Deep Upper Jurassic play evaluation in the Southern Viking Graben using cost-effective multi-azimuth streamer technology

Eric Mueller[1]*, Martin Widmaier[1] and Julien Oukili[1] demonstrate why multi-azimuth (MAZ) multi-sensor towed streamer seismic data are an efficient and competitive means to providing significantly improved imaging of South Viking Graben (SVG) margin flanks and graben centres.

Introduction

Multi-azimuth (MAZ) multi-sensor towed streamer seismic data are an efficient and competitive means to providing significantly improved imaging of South Viking Graben (SVG) margin flanks and graben centres. Flexible survey design and acquisition efficiency combined with modern processing and velocity model-building workflows create a step up in data quality to image potential new plays in the otherwise mature North Sea rift system. Data quality and MAZ illumination allow imaging of Upper Jurassic lateral successions of fault scarp graben edges, details of terrace floor gravity flow deposits, terrace incisions and basin floor fans extending out on the graben centre at current burial depths greater than 4000 m.

From novel acquisition concepts to an integrated exploration solution

In 2019 an innovative towed-streamer multi-azimuth acquisition and imaging concept branded as GeoStreamer® X was piloted in the Viking Graben (North Sea) as a cost-effective and intelligent solution for high-definition exploration. The initiative aimed to enhance the value of multi-client multisensor 'broadband' exploration data acquired in the North Sea and Norwegian Sea offshore Norway during the previous 10 years. Evolving imaging and velocity model-building technologies, e.g., full waveform inversion (FWI), as well as the need for higher resolution, improved illumination, and more accurate subsurface images for interpretation of a variety of exploration targets formed the basis for modern survey designs and advanced acquisition technologies.

Over that past decade, exploration campaigns in areas such as the Viking Graben were typically conducted using narrow azimuth towed-streamer configurations. These surveys used dual-source setups with 6 to 10 streamers spaced 100 m apart, and approximately 6000 to 7000 m in length. The legacy configurations resulted in crossline acquisition bin sizes of 25 m and thus limited resolution. The relatively sparse source-line sampling led to limited near-offset coverage, which in turn compromised imaging of the shallow overburden and introduced the so-called shallow 'acquisition footprints'. While the seismic offsets acquired during these campaigns were well-suited for reflection imaging and move-out-based velocity model-building, they were insufficient for refraction-based full waveform inversion targeting deeper exploration objectives offshore Norway.

Recent advances in seismic vessel capabilities, streamer inventory, and towing and handling systems for sources and streamers have expanded the solution space for smarter survey designs (Widmaier et al., 2019). These improvements enable better integration with advanced imaging technologies, without necessarily increasing the cost or turnaround time of seismic exploration surveys.

One of the key configuration changes compared to legacy multi-client library data was the shift from a standard dual-source setup to a wide-tow multi-source configuration, particularly the introduction of a wide-tow triple-source geometry. Increasing the number of sources from two to three reduces the crossline bin size by approximately 33%, assuming constant streamer separation, and even more when streamer spacing is reduced simultaneously.

To maintain fold and inline source sampling with the triple-source setup, the source firing interval had to be shortened. Any potential loss in acquisition efficiency due to reduced streamer separation was effectively mitigated by increasing the number of streamers to 14.

The wider towing of source arrays was introduced to improve the distribution of near-offset traces compared to legacy acquisition configurations (*e.g.* Widmaier et al., 2021). Traditionally, marine source arrays were positioned in front of the two central streamers, with a nominal source separation determined by dividing the streamer separation distance by the number of source arrays. In contrast, the wide-tow triple-source configuration introduced a source separation that exceeded the streamer separation. This adjustment significantly enhanced shallow imaging quality without compromising efficiency.

Another smart enhancement to the acquisition setup was the introduction of variable streamer lengths. For high-defi-

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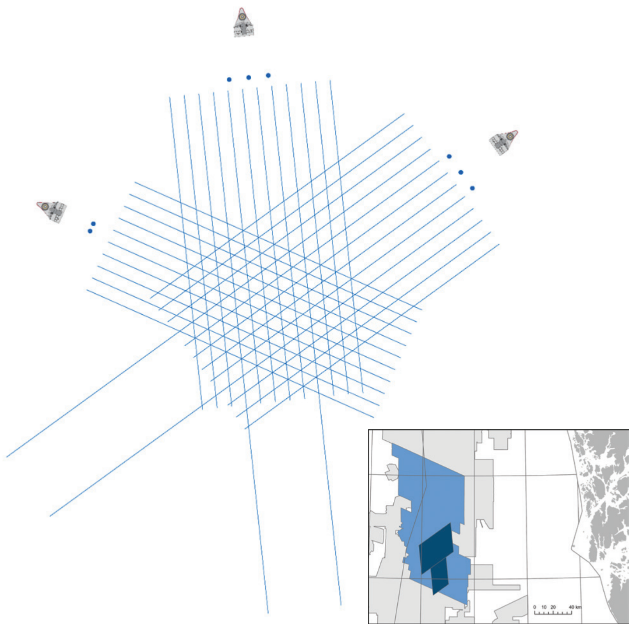

Figure 1 Adding two new acquisition directions to an existing survey. While the legacy data was acquired with dual source and standard streamer spread, the new data acquisition comprised wide-tow triple sources and streamer tails. Inset map shows MAZ (dark blue), narrow azimuth towed-streamer (light blue), and MegaSurvey data (grey) locations.

nition exploration campaigns, a high-density streamer spread optimised for high-resolution imaging was complemented by 10km-long streamer-tails. These extended streamers provide the long-offset data necessary for FWI using diving and refracted waves. Since FWI relies primarily on very low-frequency energy, the spatial sampling requirement for the long-offset data could be relaxed. This allowed for efficient integration of long-offset data without a significant increase in streamer inventory.

The wide-tow multi-source and variable streamer length configurations were combined with MAZ acquisition technology which was a well-known application from areas with complex geological targets. Key benefits of MAZ include improved azimuthal illumination and increased trace density. MAZ is a flexible and scalable approach in marine seismic acquisition,

	2019	2020	2022
number of streamers	14	14	14
streamer length tails	6000 m 10 000 m	6000 m 10 000 m	7000 m 10 000 m
streamer separation	84.375 m	93.75 m	75 m
streamer depth (tails)	25 m (28 m)	25m (28 m)	25 m (28 m)
source count	triple	triple	triple
source separation	112.5 m	125 m	125 m
crossline bin size	14.0625 m	15.625 m	12.5 m

Table 1 Configuration examples from surveys acquired with different azimuths over existing seismic data offshore Norway in 2019, 2020, and 2022. All examples comprise wide-tow triple source configurations and dense streamer spreads with streamer-tails.

typically executed with a single vessel, unlike wide-azimuth streamer or ocean-bottom node (OBN) surveys that require multi-vessel operations. Modern seismic data can be acquired in a complementary fashion over existing datasets. For example, adding two new azimuth directions to legacy data results in three dominant azimuths, significantly improving offset and azimuthal coverage.

This complementary acquisition strategy densifies legacy exploration data in both the shot and receiver domain and enhances imaging accuracy from shallow to deep targets. A schematic illustration is shown in Figure 1, and configuration examples from surveys conducted in 2019, 2020, and 2022 are provided in Table 1. Since the pilot project in 2019, several tens of thousands of square kilometres of exploration data have been acquired using this concept across the North Sea and Norwegian Sea.

Processing solution

The data processing must be optimised to fully take advantage of the complete MAZ dataset. Increased density and fold should yield better signal-to-noise ratio, thus supporting clearer imaging and interpretation. Advanced imaging techniques are necessary to ensure the illumination from all offsets and estimation of all azimuths can be recovered and combined constructively. As a result, high resolution and more detailed interpretation is achievable from shallow to deep targets. This must be followed through from the wavelet processing stage, demultiple processes, the migration stage, and final post-migration processing including optimised MAZ stacking which was described in a comprehensive review of processes and benefits by Oukili et al. (2020). The data preparation workflow prior to migration is built upon the GeoStreamer platform which provides very high fidelity broadband data with seamless merge capabilities. This allows blending of all data into a single MAZ image for interpretation, provided a reliable velocity model is available.

Velocity modelling techniques such as full waveform inversion (FWI) are now a fundamental element of any modern imaging workflows. The most advanced algorithms can make use of practically all components of the recorded wavefields and implement complex physics to yield a very accurate representation of the subsurface, and most importantly to improve resolution at greater depths. It is now well understood that such objectives can only be met if the near surface complex geology is properly resolved. The Viking Graben is notorious for having numerous challenges with complex, at times chaotic, velocity anomalies at practically any depth in the overburden. In this case, both short and long offsets, as well as the rich azimuth distribution of the MAZ datasets contributed to more reliable velocity updates at all depths.

Figure 2 illustrates the difference that can be expected when employing the same complex FWI workflow utilising both diving waves and reflections in the inversions. However, in one case the data selection is limited to the input corresponding to a narrow azimuth (NAZ) dataset (with no long streamer-tails) versus the full MAZ dataset. In this example, high velocity contrasts in the shallow subsurface cause distortions at deeper levels. The geometry of those anomalies does not fit a single azimuth and requires rich and diverse illumination to be resolved, although

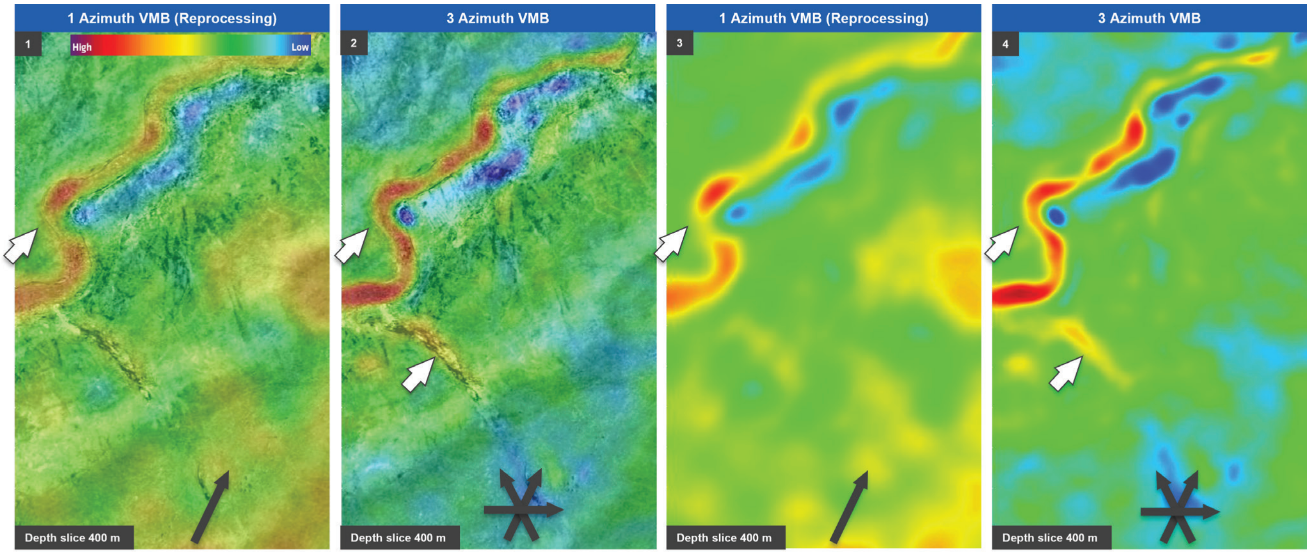

Figure 2 An example of meandering channel at 400 m depth. The infill is characterised by high velocities, juxtaposed to low velocity anomalies in certain areas. Only the MAZ simulated results allow a full recovery of all the features and velocity variations, which match well with the stack data (left images).

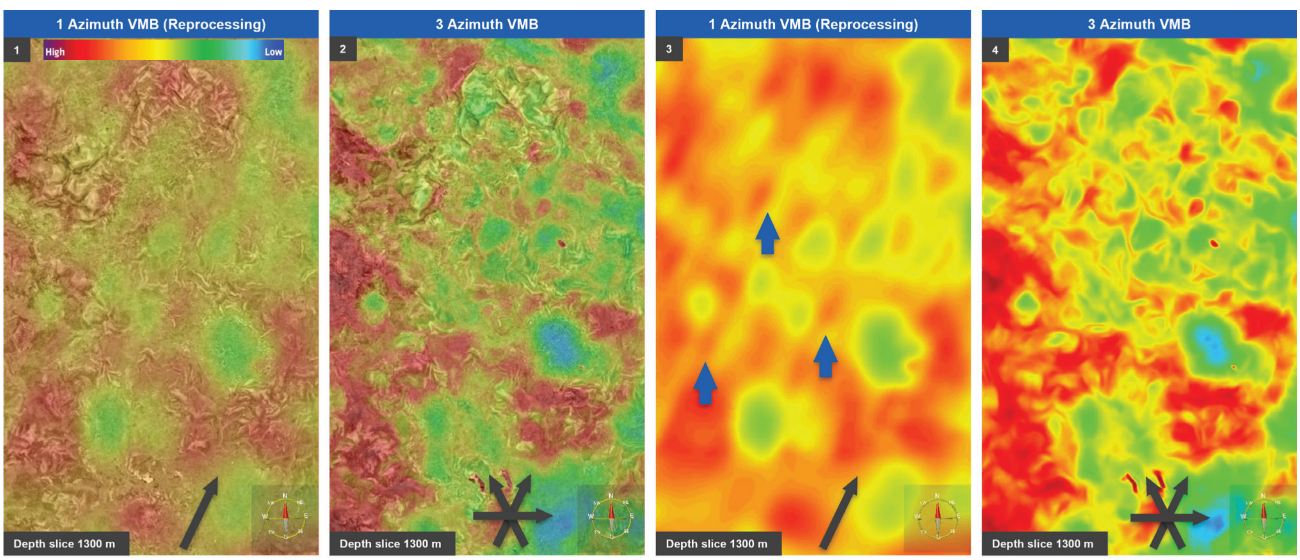

Figure 3 An example of heavily faulted interval with mud diapirs of various sizes and low velocity infills. The left images show velocity and stack overlays. Some imprint of the main azimuth of the NAZ data is visible in the '1 Azimuth' simulation, where only the largest velocity anomalies are recovered, but even so with limited dynamic range.

the NAZ data simulation shows clear indications of it whilst lacking dynamic range and missing certain details of equally high magnitude.

Limonta et al. (2021) presented the complete velocity model strategy by showing how the innovation in acquisition solutions is complemented by data-driven imaging techniques to significantly impact the interpretability of deep structures. Further demonstration of the significant uplift achieved with the modern dataset and workflow is shown in Figure 3. All overburden complexities must be addressed to reveal a clear image of the deep subsurface.

Imaging a deeply buried play in the Southern Viking Graben

The Southern Viking Graben (SVG) is a mature petroleum province where near field exploration and new approaches to field development add reserves to declining production. However, new exploration plays are in short supply and developing new targets requires cost-effective step ups in seismic data acquisition and processing technologies to detect and image challenging new traps, particularly in the largely untapped deep terraces and graben centres (sub-basins). The Upper Jurassic is of particular interest in this respect as coarser-grained clastics were intercalated in an otherwise shaly and source rock-prone Draupne Formation deposited during the graben rift phase.

The Brae Sandstone (Humber Group) is a successful Upper Jurassic play on the steep western graben flank of SVG (Turner and Cronin, 2018, and references therein). Upper Jurassic sands (Intra-Draupne sandstone) have been drilled on the Norwegian flank of the SVG but have not been major targets comparable to other reservoir sections such as the Paleocene and Middle Jurassic. Depth and the significant stratigraphical aspect of Upper Jurassic traps discourage exploration off structural highs and in the deep sub-basins.

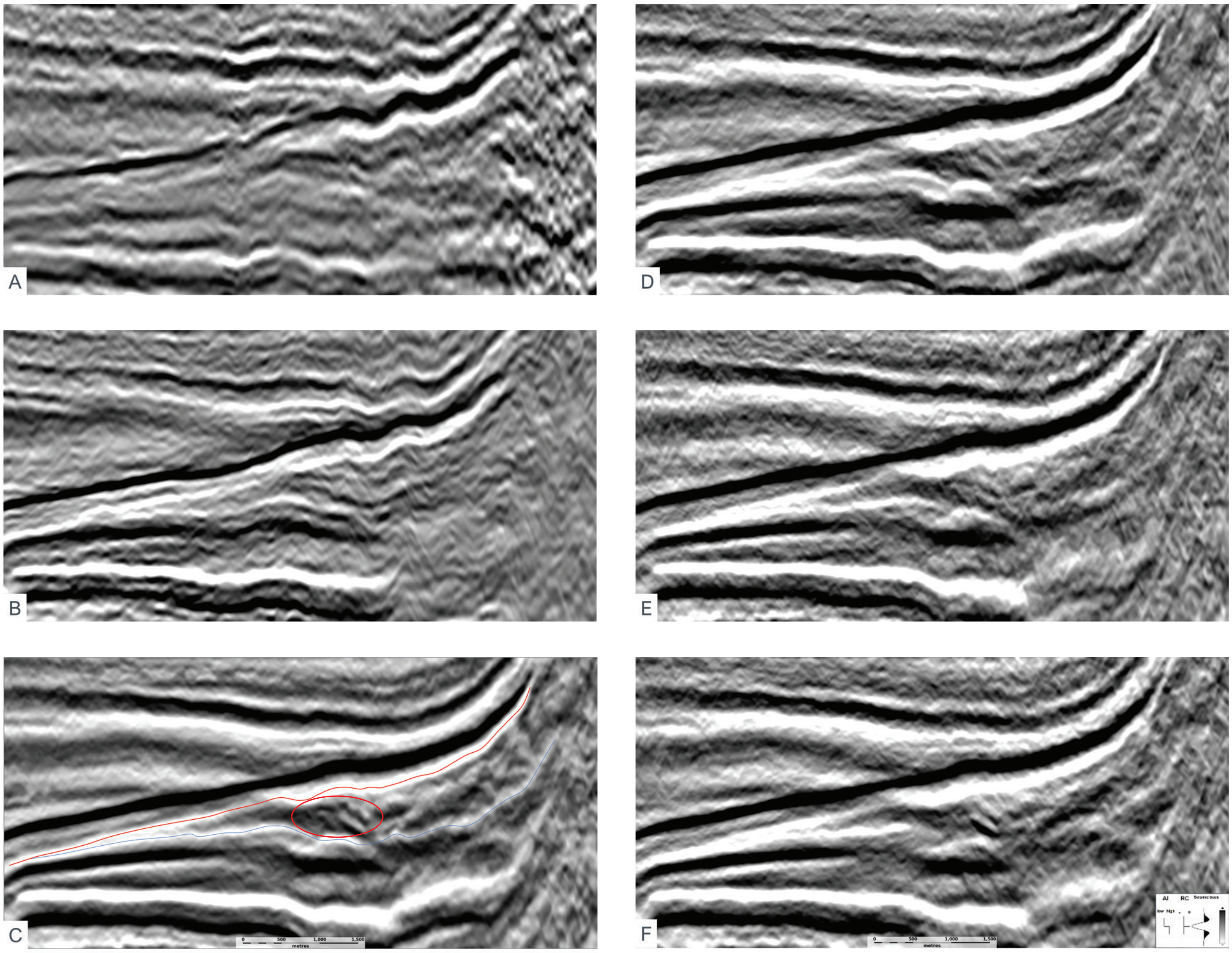

Figure 4 Comparison of an Upper Jurassic slump A) conventional 3D (MegaSurvey), B) multi-sensor streamer NAZ legacy, C) MAZ data (top and base of Upper Jurassic MTC highlighted with red and blue, respectively), and individual azimuths (Az): D) Az114 (legacy azimuth), E) Az174, F) Az234. Although visible in the individual azimuths, MAZ data provide the illumination and high signal-to-noise ratio required to interpret details of the depletion and accumulation/compressional zones (toe thrusts in C (red circle)) of the slump at a depth of around 4400 m (scale bar=1.5 km, maximum slump thickness approximately 150 m).

Upper Jurassic reservoirs represent gravity-driven sediment mass flows limited to the deeper terraces and the SVG graben centres and appear to be absent on the highs (Utsira, Heimdal). Non-commercial discoveries such as Busta 25/7-7 and Earb 25/10-11 (Figure 5A) drilled heterogenous Upper Jurassic reservoirs (sands-conglomerates) with limited connectivity at the faulted Utsira High-Gudrun/Heimdal Terrace margin. Repeat Jurassic sections in the latter are interpreted as rock-fall and attest to catastrophic failure of the graben margin during rifting. Recently, the Norma discovery 25/7-11S (Figure 5A; Sokkeldirektoratet, 2023) proved the presence of Upper Jurassic deep-water sands in the Vana Sub-basin. Petroleum is produced from Upper Jurassic reservoirs in the Gudrun field, where the Upper Jurassic is interpreted as gravity flow sediments (Hoth et al., 2018), while the Upper Jurassic in Hanz field is interpreted as shallow marine deposits (Berntsen et al., 2010). Both fields are located on structural highs, the potential of off-structure Upper Jurassic remains largely untested except for the Norma discovery.

Accessing the morphological and stratigraphic aspects of mass transport complexes (MTC) requires high quality seismic data and a source-to-sink approach to pin-point reservoir sand prone facies and accommodation areas. Towed-streamer MAZ data can reveal these details even at large burial depths due to the broadband range that preserves higher frequencies with high signal-to-noise ratio. An example of this is the imaging of the internal structure of Upper Jurassic clastic wedges that are often found close to the fault scarps. Figure 4 compares legacy conventional 3D and multi-sensor NAZ data that show parallel bedding in the clastic wedge. MAZ data indicate toe thrust of a slump with deposition in the accommodation space of the slump depletion zone between toe thrusts and fault scarp. Individual azimuths only partially reveal these features, demonstrating the benefits of MAZ illumination.

The presence of slumps suggests instant emplacement of the clastic wedge and as indicated by analogues (e.g. Kneller et al., 2016) associated sand facies can be expected on top or at the toe thrusts and in the depletion zone of the slump. Transport of sediment eroded from the exposed fault scarp after slumping will preferentially occur between individual slumps as they are morphological highs on the sea floor and divert mass transport accordingly. Maximum amplitudes extracted from the Upper Jurassic MTC layer show linear features that are interpreted as gullies emanating at the fault scarp (Figure 5B). These provide short distance sediment transport routes across the terrace into the graben centre. If sufficient coarse-grained sediment is eroded and transported from the source area, sandy basin floor fans will expand out at the base of the terrace slope onto the deep basin/graben centre floor. This seismic morphology becomes apparent in the MAZ data post-stack attribute maps (Figure 5B). Sediment sources are Middle Jurassic and older sections exposed at the fault scarps which comprise poorly consolidated reservoir quality clastics.

The Upper Jurassic MTC isopach map in Figure 5A shows that the eastern thick areas at the faulted Utsira High-Gudrun Terrace margin correlate with the location of mapped slumps (blue outlines mapped based on internal structure and reflector geometry). Depth ranges from 4 km at the fault scarp to more than 5.5 km to the west. It is only possible to regionally map the top and base of the Upper Jurassic MTC on MAZ data. Seismic data inversion and multi-attribute rotation (MARS, Alvarez et al., 2015) provide an estimate of maximum porosity in the Upper Jurassic MTC layer shown in Figure 5C. Higher porosity sediments are apparent in the gullies but not detected outboard in the area where basin floor fans are expected to be present. Gross sand thickness may be rather low as reported from the Norma well 25/7-11S (DNO, 2023) and below seismic resolution at depths of >4500 m. Elongated porosity distribution patterns are found associated with the slumps, which are interpreted to be ponded sands. These accumulate in the depletion zone of the slumps that serve as accommodation space after slump emplacement and excess rock mass piles up in the toe thrust compressional zone of the slump.

An arbitrary line through the Upper Jurassic section near the graben centre and perpendicular to the sediment transport direction displays the Upper Jurassic internal reflector geometries in the deep Vana Sub-basin where the gullies open onto the graben floor (Figure 6). The imaging quality between conventional 3D, NAZ and MAZ is compared. Impedance contrasts and reflector continuities are difficult to discern on the NAZ image and not visible on conventional 3D data. Top and base of the Upper Jurassic MTC are most continuous and mappable on the MAZ data. The section is interpreted to indicate Upper Jurassic basin floor fans near the base of slope suggesting multiple and possibly stacked fans at a depth of around 4800 m.

Summary

Smart acquisition setup using towed-streamer spreads with variable streamer lengths and modified source arrangements can be used with legacy NAZ data to produce multi-azimuthal coverage that allows imaging of challenging plays in an already mature area. Taking advantage of the full MAZ dataset and FWI modelling that address velocity heterogeneities in the entire sedimentary section provides detailed subsurface imaging even at large depths. Imaging of gravity driven mass

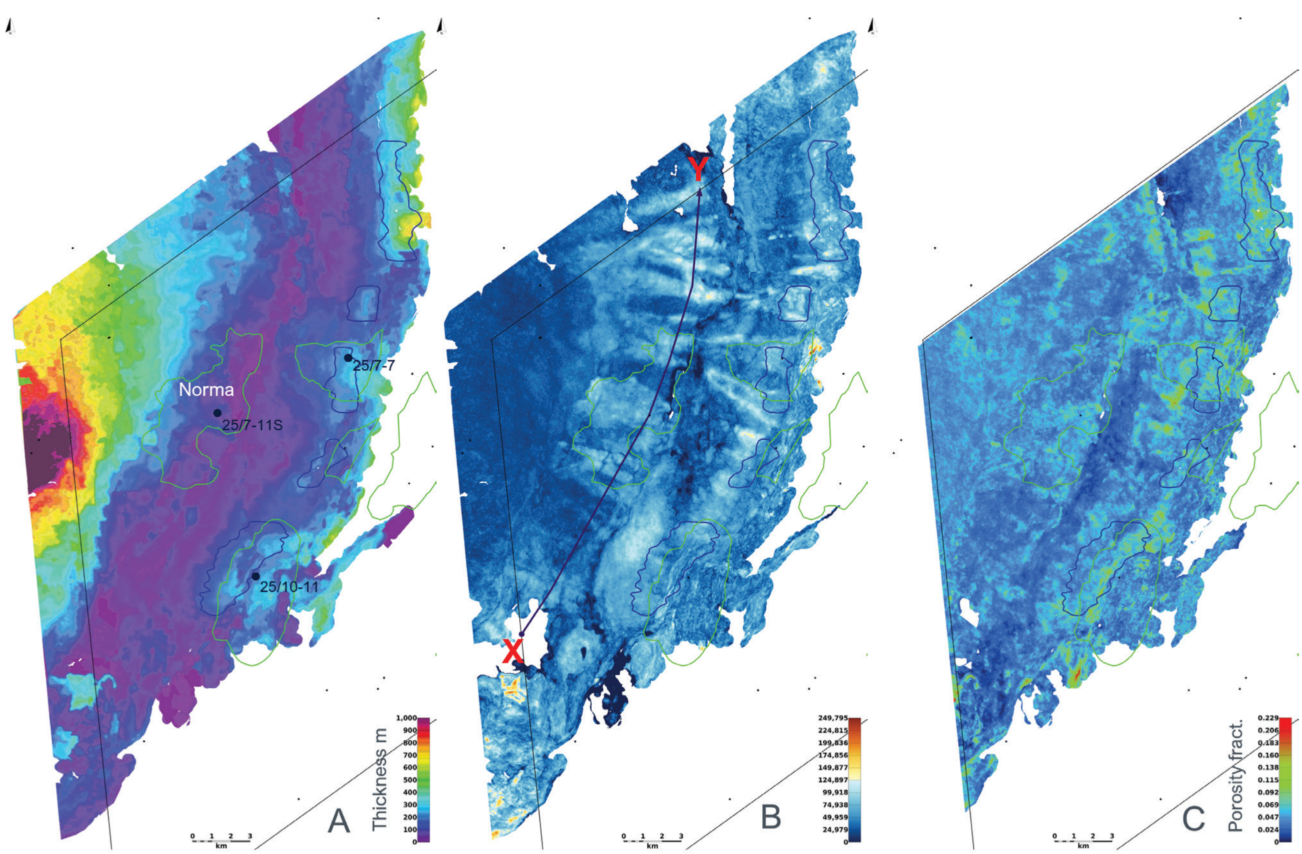

Figure 5 A) Upper Jurassic MTC isopach map, extending from the Utsira High margin to the east into the Vana Sub-basin (depth range 4 to 5.5 km from east to west). Slumps correlate with thick deposits near the fault scarp adjacent to the Utsira High to the east. Their outlines have been mapped based on internal reflectors and structure (blue polygons). B) Absolute maximum amplitude extracted from the Upper Jurassic MTC layer, C) Upper Jurassic MTC layer maximum porosity derived from inversion and multi-attribute rotation schemes (MARS). Scale bar = 3 km, green outlines are fields and discoveries.

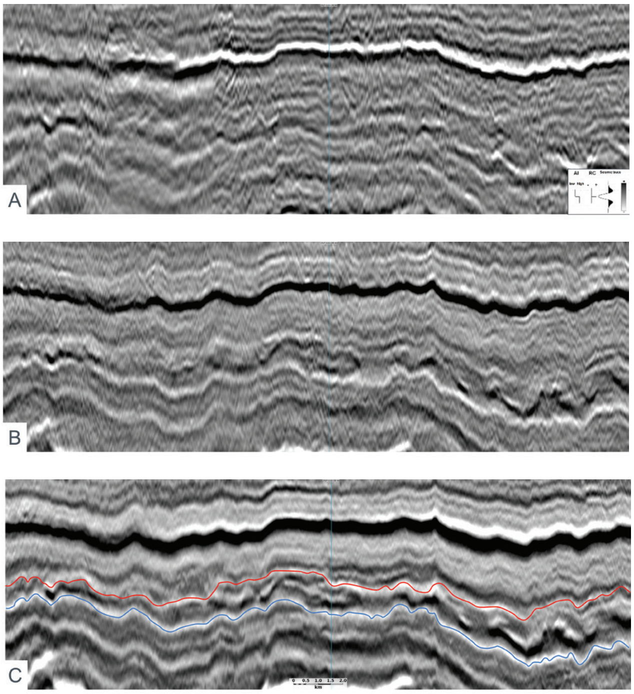

Figure 6 Comparison of an arbitrary time section (X-Y location in Figure 5B) that displays the Upper Jurassic MTC (top and base of indicated by red and blue horizons) outboard near the base of slope on: A) conventional 3D (MegaSurvey), B) legacy NAZ, and C) MAZ. Scale bar = 2 km, blue vertical line indicates surface position of well 25/7-11S (Norma discovery, top reservoir depth approx. 4800 m).

transport complexes in the deeply buried Upper Jurassic of the Southern Viking Graben demonstrates the value of MAZ data. The data allow detailed seismic morphology interpretation and in combination with post- and pre-stack attributes confirm reservoir quality clastic facies associated with MTCs in the SVG rift system.

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