EAGE 2022 Highlights

The 83rd EAGE conference was held in Madrid on 6-9 June, in a welcome return to in-person attendance. I briefly review the key technical themes and profile 12 technical presentations given my PGS authors. Topics cover Full Waveform Inversion (FWI), simultaneous inversion of velocity and reflectivity (PGS Ultima), developments in marine seismic acquisition, the inversion of reservoir properties from multi-azimuth (MAZ) seismic data, automated subsurface characterization, an integrated workflow for identifying Carbon Capture & Storage (CCS) sites, applications of deep learning to seismic data processing, and water velocity static corrections in deep water areas for 4D reservoir monitoring.

A Welcome Return to Face-to-Face Interaction

The past two years have been tough for the tradeshow business. The pandemic forced the major professional societies to convert their annual events to either hybrid or entirely virtual events with large online participation. The experience for remote participants was often unpleasant. The virtual portals were slow and buggy, chairpersons struggled to manage the technical sessions, and the Q&A was generally forgettable. From the financial perspective of the societies, the contraction in exhibition and sponsorship revenue must have hit hard. The EAGE event this year in Madrid reportedly attracted about 4 000 in-person registrations and about 1 000 online registrations. Next year in Vienna, the ambition is to revert to an in-person event only, partly because the cost of running online participation is perceived as too high. For many, however, virtual participation is the only hope to overcome the prohibitive costs of travel, accommodation, and the reluctance of many companies to send employees on international trips in a climate of global uncertainty. Can an option be developed to access recorded technical presentations before the event, and interested participants can engage in a virtual Q&A with the authors?

More of the Same, But Focused Towards New Energy

Three technology themes dominated proceedings:

1. **CCS / CCUS** was everywhere and dominated much activity. Marine minerals are also making a lot of noise, primarily in terms of companies pursuing investigative research such as the database being developed by PGS and Ocean Floor Geophysics (OFG).
2. **FWI (Full Waveform Inversion)** again had the largest share of the seismic elements of the technical program, maturing into a key standalone interpretation tool. Products such as PGS Ultima, a simultaneous inversion equivalent to performing FWI and least-squares migration (LSM) in a single framework, is clearly the way forward (refer also to **Figure 3**). 'Conventional' FWI is already being used in integrated studies to produce 3D feasibility cubes of expected rock properties and AVO signatures, and this year, Dig Science and PGS further refined their ability to combine burial and rock physics modeling for the Tablelands and North Tablelands area in offshore Newfoundland. Expect to see much closer integration between simultaneous inversion and subsurface characterization in coming years - including applications to CCS and reservoir monitoring.
3. **Marine acquisition technology** talks continued to focus on the source side and upon efficiency improvements to seafloor seismic surveys. Overall, the common element of most source developments has been an acceptance that compact air-gun sources yield perfectly good signal penetration and enable the deployment of wide-tow multi-source shooting templates for highly efficient surveys with excellent near-surface resolution. As illustrated by Lundin Energy with their Nordkapp hybrid streamer-OBN survey in the Barents Sea, towed-streamer broadband surveys complemented by an array of nodes deployed for the duration of the survey also benefit greatly from wide-tow multi-source shooting. Regards alternatives to air guns, the BASS marine vibrator (MV) being developed by Equinor and Shearwater apparently still requires another couple of years of development. It has been a long wait to see a commercial industry success in this space, but the promises keep coming. An interesting comment regarding time-lapse 3D (4D) was that MV-on-MV should work, but MV-on-legacy airgun will be far more challenging. On the land front for vibroseis sources, deblending talks fill the program. Time will tell whether the marine deployment of many simultaneously sweeping vibrators is feasible.

FWI: Removing Obstacles and Creating Opportunities

PGS gave two complementary presentations on ways to reconstruct the low-frequency content of FWI (Full Waveform Inversion) so that traditional risks of cycle skipping are reduced, and model convergence is faster and more stable. Maiza Bekara presented "A new look at autoregressive low-frequency reconstruction of seismic data", a computationally efficient solution that follows a conventional signal processing approach rather than relying upon costly offline network training. To illustrate the method in action, Ramzi Djebbi presented "Full Waveform Inversion with low frequency reconstructed data", which described how the recursive filter estimated from the high-frequency content of the data can be used to robustly reconstruct the low frequencies.

Two case studies showcased the efficacy of modern FWI solutions in large-scale 3D projects. Jyoti Kumar presented "Imaging pre-Messinian targets in the East Mediterranean Sea - A case study using FWI", wherein a velocity model building workflow using FWI and RTM gathers successfully captured historically-elusive post-Messinian and-Messinian complexities. Antonio Castiello presented "Integrating FWI and reflection tomography to rejuvenate legacy seismic data: an example from the Faroes-Shetland Basin", a robust velocity model building workflow that leveraged FWI updates and geologically constrained reflection tomography to quite seamlessly rejuvenate 38 seismic datasets, resolve sharp lateral and vertical velocity variations in the overburden, and enhance the imaging quality of the targets associated intra-volcanic and intrusive features (refer to **Figure 1**).

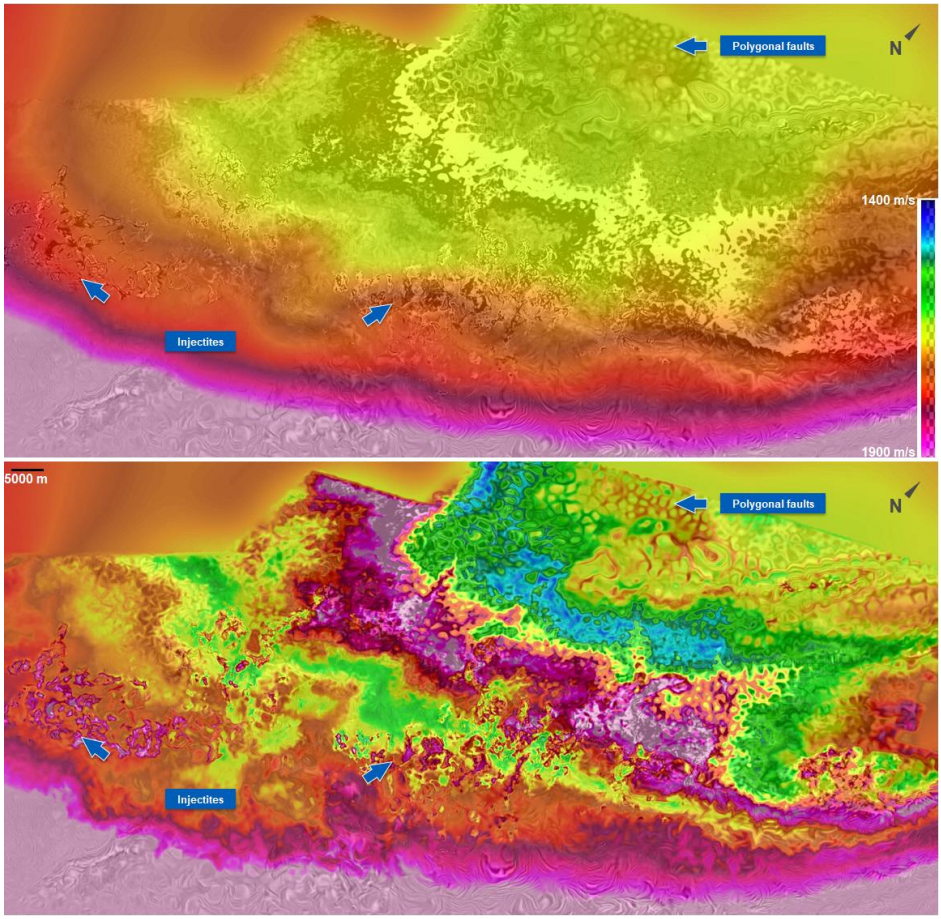
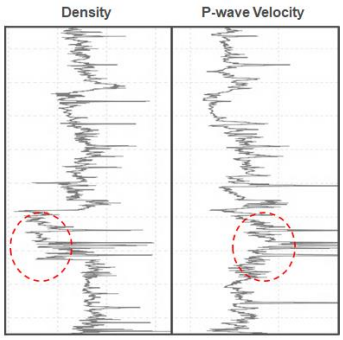


***Figure 1**: Extracted horizontal slices at 200m depth from a reprocessing project in the Faroes-Shetland Basin. In contrast to the smooth input model (upper), the output from the PGS FWI solution (lower) resolves very small features, including thin injectites, turbidites, and polygonal faults. From Castiello et al. (2022).*

PGS launched a breakthrough integration of FWI and Least-Squares Migration (LSM) in 2021, and Øystein Korsmo demonstrated the power of the solution in "Imaging by seismic inversion based on the adjoint state method". PGS Ultima can invert for the reflectivity while simultaneously refining the FWI velocity model. Critically, reflectivity changes caused by density variations are not erroneously mapped as velocity updates, and the reflectivity imaging results show significant structural improvements, more focus, and better fault imaging compared to traditional RTM.

To illustrate the key premise, Figure 2 is an example of a traditional FWI result wherein the inverted velocity model in Figure 2C is apparently 'high-resolution' because the unwanted migration isochrone contributed to the model updates. Figure 2A uses the PGS FWI solution that successfully removes the migration isochrone and recovers the background velocity model without artifacts and leakage from the density term common to almost all traditional FWI solutions. The inset panel to the right illustrates how the vertical density (left) and P-wave velocity (right) are typically **not** correlated through the reservoir interval and a common density model assumption used within traditional FWI is completely invalid.



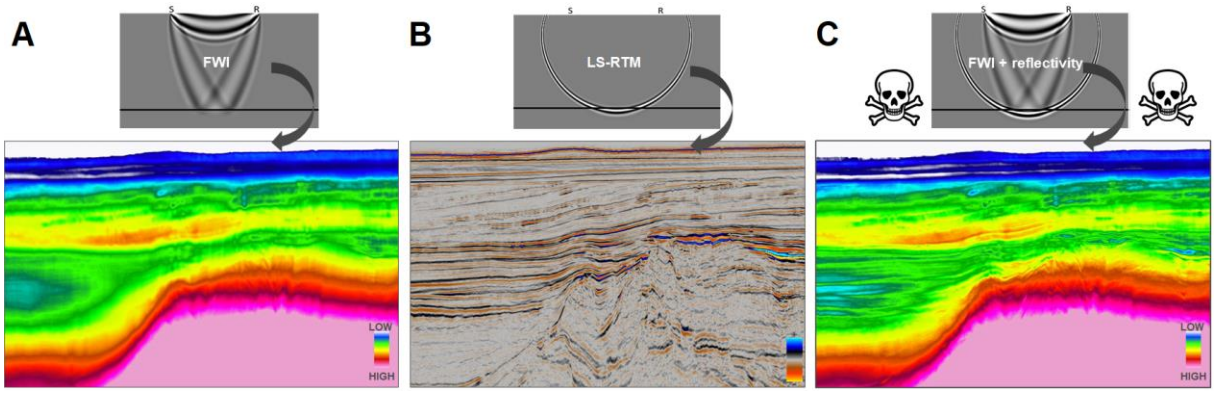


***Figure 2**: A correctly implemented FWI using model updates from both diving waves and reflections (A) will not be contaminated by reflectivity leakage. It is too easy to invert a velocity model heavily contaminated by 'high resolution' events (C) that are in fact representative of the reflectivity (B). The FWI sensitivity kernels upper parts of (B) and (C) also demonstrate how the migration isochrone effectivity removed in (A) is the source of the invalid 'high resolution' velocity model features. Courtesy of Øystein Korsmo (PGS).*

In contrast, **Figure 3** from Korsmo et al. (2022) shows the power of the PGS Ultima solution to simultaneously invert the optimized resolution reflectivity and velocity models. In the next Industry Insights newsletter, I will highlight the ability of PGS Ultima to recover high-resolution density models in a significantly more elegant manner than is pursued using traditional cascaded workflows of low-frequency model building and simultaneous pre-stack AVA inversion.

More (and New) Sources, and More Azimuths

The most significant development for towed-streamer seismic in recent years has been the commercialization of wide-tow multi-source shooting, with up to six sources towed with a combined separation of almost 450 m. Martin Widmaier presented a workshop (W12) talk titled "Recent advances with wide-tow multi-sources in marine seismic acquisition and imaging", which charted the engineering achievements that have enabled highly efficient acquisition configurations to also deliver remarkable spatial sampling and near-surface image resolution and quality previously unimaginable. Now that wide-tow multi-source shooting is standard across the PGS fleet, novel streamer configurations are starting to emerge too. Correspondingly, Martin will also presented "Combining wide-tow multi-sources with a non-uniform streamer configuration: A case study from the Sarawak Basin", wherein wide-tow multi-sources with a non-uniform streamer separation were deployed for the first time in a seismic survey in offshore Malaysia.

Stian Hegna dispensed with traditional seismic sources altogether in "The acoustic wavefield generated by a vessel sailing on top of a streamer spread", and instead used the broadband (4-250 Hz) acoustic wavefield generated by a seismic vessel to image the Earth. The test was part of a world-record source-over-streamer survey towing six sources in wide-tow mode. Encouragingly for the future of this novel approach in areas where active seismic sources are not permissible, the acoustic wavefield emitted by the vessel appears to be very broadband and almost omnidirectional with only minor variations related to emission angle.

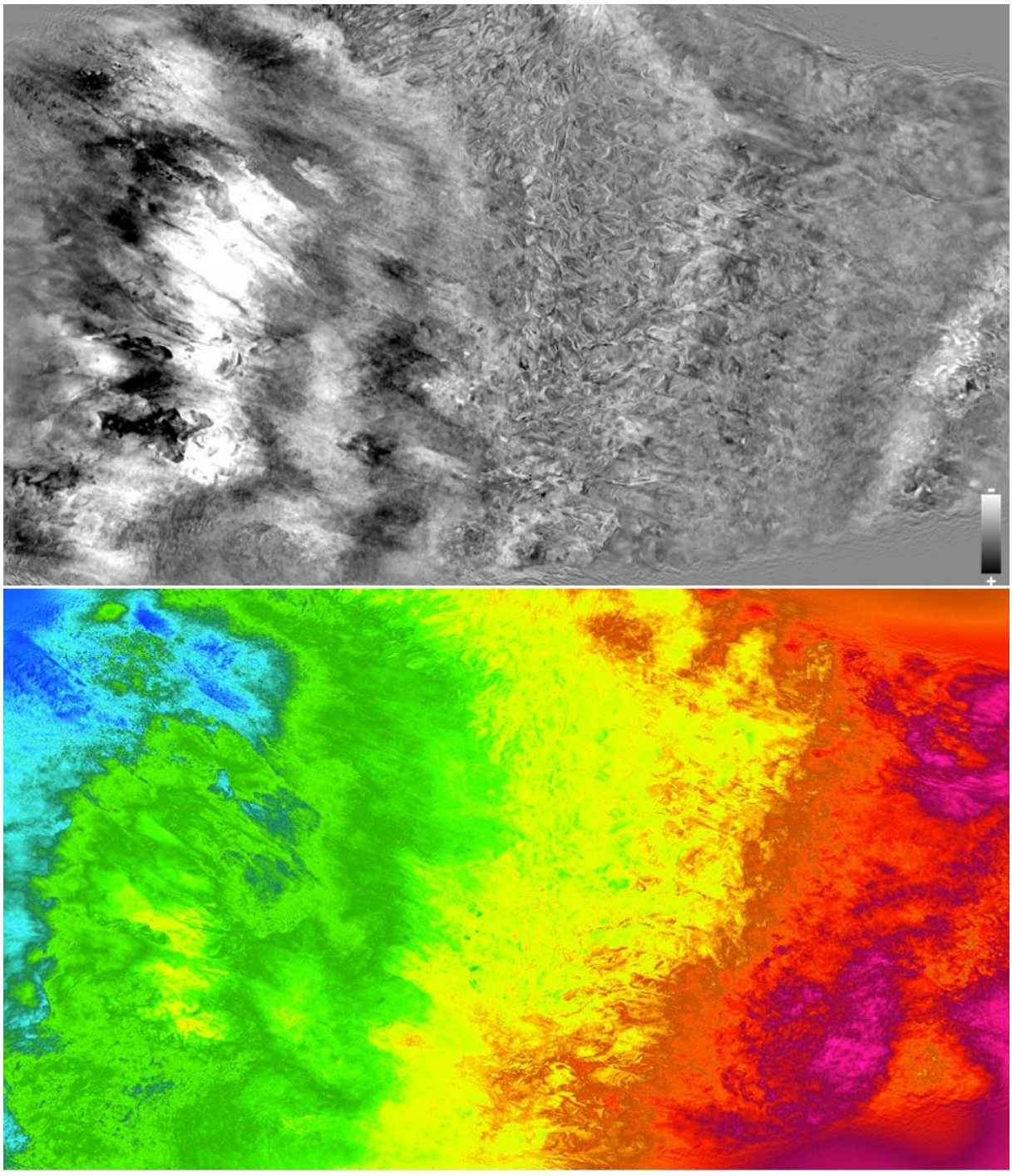


***Figure 3**: Inverted reflectivity at 3400m depth (upper) and simultaneously inverted velocity model (lower) using PGS Ultima. Plotted velocity range is 1600-2000 m/s and maximum frequency inverted is 25 Hz. As the augmented wave equation used within the simultaneous inversion of PGS Ultima has no density term, there is zero leakage of density information into the velocity model, and the high-resolution features are legitimate. From Korsmo et al. (2022).*

Multi-Azimuth (MAZ) shooting, which has been applied for two decades now, benefits from the applicability of traditional imaging workflows. Consequently, the rejuvenation of legacy datasets via the acquisition of a new survey azimuth(s) is becoming commonplace in many regions. Roberto Ruiz and Cyrille Reiser co-authored two

quantitative interpretation case studies that also showcase the value of jointly inverting the pre-stack data from each azimuth to create opportunities for near-field exploration. The abstract by Roberto titled "Mature Paleocene South Viking Graben play derisked with multi-azimuth Seismic data, a Norwegian case study" demonstrated how the integration of MAZ broadband seismic data in AVA analyses can help discriminate the response of volcanic tuffs facies from deep-water marine sandstone facies at the Paleocene level in the prolific South Viking Graben. In a complementary presentation, Cyrille used "Data-driven reservoir properties estimation using MAZ towed multisensor streamer seismic: A Norwegian case study" to go a step further by estimating reservoir properties such as volume of shale and porosity (refer to **Figure 4**). Of other significance, no low-frequency model was necessary to achieve absolute reservoir properties.

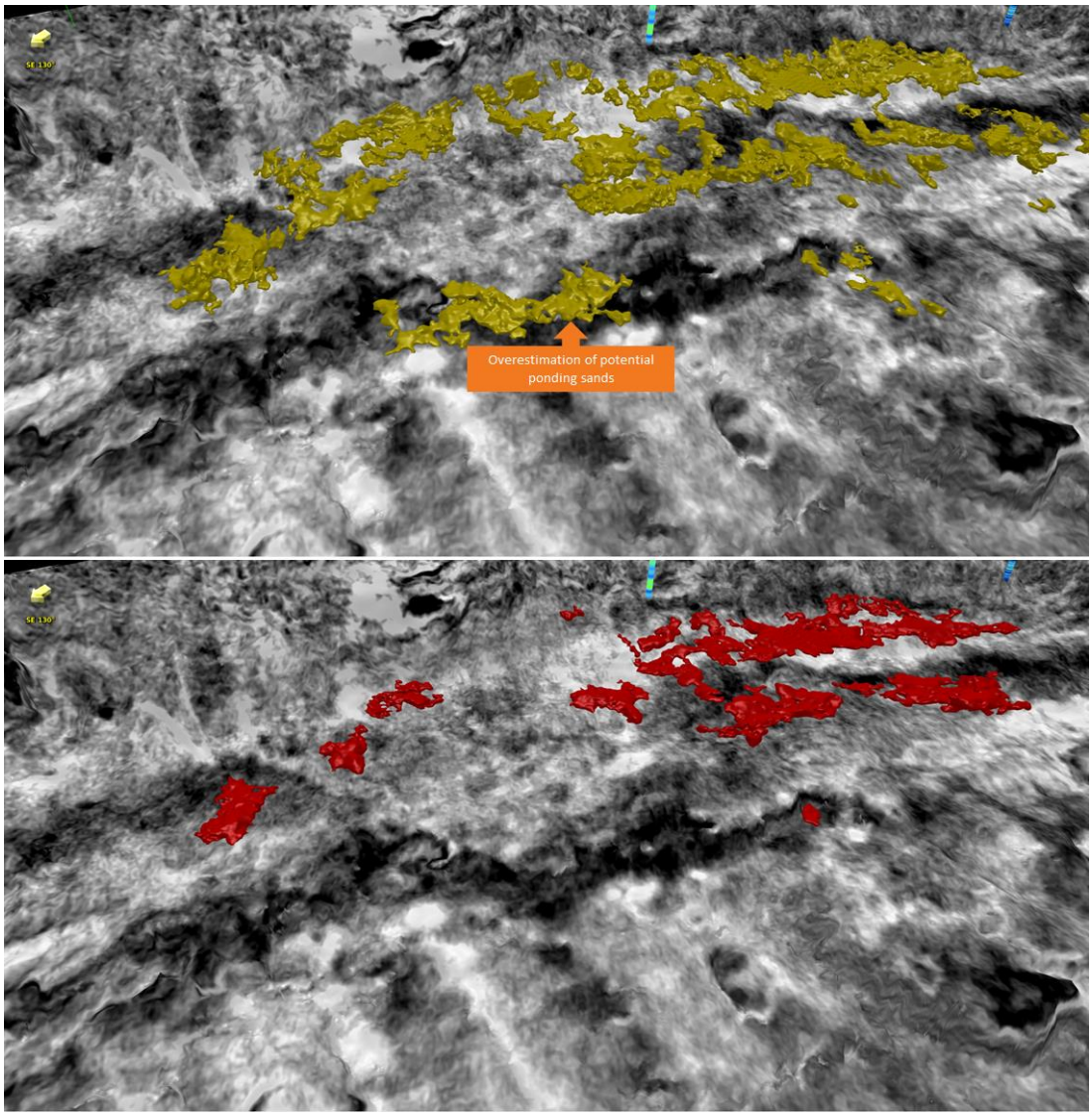


Figure 4*: Comparison of geobody extraction for estimated porosity > 8% using data acquired during a GeoStreamer X survey in the South Viking Graben. A narrow-azimuth pre-stack simultaneous inversion result (upper) has a significant over-prediction of sands and the resulting extracted geobodies are inconsistent with the geological model as a mix of sands and shales are picked. In contrast, Reiser and Ruiz (2022) demonstrated how the complementary information from different azimuths stabilizes the Gradient term in a multi-azimuth pre-stack simultaneous inversion result (lower).*

Automation Creating Value for Subsurface Characterization

The First Break paper by Per Avseth and others from Dig Science and PGS in 2020 titled "Exploration workflow for real-time modeling of rock property and AVO feasibilities in areas with complex burial history — a Barents Sea demonstration" showcased the value of burial-constrained rock physics modeling to generate AVO feasibility cubes. The workflow included low-frequency model building based upon FWI velocities and enabled efficient and geologically consistent DHI derisking of leads and prospects in any geological context. In another collaboration with PGS, Per Avseth from Dig Science used "Combined burial and rock physics modeling to explore the complex velocity and AVO depth trends offshore Canada" to showcase how a workflow with burial-constrained rock physics modeling in the Tablelands and North Tablelands areas of offshore Canada can be adapted to accommodate a natural ambiguity between the temperature and burial histories of the region. The multiple rifting history and complex tectonics during late Jurassic/early Cretaceous make it challenging to separate burial from thermal effects on elastic properties. Nevertheless, AVO scenario cubes were successfully generated to screen and de-risk leads and prospects in the area from calibrated inversion data. Such flexibility is particularly applicable when high-quality petrophysical data calibrations are available. In a relevant workshop (W4) presentation Cyrille Reiser showed the successful application of machine learning to predicting incomplete data in "Data mining for prediction of petrophysical properties from well logs".

The use of integrated G&G screening workflow to consider both the container and containment aspects of CCS was described by Noémie Pernin in "Integrated workflow for characterization of CO2 subsurface storage sites". The site assessment workflow allows the validation of various technologies on a local scale, with the option and feasibility to be expanded regionally (refer to **Figure 4**).

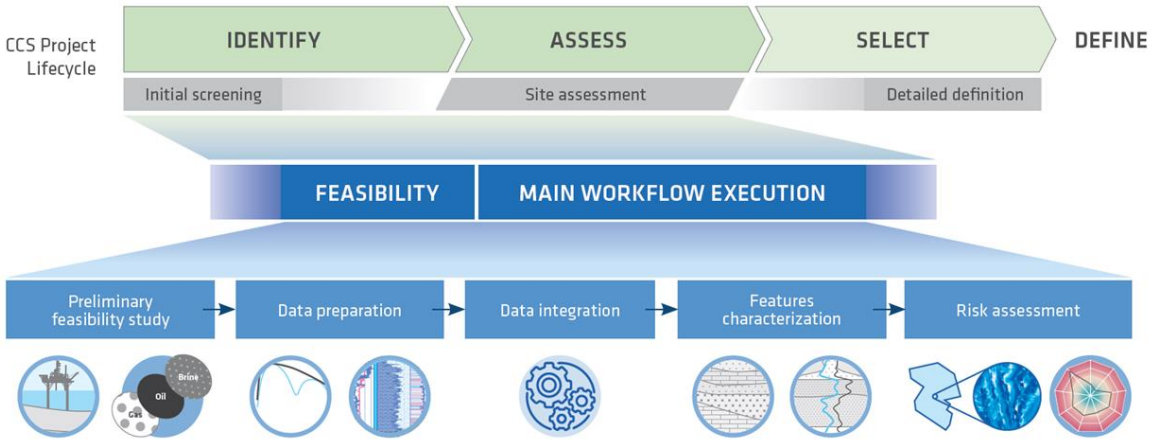


***Figure 4**. Schematic summary of the integrated workflow for CCS site selection used by Pernin et al. (2022)*.

Two complementary PGS papers addressed fundamental ways to use deep learning / dictionary learning to streamline and optimize traditional signal processing workflows. Bagher Farmani illustrated how deep learning models trained from multisensor streamer data can be used to automatically classify various noise types in noise attenuation workflows and pursue automated and targeted noise removal in "Stepping towards automated multisensor noise attenuation guided by deep learning". The advantages to turnaround and quality that arise were abundantly clear in the examples shown: under most circumstances, there is no need for denoise testing ahead of production, the automation of the noise classification reduces the workload on the traditional user, and the user more productively uses their time to detect and resolve any ambiguities. At a more fundamental level, Mohammed Faouzi Zizi used "Simultaneous dual-sensor wavefield separation and seismic data compression using constrained dictionary learning" to show an automated method that pursues multisensor wavefield separation process in a compressed domain. Advantages include being robust to aliasing without the need for data preconditioning, the method involves significant data compression of the data, and requires less time and human resources.

The Power of Integration to Resolve Small Details

Finally, Didier Lecerf used "Water column corrections, joint water velocity inversion for 4D surveys" to present a new methodology for correcting the effect of the water layer variability on time-lapse seismic datasets that is significantly beneficial for deepwater '4D friendly' data. The main difference from conventional approaches is the simultaneous use of both 4D datasets to estimate the water velocity changes and therefore minimize the seismic difference in the overburden. Inversion is performed in the image domain using cross-image CDP gathers built from cross-correlations of acquisition sequences of migrated data.

Special Events by PGS at EAGE 2022

As always, PGS ran a Lunch & Learn technical session to a full house each day. Topics presented were as follows:

- "PGS Ultima – Advancing simultaneous velocity and reflectivity inversion to deliver reliable images", by Øystein Korsmo
- "Carbon storage site characterization and monitoring", by Allan McKay & Cyrille Reiser
- "GeoStreamer X and Beyond - From innovative acquisition and imaging solutions to accurate reservoir estimates", by Martin Widmaier & Roberto Ruiz

PGS has a collaboration with OFG (Ocean Floor Geophysics) and their P-Cable ultra-high-resolution (UHR) towed streamer solution purchased from NCS Subsea in 2022. Three New Energy sessions were also given to full houses as follows:

- "P-Cable UHR3D for Renewables", by Larry Scott (NCS Subsea, now an Ocean Floor Geophysics company)
- "Lessons learned from 15 years of seafloor sulphide exploration", by Peter Kowalczyk (Ocean Floor Geophysics)
- "A masterclass in ultra high resolution geophysics for CCS, renewables and minerals", by Larry Scott (NCS Subsea, now an Ocean Floor Geophysics company) & Peter Kowalczyk (Ocean Floor Geophysics)

Relevant Webinars

- PGS Live | GeoStreamer X - What, Where, Why: Ask the Experts
  - Find out how GeoStreamer X is redefining multi-azimuth streamer acquisition, creating opportunities in different regions. This one-hour recorded webinar includes two short presentations and an expert panel discussion.
- PGS Live | PGS Ultima - Better Images Faster
  - PGS has combined FWI and LSM in a single simultaneous inversion to deliver accurate velocity models, and images with reliable attributes quicker. Speed up your decision-making process with PGS Ultima. P
- rockAvo | Experience Realtime Exploration Analysis and Rock Property Perturbation
  - rockAVO provides petrophysics and rock physics expertise to help geoscientists achieve faster lead analysis and prospect derisking, plus QC of integrated AVO-compliant seismic and well data. Roberto Ruiz demonstrates rapid screening for analogs, and scenario testing of lithology, fluids and porosity.
- PGS Live | Carbon Storage
  - Find out how PGS can help plan, develop and operate carbon storage sites efficiently and safely. Our panel of experts will be on hand at this live event to answer your questions about our CO_2 storage services.
- CO_2 Site Characterization | Appraise Capacity, Ensure Containment
  - Noémie outlines a risking workflow for the efficient characterization of viable carbon storage sites (CCS) based on the high-quality data from PGS MultiClient library, including seismic, wells and interpretation, and integrated G&G expertise and technology, from acquisition to imaging, interpretation, and understanding the subsurface.