# Quaternary and Neogene Reservoirs of the Norwegian Continental Shelf: Evidence from New 3D Seismic Data

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Quaternary and Neogene sediments are commonly known for their sealing properties and potential drilling hazards. However, examples such as the Peon and Aviat discoveries in the North Sea show that shallow reservoirs can be prospective. In this study, we use 2D and 3D seismic data combined with well information to document new unconventional play models from the shallow subsurface of the Norwegian Continental Shelf. These plays include (i) glacial sands in an ice-marginal outwash fan, sealed by stiff subglacial tills formed by repeated glaciations (the Peon discovery in the Northern North Sea), (ii) fine-grained glacimarine sands of contouritic origin sealed by gas hydrates, (iii) remobilized oozes above large evacuation craters and sealed by megaslides and glacial muds, and (iv) Neogene sand injectites. The reservoirs are characterized by phase-reserved reflections with anomalously high amplitudes in the seismic data and density and velocity decreases in the well data. Extensive new 3D seismic data are crucial to correctly interpret glacial processes and distinguish shallow reservoirs from shallow seals. The data indicate a variety of play models with the potential to have gas in economic quantities and enable the identification of the optimal drilling targets at stratigraphic levels often considered to be not prospective.

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## 1. Introduction and Study Area

The Quaternary stratigraphy along the previously glaciated NE Atlantic margins comprises several hundred meters thick packages of glacigenic sediments, all belonging to the Naust Formation. Although these sediments are dominated by densely packed glacial muds, they strongly vary in grain size from fine-grained clay to coarse-grained sand. The underlying stratigraphic interval is dominated by biosiliciclastic oozes, shales and sandstones of the Neogene Kai Formation and Paleogene Brygge Formation.

The Norwegian Continental Shelf is a prospective petroleum province, where most discoveries are made in the Paleocene to Jurassic age stratigraphic interval. Despite an overburden thickness of 200-2000 m dominated by glacial muds, unconventional shallow reservoirs have been underestimated in prospectivity evaluations. Discoveries within the shallow subsurface include the Peon and Aviat fields within the Quaternary, as well as the Volant and Viper-Cobra in the Neogene. While the shelf environment has been thoroughly investigated and explored, larger 3D seismic cubes from the underexplored slope domains have not been available until 2017 to 2019 (Fig. 1). Here, we present new Quaternary and Neogene play models from the Norwegian Continental Shelf based on a combination of new high-quality 3D seismic data, high-resolution 3D seismic data and existing wells (Fig. 1).

## 2. Data and Methods

We use industry processed high-quality 3D seismic data, P-Cable 3D high-resolution seismic data, and well information to characterize Neogene and Quaternary reservoirs and seals of the NE Atlantic margins (Fig. 1). We use three large seismic volumes covering an area of c. 48,000 km$^2$ (horizontal resolution of 10 m, vertical resolution of 2 m for the shallow subsurface) on the continental slopes. In addition, a high-resolution P-Cable 3D seismic cube with an extent of 150 km$^2$ and a horizontal resolution of 6 m and a vertical resolution of 2 m has been interpreted to highlight shallow prospectivity in the Northern North Sea. We conducted horizon picking, gridding and attribute analysis as well as seismic geomorphological interpretation to characterize petroleum plays in the shallow subsurface. The interpreted horizons were tied to the Peon (35/2-1), Havsule (6404/11-1) and Solsikke (6403-10/1) wells, for which geophysical and biostratigraphical information are available.

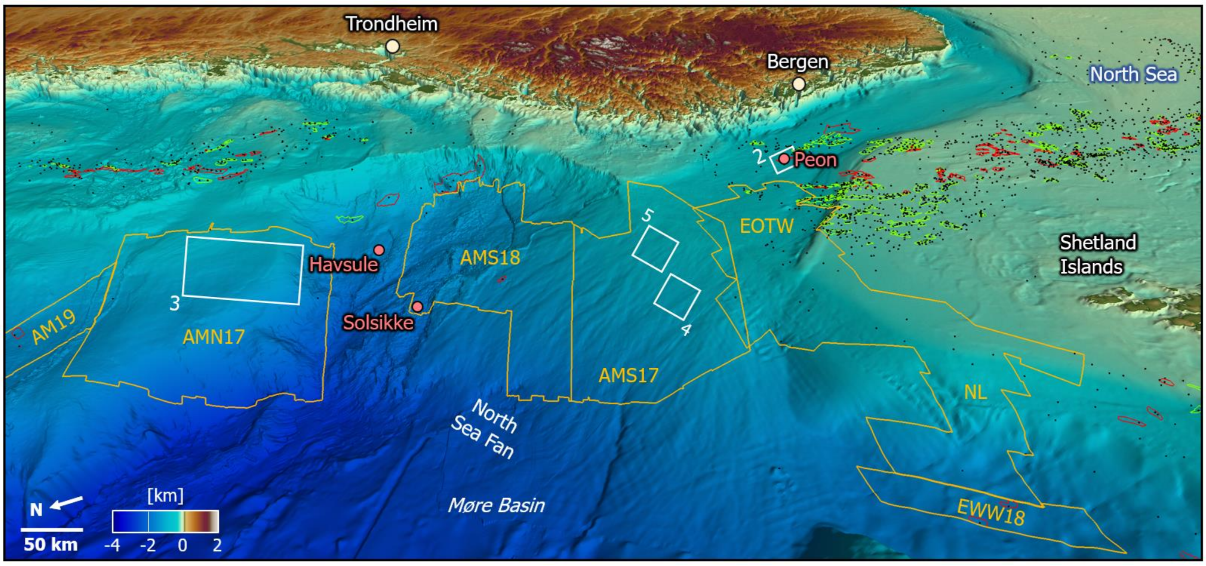

***Fig. 1.*** *Mid-Norwegian continental margin, North Sea Fan and Northern North Sea. Seismic examples from P-Cable data (outwash fan on shelf, Fig. 2), AMS17 and AMS18 (sand injectites and remobilized oozes, Figs. 4 and 5) and AMN17 (contourites and gas hydrates, Fig. 3). Wells (black dots), wells used in this study (red dots), gas fields (red outlines), oil fields (green outlines), and new 3D seismic cubes (yellow outlines) are indicated.*

## 3. The Peon Discovery: A Glacial Outwash Fan Sealed by Stacked Sequences of Glacial Till

The Peon gas discovery in the Northern North Sea consists of an up to 50 m thick sandstone (Fig. 2a) with c. 20 x $10^9$ $Sm^3$ of recoverable gas. P-Cable data show that Peon is characterized by a high-amplitude phase-reserved reflection at the top and low-amplitude seismic reflections within the sandstone body. The sandstone reservoir, deposited directly above a glacial unconformity at a subsurface depth of c. 200 m, is overlain by eight units of subglacial till, separated by high-amplitude seismic reflections (Fig. 2a, H1-H7). Iceberg ploughmarks, glacial lineations and pockmarks are expressed on the grids of these seven reflections within the overburden. Well 35/2-1 shows that the overburden is dominated by muddy sediments with densities >2.2 g/$cm^3$ and velocities >1.8 km/s, whereas the reservoir is characterized by sandy sediments with densities of c. 2 g/$cm^3$ and velocities <1 km/s (Fig. 2b). We suggest that the Peon reservoir is a gas-charged porous sandy outwash fan formed at the ice-stream margin of the Fennoscandian Ice Sheet (Fig. 2c). The overburden consists of stacked units of overconsolidated subglacial till, formed during ice-sheet oscillations, which slightly modified the shape of the reservoir. The charging of the Pleistocene reservoir occurred along progrades below the glacial unconformity, visible as dipping high-amplitude reflections (Fig. 2a).

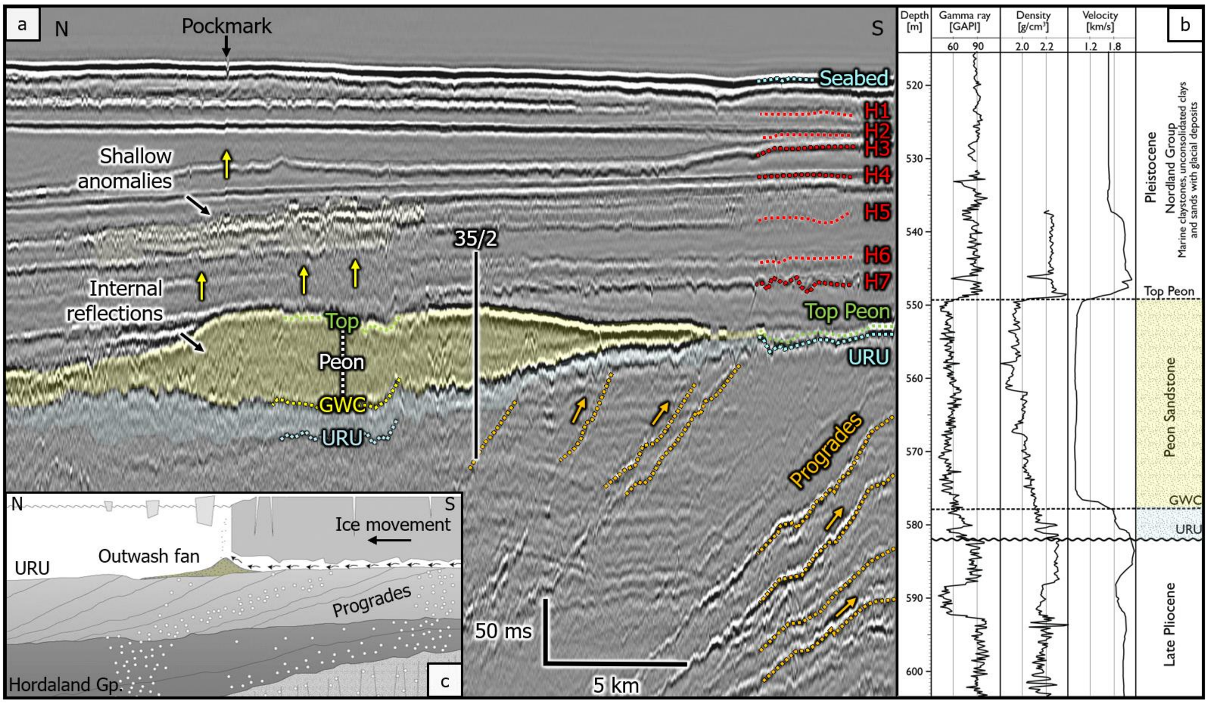

***Fig. 2.*** *Glacial outwash fan forming the Peon gas discovery.* ***a)*** *P-Cable 3D seismic profile showing the stratigraphic setting of Peon. H1-H7: Interpreted glacial horizons. Arrows show fluids charging the reservoir (orange) and fluid escape within the overburden (yellow). Black bar indicates location of well log in Fig. 2b.* ***b)*** *Well 35/2 through the reservoir sandstone, characterized by a pronounced drop in density and velocity at the top of the reservoir.* ***c)*** *Conceptual sketch for the formation of the Peon sandstone. Fluid migration (white circles) and subglacial meltwater flow (black arrows) are shown. GWC: Gas water contact, URU: Glacial unconformity. Seismic data courtesy: Equinor.*

## 4. Contouritic Sands Sealed by Gas Hydrates and Fine-grained Debris Flows

The Pleistocene Naust Formation is dominated by glacimarine sediments and glacigenic debris flows. A phase-reserve bottom-simulating reflection (BSR) is cross-cutting the strata in the eastern part of AMN17 c. 280 to 420 ms below seafloor, separating high-amplitude reflections below from low-amplitude reflections above the BSR (Fig. 3a). The high-amplitude reflections below the BSR follow the existing eastwards-dipping stratigraphy and are limited by the BSR to the west. We interpret these continuous strong, negative-amplitude reflections as gas-charged sandy sediments of contouritic origin. The BSR most likely represents the contact between gas hydrates and free gas, as suggested for the Nyegga area (Buenz et al., 2005). Thus, gas hydrates act as a seal for stratigraphy-bound free gas below. The BSR is sealing gas within estimated 60 m thick beds over an extent of c. 1400 km$^2$ for Naust U, and the rock reservoir volume has been estimated to 132 x 10$^9$ km$^3$ (Fig. 3b). Additional potential gas reservoirs are suggested in more porous glacimarine sediments at the base of Naust T, in the lower part of Naust S, at the base of Naust U, and at the top of Naust N/A (Fig. 3b). Upward-bended reflections cutting continuously deposited glacimarine sediments are interpreted as blow-out pipes (Fig. 3a) and indicate overpressurized layers at shallow levels and gas-hydrate seal breakage at several locations. The pipe structures rise from >2.1 s twt, corresponding to 800 m bsf, to the seabed.

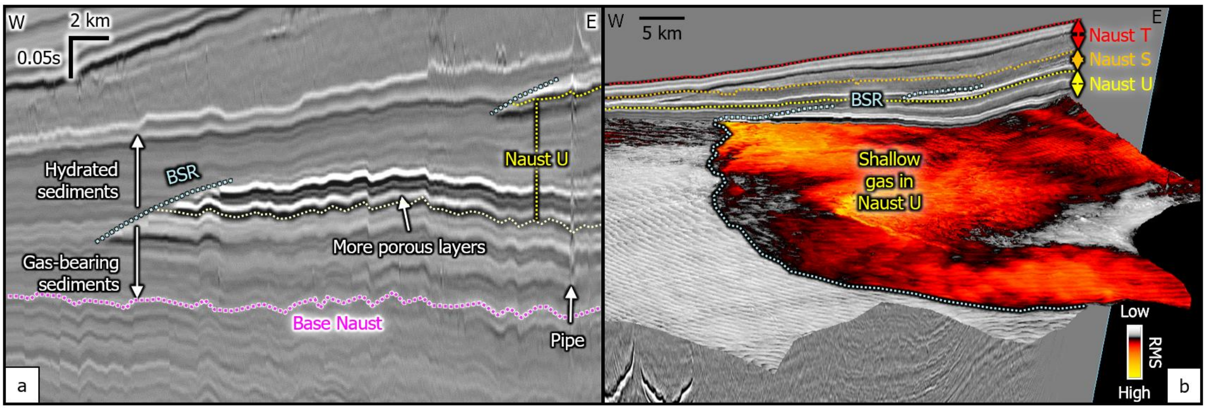

***Fig. 3.*** *Gas-charged contourites within Naust Unit U sealed by gas hydrates.* ***a)*** *Bottom-simulating reflection (BSR) cross-cutting continuously deposited sediments, interpreted as glacimarine contourites. Strong seismic amplitudes represent stratigraphy-bound gas-charged layers.* ***b)*** *Naust Formation and its units characterized by glacimarine sediments. Surface shows RMS amplitude within Naust U. The BSR limits the western extent of the gas-charged layers. Seismic data courtesy: TGS.*

## 5. Remobilized Oozes

The Base Naust reflection in the Vøring Basin separates biosiliciclastic oozes of the Brygge Formation from glacigenic sediments of the Naust Formation and is characterized by large evacuation structures with depths of c. 200 m (Riis et al., 2005) (Fig. 4). The base of the evacuation structures correlates with the depth of the Opal A/CT boundary. These evacuation structures correlate with chaotic mounds at two levels of the stratigraphy above. The reflection defining the top of the mounds is the strongest negative-amplitude reflection in the uppermost two kilometers of the stratigraphy. These mounds are up to 300 m thick, have extensions of 1 to 150 km$^2$ and represent the remobilized oozes of the craters. Log-data from the Havsule and Solsikke wells show a strong density decrease from the overlying glacigenic sediments into the remobilized oozes (from 2.2 g/cm$^3$ down to 1.2-1.5 g/cm$^3$) (Riis et al., 2005). The internal character of the mounds is further characterized by a positive-amplitude reflection, which either indicates a change in geology or a fluid contact. Structure maps of the top of the evacuation structures allow to distinguish the remobilized oozes (rough morphology) from the neighboring glacimarine sediments (smooth morphology). We suggest these mounds to be formed by abrupt events of overpressure release, and subsequent gas migration to charge these remobilized oozes that are expressed by a strong negative-amplitude reflection at their upper surfaces.

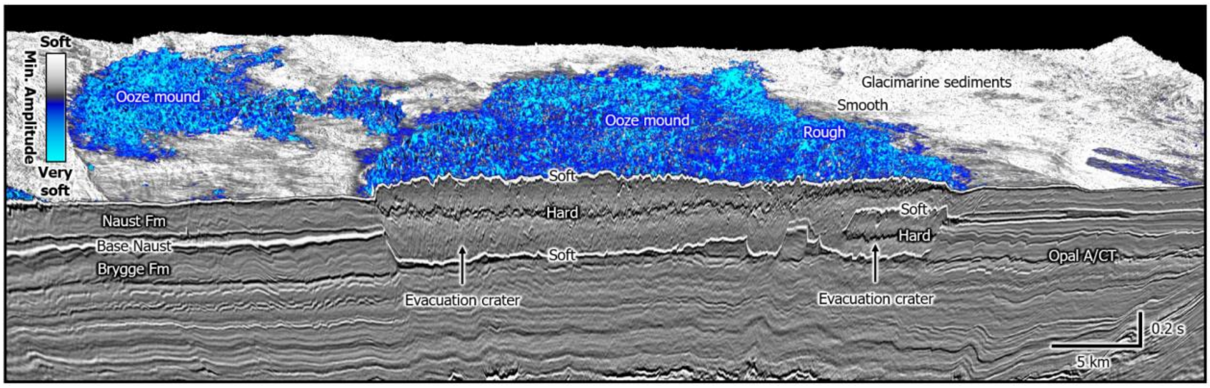

***Fig. 4.*** *3D chair view into remobilized oozes. Evacuation craters are expressed along the soft Base Naust reflection. Note the very soft reflection shaping rough remobilized ooze mounds above the craters and a hard, chaotic reflection between the top ooze mound and the base of the evacuation craters. The horizon map is a blend of structure and minimum amplitude. Seismic data courtesy: TGS.*

## 6. Sand Injectites

An area covering c. 3,600 km$^2$ in depths of c. 2 km below seabed at the uppermost slopes of the North Sea Fan is characterized by structures with a chaotic internal seismic facies (Fig. 5a). The geometry of these chaotic expressions varies from isolated mounds and saucer-shaped sills to more lateral extensive sills, which crosscut more than 300 m of continuous high-amplitude reflections of the Brygge Formation (Fig. 5b), almost reaching the Base Naust reflection (Fig. 5a). The bodies are surrounded by upwards-bended beds and have occasionally strong soft tops with weak flat events 40-60 m below. We suggest this chaotic facies formed by injection of fluidized sand in response to the failure of a low-permeability sealing lithology. We interpret these reflections as sand injectites with an estimated reservoir thickness of c. 50 m, like the extensively mapped sand injectites in the upper Pliocene of the North Sea (Cartwright, 2010). The sand injectites are trapped by a structural 4-way dip closure of Paleogene oozes, are most likely sourced from Eocene sands, and most likely characterized by a good connectivity and permeability. The underlying, several 100 m thick stratigraphical interval potentially represents sand injectite veins. The base of the sand injectite bodies correlates with the base of the evacuation structures. We thus think that the evacuation structures and ooze mounds are associated structures, and that both injectite movement and ooze remobilization occurred related to Quaternary sedimentation.

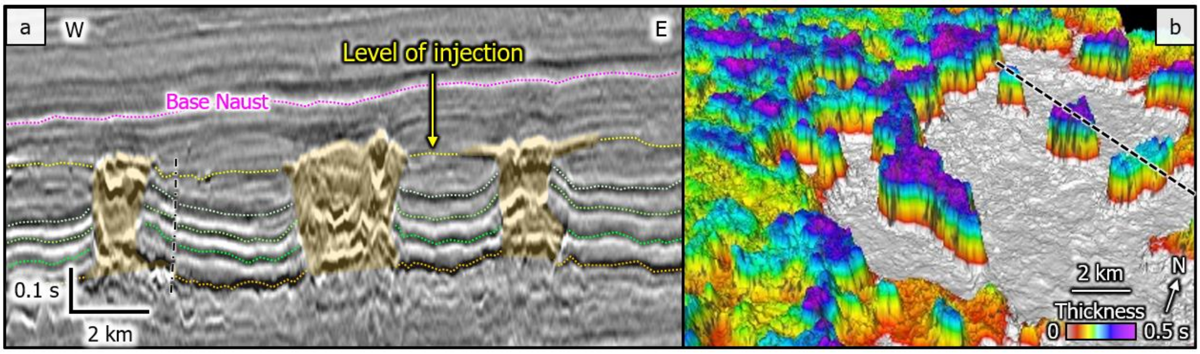

***Fig. 5.*** *Sand injectites within the Neogene sediment packages.* ***a)*** *Seismic expression of three isolated injectite mounds with internal chaotic seismic facies (yellow).* ***b)*** *Isopach map blended over structure map showing geomorphology and thickness of the injectites. Seismic data courtesy: TGS.*

## 7. Conclusions

The Quaternary and Neogene stratigraphy of the Norwegian Continental Shelf comprises several unconventional plays characterized by promising seismic anomalies and geophysical well trends. The plays span over large extents and incorporate economic volumes. Different play types are identified at the same geographic locations, but at different stratigraphic levels. These plays could therefore be tested by single wells targeting multiple stratigraphic levels. Seismic attribute analysis and geomorphological interpretation show huge lateral variations along the mapped horizons. The use of new high-quality 3D seismic data allows new conclusions about geological processes forming shallow reservoirs, estimations of reservoir volumes, and the selection of the best drilling targets.

## References:

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