Integrated Exploration Workflow for Maturing the Shallow Gas Play*

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Abstract

Recent exploration activities in two of the largest deltas in the world, the Nile delta and the Cenozoic Southern North Sea (SNS) deltas, proved the economic potential of shallow gas resources. Like in many other parts of the world, including the Gulf of Mexico and offshore West Africa, the Nile Delta and SNS shallow gas was previously seen as a hazard or, at its best, as exploration tool for deeper HC"s. More and more, the shallow gas accumulations are seen as a valuable additional hydrocarbon resource, especially if located near existing infrastructures. Nonetheless, shallow gas production is still limited due to a lack of insight in the petroleum system, especially with respect to the relation between the anatomy of the delta and charging/trapping conditions. In order to mature the shallow gas play, a multidisciplinary workflow was applied to the SNS delta that involves 1) the reconstruction of the internally complex delta body, 2) a combined deterministic/stochastic approach to make reservoir property predictions, 3) evaluation of the HC origin, and 4) a grain-size based method to predict the seal-integrity of the sealing clay layers. The results present the first steps towards de-risking the shallow gas play in terms of trapping geometry, seal capacity, sourcing and migration. The presented workflow is applicable to areas were limited exploration data is available, but where critical production data is (still) missing. One such an area is the Nile delta. By reviewing the HC systems of the Nile and SNS deltas many similarities emerge that are expressed by 1) the control of sea-level and climate on the distribution of reservoirs, seals and organic material, 2) the presence of stratigraphic traps and 3) the role of deeper salt and faults in the formation of structural traps. For both settings, the origin of the shallow gas may be deep subsurface thermogenic sources or biogenic sources in shallower strata, or a mixture. For both areas, reserve estimates for shallow gas are often hard to make using conventional exploration techniques due to the inability to discriminate high vs. low saturation shallow gas. We briefly elucidate on the incorporation of pre-stack seismic inversions and other geophysical techniques such as CSEM that may appear essential in further maturing the Shallow Gas play.

Introduction

Traditionally, shallow gas occurrences in the Southern North Sea (SNS) were considered non-economic due to their low gas saturations ("fizz gas") or even as hazardous. However, shallow gas is presently being produced in the area despite its challenging nature, e.g. overpressures, risks for sand- and/or early water production in highly permeable and unconsolidated sediments.

In this area, gas resides in shallow marine to continental (deltaic) deposits of Plio-Pleistocene age (Figure 1). It is either structurally trapped in anticlines above salt domes, associated with lateral fault seals, or in stratigraphical traps (Figure 2). Sediments with gas contents- of at least a few percent, typically display high reflectivities ("bright spots") on seismic. This way location and size of the fields can be determined. According to Kuhlmann and Wong (2008), these potential gas occurrences (or rather, their bright spot displays on seismic), are associated with specific (deltaic) sub-environments and stratigraphical intervals related to the onset of Late Cenozoic glaciations. This study contributed to understanding the regional extent and characteristics of the delta and was instrumental in illustrating its importance for the business. Stuart and Huuse (2012) focused on the interpretation of several bright spots in terms of fluid and lithological content through well log and seismic facies analysis in order to discuss the origin of these features. None of these studies, however, successfully linked bright spot properties (e.g. estimation of gas saturations) to their quantitative volumes as contained in each trap.

In the present study, a comparison will be made between the SNS delta and the present Nile delta, arguably being one of the most mature analogues for the SNS delta in terms of sourcing, charging and trapping mechanisms.

Aim and Workflow

The initial aim of this study was to develop a reliable and effective workflow to de-risk observed bright spots, i.e. to distinguish between economic and fizz gas. As estimating gas saturations appears virtually impossible in the absence of actual well measurements, this aim needed slight adjustment. By applying the workflow, the user should be able to de-risk the shallow gas plays based on location and quality of the reservoirs and seals, using available static and dynamic data of the rock layers in which the bright spots appear. Both types of data directly or indirectly relate to the original position (in time and space) within the delta environment and any changes that took place during later processes and up until present-day. To that end a robust understanding of the reservoir anatomy (i.e. internal organization and function) and in addition of gas generation, -migration, -accumulation and/or –leakage is required.

The workflow as presented here was developed for the Joint industry Project "Shallow Gas" (ten Veen et al., 2011, 2013) in which several major HC companies operating in the Southern North Sea participated. Although the examples pertain to this area, its applicability to other area, i.e. the Nile delta, will be discussed further on in this paper.

Depositional Model

Perhaps the most remarkable aspect of the Neogene SNS succession is the strong coupling of sediment deposition and climate. The delta sediments were deposited at the onset of Scandinavian shield glaciation. This resulted in a series of glacial-interglacial cycles that strongly affected delta behavior and associated basin-fill.

An excellent chronostratigraphic framework is available for the SNS succession because of the availability of:

- Accurate geomagnetic polarity data from the A15 key well enabling the precise coupling to global standards (i.e. $\delta^{18}O$) by a number of well-calibrated biostratigraphical events.
- Quantitative palynological data (pollen) enabling to calculating ratios between groups with clear environmental affinities.
- Sporomorph/dinocyst ratio, providing information on terrestrial vs. marine environments. This is a measure for the relative distance to the coast (see e.g. Donders et al., 2009), which varies with sea level and progradational changes in the basin.
- AP/NAP ratio (i.e. tree pollen over non-tree pollen) being a paleo-temperature indicator.

Based on above data several important conclusions regarding the coupling between paleoclimate and sediment properties could be drawn. It appears that glacial-interglacial cycles show a marked contrast in grain size, sea surface temperature and climate and are the key control on the presence and distribution of potential sealing clays and coarser-grained reservoir units (Figure 3). The main characteristics of, and differences between these cycles are listed in Table 1. The sea level trend is in line with the expected trend associated with ice sheet build-up: i.e. high sea levels during the interglacials and low sea levels during the glacials. The relevance of these climatic cycles is that they occur on a basin-wide scale and control the deposition of clay-silt couplets. Consequently, a record consisting of intercalating clays (having a good sealing capacity) and reservoir bodies (containing enhanced TOC) can be demonstrated (Figure 3).

Reservoir Architecture and Sequence Stratigraphy

Twenty-five seismic horizons in the Plio-Pleistocene interval were interpreted, forming the basis for a regional geological model ("reservoir model") that represents the internal architecture ("anatomy") of the SNS delta. Subsequently, the reservoir model is used to distribute lithological and petrophysical properties, such that a property model is obtained.

All interpreted horizons delineate the top surfaces of distinct clinoforms and have a significant sequence stratigraphical message (Figure 4). For all these surfaces the distribution of delta elements such as of topset-, foreset- and toeset-to-prodelta has been determined, resulting in associated zonal maps (Figure 4). Determination of delta element types is based on 1) surface geometries, 2) palynological properties, 3) seismic attribute analyses, 4) the relationship with internal geometries of the zones beneath and above (i.e. downlap, toplap, etc.). This in turn forms the basis for 5) the sequence stratigraphical interpretation of the clinoforms.

Sourcing

There is an on-going debate about the origin of the gas in SNS delta deposits. It is either biogenic, thermogenic or a mixture of both. Geochemical and isotopic analyses on gas samples in the area show that the gas is typically very dry (> 99% of methane) and depleted in 13C/C1 (-70% dC13/C1). Such compositional characteristics point at a biogenic origin of the gas. However, the presence of chimneys and acoustic turbulence zones on seismic and the fact that many shallow gas accumulations occur in association with salt domes and/or faults suggest that the gas has migrated upward from deeper levels.

Timing and quantification of microbial gas generation in the SNS delta was studied using a combination of different modeling techniques, and included new, detailed basal and surface thermal boundary conditions. 3D basin modeling provided the input data (e.g. geothermal gradient, sedimentation rate, lithology, sediment water interface temperature) for a dedicated 1D modeling exercise of microbial gas generation at 25 wells penetrating the SNS delta deposits.

In order to establish a range of the amount of biogenic gas in the study area, several scenarios were modeled using different temperatures (based on global mean surface palaeotemperatures and basal heat flow) and TOC values (ranging between 0.55-3.5%). This approach is based on a technique described by Clayton (2010) and estimates the potential yield of gas from the mass fraction of carbon lost from the sediments in the methanogic zone. A cubic meter of sediment containing 1% total organic carbon will yield approximately 4.9 m^3 of gas under optimum conditions. This is equivalent to a conversion of about 10% of the total organic matter. In an earlier publication, Clayton, (1992) states that enough methane could be generated under hydrostatic conditions from sediments with at least 0.12% total organic content. In case of highly overpressured conditions, "the sediments containing greater than 0.2% of TOC can potentially generate a free gas phase". This can potentially be trapped in case of sufficient isolated reservoir intervals. Most recognizable biogenic gas accumulations, however, yield low to subnormal reservoir pressures due to their shallow burial depths. Underpressures result from dilation of pore volume, probably related to the removal of overburden or uplift and cause the expulsion of the gas. This leads either to trapping elsewhere or to venting at the seafloor (Rice and Claypool, 1981). In general, the generation of microbial gas is favored by sediment accumulation rates in the range of 200 to 1,000 m/Myr, which needs to be taken into account as well.

The combined modeling approach applied (Figure 5) demonstrates that the SNS delta deposits form an important source of microbial gas; these sources are at maximum depths and temperatures today; in the deepest part of the delta, microbial gas generation started at the beginning of the Pleistocene (onset of glacial-interglacial cycles) and still continues today; the youngest delta deposits have not yet reached the optimum window for microbial gas generation. It should be emphasized that the potential for biogenic gas generation does not exclude the presence of thermogenic gas or a mixture thereof.

Bright Spot Properties

The main objective of this study is to predict relevant properties for all bright spots identified. The method described here focuses on honoring the reservoir properties at the well location, since many bright spots are penetrated by (or in close vicinity to) wells (Figure 6). The property modeling is also aimed at acquiring insights in the regional distribution of relevant properties and forms the basis for the discussion on shallow gas scenarios. However, some relevant properties, such as gas saturation, are not easily extrapolated from gas-free to gas-containing strata and require different prediction methods as compared to reservoir properties that are considered unrelated to gas content.

Seal Integrity and Gas Column Heights

Seismic attribute analysis suggests that the presence of salt structures is important, or used to be important in the past, in conducting fluids/gas from deeper levels (ten Veen et al., 2011). At present migration and charging of gas within the SNS delta takes place under normal to close-to-

normal pore pressure conditions (Verweij et al., 2012). The seals of the shallow gas occurrences are formed by siliciclastic intra-delta mudstones with higher capillary entry pressures and lower permeabilities than those of the underlying reservoirs.

By using grain-size distribution data, the seal integrity analyses focus on the evaluation of the capillary seal capacities and permeabilities of mudstones in the Plio-Pleistocene delta deposits in the Dutch northern offshore. The evaluation is restricted to wells that have penetrated actual bright spots. The grain size analyses of 77 samples from 45 sealing mudrocks in 10 wells, in combination with the grain size based systematic approach to evaluate porosities, permeabilities, pore throat sizes and capillary seal capacities have resulted in a database of relevant seal properties. It shows that vertical permeabilities vary between 2.8E-20 and 1.1E-18 m^2. Most of the pore throat radii of the mudstones vary between 0.5 and 1.5 μm. The associated capillary seal capacities of the mudrocks vary between ±10-24 m (depth: 400-900 m) and increase with depth.

Comparison of the gas column heights estimated from pressure data and log information with those calculated from grain size distributions, yields promising results but is not always straightforward (as shown in Figure 7). It requires fulfillment of a set of subsurface conditions with regard to charging and leaking of shallow gas reservoirs and the availability of measured data (e.g. pressure data, or reported GWC).

As capillary seal capacity is a multi-scale property, mudstones typically act as permeability seals and faulting and fracture zones, within the mudstones, influence the sealing capacity, the presented grain size-based method should be seen as a first pass only of a more comprehensive approach to estimating preserved gas columns in bright spots. The method to calculate mudstone properties from grain sizes strongly depends on its clay content. It is envisaged to make the method more widely applicable to establish a relationship between clay content, derived from grain size analyses and log-derived clay content.

Although only a limited number of samples were used to derive gas-column heights using the grain size based method, a positive relationship does exist with the estimated height of the BS based on seismic analysis. The computed column heights are in reasonable good agreement with column A12-03 is not cutting through top of reservoir: maximum gas column height in reservoir is > 10 m: acc. to cross section: 3/2 x 10 ~ 15 m heights derived from NPHI-RHOB crossover plots. Despite the linear trend, it is also shown that BS heights from seismic analysis tend to overestimate real heights. This may imply that resource estimates are too high if they are based on BS heights only. Moreover, it stresses the unknown relationship between gas saturation and BS extent or intensity.

Comparison of SNS Delta and Nile Delta - Discussion

The present Nile delta area covers approximately 60,000 km^2 and with 58 Tcf of gas reserves discovered so far (Nini et al., 2010), the fields in this area provide about two-thirds of Egypt's gas production. Recent exploration activities in the offshore Nile delta have demonstrated the Basal and Mid Pliocene slope channel play (including incised channel fills, and deep-water slope and fan sandstones) to be highly prolific with over 30 Tcf of gas (Horscroft and Peck, 2005). In early exploration time, the encountered dry gas was considered of biogenic origin because of it carbon-isotopic signature. However, recent basin analyses adopt a more holistic approach that also incorporates the Mesozoic section that contains thermally mature source rock with a mixed oil and gas kerogen. Geochemical analyses in the Pliocene reservoirs point at a thermogenic source and that no contribution from a biogenic source is required. The presence of gas condensate in the Oligocene-Miocene

reservoirs would indicate that the source rocks could have reached a stage of post-mature maturation. Through time, hydrocarbons moved vertically and were fractionated into lighter hydrocarbons. This explains that, from deep to shallow, there is a progressive change in hydrocarbon type with oil within the Mesozoic section to rich gas/condensate with Oligo-Miocene reservoirs, to predominately methane gas trapped within Pliocene reservoirs. The Plio-Pleistocene fields are closely related to deep-seated paleo-faults that were reactivated since the Early Pliocene. Many gas chimneys are associated to these structural and morphological features (Barsoum et al., 2000) and link the pre-Messinian kitchen section to the Plio-Pleistocene reservoirs.

Although the origin of the gas in the SNS delta is still a matter of debate, the vertical stacking of oil prone reservoirs and gas condensate in the Upper Cretaceous and dry gas in the Cenozoic section hints at comparable mechanisms for sourcing and charging. Several major faults, often associated with deeper-seated salt structures, appear essential in conducting gas from deeper, sub-salt levels. The continuously active salt doming is regarded instrumental in the generation of anticlinal traps in the Cenozoic overburden, where the gas is retained. Though regarded as a regional seal, which would explain the local overpressure conditions in the sub-salt reservoirs, also the Messinian evaporites underneath the Nile Delta reservoirs play a key role in gas migration to the Pliocene reservoirs.

After the Messinian salinity crisis, resulting in the accumulation of thick sediment packages, salt tectonics became very active resulting in the downslope gravity sliding of the evaporites and the sedimentary overburden. This thin-skinned synsedimentary deformation still strongly affects the middle and lower Nile Fan, where the seafloor is shaped by numerous salt-tectonics related features, such as growth faults, salt diapirs and crestal grabens. Related fluid leakage through faults contributes to both the accumulation of gas in and seepage activity at the seabed (Loncke et al., 2006).

Acknowledgments

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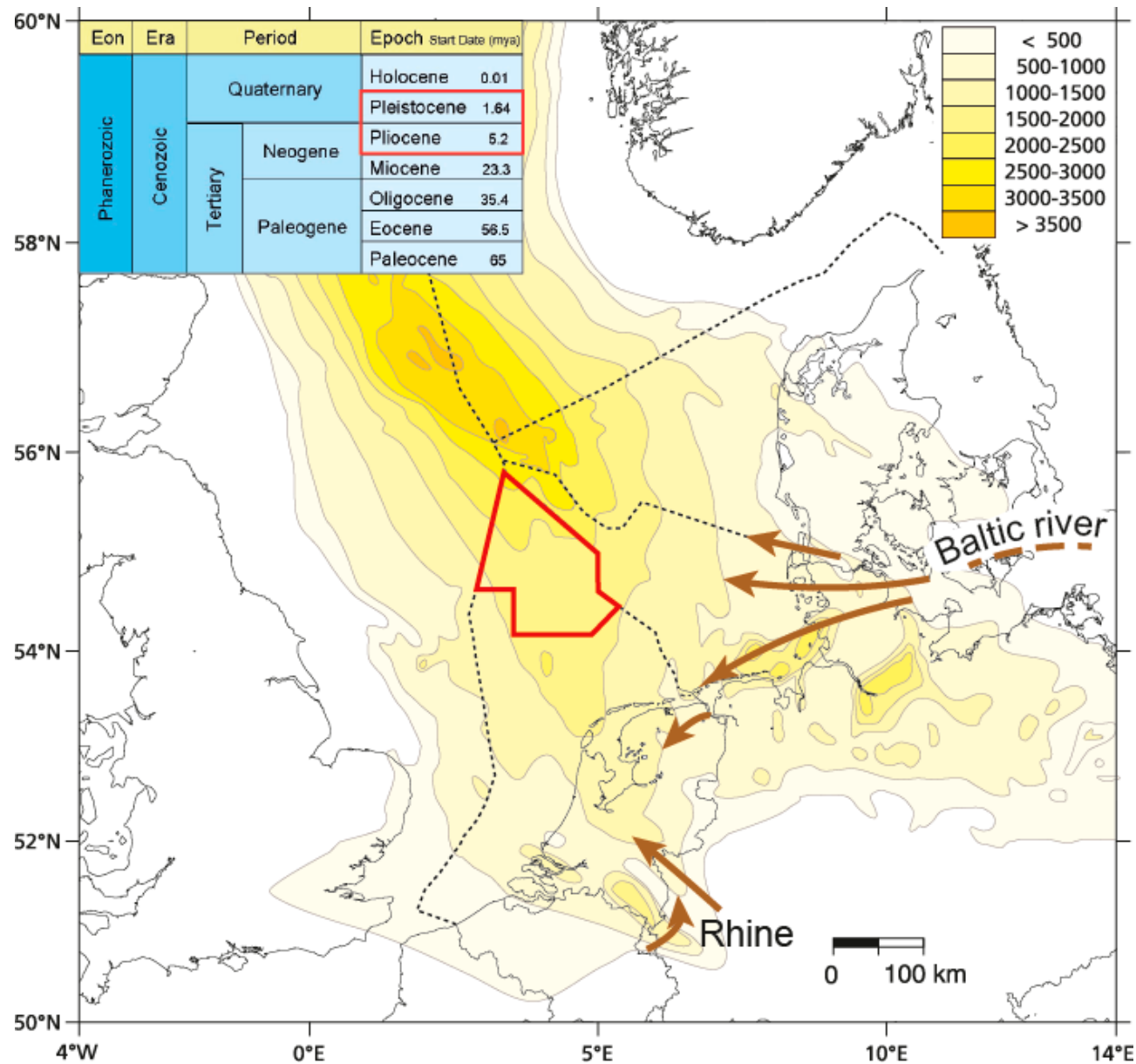
Figure 1. Map showing outline of Southern North Sea (SNS) Basin with thickness (metres) of Cenozoic sediment, after Ziegler (1990) and Huuse (2002), modified from Wong et al, 2007. Arrows show course of Baltic river systems that fed the SNS Basin. Inset show stratigraphic interval of interest.
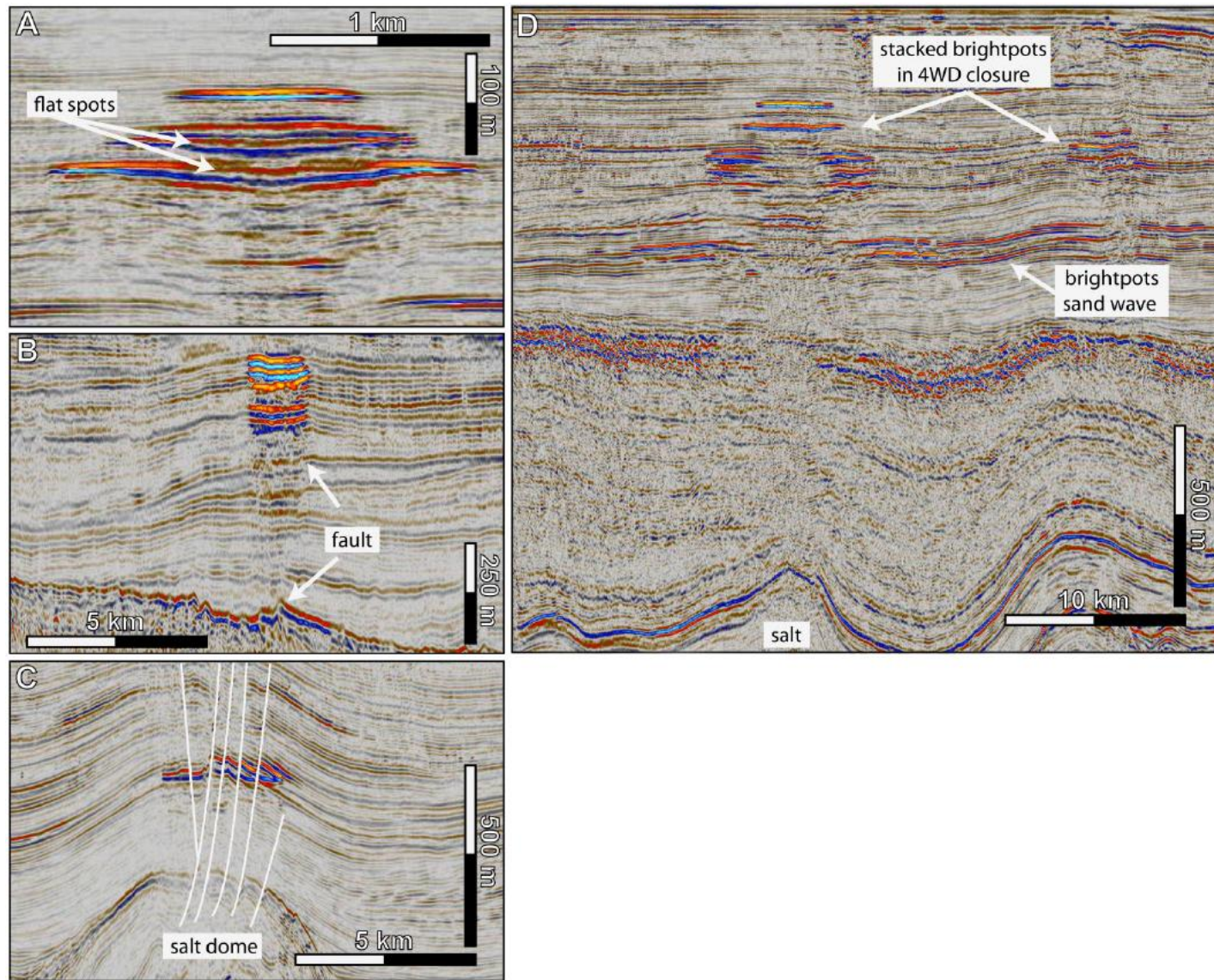
Figure 2. Seismic sections of the Dutch Northern offshore with various types of Bright Spots. A) Stacked bright spots indicative of multilayered gas fields, each with their own GWC (flat spot). B) Multilayered bright spots above acoustic turbulence zone that hint at gas expulsion from faulted zone below. C) Bright spots with lateral fault seal. D) Stacked bright spots in anticlinal (4WD) closure above salt domes. Note the acoustic attenuation below the BS that is interpreted as gas chimney. The lower BS is produced by (presumably) low saturation gas fetched in sand dunes fields. These bright spots can have dimensions up to several 10's of kilometers.
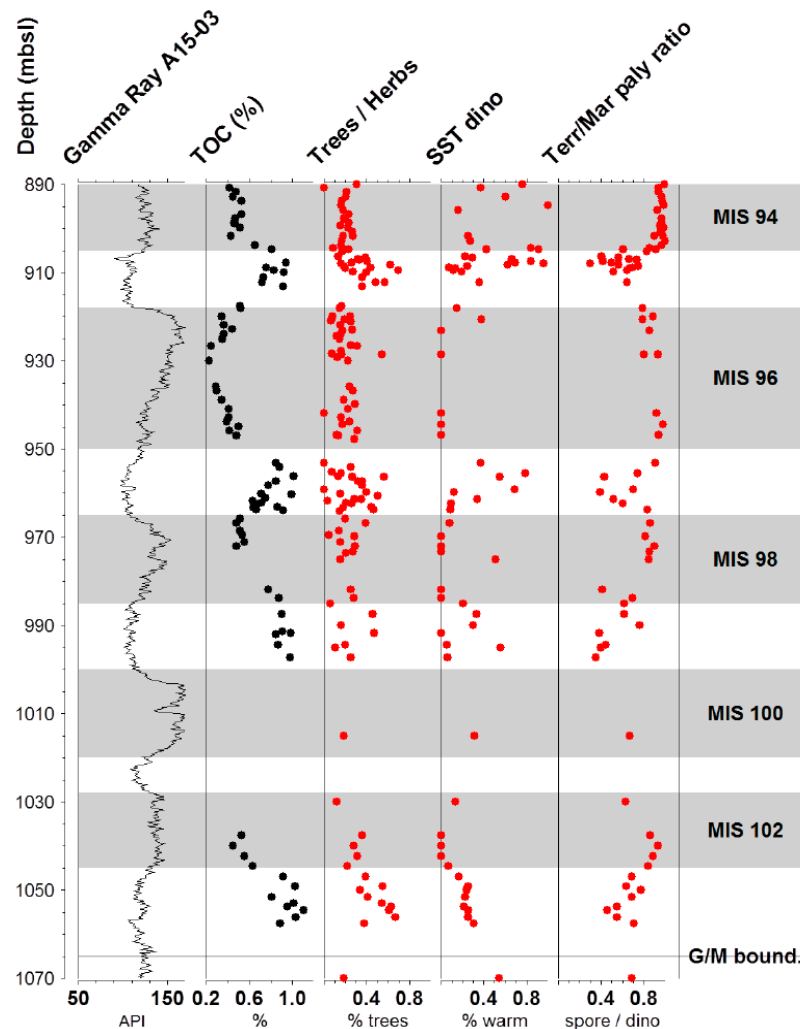
Figure 3. Detailed palynological and geochemical data summary of clay-silt couplets in key well A15-03 (Dutch Northern offshore) representing the interval with the first glaciations of the Pleistocene. The climatic signatures of these cycles provide ground for regional correlations across the basin and explain the origin of the sedimentary cycles and organic matter variations. GR = gamma ray; TOC = total organic carbon; Trees/Herbs = ratio of tree to non-tree pollen indicative of temperature changes on land; SSTdino = relative sea surface temperature changes based on indicative dinoflagellate cysts; Terr/Mar play ratio = sporomorph to dinocyst ratio showing relative contribution of terrestrial vs. marine organic matter input and distance to the coast; Grey shaded areas indicate position of marine isotope stages (MIS) glacial intervals based on stratigraphic correlation; G/M = Gauss-Matayama palaeomagnetic reversal (2.56 Ma), which marks the Plio-Pleistocene transition.
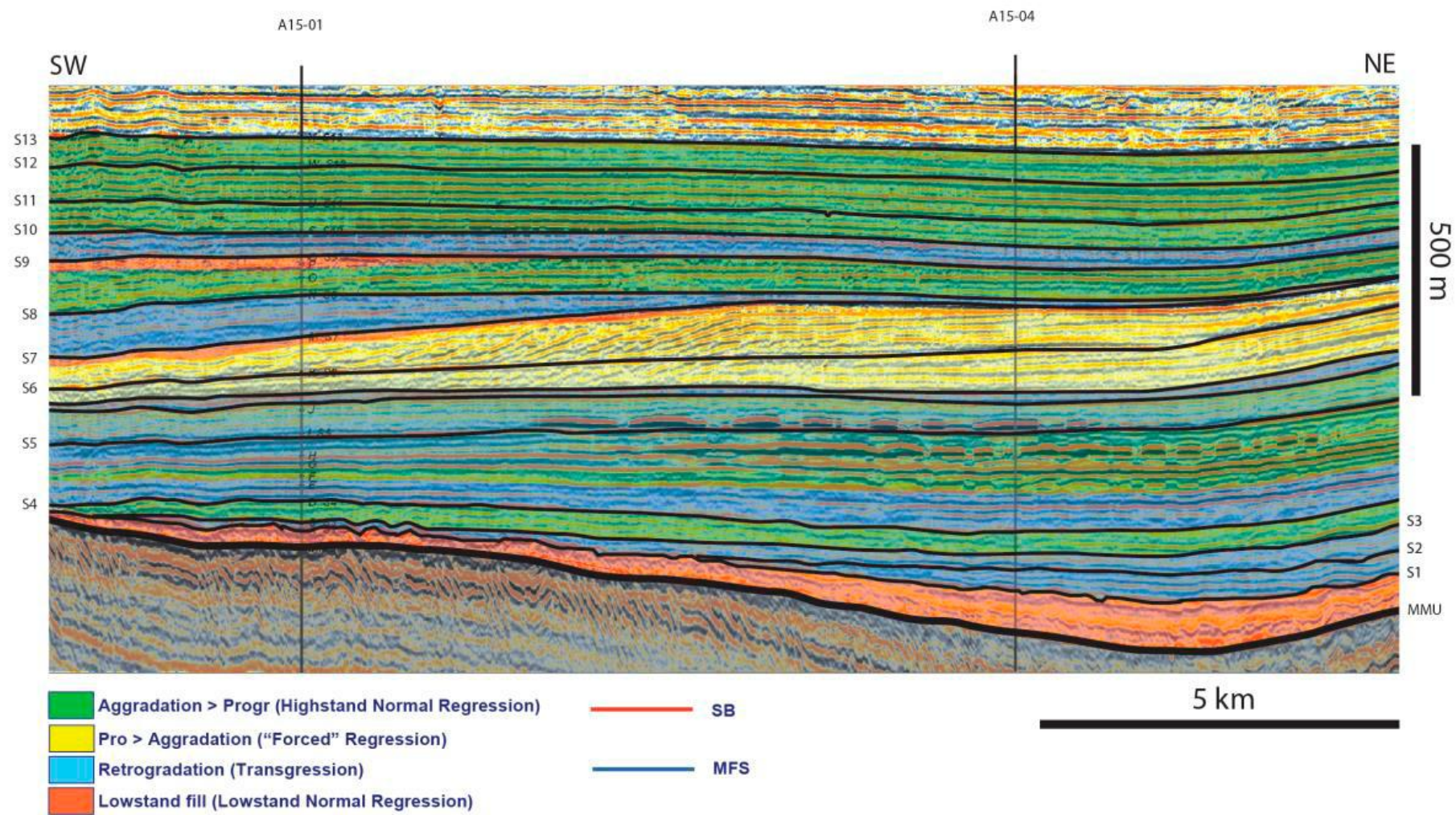
Figure 4. Seismic section through part of the SNS delta with sequence-stratigraphic interpretation.
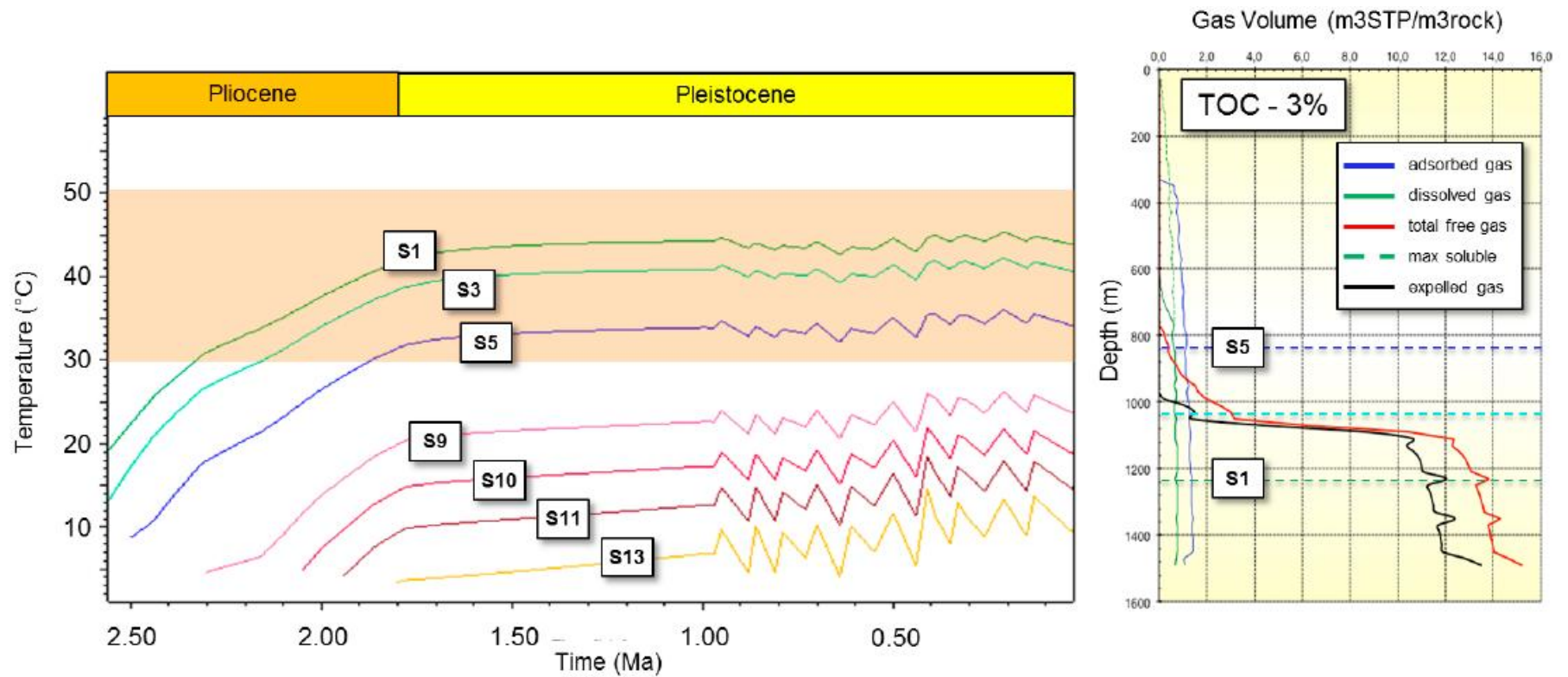
Figure 5. Petromod© model (left) results show that delta horizons S1-S5 are in the optimum temperature window for biogenic gas generation and starts at the Plio-Pleistocene transition. Biogenix© model (Clayton, 2010) results indicate the amount of gas generated vs. the amount of gas expelled.
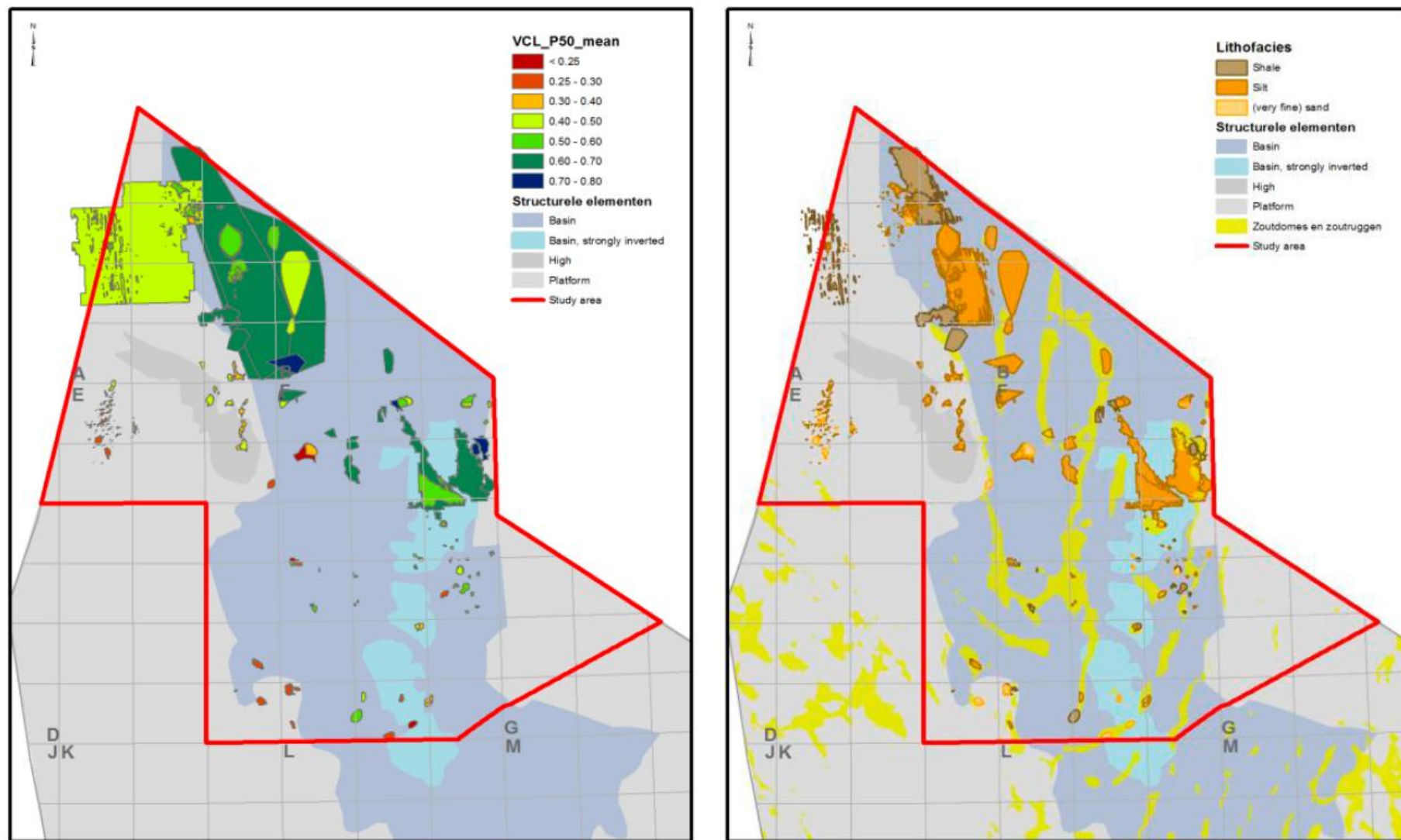
Figure 6. Distribution of Bright spots with VClay (left) and lithofacies (right).
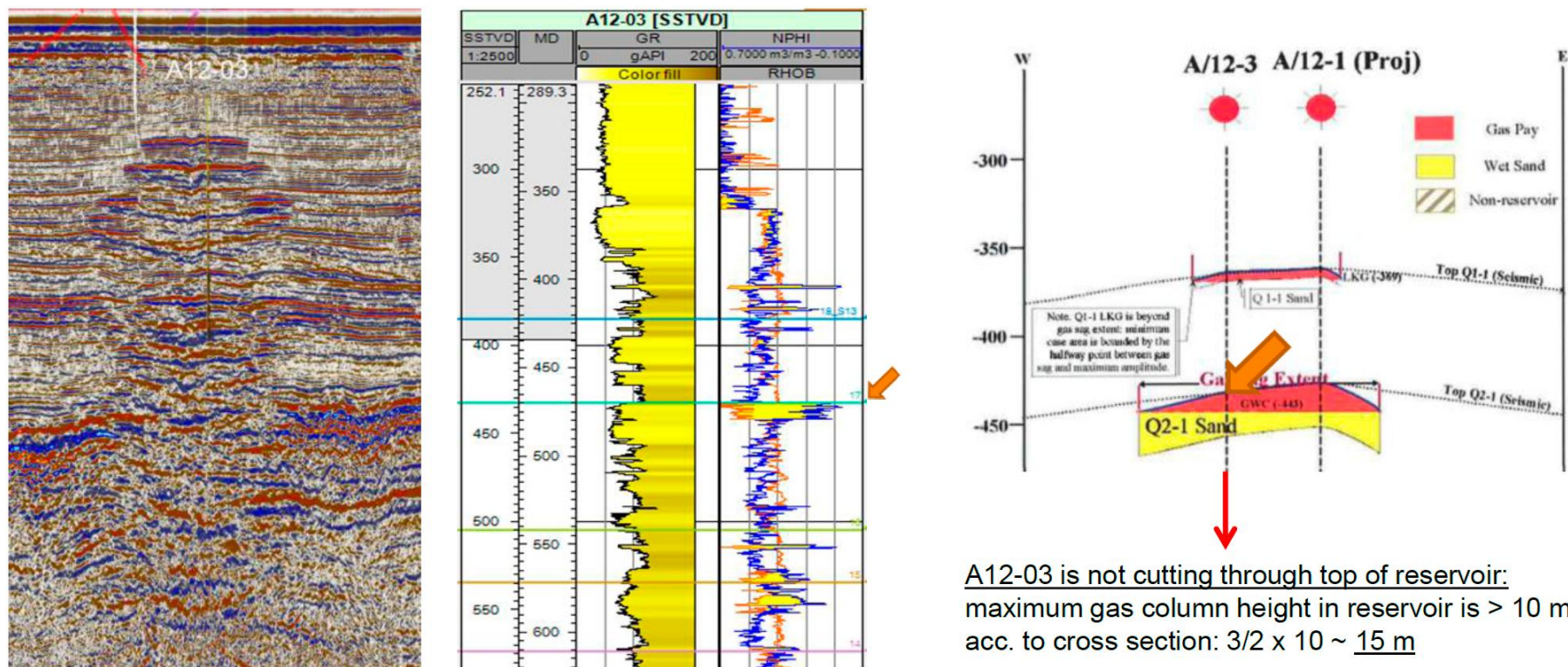
Figure 7. From left to right: 1) seismic section showing location of well A12-03 penetrating stacked bright spots; 2) Gamma ray, neutron (NPHI) and density (RHOB) logs; NPHI-RHOB crossovers indicate presence of gas; arrow indicates location of mudstone samples; The grain size base method derives at a maximum HC column height of 15 m, whereas the cross-over plot indicates 10 m only. This illustrates that the geometry of the reservoir should be taken into account and that the grain size method gives maximum numbers that account for the crest of the structure only as is shown in 3) Cross-section showing geometry of top gas reservoir/base mudstone seal; arrow indicates location of mudstone samples (figure derived from production plan A12 field).

Glacial	Interglacial
Relatively cold climate	Relatively warm climate
Relatively low Sea Surface Temperatures	Relatively high Sea Surface Temperatures
Almost no freshwater input	High freshwater input at the base of the interglacials
Relatively restricted marine conditions (water stratification)	Relatively open marine conditions
Very fine grain sizes (excellent seal properties)	Relatively coarse grain size
Relatively low sea levels	Relatively high sea level
Relatively low TOC content	Relatively high TOC content

Table 1. Characteristics of glacial vs. interglacial reservoir properties.