Shale Gas and Muddy Shelves: Comparing the Neogene-Quaternary Eridanos System (NW Europe) with the Devonian Catskill Delta (USA)*

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Abstract

The recent worldwide focus on gas and oil shales contrasts with our limited knowledge of the processes and geological context of environments dominated by fine clastic sedimentation. Development of such resources requires refined models that relate biogenic gas generation and storage to facies and architectural elements at depositional system scale, and to systems tracts and geotectonic setting at basin scale. A comparative research approach can relate palaeoenvironmental conditions and allogenic forcing of well studied depositional systems with those of shale prospects still under exploration.

We discuss sedimentological and architectural analogies and differences between the Neogene-Quaternary ‘Eridanos Delta’ of northern Europe, which drained the Fennoscandian and Baltic shields westward through the present-day Baltic Sea, and the Devonian ‘Catskill Delta’, which prograded into the Appalachian Foreland Basin (eastern USA) during the Acadian orogenic phase. In spite of their common denomination as ‘deltas’, these clastic wedges actually represent fluvial to coastal environments linked to shallow-marine, mud-dominated shelves in a proximal-to-distal continuum. The Eridanos system hosts numerous productive shallow-gas plays in the southern North Sea offshore, whereas the Catskill system contains important black-shale formations (Marcellus, Rhinestreet, Dunkirk, etc.) that charge an Appalachian hydrocarbon system.

Changes in base level and sediment supply, partly influenced by climate during the Plio-Pleistocene onset of glaciation, controlled the complex proximal architecture of the Eridanos Delta, and they are reflected by compositional and architectural changes in its mud-prone, basinal portion. The Eridanos Delta provides an example of well constrained relationships between different forcing factors, sedimentary properties and the hydrocarbon potential of its shaly domain. These insights may support new predictive genetic models for black shales of the Catskill and other systems, especially if applied to high-order heterogeneities within and between shale bodies which were probably driven by allogenic factors at time scales of millions of years and shorter. The potential for future hydrocarbon production from such plays, especially in areas with
surface footprint constraints (e.g., Europe), depends on the ability to unravel their internal variability, and thus, to target intelligently the most productive stratigraphic intervals.

**References Cited**


**Website**

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About TNO

TNO is a technology development and consulting company with over 30 years of experience in the Oil & Gas industry.

- Technology development, consulting, and contract R&D
- Approximately 4500 employees
- 2/3 revenue from industry, 1/3 Dutch government
- Active in many other markets
Shale reservoirs are not new...

- First commercial production 1821 (Fredonia, NY)
- Over 28,000 wells
- Recent boom through technical advancements

But..
- Knowledge on the processes and geological context of environments dominated by shale sedimentation is in a juvenile stage

- This contrasts with our in-depth knowledge/concepts of clastic- and carbonate reservoirs that more successfully serves exploration
Icehouse vs. Greenhouse gas shales

- Much of the geological concepts based on greenhouse world organic-rich rocks (ORR)

- Are these greenhouse concepts applicable to ice house world?

NO?
(classical)
Greenhouse Transgression
- Low dilation potential
- GR peak = maximum flooding
- High TOC at transgression and MFS

ICEHOUSE vs GREENHOUSE

Icehouse Regression
- Reduced clastic/nutrients influx
- Higher clay content/no organics
- GR peak = maximum glaciation
- High TOC during highstand progradation
TOC of organic-matter-rich rocks (ORR’s)

Passey et al., 2010, SPE 131350
Episodes of black shale sedimentation related to 2nd order tectonic phases control the distribution of the ORR.

3rd order sequences and parasequences, control the distribution of the ORR.

Passey et al., 2010, SPE 131350; Kohl et al. (2013)

From Ettensohn (1994)
Catskill depositional model

- ORR during transgression & highstand
- Higher supply at relative lowstand
- Low eustatic amplitude
- Greenhouse world

Modified from Ettensohn, 1994, 2008
High GR = MFS = high TOC = high brittleness

Hill et al., 2004

Lash & Engelder, 2011
Applicability of concept to other greenhouse world shales – the Posidonia FM (UJ Europe)
Similar carbonate-dominated shallow-marine domains...

Similar basin-centered ORR

distribution of the bituminous facies:
- YB: Yorkshire Basin
- NWGB: NW German Basin
- SWGB: SW German Basin
- PB: Paris Basin

emerged areas:
- LBM: London-Brabant Massif
- RM: Rhenish Massif
- BM: Bohemian Massif
- VH: Videlician High
- AM: Americanian Massif
- MC: Massif Central

shallow water
Biofacies zonation

Global $^{13}$C event

LOON OP ZAND-01

Palaeoenvironmental development

- Warm and dry climate
- Gradual return to normal marine conditions
- Decrease freshwater influence nearshore
- Second Tasmanites acme
- Decrease swamps
- Increasing aridity
- End of anoxia in basin center
- Freshwater influence far offshore is waning
- Vegetation change > expansion of swamps
- Stratification of water column
- Increased river activity
- Strong stratification; persistent low salinity surface layer
- Increase in runoff; first Tasmanites acme; start stratification
- Warm and dry climate
- Normal marine conditions
For shale gas exploration it is important to identify “sweet spots” and “pay zones”

Gas readings in mud log: correlation between gas content and stratigraphy

Biofacies map: correlation between production and biofacies

A = anoxic, high TOC, clastic river plume input
B = anoxic conditions, high TOC
C = disoxic conditions, some biogenic sedimentation, low TOC
For shale gas exploration it is important to identify “sweet spots” and “pay zones”

Gas readings in mud log: correlation between gas content and stratigraphy

Biofacies map: correlation between production and biofacies

Link between heterogeneous gas content and
- gas-prone palynomorphs (biogenic gas)
- favourable mineralogy/texture zones
- higher TOC
Sweet spot identification?

A possible link between heterogeneous occurrences of high gas content and
- gas-prone palynomorphs (biogenic gas)
- favourable mineralogy/texture zones with high fracturing potential
- higher TOC
Log zonation and biofacies zonation

- **2nd Tasmanites acme**
  - Max isotope shift
  - Isotopes back to normal
  - Gradual transition to normal marine
  - Normal marine

- **1st Tasmanites acme**
  - Normal marine

- No anoxia
  - Intense anoxia
Shale reservoirs within a seq-strat framework

Creaney & Passey, 1993, AAPG Bull:

(1) Total organic carbon (TOC) in marine source rocks is distributed in predictable vertical patterns. The simplest pattern forms a “high TOC at the base, decreasing upward” (HTB) unit. These units can occur singularly or in a stacked succession. A simple model to explain the observed patterns relates TOC to sedimentation rate under anoxic conditions. High TOC values correlate to increased sediment starvation and tend to be oil prone; upward decreases in TOC relate to clastic dilution by progradation and are less oil prone.

(2) The thickness and richness of organic-rich, marine, oil-prone mudrocks depends on their paleogeographic position. These source rocks are most frequently developed within condensed section facies that can occur in the extreme distal portions of all systems tracts.

(3) In a basin center, source rock accumulation begins earlier and persists longer than in shelfward age-equivalent rocks. The maximum TOC values in both locations should occur at the time of maximum flooding. The peak TOC in a marine-TOC profile is most likely to be a time-synchronous marker, often correlatable across much of the basin.
Eridanos mud-dominated clastic wedge
13 NE→SW parasequences (L. Miocene–E. Pleistocene)

- Top Chalk (Mid-Paleocene)
- Mid-Miocene Unconformity (MMU)
- Salt Domes
- High amplitude reflections due to gas escapement
- Gas escapement
- NE→SW parasequences (L. Miocene–E. Pleistocene)
- TWT [ms]
- ~1000 m
- ~70 km
- V.E. = 18x
Alternation of organic-rich silt and grey mud
The Eridanos delta

- Oligocene – Pleistocene river-delta systems
- In NL: Late Miocene - Pleistocene
Eridanos (or SNS) delta on a world scale
Repeated glacial advance during Gelasian
Sea-level drops of 100 m or more
Pleistocene (Gelasian) climate and deposition

- The Gelasian climate was characterized by repeated glacial advance
- At glacial stages, sea-level drops of 100 m or more occurred

GLACIAL  INTERGLACIAL

- IG: Strong progradation without iceberg scours
- IG: Progradation accompanied by failure (Sed. supply >> Accommodation)
- G: Progradation culminated in shelf erosion (incised valleys)
- G: Iceberg scouring on aggrading shelf
Recoverable depositional geometry?

~300 m

5 km
Recoverable depositional geometry?

Outcrop scale?

Well-log scale?

Basin scale

~300 m

5 km
Temperate Climate Shallowing Sequence (MMU-Pliocene)

- Base - deep water (MMU)
- Top - shallow marine / fluvial
- Strong contour currents
- Steep-dipping, high-relief clinoforms at top
- Supply-driven system, sea-level fluctuations higher order cycles

Long-term cooling (SST), many trees (AP)
Shallowing, but continuously marine (SD)
Alternation of Warm and Cold Periods (S5-S7)

- Alternation of glacial and Interglacial periods
- Climate controls sediment quantity and type
- Glacial plough marks
- Sealing clays
- TOC variations

Cycles in clays, depth (SD) and temperature (SST/AP)
Arctic Infill (S8-S13, 2.2 – 1.8 Ma)

› Shallow sea (compared present) under arctic conditions with sea ice cover.
› Periods with an open vegetation during warm climatic pulses with open marine conditions.
› Low relief, low-angle progradations.
› Hiatuses
Seismic sequence stratigraphy

Courtesy of dGB
Depositional model: coupling climate to (bio)facies
Icehouse world model

Greenhouse world model

Based on Union Spring Mbr, Lash & Engelder, 2011

Based on Cenozoic, Eridanos Δ, this study
ICEHOUSE vs GREENHOUSE

(classical)
Greenhouse Transgression
- Constant clastic influx
- High clay content (flooding)
- GR peak = maximum flooding
- High TOC at MFS

Icehouse Regression
- Reduced clastic/nutrients influx
- Higher clay content/no organics
- GR peak = maximum glaciation
- High TOC during highstand progradation
Concluding remarks

› In greenhouse world high TOC zone (GR peaks) might correlate with TST and MFS
› Effects of climate-induced nutrient input and water column should be considered
› In icehouse worlds peaks in TOC/GR correlate with max glaciation (LST)
› More work, thoughts and input to support concepts are needed

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