The Permian Zechstein Formation as a Potential Hybrid Unconventional Reservoir: A Sequence Stratigraphic and Sedimentological Evaluation of Organic-Rich Carbonates and Mudrocks from Shelf to Basin, Northern Germany*

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Abstract

The Upper Permian Zechstein Formation in northeastern Germany has been a prolific conventional oil-producing formation primarily from shelf and slope carbonates that rimmed a basin extending from eastern England through the Netherlands and Germany to Poland. Main reservoirs to date are grainstones rimming islands created by pre-existing paleohighs, from platform-rimming shoals, and slope carbonates. Lagoonal evaporites formed the seal for these carbonate and underlying sandstone reservoirs. The objective of this investigation is to evaluate potential unconventional reservoirs in lagoonal, slope, basinal, and organic-rich, fine-grained and/or tight lithologies of this formation. Therefore, a comprehensive, basin-wide study was conducted that included sedimentology, sequence stratigraphy, and geochemistry. The Zechstein Formation is divided into seven 3rd-order sequences that are dominated by regressive and transgressive cycles of shelf origin. Sequence stratigraphic correlations from shelf to basin are crucial in establishing a framework that allow correlation of potential productive facies in fine-grained, organic-rich basinal siliceous and calcareous mudstones or interfingering tight carbonates and siltstones ranging from the lagoon to slope.

Most organic-rich shales worldwide are associated with 2nd- to 3rd-order eustatic transgressions. The basal Zechstein cycles, Z1 and Z2, contain organic-rich siliceous and calcareous mudstones and carbonates that form the transgressive deposits in the basin. Tight dolomitic layers, marlstones, and organic-rich limestones interfingering with organic-rich siliceous and calcareous mudrocks are candidates for forming a hybrid unconventional reservoir. A comprehensive database composed of core, wireline logs, and outcrop is used to analyze the organic-rich mudstones and carbonates. Maturities range from overmature (gas) in the basin to oil-generation on the slope with variable TOC contents. This sequence stratigraphic and sedimentologic evaluation of the transgressive facies in the Z1 and Z2 intervals, in conjunction
with chemostratigraphy, evaluates the potential for shale gas/oil and hybrid unconventional plays where interfingering organic-rich mudstones and carbonates might present new exploration possibilities and serve as analog to other hybrid plays, such as the Bakken or Pearsall Formations in the USA.

**Selected References**


**Website**


Issues

- Comprehensive facies and sequence stratigraphic model across lower (Z1 and Z2) Zechstein basin from Poland to UK missing.
- Most publications and research concentrated on localized studies of classic stratigraphy and geochemistry (e.g., Kupferschiefer).
Goals

- Evaluate Upper Permian Zechstein Z1 and Z2 mudrocks, shales, and carbonates for shale-gas/oil potential, hybrid, and conventional reservoirs.
- Establish facies and sequence stratigraphic model from shelf to basin – establish regional framework.
Late Permian (260 Ma)
Paleogeography
Northern Europe
(from Blakey Paleomaps 2012)
Paleogeography

Transgression
(flooding of a sub-sea-level intracratonic basin)

- Late Permian (Zechstein)

1-2 km of clastics, carbonates and evaporites

(Northern Permian Basin)

(Southern Permian Basin)

(Ziegler 1990)
Zechstein Stratigraphy

(from Kaiser et al., 2003)
Zechstein Study Area – northern Germany
Brandenburg
Mecklenburg-Vorpommern
Tiefenlage der Präzechstein-Oberfläche

- 0-1000 m
- 1000-2000 m
- 2000-3000 m
- 3000-4000 m
- 4000-5000 m
- > 5000 m

Präzechstein ± zutage tretend

PZ: Bohrung Offshore-Bohrung

0-1000 m
1000-2000 m
2000-3000 m
3000-4000 m
4000-5000 m
> 5000 m

Präzechstein ± zutage tretend

PZ: Bohrung Offshore-Bohrung

Berlin
Paleogeo-morphology (from Franke, 2012)
Database

- Cores and logs from German State offices in Brandenburg and Mecklenburg-Vorpommern (Research wells from Hoth et al. (1993))

Cross Sections Z1 and Z2

Zechstein Z2 cores sampled and described
Zechstein Z1 cores sampled and described
Underlain by conglomerate or Weissliegendes sandstone.

Kupferschiefer (black, clay-rich, massive mudstone, partly calcareous, bituminous shale)

Massive, laminated and bioturbated calcareous mudstones (Zechsteinkalk).

Carbonate facies composed of wackestone, grain- and packstones

Werra Anhydrite: nodular, massive, and chicken-wire anhydrite facies
Z1 Basin: Oranienburg

1 m
Z1 Third-order basinal sequence

- Laminated, bituminous, calcareous mudrock
- Laminated calcareous mudstone
- Thrombolite intraclast packstone
- Crinkle-laminated Calcareous (dolomitic) mudstone
- Massive Anhydrite (Werra)
Platform/Lagoon: Spremberg
(courtesy of Michael Krause U Potsdam)

Anhydrite
Dolomite
Limestone
Lime-Mudstone
Rotliegendes
Kupferschiefer
Sandstone
Note: thickness double as in basin!
Anhydrite
Dolomite
Limestone
Lime-Mudstone
Kupferschiefer
Rotliegendes

Note: thickness double as in basin!
TOC ZECHSTEIN Z1

Kupferschiefer

Z1 Carbonates
# Zechstein Stratigraphy

(from Kaiser et al., 2003)
Zechstein Facies and Sequences Z2
(from bottom to top)

 Underlain by Werra Anhydrite
 Shales are calcareous, laminated mudstones (Stinkschiefer)
 Limestones characterized by laminated, slightly dolomitic, calcareous mudstones with crinkle-laminated beds (Stassfurt carbonate, Stinkkalk)
 Basal Anhydrite, nodular, massive, and chicken-wire anhydrite facies.
Z2 Basin
Parchim
Z2 Third-order basinal/slope sequence

- **Crinkle-laminated** calcareous, dolomitic mudstone
- **Chicken-wire Anhydrite** (Basal)
- **Grainstone blocks** in laminated mudstone slope facies
- **Laminated calcareous Mudstone with micro-stylolites**
- **Laminated, bituminous** Calcareous mudstone
Z2 Platform Facies

(courtesy of M. Krause, U. Potsdam)
Z2 Platform
Facies
(courtesy of M. Krause, U. Potsdam)
Z2 Platform Facies
(courtesy of M. Krause, U. Potsdam)
TOC Z2 Germany and Holland
Maturity

Modified from Hartwig and Schulz (2010)
Geochemistry
Mo versus TOC relationship

Molybdenum vs. TOC

$R^2 = 0.7017$

Mo (ppm)

TOC (%)
Geochemistry - XRD

The diagram shows a ternary plot with the following components:

- Quartz
- Clay
- Carbonate

There are two sets of data points:

- Green points labeled Z1, Ca1
- Red points labeled Z2, Ca2

A label marked 'Kupferschiefer' is noted near the green data points.
Conventional, hybrid, or resource play?

PROXIMAL

- Conventional (e.g., ooid/platform carbonates)
- Hybrid (e.g., interfingering platform carbonates, turbidites and mudrocks)

DISTAL

- Resource (laminated bit. mudstones)

Legend:
- Platform-derived carbonates
- Slope carbonates/mud-wackestones
- Organic-rich mudrocks (slope)
- Organic-rich mudrocks (basin)
Conclusions

- Bituminous, laminated, calcareous mudstones and mudrocks are present in the Zechstein Z1 and Z2 basins.
- Z1 mudrocks show high TOC and maturities ranging from oil to gas window.
- Z2 mudrocks show low TOC and maturities ranging from oil to gas window.
- Interfingering organic-rich mudstones and grain/packstones and dolomites might present new exploration possibilities and serve as analog to other hybrid plays.
- Further evaluation and expansion of the study area is necessary to assess the full potential of the Zechstein unconventional reservoirs.