences and engineering enterprises are required, so one hopes this rapidly translates to employment growth for those displaced by several years of industry cuts. Some examples of immediately transferable practices are the identification of regional fill-and-spill fairways, investigating whether depleted or producing reservoirs can be repurposed for CCS, injection of CO2 into saline aquifers, developing regional risk maps for CO2 injection well planning and optimization as part of long-term CCS planning, and so on. Several candidate storage sites are being evaluated globally in a variety of settings, with long term simulations up to 20 000 years being used to model the evolution of structural, residual and solubility trapping over time. Over this timeframe, the majority of the injected CO2 will be dissolved in brine, while the remainder is trapped by the caprock and reservoir pore space. The pursuit of CCS in depleted reservoirs, or in locations with pressure communication to hydrocarbon production, is of high interest. In the latter scenario, the interplay between depletion and the amount of CO2 injected will affect the storage capacity. New storage mechanisms such as extrusive basaltic sequences are also being considered but require considerable research. Four dedicated sessions at EAGE 2021 address CCS topics, a variety of other content also has relevance, and these suggest CCS will play an increasingly dominant role in future conference events.

Three themes at EAGE 2021 involved surface seismic monitoring and characterization of injected CO2, the complementary use of fiber optic distributed acoustic and temperature sensing (DAS and DTS) for monitoring applications, and the complex geochemical factors that affect rock-fluid interactions and net storage capacity.

Seismic Monitoring and Characterization

CCS monitoring with surface seismic methods is constrained by the achievable vertical and horizontal image resolution in 4D difference images, and the precision of 4D time shifts detectable above the background noise levels. Wierzchowska et al. used the Sleipner CCS project (refer to Figure 1) to illustrate how deep-tow multisensor streamer acquisition combined with bespoke broadband processing flows, including time-warping to enhance the detection of time shifts many times smaller than the sample rate, enhances the resolution of small-scale features within the CO2 layering. It has also been shown previously by PGS and ENI how decoupled small time shifts and amplitudes changes enable the spatial delineation of subtle pressure and saturation changes during reservoir depletion. Such insights are relevant to CCS monitoring if the rock and fluid properties can be translated to petrophysical measurements by appropriate rock physics transforms. Common to the success of time-warping efforts, authors such as Carpentier et al. from TNO showed that high signal-to-noise ratio (SNR) within broadband seismic data will be critical to translate CCS quantitative interpretation (QI) workflows developed with synthetic seismic data to real world datasets.

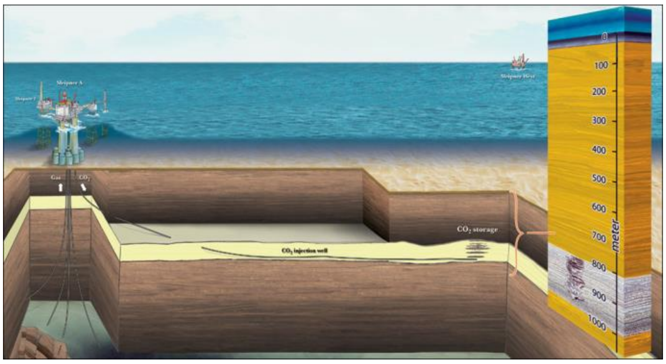


Figure 1. Geological setting of the Sleipner CO2 storage area. From Wierzchowska et al., Figure 1.

The Fluids Always Matter

Several presentations addressed the complementary use of fiber optic distributed acoustic and temperature sensing (DAS and DTS) for monitoring applications—in particular by the long-running CSIRO in both Western Australia and Victoria. Where borehole casing failures are likely, CCS monitoring could provide continuous observations as well as traditional monitoring of the injected CO2 plume. Passive monitoring of induced seismicity caused by various injection processes in the subsurface is also relevant.

Injected CO2 can exist in several fluid states that can change over time. The injection of supercritical CO2 into deep saline aquifers influences their petrophysical character and their sealing efficiency. Seal integrity of the caprock is affected by various interactions between CO2, brine and the minerals within the caprock—resulting in either porosity enhancement or diminishment. Brine composition can affect the CO2 solubility in the aqueous phase, increasing with pressure increase, and decreasing with temperature increment. The net effect upon brine pH is relevant to the degree of rock-fluid interactions and rock dissolution. Such observations motivate the development and application of geophysical QI workflows and tools able to complement in-situ geochemical monitoring. Geomechanical property understanding of the overburden for CCS is also particularly important for seal and caprock integrity, with related significance for FWI or high-resolution velocity model building.

Seismic Acquisition Continues to Blossom

Several EAGE 2021 presentations addressed the increased use of OBN (ocean bottom node) surveys as a complement to towed streamer acquisition in marine seismic surveys. Much of the growth in OBN has been driven by the commoditization of FWI for velocity model building, and the traditional dependence of FWI upon long offsets not historically afforded by streamer acquisition FWI technlogy continues to change rapidly, but it can generally be observed that ‘hybrid streamer-OBN’ surveys are more common with ‘sparse’ OBN deployment driven by the fact that OBN acquisition remains expensive. Indeed, PGS recently completed the acquisition of a truly innovative combined wide-tow hexa-source towed streamer survey with the sources towed over the streamers (refer to Figure 2), and about a thousand OBN sensors on a regional grid used to simultaneous record the entire survey. You can read about the exciting results in the recent IMAGE21 presentation by Dhelie et al. of Lundin Energy titled ‘Combining nodes and streamers to tackle the imaging challenges of salt basins in the Barents Sea’.

Towed streamer technology is also improving, and wide-tow multi-source acquisition has revolutionized the high-resolution imaging of shallow geology during high-efficiency towed streamer surveys. In addition, the use of long streamer ‘tails’ now enables much deeper FWI model updates; and where desired, multi-azimuth multisensor acquisition combines dense subsurface illumination and AVO-compliant imaging at much higher efficiency than OBN surveys. There is still much scope to explore with towed streamer survey designs, and the collective platform at the heart of several PGS presentations at EAGE 2021 is known as ‘GeoStreamer X’.

Figure 2. Recent world record PGS wide-tow hexa-source configuration (437.5 m between outer sources).

Oukili et al. used 'High resolution meets high efficiency with an ultra-wide-tow penta source solution in the Barents Sea' to showcase how an efficient ultra-wide-tow penta source set-up improved trace density and near offset coverage in a Barents Sea survey with various near-surface challenges. The CMP grid was 6.25 x 5.625 m, and the shot interval was only 7.5 m, with demonstrable benefits for higher fidelity imaging workflows. In a related presentation by Limonta et al. titled 'Novel acquisition design to improve illumination for velocity estimation and imaging North Sea case study', a novel marine multi-azimuth acquisition solution that included long streamer 'tails' enabled better illumination below and within complex velocity structures in the Viking Graben area of the North Sea, with demonstrable benefits for deep and high-resolution FWI model building, improved multiple removal, and consistent image quality from the seafloor to basement. Reiser and Bird also used 'Multi-azimuth quantitative Interpretation: A case study from the South Viking Graben, Norway' to emphasize how elastic attributes derived from multi-azimuth data enabled the computation of better reservoir attributes, identified several untested (likely) oil accumulations, and overall, yielded much richer subsurface information. An interactive rock-physics modeling platform named 'rockAVO' was used to assess the variation and sensitivity of both elastic properties and pre-stack seismic responses to changes in reservoir properties. The multi-azimuth GeoStreamer X data was shown to delineate and map the various known fields and discoveries at all stratigraphic levels in a superior manner, as well as highlighting new near-field exploration leads and opportunities.

PGS continues to also deliver new paradigms in marine seismic technology. Hegna used 'Continuous Wavefields Method - The acoustic wavefield generated by the seismic vessel' to show how to image the subsurface without an active source: the acoustic signals associated with the seismic vessel may instead provide a viable seismic solution in the most environmentally-restrictive settings. Note that this application is an extension of the 'Continuous shooting and recording methodology' known as 'eSeismic', and is another reminder that continuous source wavefields in various forms may soon play a more prominent role in marine seismic.

As noted earlier, OBN acquisition is growing, but OBN processing presents many unique challenges—one of which is the long-standing topic of solving for cold-water statics. Bekara et al. presented 'Parametric inversion of water column velocity for cold water statics correction in Ocean bottom seismic surveys', which described a methodology to compute time-varying, depth-dependent water column interval velocity profiles from OBS data. Signal processing challenges related to wavelet phase are always fundamental to successful imaging, and Bekara used 'Mixed phase seismic wavelet estimation using the Bispectrum' to demonstrate how the stable estimation of mixed phase wavelets can be improved, particularly when the wavelet length is increased—also relevant to the low frequency topics below.

Moving Beyond the Dogma of Cascaded Model Building and Migration

Seismic processing and imaging has historically been divided into two broad categories: everything associated with many 'preconditioning' steps such as designature, denoise/demultiple and data regularization prior to migration; and the migration step itself which comes in many flavours. The long-awaited commoditization of FWI has changed this traditional viewpoint, as

- FWI is applied to field gathers with minimal pre-processing,
- FWI itself uses a powerful depth imaging kernel (reverse time migration; RTM) that includes the modeling of multiples and a least-squares framework to derive a highly accurate velocity model, and
- FWI has in recent years been uses as a proxy for traditional migration—via spatial derivatives of the estimated velocity model to yield an 'FWI image'.

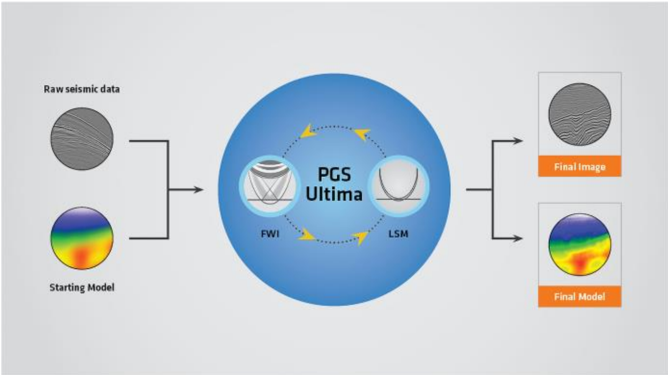
The latter product circumvents traditional cascaded processing flows of many stages by yielding an interpretation product 'in one step'—at high computational cost (for the model building part run to high frequencies), and inclusive of several approximations and assumptions. So it is understandable that FWI again had several dedicated oral and ePoster sessions, and played a part in several workshops, including 'WS09: High Resolution Full Waveform Inversion: Is It Only Cosmetics, or Is There Any Value for Imaging and Interpretation?'.

PGS had three significant contributions to the FWI journey. The first two FWI presentations built upon important PGS contributions in recent years: Martinez et al. pioneered the use of a weighted 'inverse scattering' imaging condition in 2016 to remove the high-wavenumber migration isochrones from the velocity kernel in FWI, thereby enabling accurate low-wavenumber model building to large depths with both transmitted and reflected wavefields; and Whitmore et al. later developed a new version of the acoustic wave equation known as 'vector reflectivity' to accurately initiate reflections during forward modeling—without any use of a density model, and even when the model is smooth and immature.

At EAGE 2021, Korsmo et al. presented a joint paper with BP authors titled 'FWI to full bandwidth with Vector Reflectivity and Inverse Scattering Imaging Condition, Clair field OBN'. FWI run to 60 Hz on a high-density ocean bottom node (OBN) dataset benefitted from the ability to solve for the background model without artifacts, before inverting to high frequencies. The FWI model correspondingly captured significant high-resolution details at a large range of depths. Huang et al. presented 'Extended domain FWI via time warping', which described a new FWI method that uses time-warping as the extension domain to overcome cycle-skipping in an extremely robust and computationally efficient manner. Dependence upon accurate starting models and / or the acquisition of low-frequency data is reduced, and the retrieval of high-resolution velocity models from simple initial models is faster and requires minimal pre-processing.

Before I mention the third new PGS contribution to FWI, I note that the classic imaging workflow includes two sequential tasks based upon scale separation: building a long wavelength velocity model, and imaging the subsurface reflectivity associated with higher wavenumber geological components. In recent years, the best-practice imaging platform has been least-squares migration (LSM) to optimize the spatial resolution and amplitude illumination of migrated images. Korsmo et al. correspondoingly presented 'Least-squares Kirchhoff PSDM with a local based inversion approach and compensation for limitations in modeling', which used a newly-developed local calibrated image-domain Kirchhoff LSM to optimize pre-stack image gathers for quantitative interpretation (QI) applications to a dataset covering the Verdandi/Lille Prinsen discovery in the Viking Graben.

LSM can be implemented in many ways, but in any version will improve the reflectivity and spatial wavenumber content of migrated data without changing the velocity model. The grand ambition for several decades has, however, been to simultaneously invert for an optimized velocity model and an optimized reflectivity image. The first-ever commercial realization of this dream was presented by Yang et al. as 'Simultaneous velocity and reflectivity inversion: FWI + LSRTM'. FWI is combined with LSM into a single simultaneous inversion framework, with significant reduction in turnaround time for a model building and imaging project. If you would like to learn more about this solution, please register for the webinar titled 'PGS Ultima'.



More on Very-Low Frequencies

PGS also had two contributions to the two Dedicated Sessions titled 'Low Frequency Seismic Data Acquisition and its Impact on Imaging and Inversion'.

Reiser demonstrated how to apply stable rock-physics transforms to FWI models in 'Additional low frequencies in broadband seismic deliver increased confidence in prestack inversion and prospect de-risking'; thereby building elastic low-frequency models that overcome the traditional 'low frequency gap' that confronted quantitatively accurate pre-stack simultasneous AVA inversion. Note that any such application of FWI must implicitly be able to use data lacking the same low frequencies confronting the inversion of elastic attributes. In other words, the capacity of the PGS FWI solution to avoid cycle-skipping effects when using multisensor GeoStreamer data—naturally richer in low frequency content—is validated by the quantitative accuracy of the case study shown.

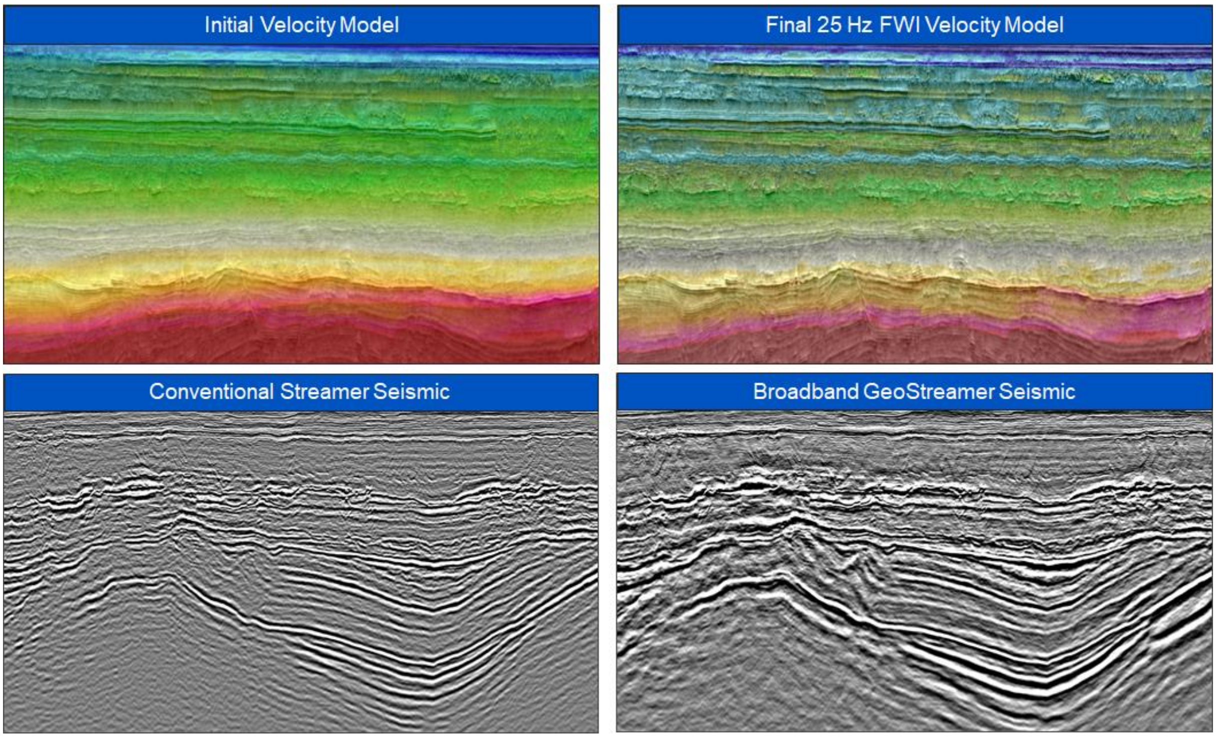


Figure 3. High resolution FWI velocities and broadband seismic data were shown by Cyrille Reiser to overcome the traditional 'low frequency gap' that has challenged quantitatively accurate seismic inversion.

Hegna et al. continued their development of the continuous shooting and recording methodology known as 'eSeismic' by presenting 'Continuous Wavefields Method – Low frequency considerations'. Applicable also to towed marine vibrators, or even to the vessel noise wavefield, the eSeismic method most commonly involves the triggering of individual air-gun, and the iterative deconvolution of common receiver gathers from the entire sail line of acquisition recorded as a single continuous record. From the low frequency perspective, Hegna addressed the reduced correlation between signal and noise and denser enabled by dense spatial sampling of a source wavefield approaching the properties of white noise.

Summary

Technical developments at EAGE 2021 particularly showcased the virtues of integration on many levels: complementary seismic acquisition and imaging solutions, the realization of long-held ambitions to consolidate model building and imaging workflows, and the ability to better characterize the subsurface in terms of both conventional hydrocarbon recovery and the pursuit of large scale CCS efforts. Far from being a discipine in decline, geoscience can enter a new era of significance—if the industry can attract, develop and nurture the next generation of contributors, as well as adapt the global population of skilled talent to an energy landscape that pragmatically incorporates decarbonization goals with demonstrable commercial incentives for all stakeholders.