Tectonic Evolution and Hydrocarbon Exploration of a Multiple Overprinted Caledonian Continental Collision Zone in the German Baltic Sea*

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Abstract

The review of legacy data and the subsurface remapping of a ~4,000 km^2 area in the German Baltic Sea east of Rügen Island are reported. The area was previously explored by Petrobaltic, a consortium between USSR, Poland, and GDR (1975–1990); ~8000 km of 2-D seismic were acquired and four deep offshore wells (G14, H2, H9, K5,) were drilled. The area is located in a complex tectonic setting. It straddles four superimposed basins created by Caledonian, Variscan, and Permian events. All four contain potential reservoirs. They are overlain by non-prospective Mesozoic sediments. The Caledonian crustal domain contains the collisional boundary between the Precambrian continents of Avalonia and Baltica. It hosts Ordovician turbidites of the accretionary prism (H2, H9) thrusted northward onto the undeformed, starved Cambro-Ordovician foreland sequence on the Baltica shelf (G14). The Variscan Rhenohercynian basin contains Devonian continental clastic rocks associated with post-Caledonian rifting, covered by marine carbonates. These are overlain by Carboniferous marine carbonates and continental flysch related to the Variscan orogeny. The area also straddles the Gryfice graben (K5), a pull-apart basin linking the two branches of a 2000-km long, dextral-transtensional, Permian intracontinental rift. The graben Upper Carboniferous to Lower Permian volcanic rocks and clastic sediments. Younger marine Zechstein carbonates and evaporites form the northern margin of the Northeast German Permian basin which record late Early Permian thermal sagging that prevailed to the Early Cretaceous. The prospectivity of the area was re-evaluated by integrating 3320 km of re-interpreted, reprocessed seismic data with well data and field analogs from onshore East Germany and Poland. As a result, prospectivity domains based on structure and sediment distribution were mapped. In particular, the areal extent of potential Devonian and Carboniferous reservoirs is much larger than

mapped previously. It is shown that the historic wells were poorly placed and are not representative of the local prospectivity, and that undrilled structures with multiple, stacked targets exist in the area.

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Kraus & McMechan (2017)

Outline

Purpose of Work and This Presentation

Exploration History

Geological Setting

Basin Development

Wells Wells Wells (4 German and 3 Polish offshore, 7 on Rügen…compact)

Results of Seismic Interpretation

Concluding Remarks

Purpose of Work and This Presentation

Work performed:

…to better understand the geology and therefore the prospectivity of the block and the surrounding areas

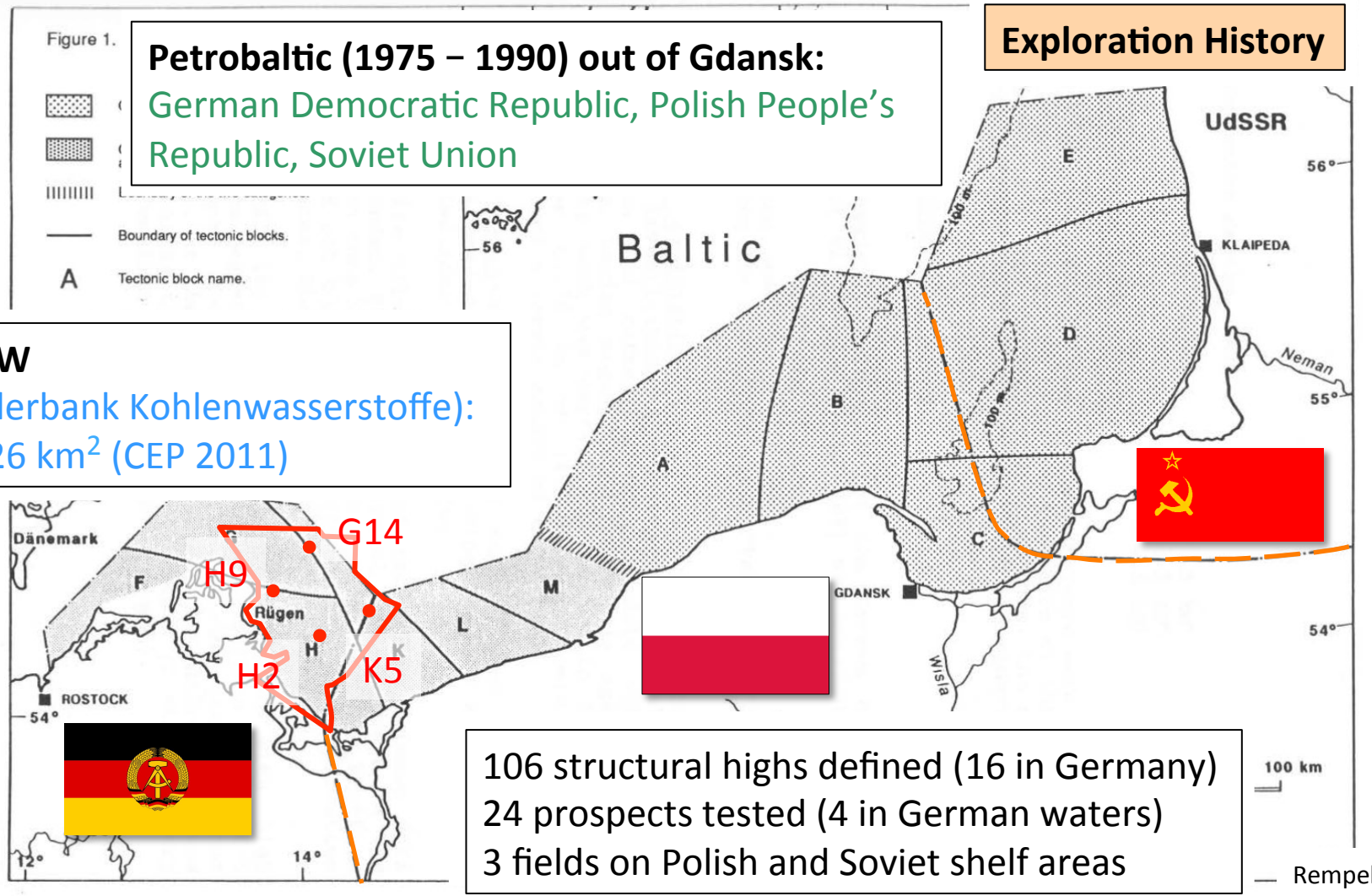
This presentation:

…aims to present the current status of hydrocarbon exploration on the German shelf east of Rügen Island

Exploration History

Petrobaltic (1975 – 1990) out of Gdansk:
German Democratic Republic, Polish People's Republic, Soviet Union

OKW
(Oderbank Kohlenwasserstoffe):
4626 km^2 (CEP 2011)



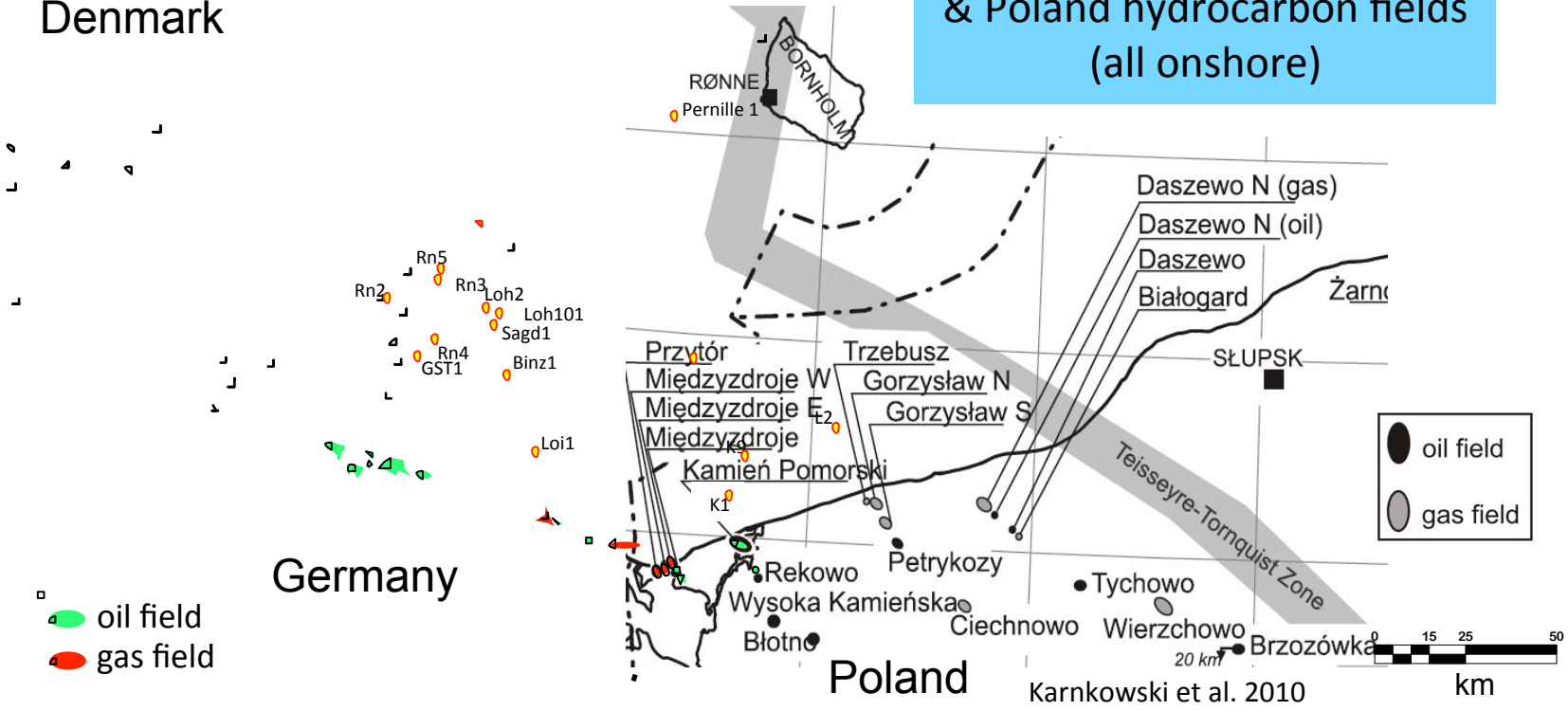
106 structural highs defined (16 in Germany)
24 prospects tested (4 in German waters)
3 fields on Polish and Soviet shelf areas

Rempel 1991

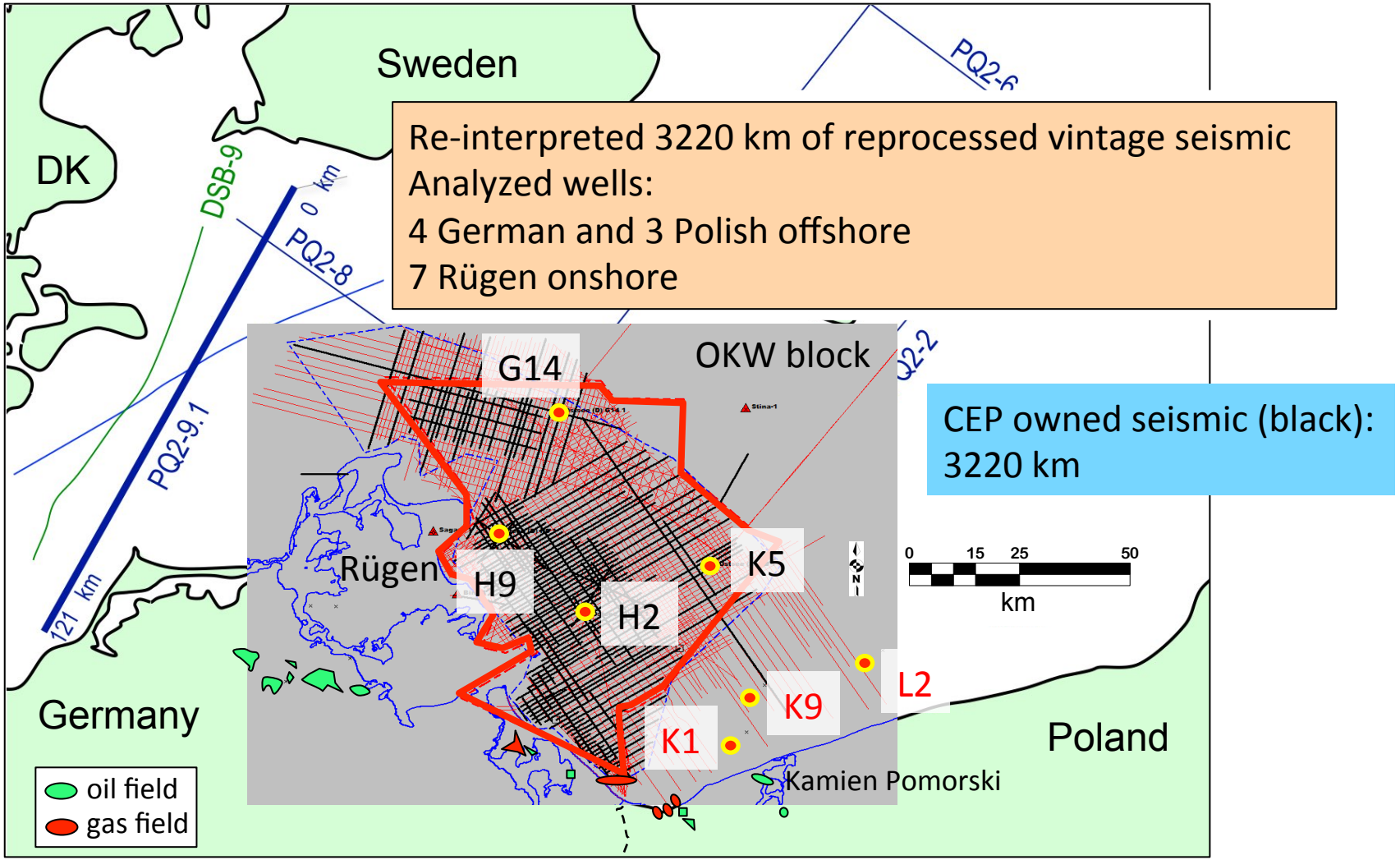
Onshore Pomerania:
-4 oil fields in Cambrian sandstones (Baltica)
-7 gas fields in Carboniferous sandstones
-6 gas fields in Saxonian sandstones
-11 oil fields in the Zechstein (Ca2)

Basemap after
Krawczyk et al. (2002)

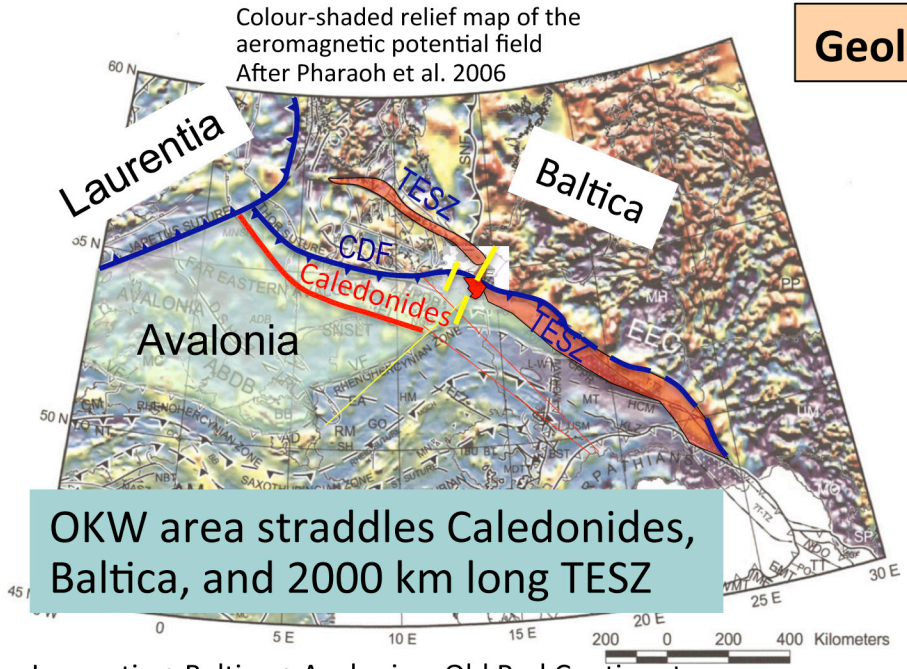
Northern East Germany & Poland hydrocarbon fields (all onshore)



Karnkowski et al. 2010


Sweden
DK
Germany
Poland
DSB-9
PQ2-8
PQ2-9.1
PQ2-6
PQ2-2
0 km
121 km
Re-interpreted 3220 km of reprocessed vintage seismic
Analyzed wells:
4 German and 3 Polish offshore
7 Rügen onshore
G14
OKW block
Rügen
H9
H2
K5
K9
K1
L2
Kamien Pomorski
CEP owned seismic (black):
3220 km
0 15 25 50
km
oil field
gas field

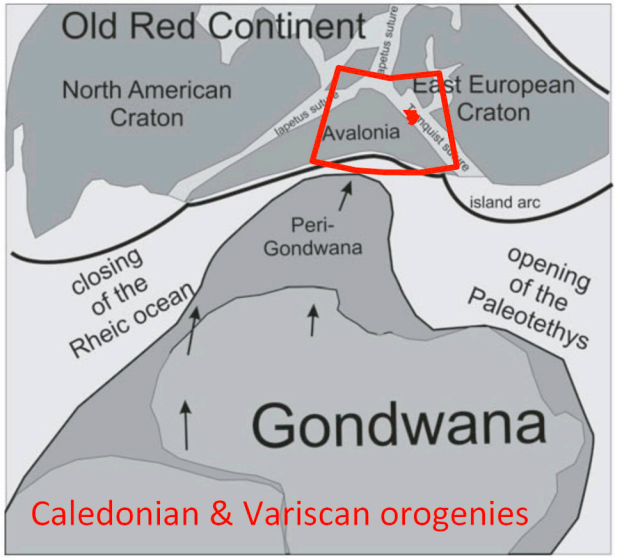
Geological Setting



OKW area straddles Caledonides, Baltica, and 2000 km long TESZ

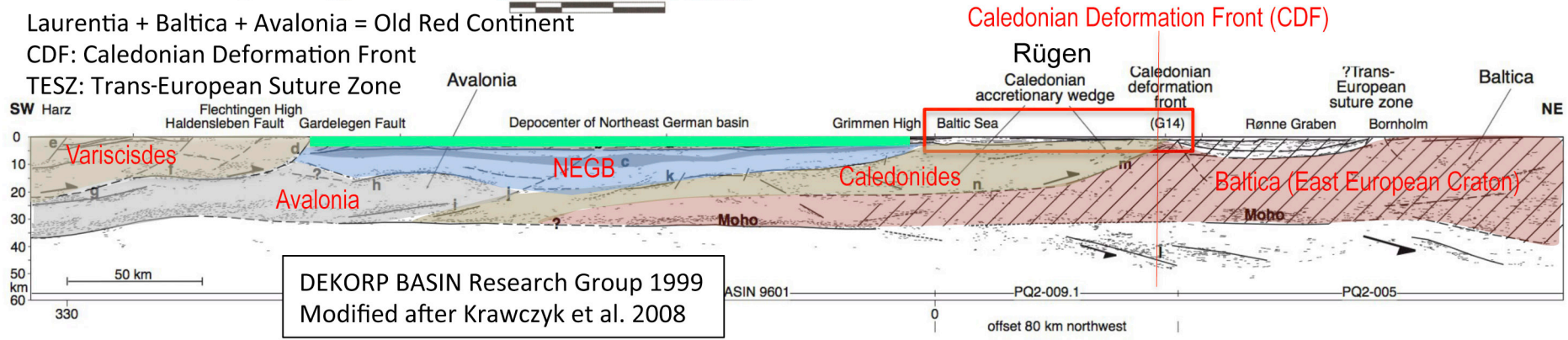
2 Caledonian sutures:
Tornquist: Upper Ord.
→ Baltica
Iapetus: Silurian
→ Old Red

"N. German – Polish Caledonides"



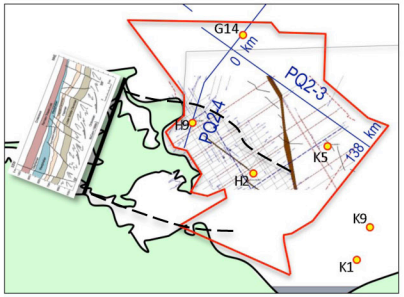
Kroner et al. 2007

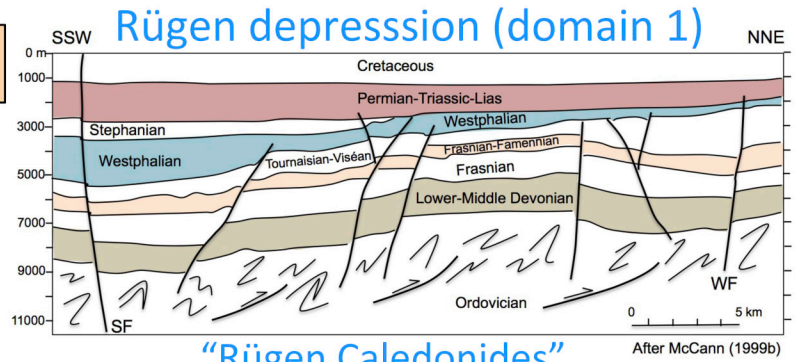
Laurentia + Baltica + Avalonia = Old Red Continent
CDF: Caledonian Deformation Front
TESZ: Trans-European Suture Zone



DEKORP BASIN Research Group 1999
Modified after Krawczyk et al. 2008

Basin Development





Main Devonian reservoirs:
Middle Devonian marine sandstones (Old Red facies)
Upper Devonian shallow marine carbonates

open shelf

deeper marine Frasnian carbonates

continental to shallow marine

Middle Devonian qtz-sandstones

System	Subsystem/ Series	Stage	Age (Ma)
Carboniferous	Mississippian	Tournaisian	recent
Devonian	Upper	Famennian	372,2–358,9
		Frasnian	382,7–372,2
	Middle	Givetian	387,7–382,7
		Eifelian	393,3–387,7
	Lower	Emsian	407,6–393,3
		Pragian	410,8–407,6
		Lochkovian	419,2–410,8
Silurian	Pridoli	no faunal stages defined	older

Subdivision of the Devonian System according to the ICS.[1]

Seal
Res.
Res.

convergence:
compression, uplift

extension:
rifting,
subsidence

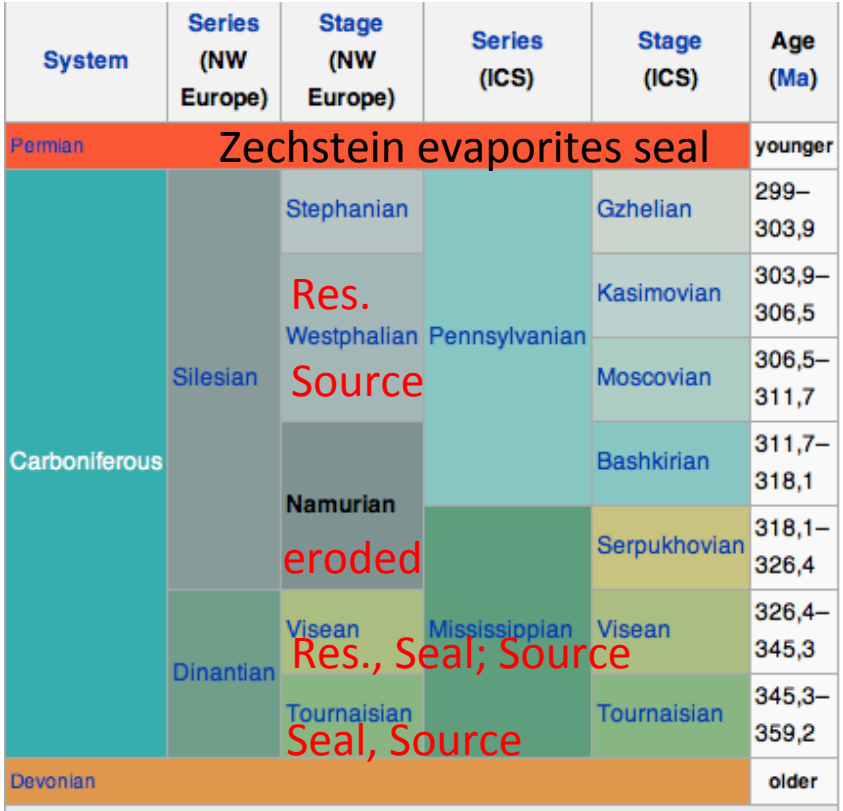
Variscan basin initiation in the Early Devonian: continental deposition (Old Red Sandstone)

Main Carboniferous reservoirs:
Westphalian continental sandstones
Viséan carbonates (flowed oil in Hiddensee 3 test)

Main Zechstein reservoir:
Ca2 (Stassfurt carbonate)
→ Kamien Pomorski, Lütow

continental:
molasse sandstones
(fluvial, lacustrine)

shallow marine:
carbonates w. minor
clastic rocks

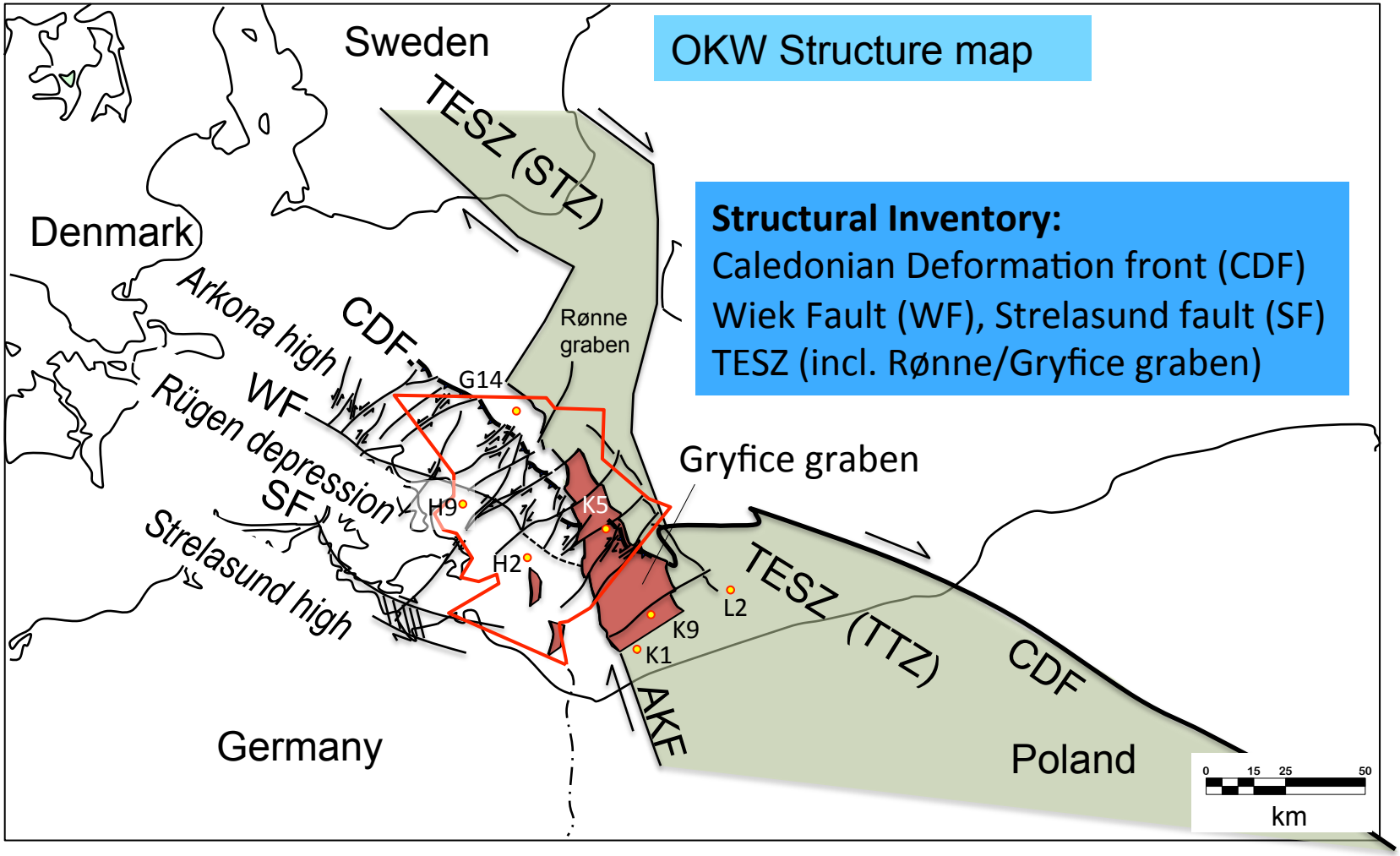


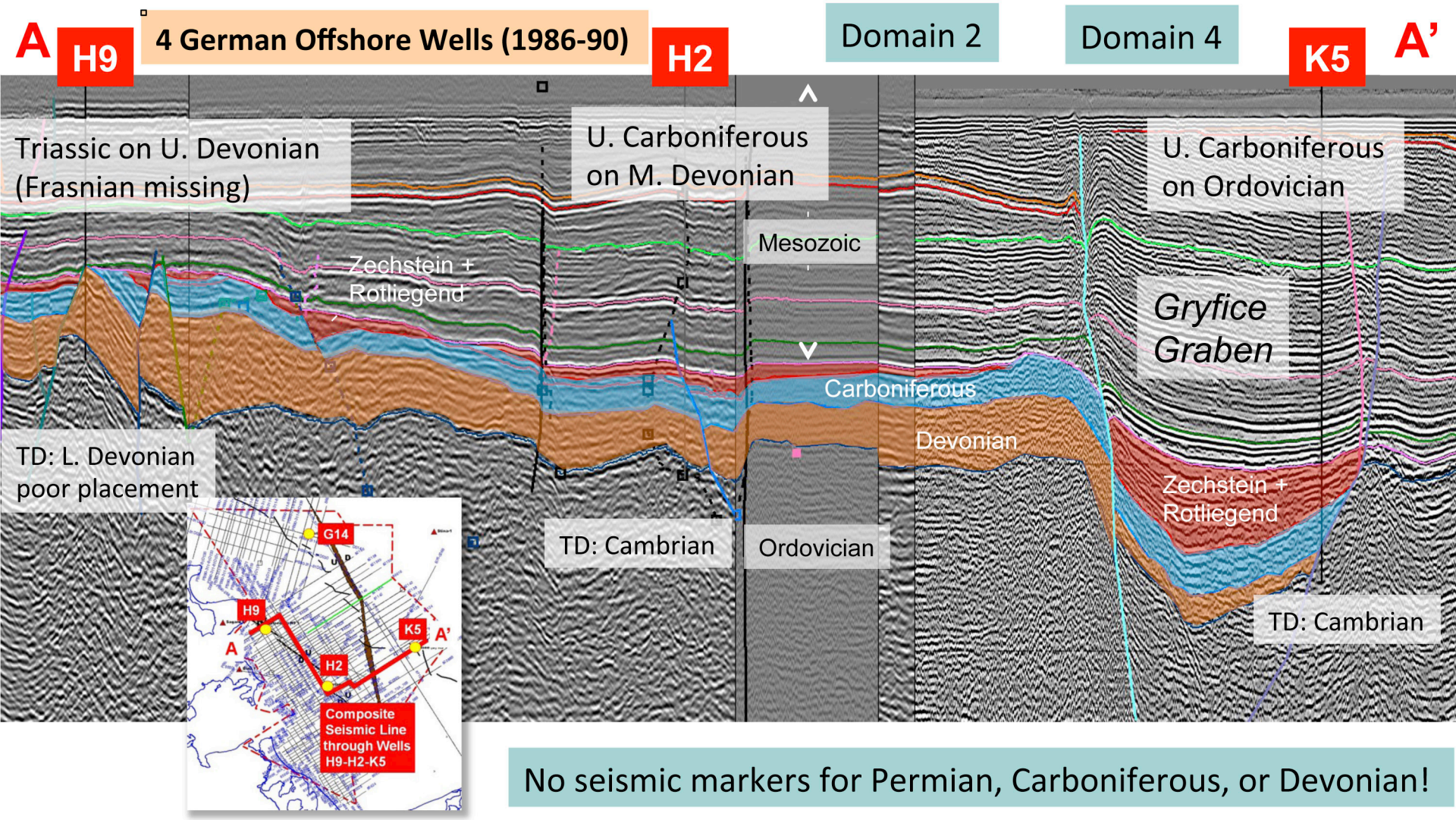
Subdivisions of the Carboniferous system in Europe compared with the official ICS-stages.

dextrally transtensional

early terminal collision:
post-Viséan uplift
("sudetic discordance")

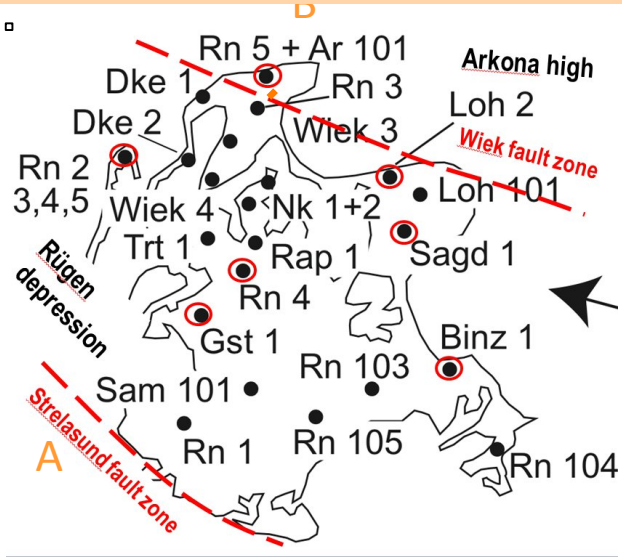
compression:
Variscan orogeny


OKW Structure map
Structural Inventory:
Caledonian Deformation front (CDF)
Wiek Fault (WF), Strelasund fault (SF)
TESZ (incl. Rønne/Gryfice graben)
Sweden
Denmark
Germany
Poland
TESZ (STZ)
TESZ (TTZ)
CDF
CDF
Arkona high
WF
Rügen depression
SF
Strelasund high
Rønne graben
Gryfice graben
AKF
G14
H9
H2
K5
K9
K1
L2
0
15
25
50
km


A
H9
4 German Offshore Wells (1986-90)
H2
Domain 2
Domain 4
K5
A'
Triassic on U. Devonian
(Frasnian missing)
U. Carboniferous
on M. Devonian
U. Carboniferous
on Ordovician
Mesozoic
Zechstein +
Rotliegend
Gryfice
Graben
Carboniferous
Devonian
Zechstein +
Rotliegend
TD: L. Devonian
poor placement
TD: Cambrian
Ordovician
TD: Cambrian
G14
H9
K5
A
A'
H2
Composite
Seismic Line
through Wells
H9-H2-K5
No seismic markers for Permian, Carboniferous, or Devonian!

7 Rügen Onshore Wells (1964–1973)

…out of 32 between 1962 and 1986



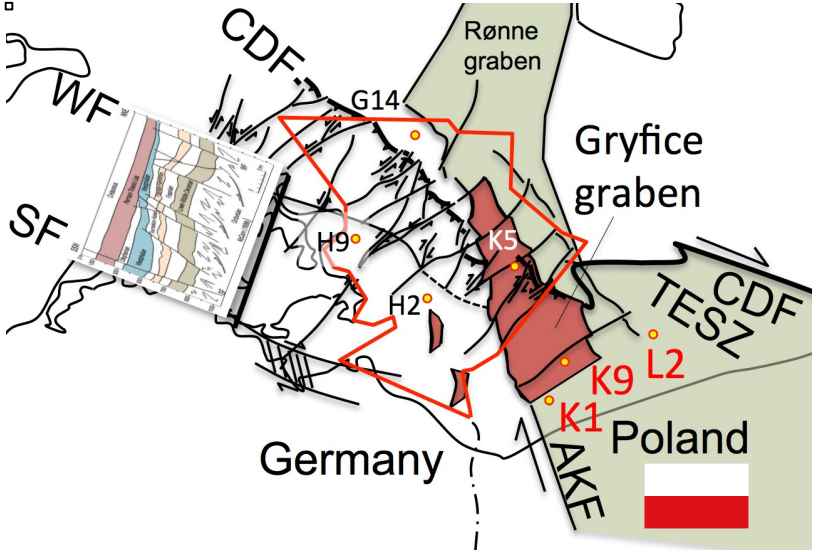
Paleozoic targets
No HC shows
only indications

7 wells examined (6 within Rügen depression cf. H2 & H9); all drilled on local highs!

Prognosed stratigraphic section missing:
e.g. 70% of U. Devonian in Binz 1/73

Effective porosity of M. Dev. sandstones is entirely depth dependent

3 Polish Offshore Wells (1986–1989): K1, K9, L2



K1 and K9 in similar setting as K5 (Gryfice graben)

Ca2 without reservoir quality (K1, K9))

Where do we have production onshore?
→ Composite Polish onshore gas and/or oil deposit

Pre-Permian:

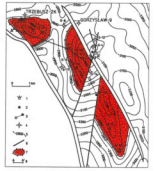
Geological Setting: TESZ; eastern extension of Rügen depression
Reservoir: mainly Westphalian sandstones; minor Viséan carb./ss
Trap: NNW to NW trending Alpine inversion anticlines against TESZ-related faults
Seal: mainly Zechstein salt and anhydrites; lesser intraformational
Source: mainly Tournaisian (Lower Carboniferous) shales

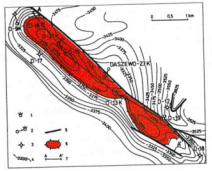
Late Alpine uplift vs. early Variscan uplift

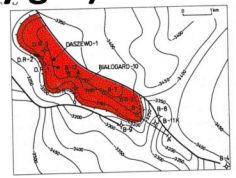
Permian:

Geological Setting: same as above
Reservoir: Ca2 (Stassfurt carb.), Rotl. sandstone
Trap: same as above
Seal: same as above
Source: Ca2, Carboniferous

Pre-Permian deposits (mainly gas)

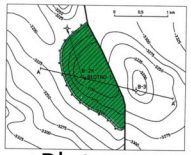

Goryslaw

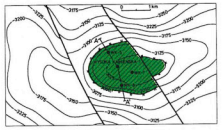

Daszewo North

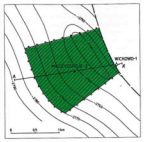

Bialogard

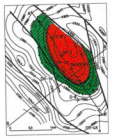
Permian deposits (mainly oil)

Karnkowski (1999)

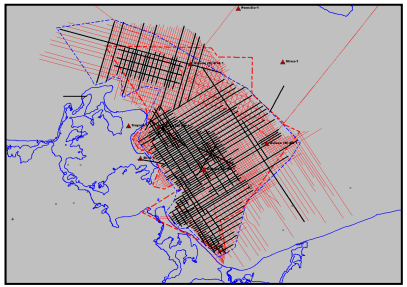

Blotno


Wysoka


Miedzyzdr.


Daszewo

Results of Seismic Interpretation



No Devonian?
No Carboniferous?

A

G14

H9

K5

H2

B

Petrobaltic subsurface mapping:
Pre-Permian Surface

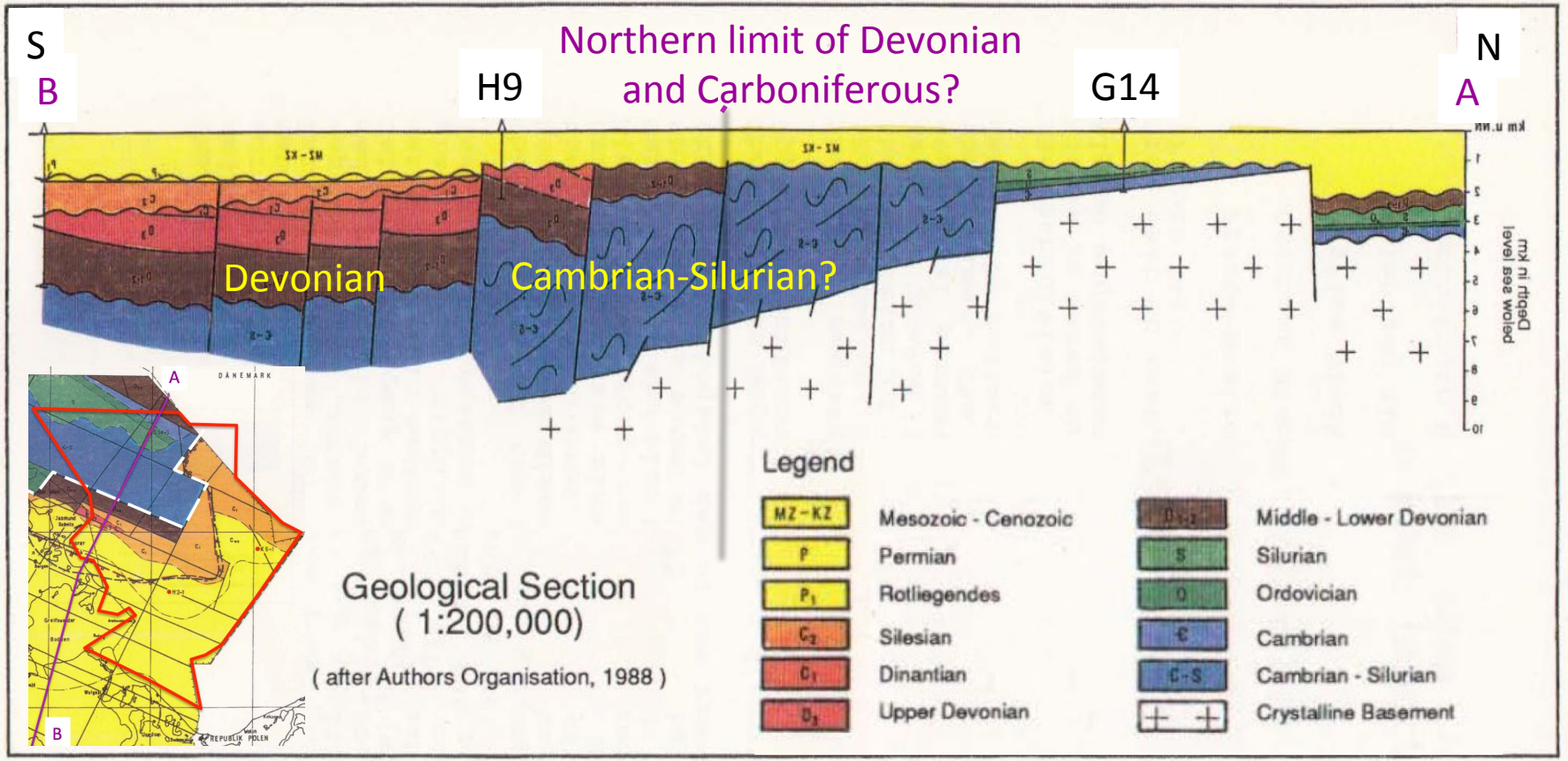
Rempel (1991)

Figure 7. Schematic Geological Map of the Pre-Permian Surface (cover removed) (1:500,000)
(after Muller, Franke, Rasch, 1988, Neumann, Giesemann, Kosjak, 1988, Giesemann, Ryba, 1990)

Limit of distribution of different stratigraphic units at the Pre-Permian Surface (subcrop lines)
Fault
Limit of distribution of marine Zechstein
Limit of distribution of marine Rotliegendes
G1-1 Offshore exploration well

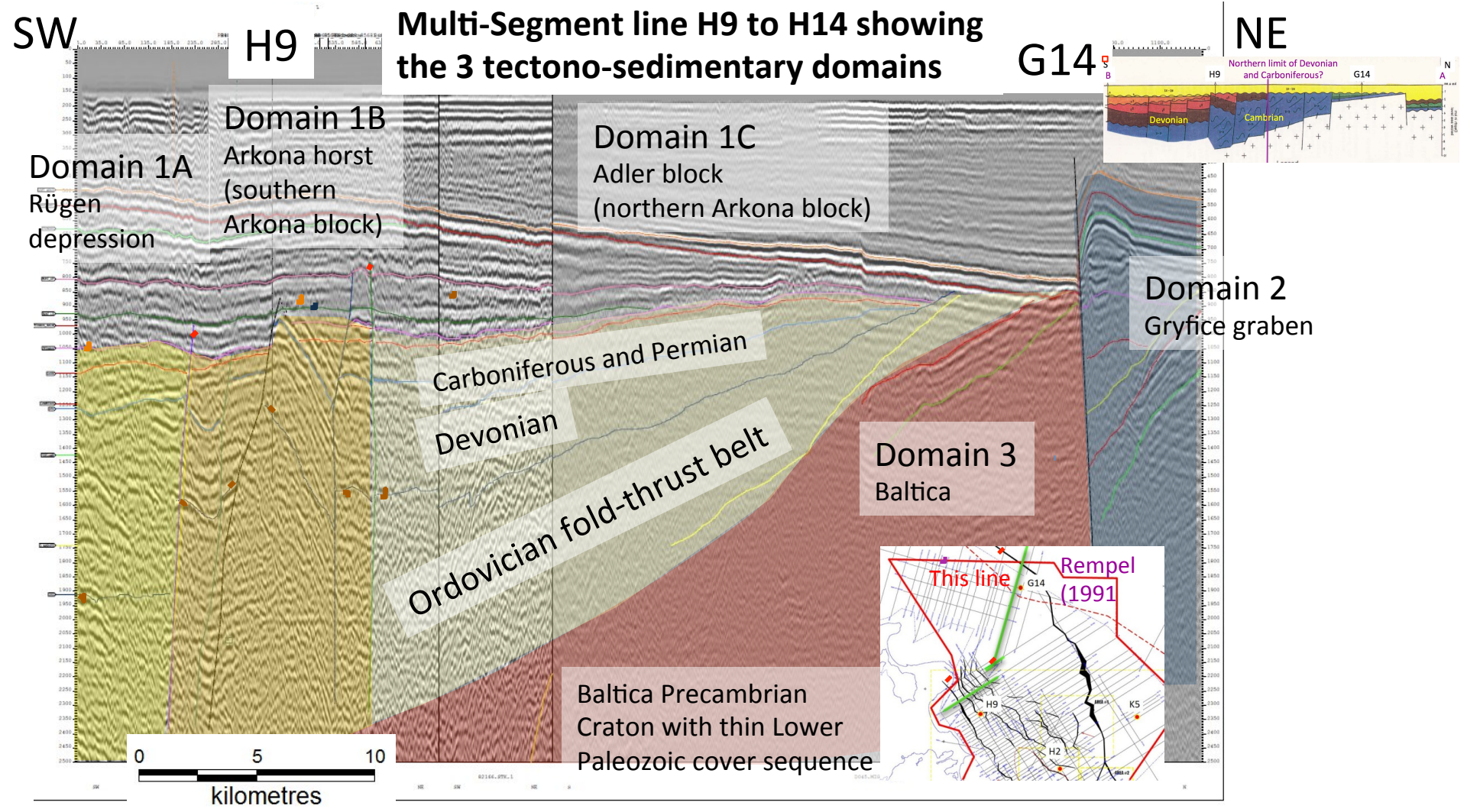
Cst Cws Stefanian, Westfalian
C1 Lower Carboniferous
D3 Upper Devonian
D1-2 Mid Devonian
S Silurian
O Ordovician
C Cambrian
C-S Cambrian-Silurian

DÄNEMARK
GERMANY



Actual section is side reversed!

Rempel (1991)


SW
H9
Multi-Segment line H9 to H14 showing the 3 tectono-sedimentary domains
G14
NE
Northern limit of Devonian and Carboniferous?
S
B
H9
G14
N
A
Devonian
Cambrian
Domain 1A
Rügen depression
Domain 1B
Arkona horst (southern Arkona block)
Domain 1C
Adler block (northern Arkona block)
Domain 2
Gryfice graben
Carboniferous and Permian
Devonian
Ordovician fold-thrust belt
Domain 3
Baltica
This line
G14
Rempel (1991
H9
K5
H2
Baltica Precambrian Craton with thin Lower Paleozoic cover sequence
0
5
10
kilometres

Domain 3
Baltica

Domain 1C
Adler block
(northern Arkona block)

Domain 1B
Arkona horst
(southern Arkona block)

Domain 1A
Rügen
depression

Domain 2
Gryfice graben (TTZ)

G14

H9

H2

K5

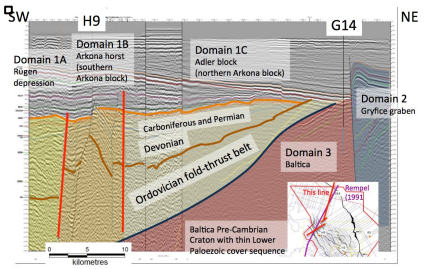
Devonian extensional faults
inverted in Namurian and Cretaceous

AREA #1

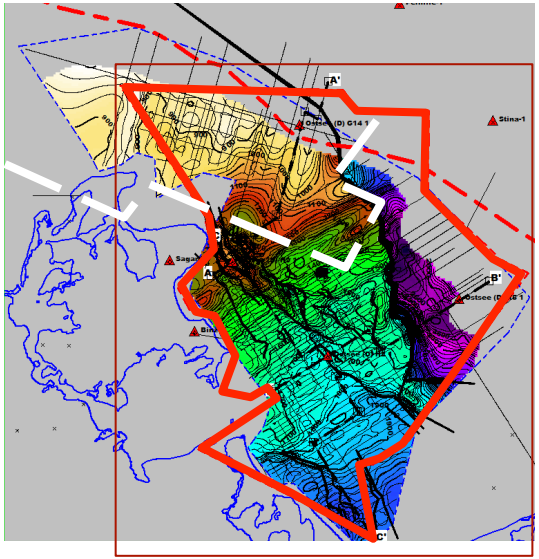
AREA #2

Adler-Kamien fault:
Silurian initiation?
Namurian inversion
Permian to Jurassic growth
Cretaceous inversion

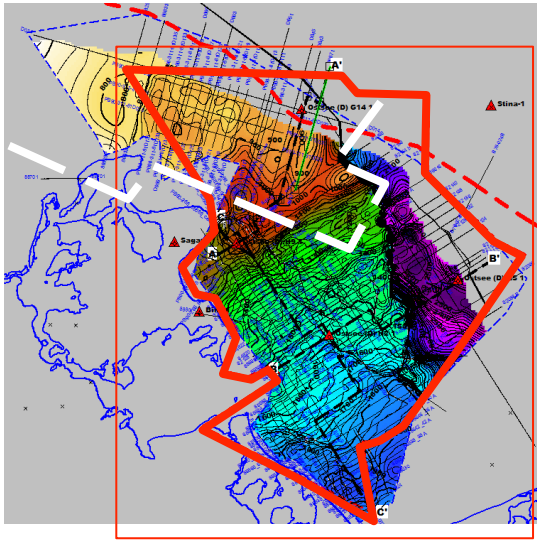
The 3 OKW Tectono-sedimentary Domains
(based on Variscan and post-Variscan block faulting)



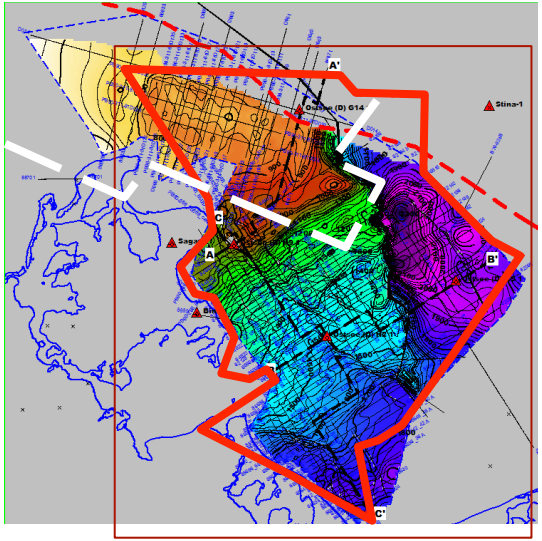
TIME STRUCTURE MAPS



Top Devonian

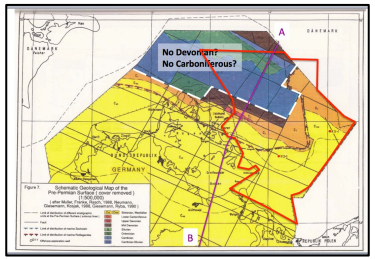


Top Carboniferous

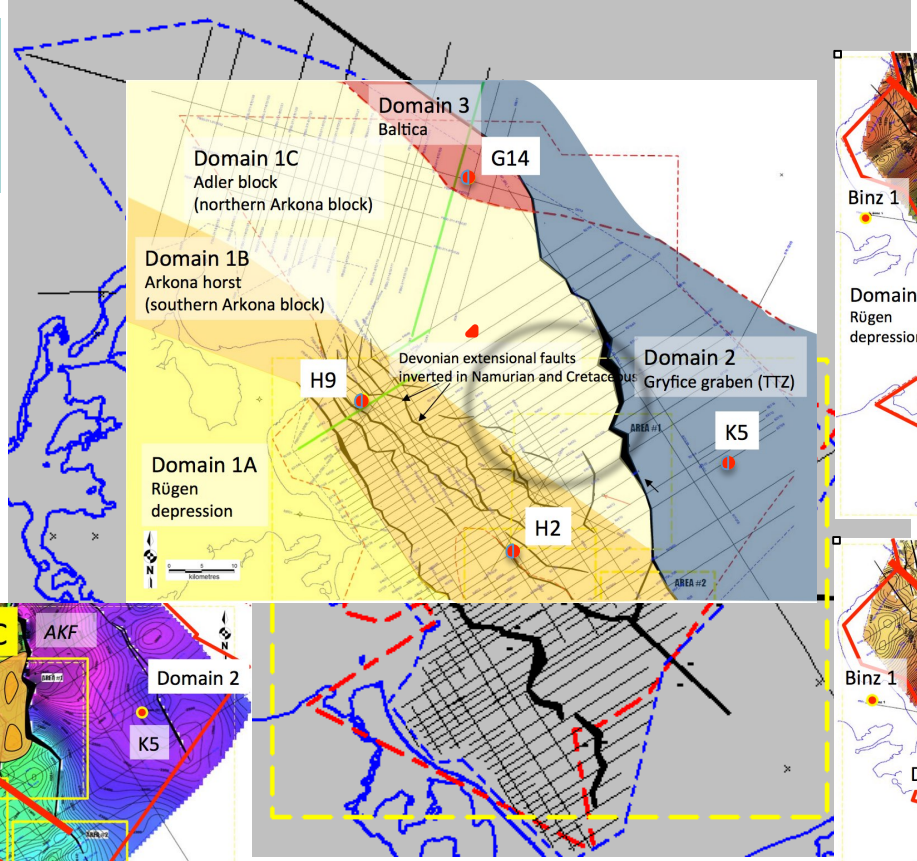


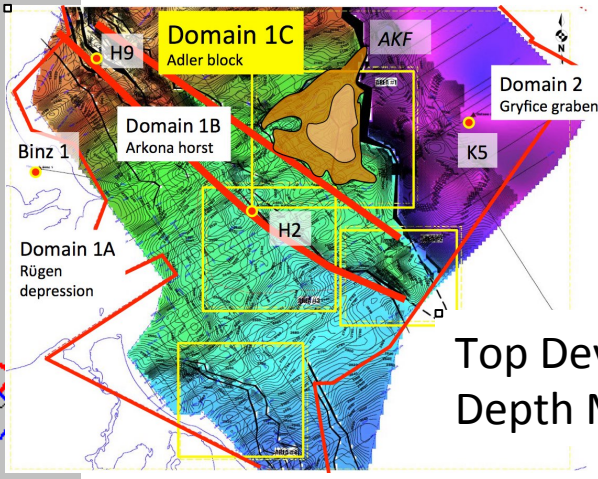
Top Permian

Devonian and Carboniferous extend more outboard than mapped by Petrobaltic. The packages are above the 2500 m porosity cutoff (for the M. Devonian)



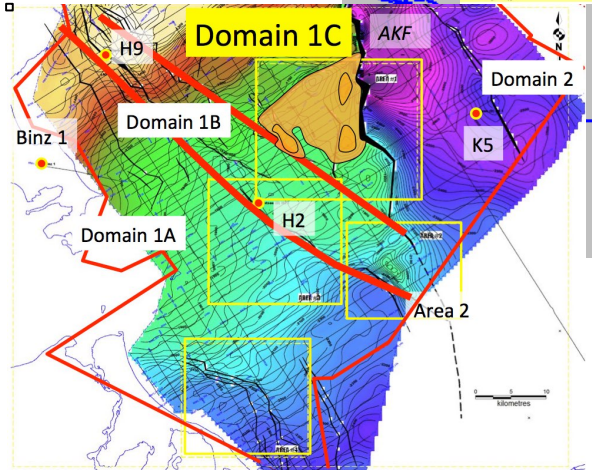
OKW Prospectivity: Seismic

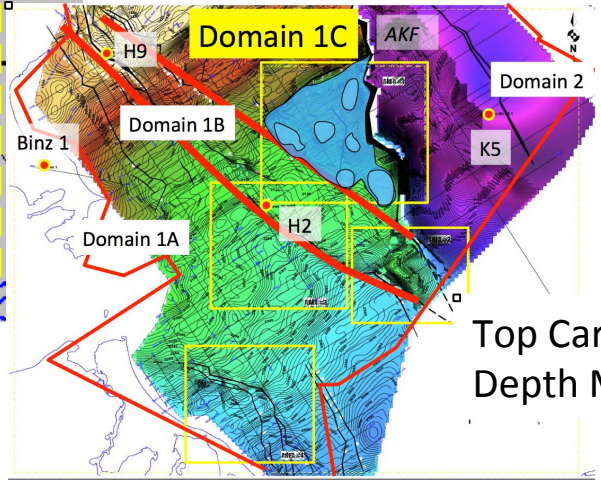




Top Devonian Depth Map

Top Permian Depth Map





Top Carbonif. Depth Map

SEISMIC BASEMAP W/ BOUNDARY OF ZOOM-IN

Concluding Remarks

Devonian and Carboniferous areal extent is much larger than previously mapped;
→ the newly mapped stack contains prospects and leads that need to be tested.

Upper Carboniferous and Zechstein have been identified as the main reservoirs.

Upper Carboniferous has a top seal issue that needs to be resolved.
Zechstein is best developed in the Gryfice graben and has unpredictable reservoir qualities.

Alpine inversion anticlines associated with NNW-trending TTZ-related faults are the main traps − they postdate early migration phases from Lower Paleozoic sources but pre-date late migration as well as Zechstein oil migration.

Prospects may be stacked: several targets can be tested with a single vertical well.

Additional seismic is required for key areas.

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