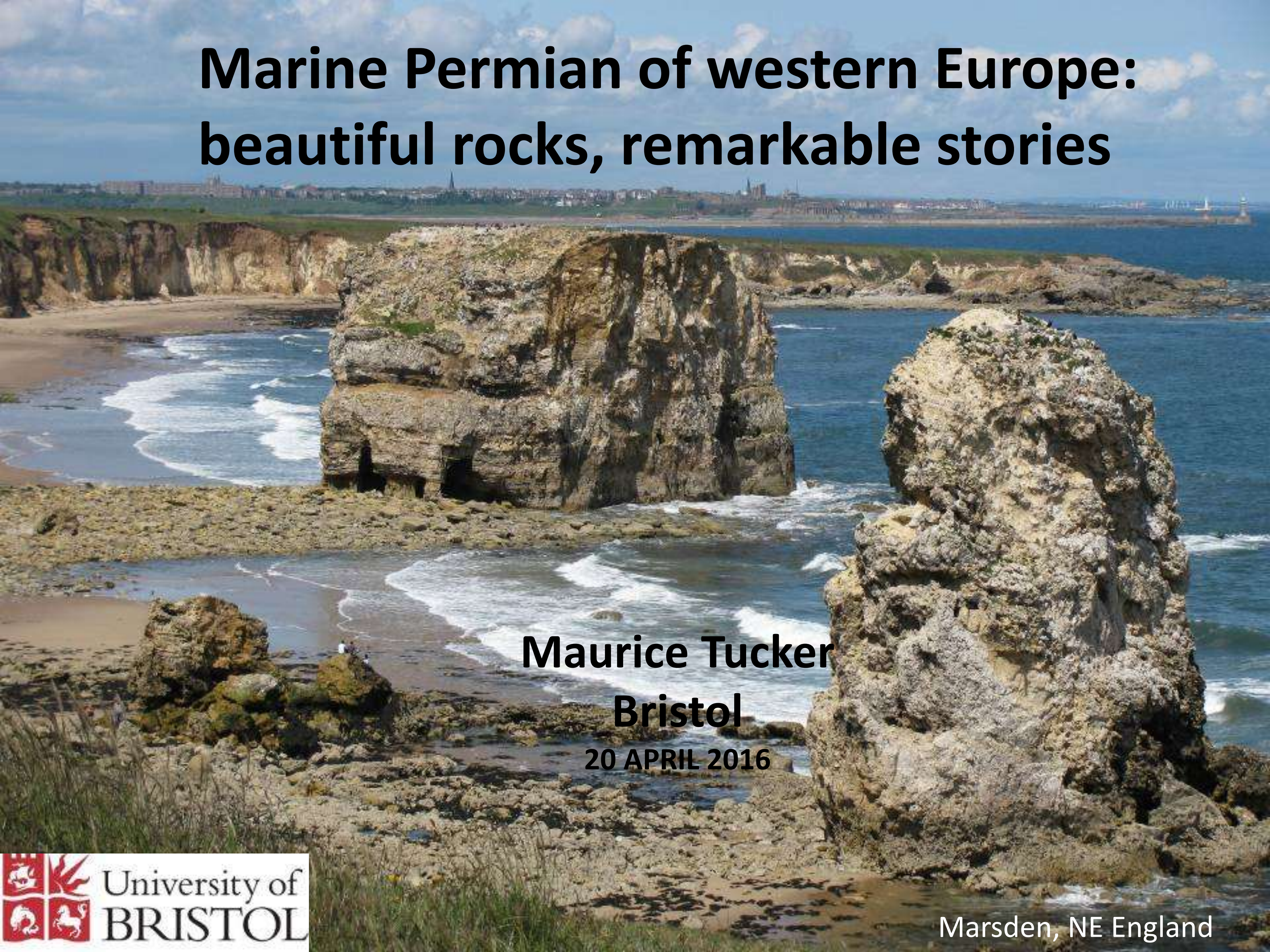
Marine Permian of western Europe: beautiful rocks, remarkable stories

Maurice Tucker
Bristol

20 APRIL 2016



Marsden, NE England

University of BRISTOL

THE ZECHSTEIN: TALK OUTLINE

Zechstein sequence stratigraphy: some points of view, carbonate-evaporite systems

Zechstein reservoirs: oolites, reefal-buildups and microbialites, slope facies, breccias

Zechstein source rocks: biomarkers, basin redox

using data from outcrop (North East England – North Germany) and the subsurface to discuss stratigraphy, facies, diagenesis, porosity and biomarkers.

Claxheugh Rock, NE England

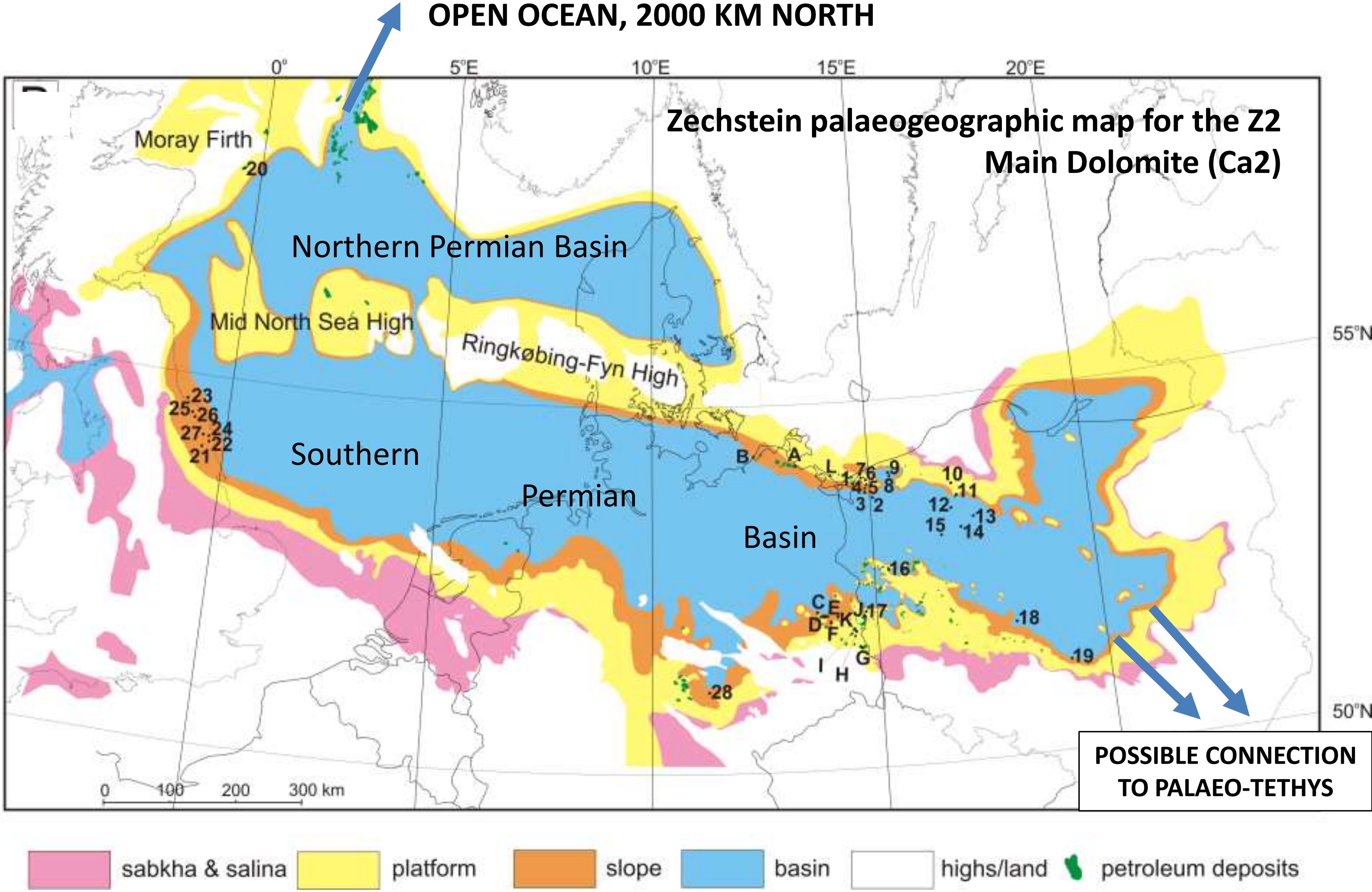
LATE PERMIAN PALAEOGEOGRAPHY FROM BLAKELY (2014)

Zechstein Sea connected to Panthalassa Ocean 2000 km to north/northeast.

Possible connection to Palaeo-Tethys through the Polish Sub-basin to the southeast (??)

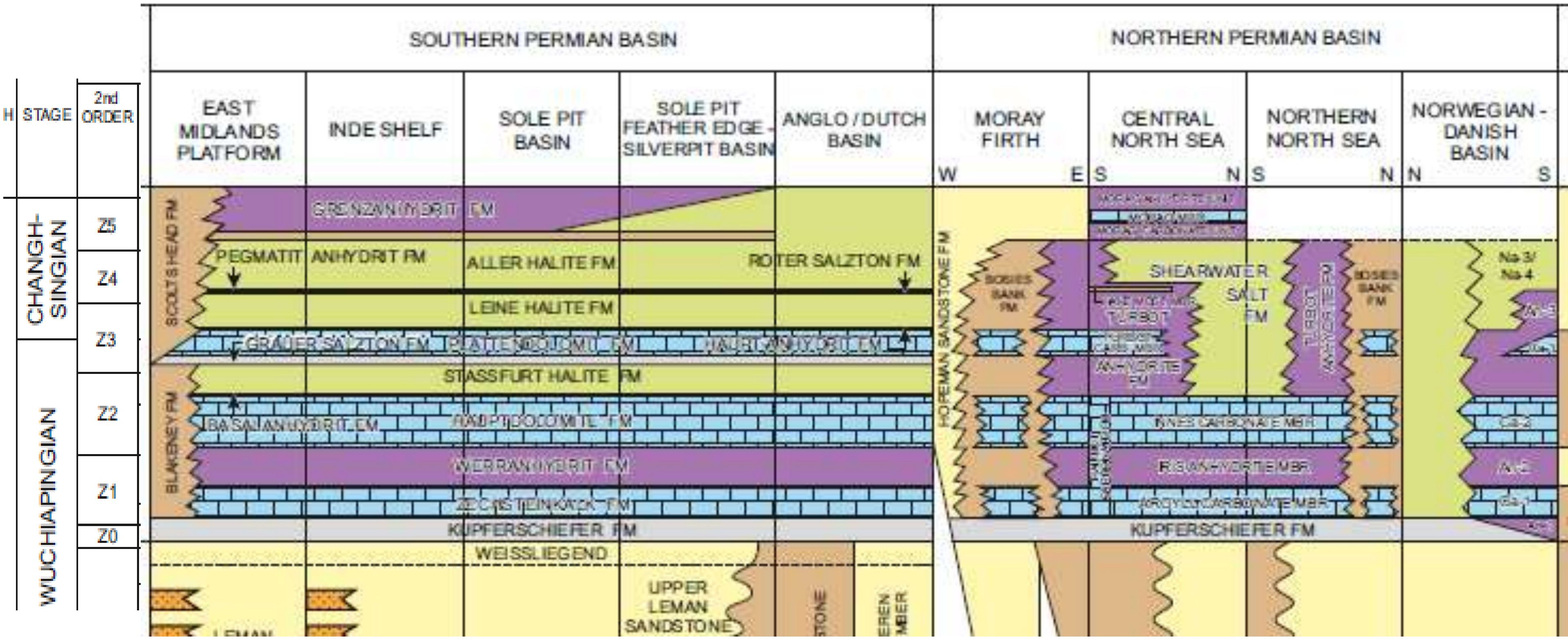
Palaeo-latitude: 10-20°. Climate extremely arid.

Upper Permian, Zechstein outcrops: NE England, Germany, East Greenland.



Wells marked are those used in recent biomarker and facies study (Slowakiewicz, Tucker et al. 2013, 2015, 2016)

Zechstein correlation: Southern to Northern Permian Basin



ZECHSTEIN STRATIGRAPHY TRADITIONALLY DIVIDED INTO CARBONATE-EVAPORITE CYCLES

From TGS website

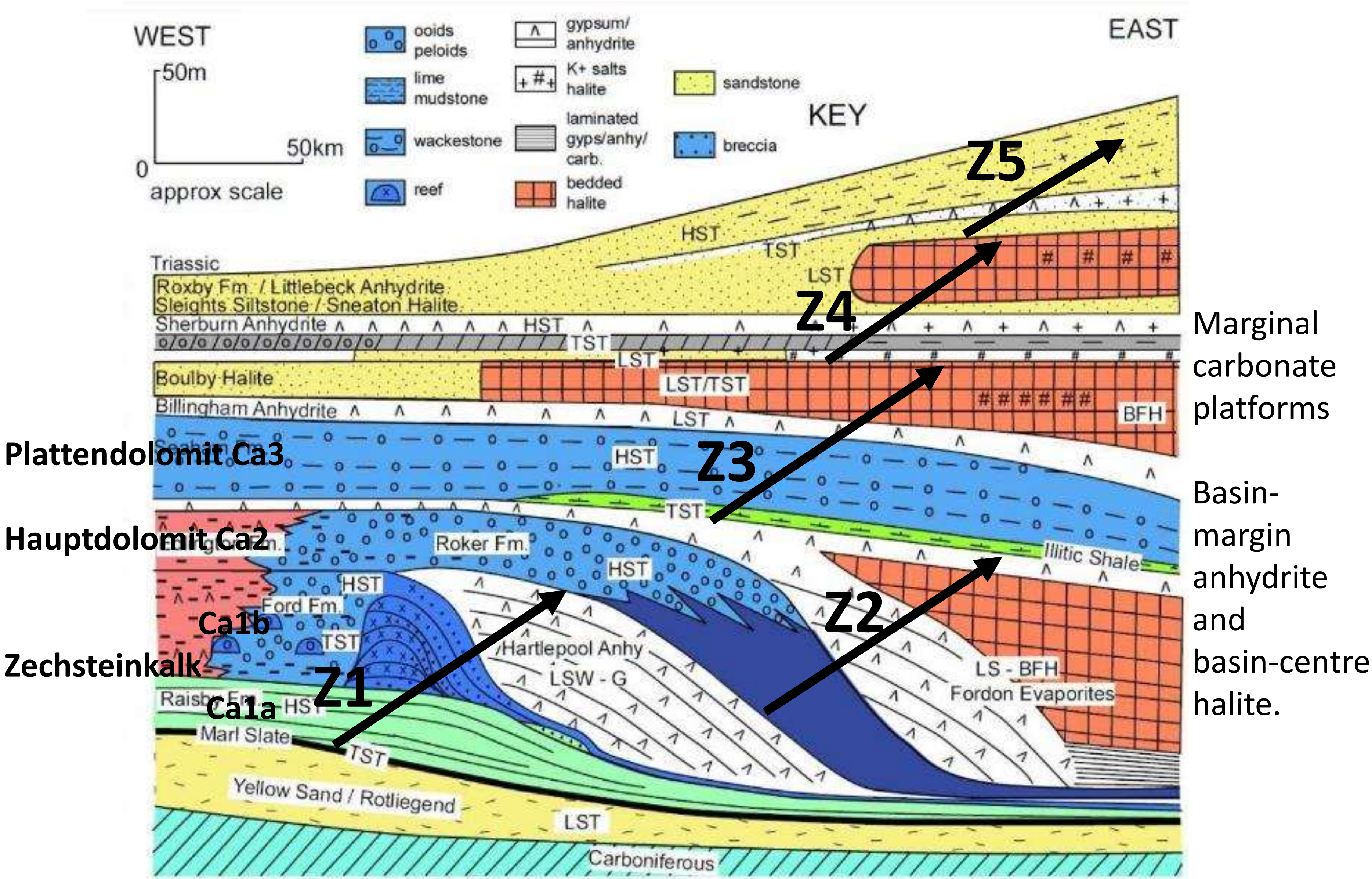
Cycles can be correlated SPB to NPB: facies similar but some differences in thickness, reflecting subsidence / faults. In NPB: more local clastic input, some younger carbonates (Z4).

Continuity of strata across the 2 basins – although strong facies and thickness changes, especially in the carbonates and anhydrite.

But some useful gamma-ray peaks (Kupferschiefer, Sapropelic Marker).

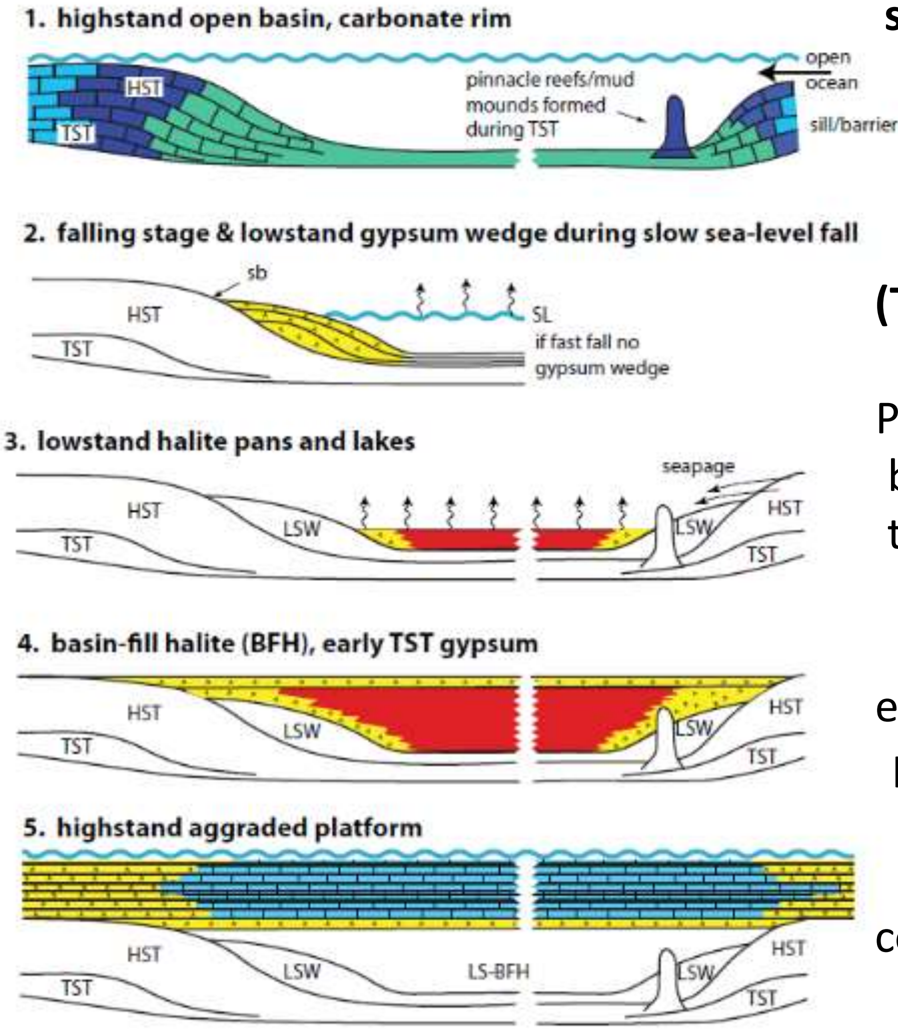
Correlation of well-logs may be hampered by evaporite dissolution and/or halite diapirism.

ZECHSTEIN CARBONATE – EVAPORITE CYCLES: Lithostrat for NE England



Zechstein cycles Z1 (Werra), Z2 (Stassfurt), Z3 (Leine), Z4 (Aller), Z5 (Ohre)

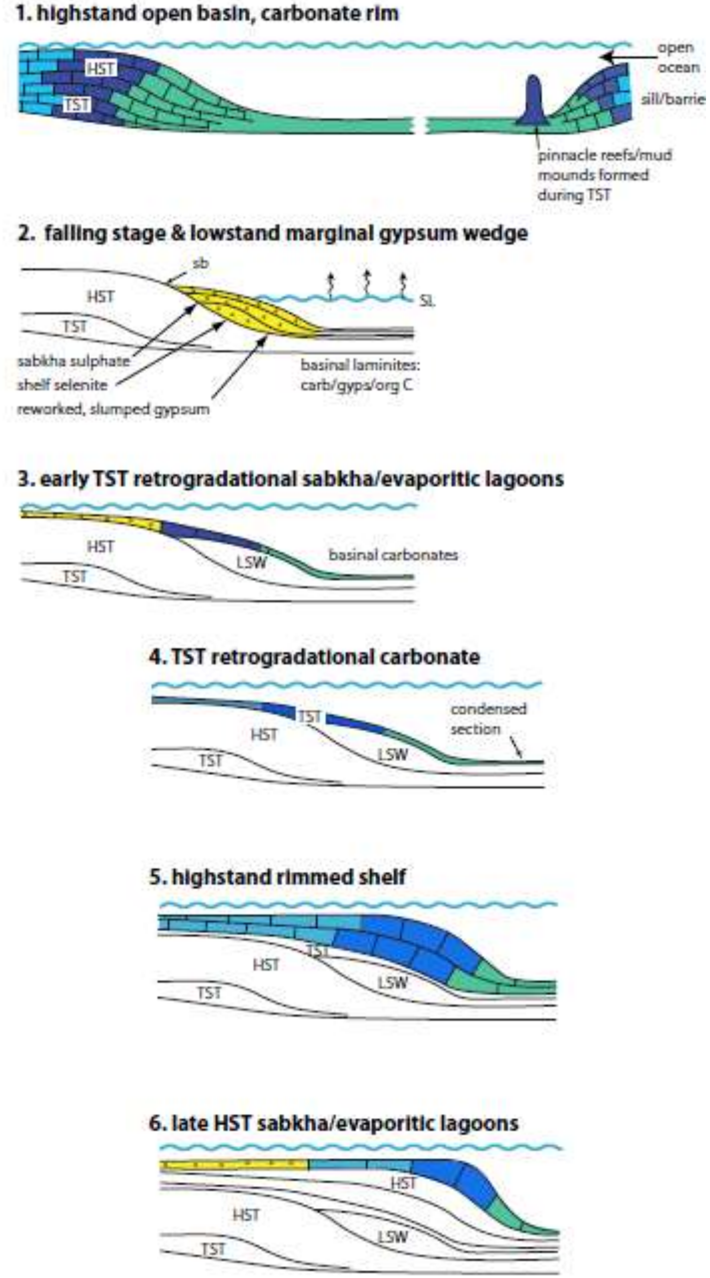
APPLICATION OF SEQUENCE STRATIGRAPHY



Sequence stratigraphic models for carbonate evaporite Basins (Tucker 1991)

Point to note: basin needs to be cut-off from open ocean for evaporites to precipitate.

2 models: complete and incomplete drawdown.



Evaporites also precipitated on platform during TST-HST.

SCHEME OF TUCKER (1991) FOR NE ENGLAND AND ADJACENT NORTH SEA

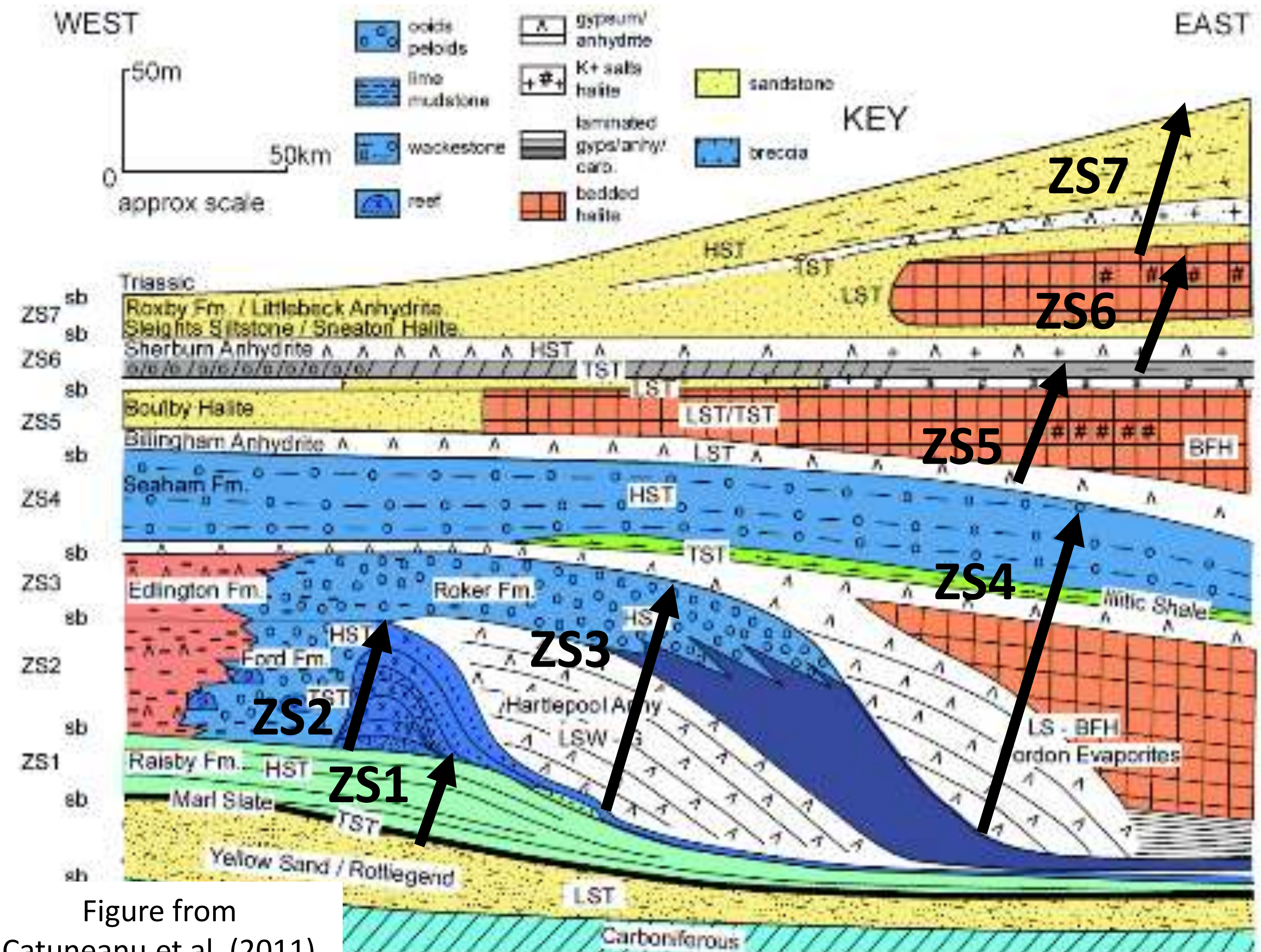


Figure from Catuneanu et al. (2011).

Premise: basin-centre evaporites are lowstand (LST); carbonates are TST-HST.

Note: 2 sequences in Z1 carbonates, ZS1, ZS2, then 2 evaporite-carbonate sequences ZS3, ZS4, and then 3 evaporite-clastic sequences ZS5, 6, 7.

Other schemes, e.g. Strohmenger '96, where SB in middle of evaporites, so they are TST-HST / LST.

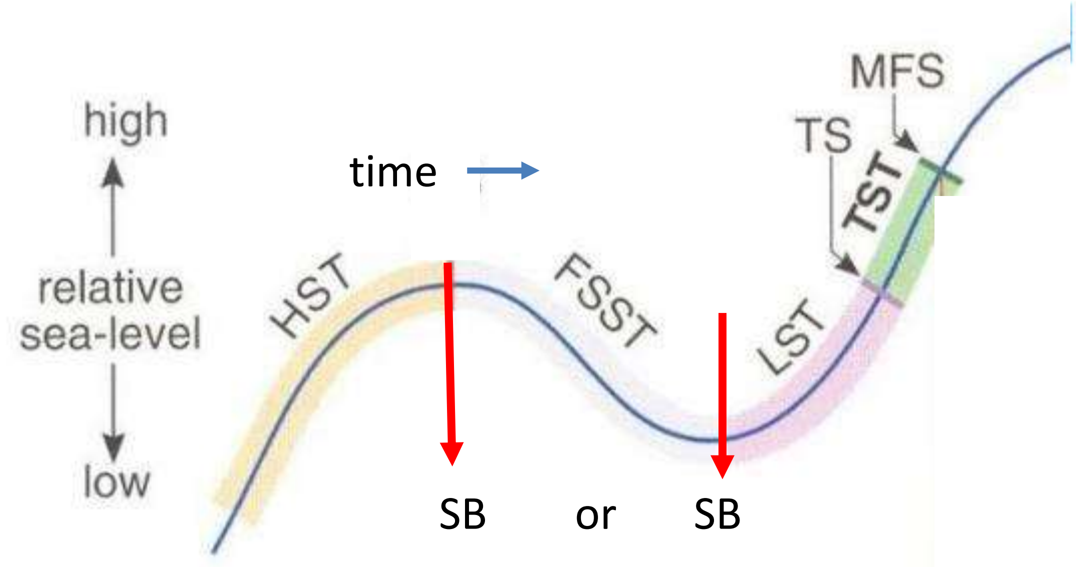
SEQUENCE STRATIGRAPHY TODAY:

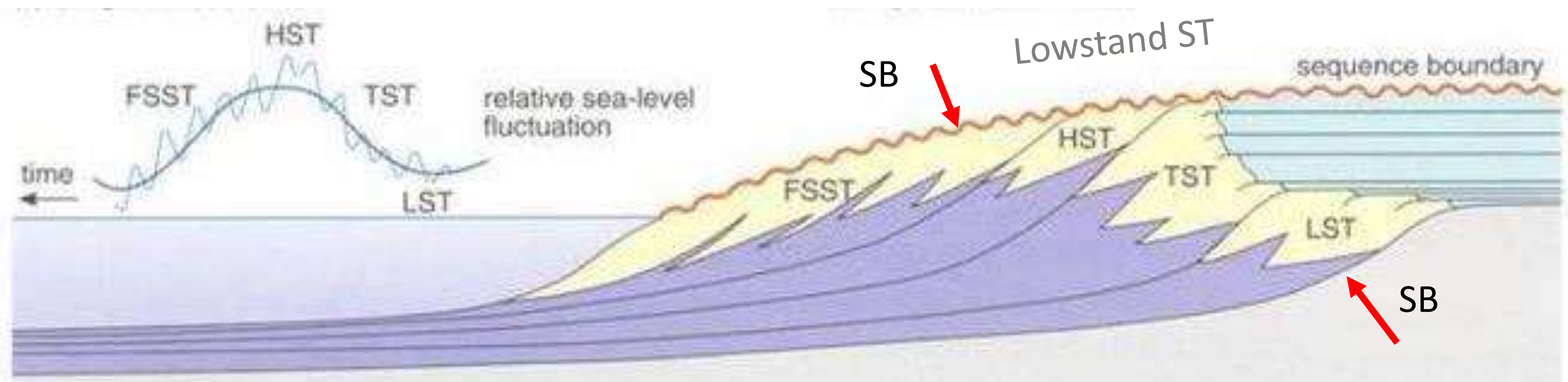
(see Catuneanu et al. 2011 for review)

4-systems tract model (rather than 3) now regularly applied in sequence stratigraphy: the FSST for sediments deposited during sea-level fall: FALLING STAGE SYSTEMS TRACT.

Not all systems tracts always developed in each sequence, or in all areas of the basin.

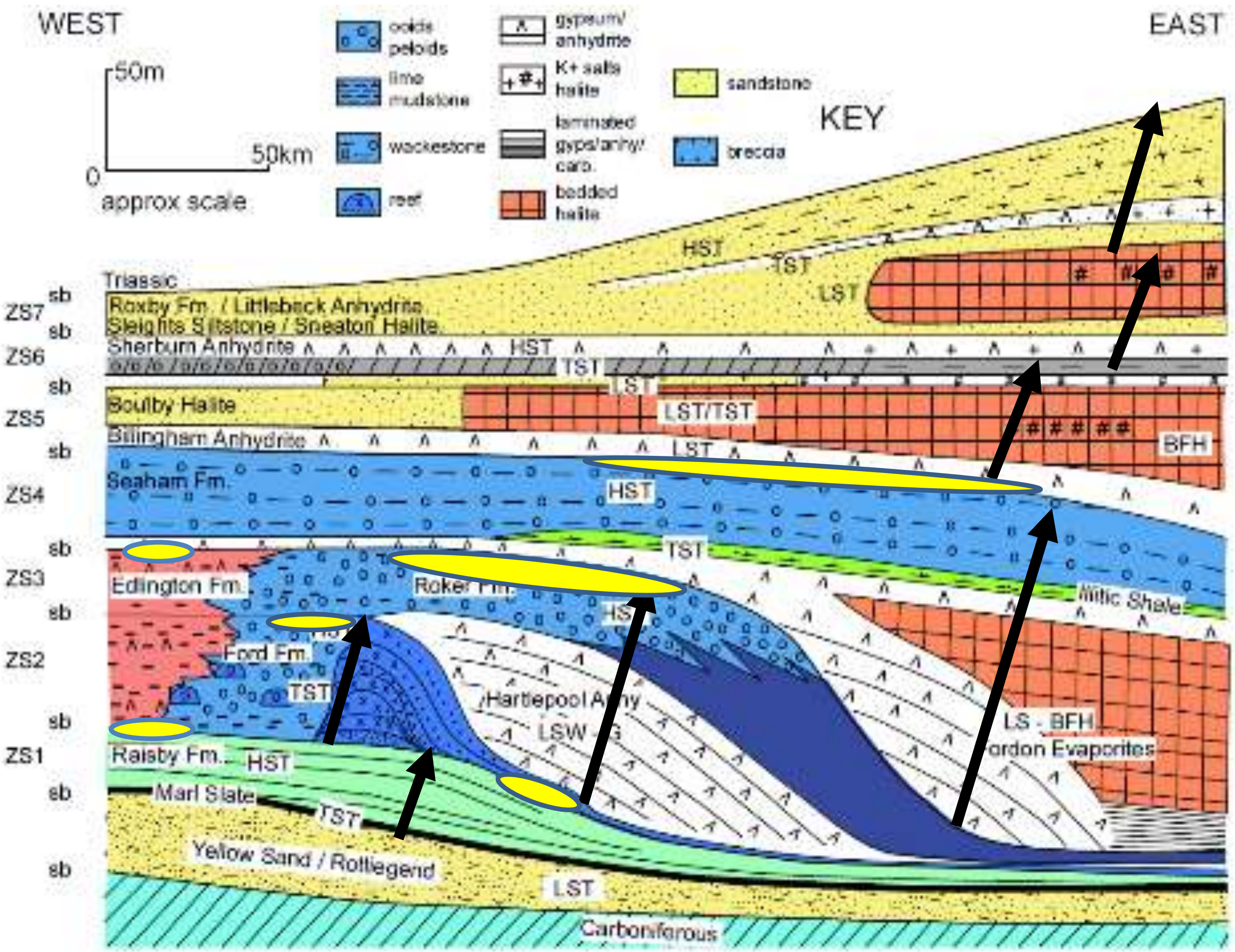
SB can be placed below or above FSST – wherever most appropriate.





4-systems tract sequence stratigraphic model showing higher-frequency cycles (parasequences) and sequence boundary above the FSST and below the LST. From Coe et al. (2003) based on Hunt & Tucker (1992).

EARLIER SCHEMES HAD 3 SYSTEMS TRACTS, NOW 4



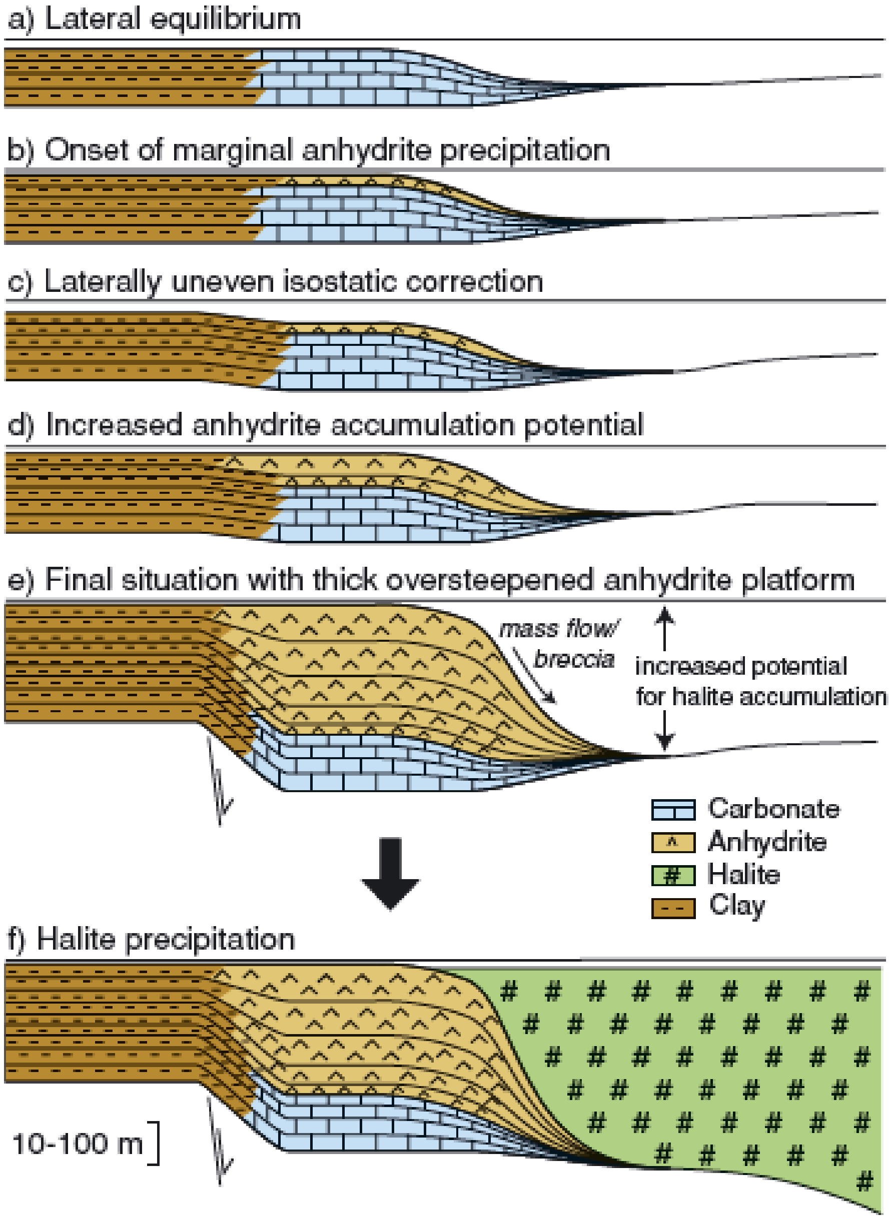
FSST FACIES CAN BE RECOGNISED AT TOP OF EACH CARBONATE PLATFORM: RAISBY (Ca1a), FORD (Ca1b) ROKER (Ca2) and SEAHAM (Ca3) in NE England and elsewhere in SPB.

= FSST

FSSTs ARE CARBONATES – SO LOGICAL TO PLACE SB ABOVE FSST

Sequence stratigraphy still useful !

BASIN-MARGIN AND BASIN-FILL EVAPORITES:



The role of evaporites in loading and increased subsidence

A shallow-basin model for 'saline giants' based on isostasy-driven subsidence.

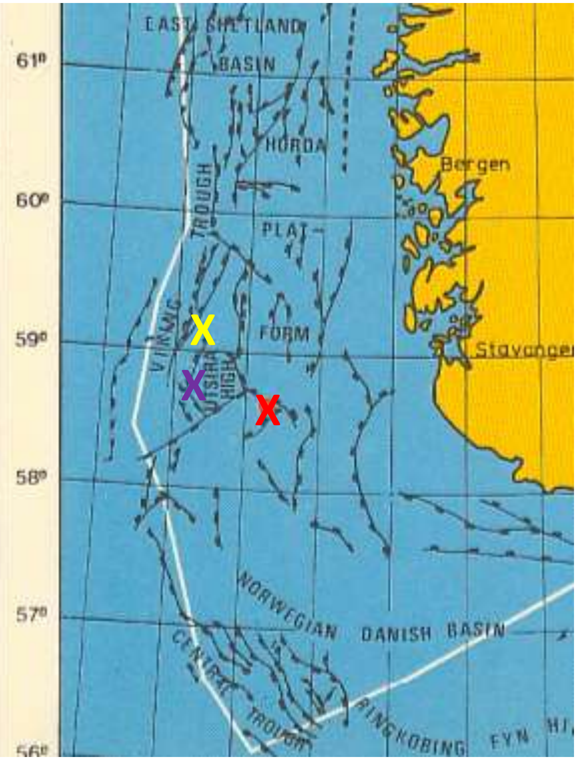
Papers by van den Belt & de Boer (2007, 2014).

Zechstein strata consists of:

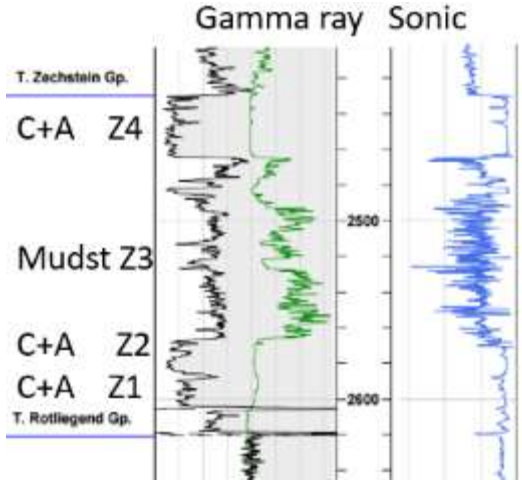
thick basin-margin carbonates,
thick basin-margin gypsum wedge or isolated platform, and
thick basin-fill salt, with
extremely thin basin-floor carbonate or gypsum.

However, salt dissolution-diapirism and anhydrite dissolution can complicate matters; plus synsedimentary tectonics.

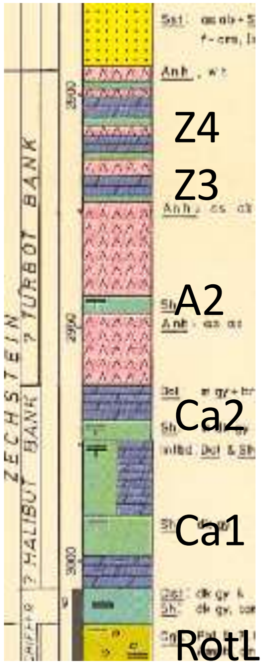
GREAT THICKNESS AND FACIES VARIATIONS: E.G. NORWEGIAN SECTOR.

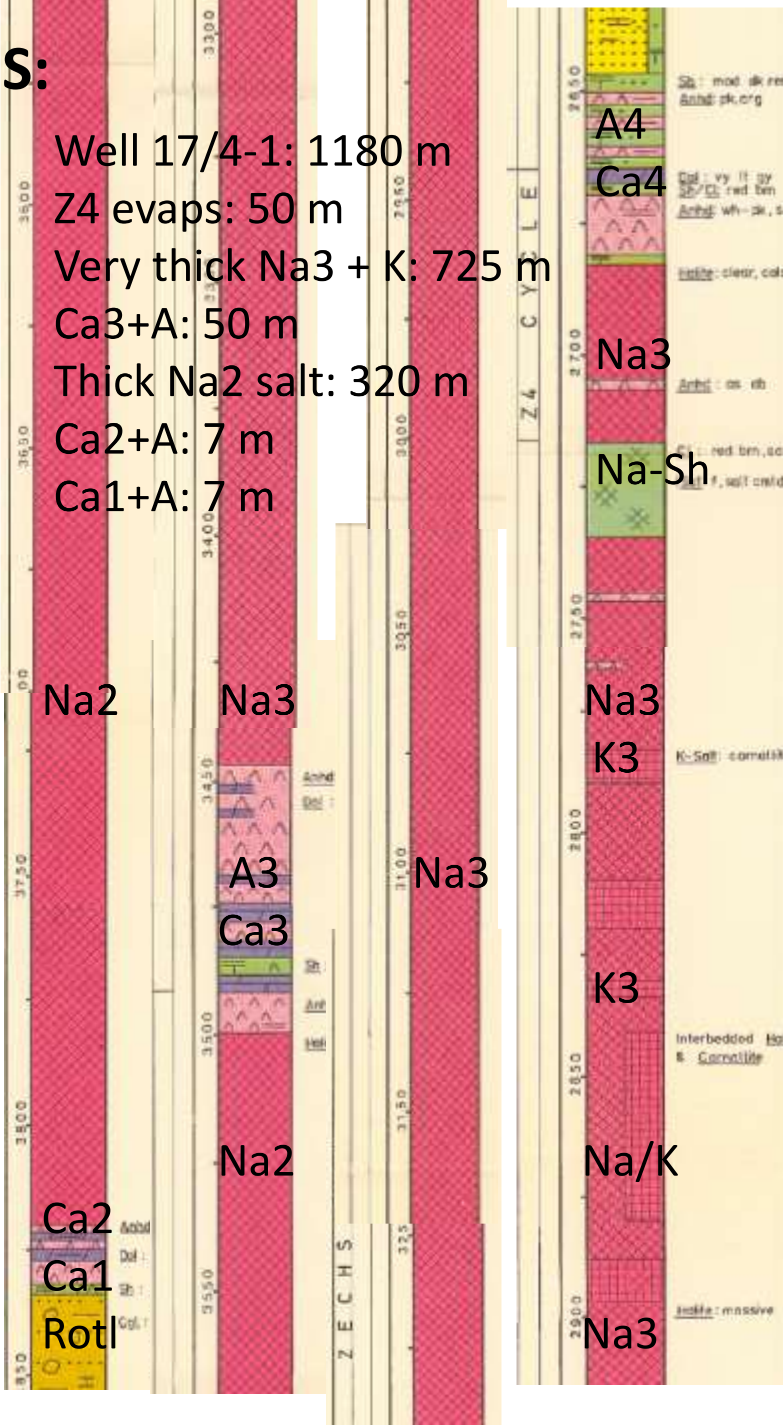


Well 16/4-1



25/10-2R





X 17/4-1 Ling Graben – 1180 m

X 25/10-2 Utsira High – 110 m

X 16/4-1 margin Utsira High – 190 m.

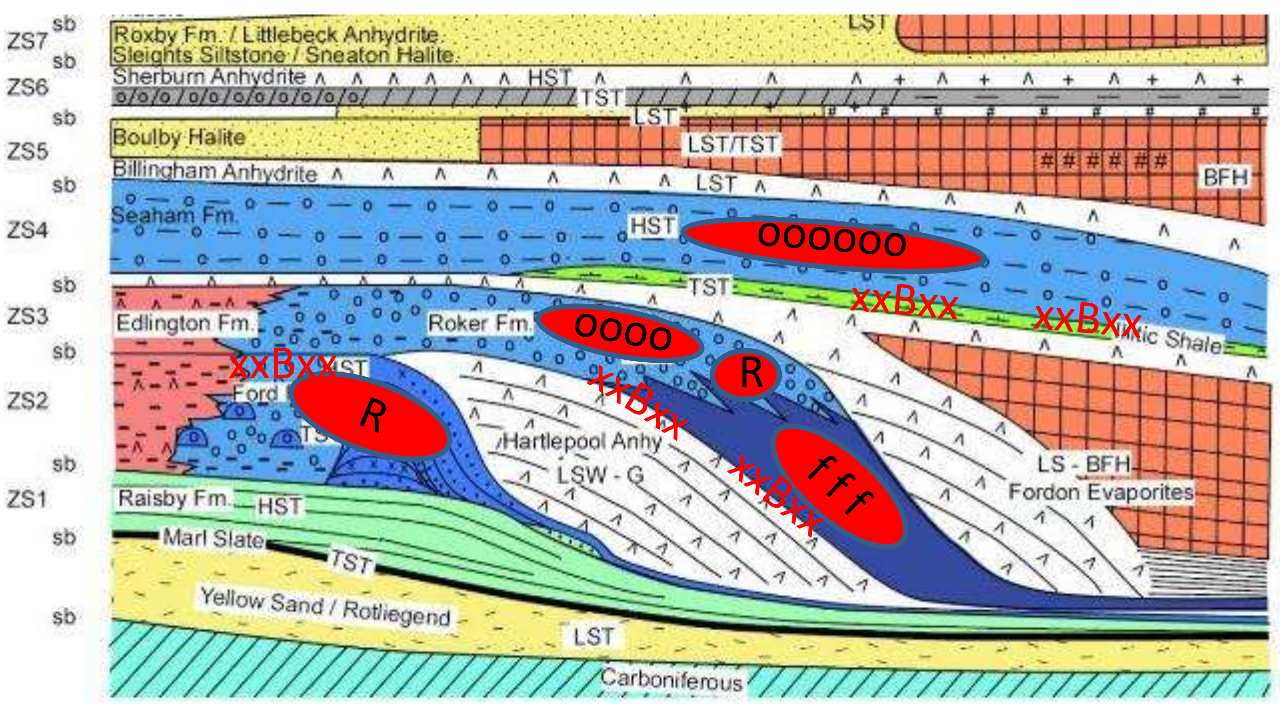
Logs and data from NPD.

Topographic-tectonic control + possible salt dissolution-diapirism.

ZECHSTEIN RESERVOIRS

Different types: oolites (oooo), reefal-buildups (R), slope facies (+ fractures, fffff), and breccias (xxBxx).

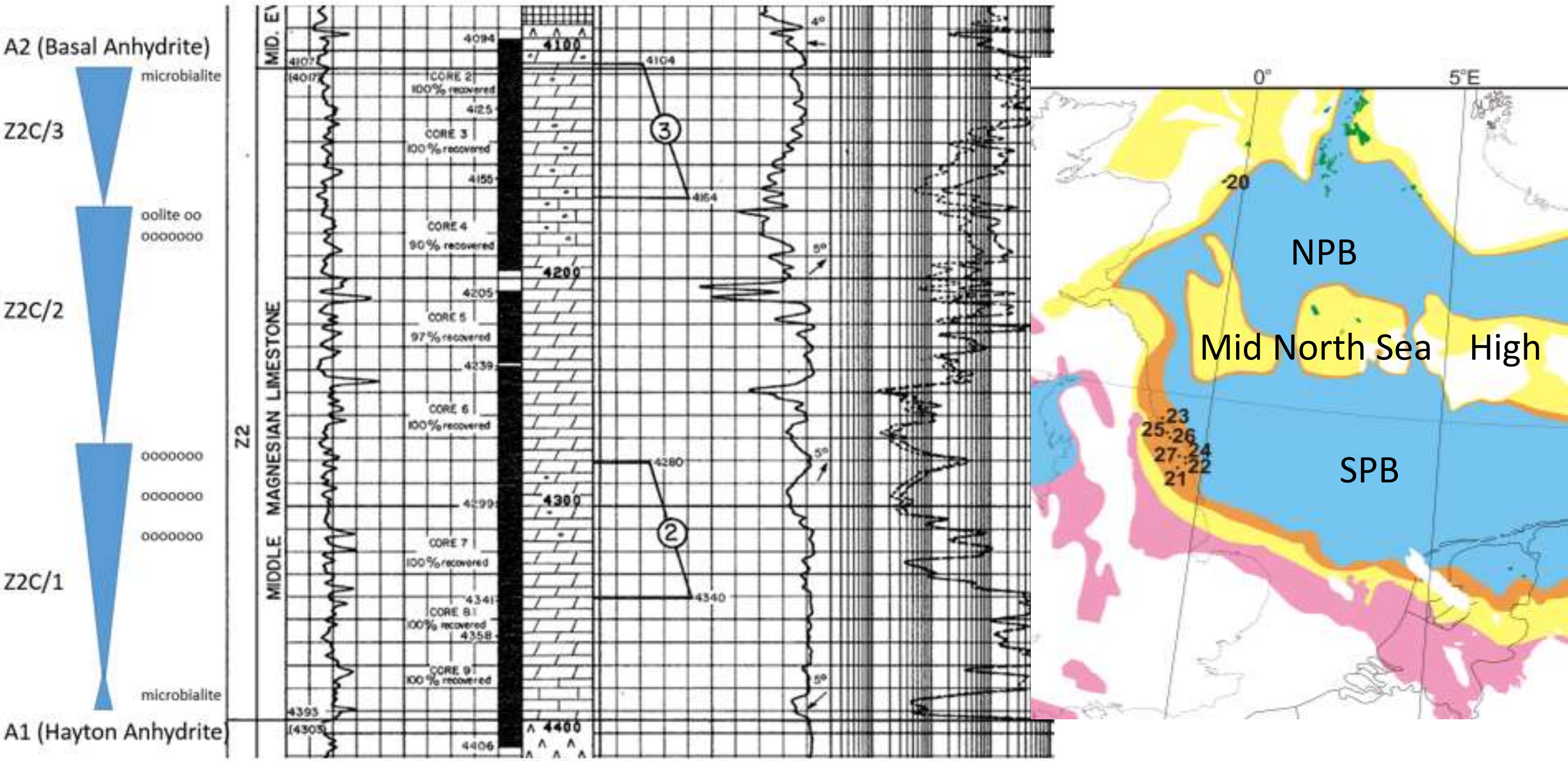
OOLITES: Ca2 especially, also Ca3; **REEFAL-BUILDUPS**: Ca1, Ca2; **SLOPE FACIES**: Ca2



BRECCIAS – different types: evaporite dissolution-karst collapse; limestone karst; reefal debris; resedimented slope facies; tectonic; hydrofractured-hypogene.

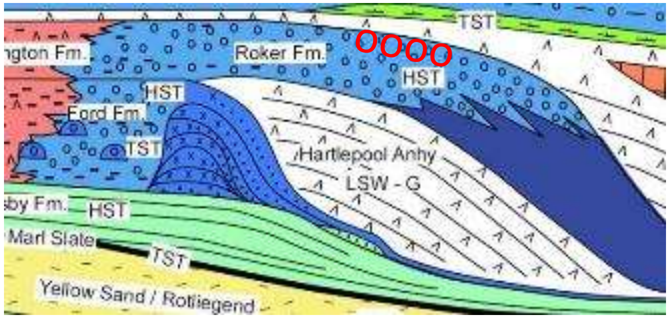
OOLITE RESERVOIRS: NE YORKSHIRE, THE NETHERLANDS, GERMANY, POLAND
PLATFORM-MARGIN GRAINSTONES

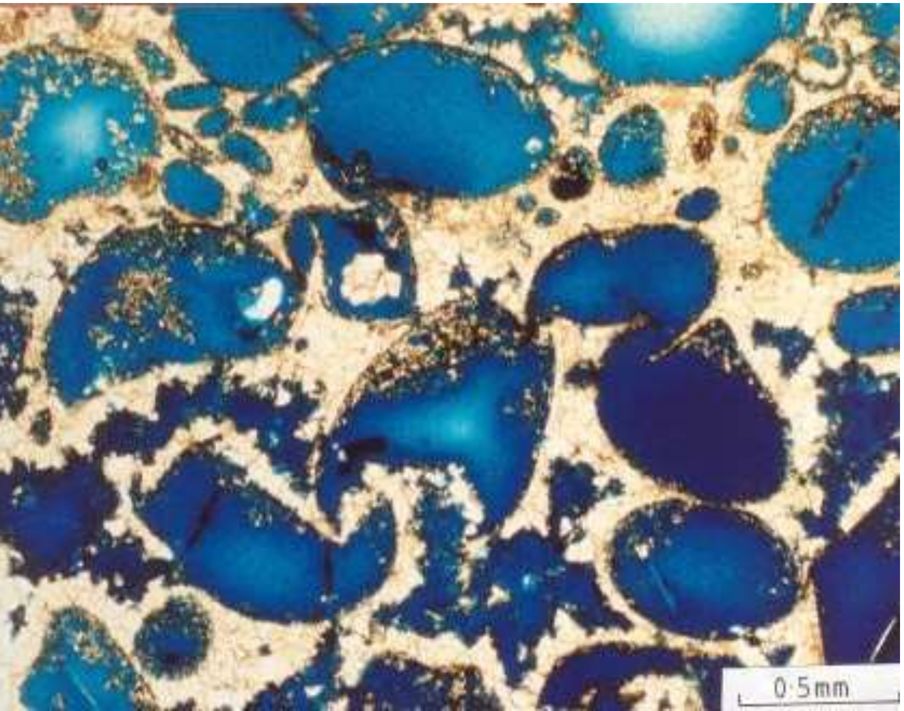
NE ENGLAND SUBSURFACE – MALTON-4 well, North Yorkshire



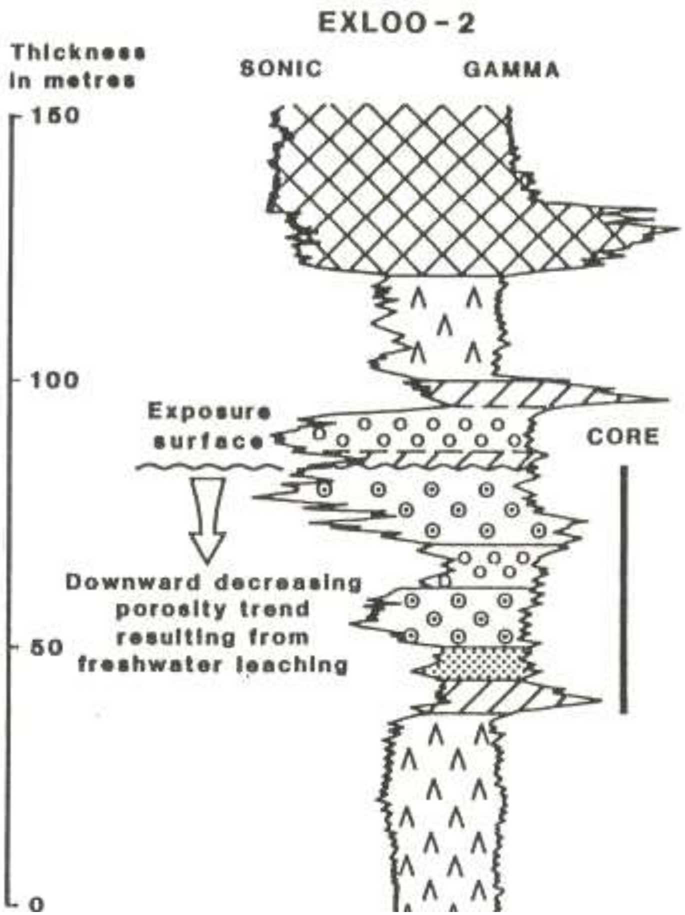
Well log of Malton-4 (21 on map) showing location of oolite units, towards top of likely high-frequency cycles. Parasequences in Ca2 can be recognised quite widely across SPB. Gas reservoir.

OOID SHOAL FACIES WITH OOMOLDIC POROSITY. MALTON-4 (4190', 4183')



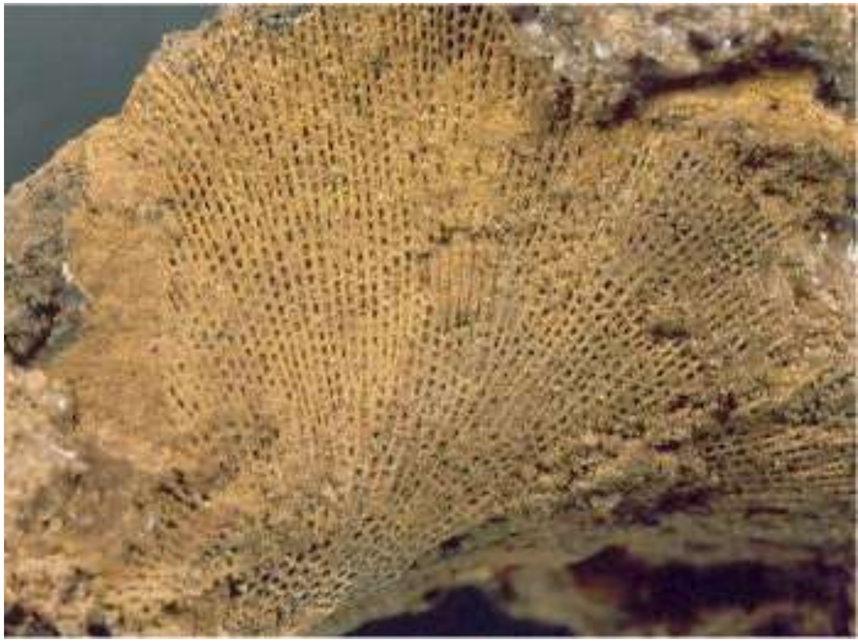


$\delta^{13}C$ 6.3 ‰,
$\delta^{18}O$ -2.2 ‰.



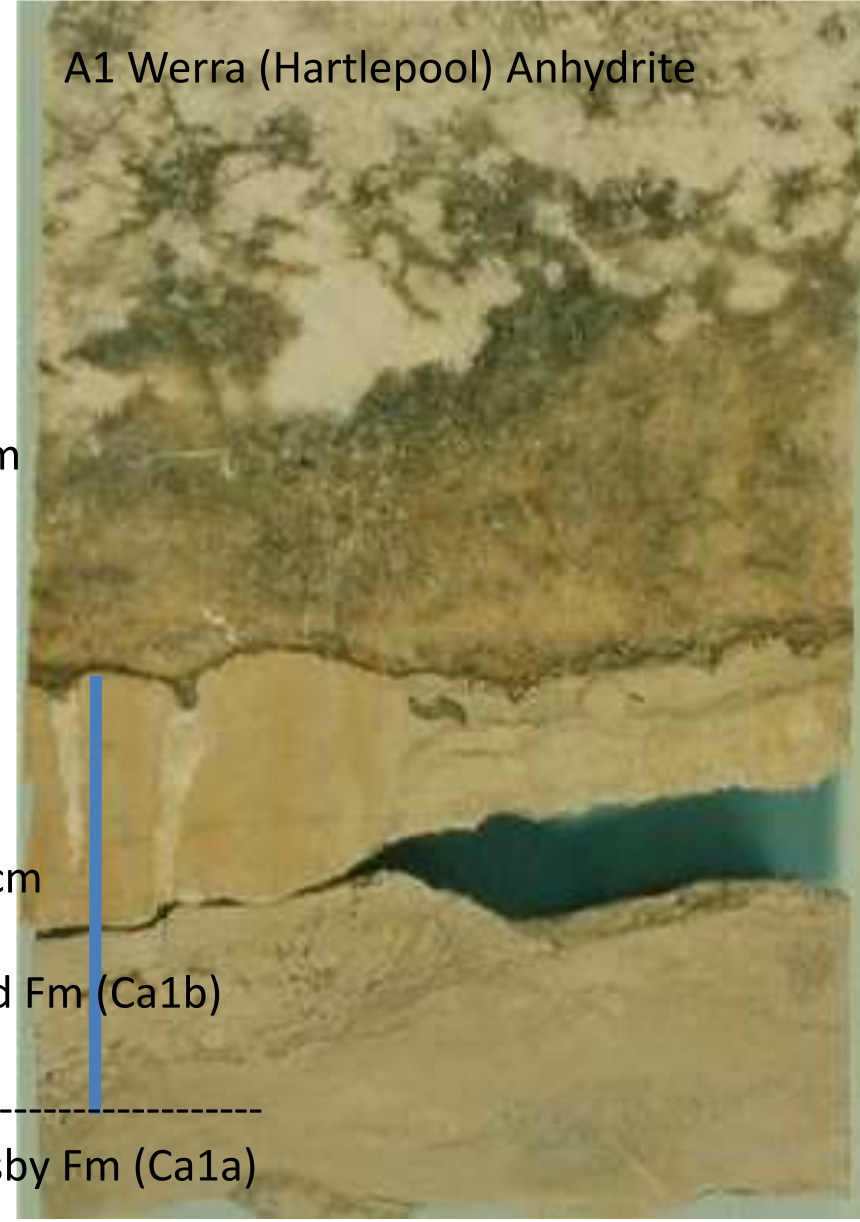
Leaching profiles revealed in sonic logs from the Z2 carbonate (well Exloo-2), the Netherlands. Clark, 1987.

REEFAL-BUILDUP RESERVOIRS



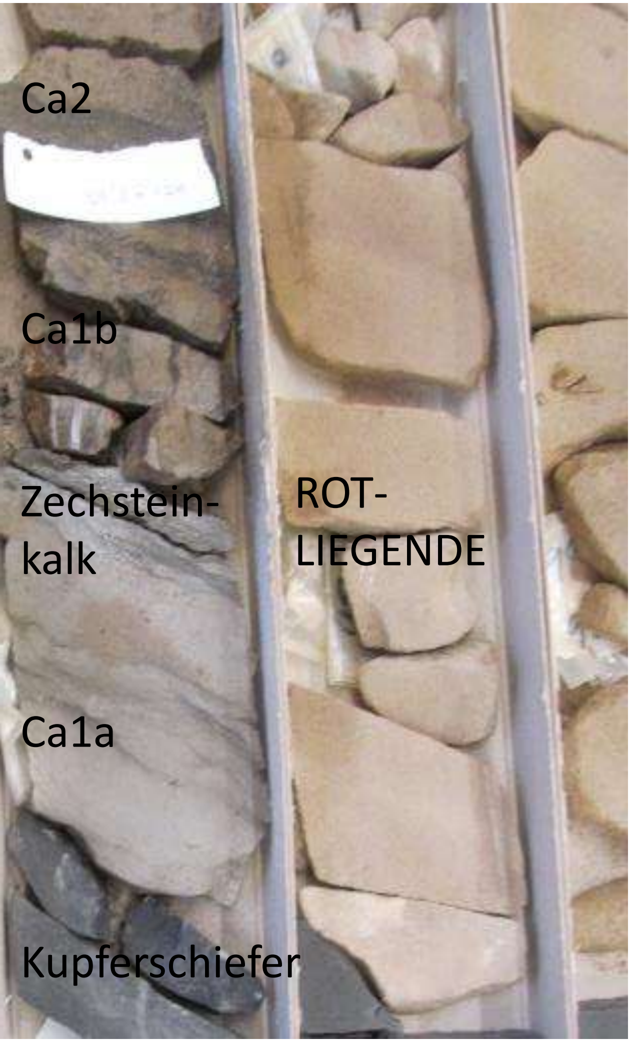
Ford Formation, reef, back-reef, fore-reef facies.
Bryozoan-microbial reefs with other biota. Much marine cement.

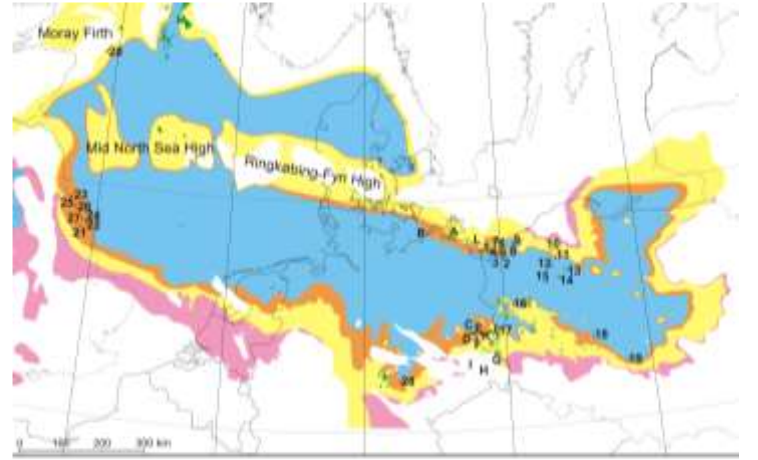
BASINAL REEF EQUIVALENT



Reefal basin facies (Ca1b): The Trow Point Bed: a 10-50 cm bed of microbial laminites and oncoids = 100 metres of reef, which can be traced from NE England to Poland. Zechstein basin floor starved of sediment.

CONTINUITY OF ZECHSTEIN STRATA:

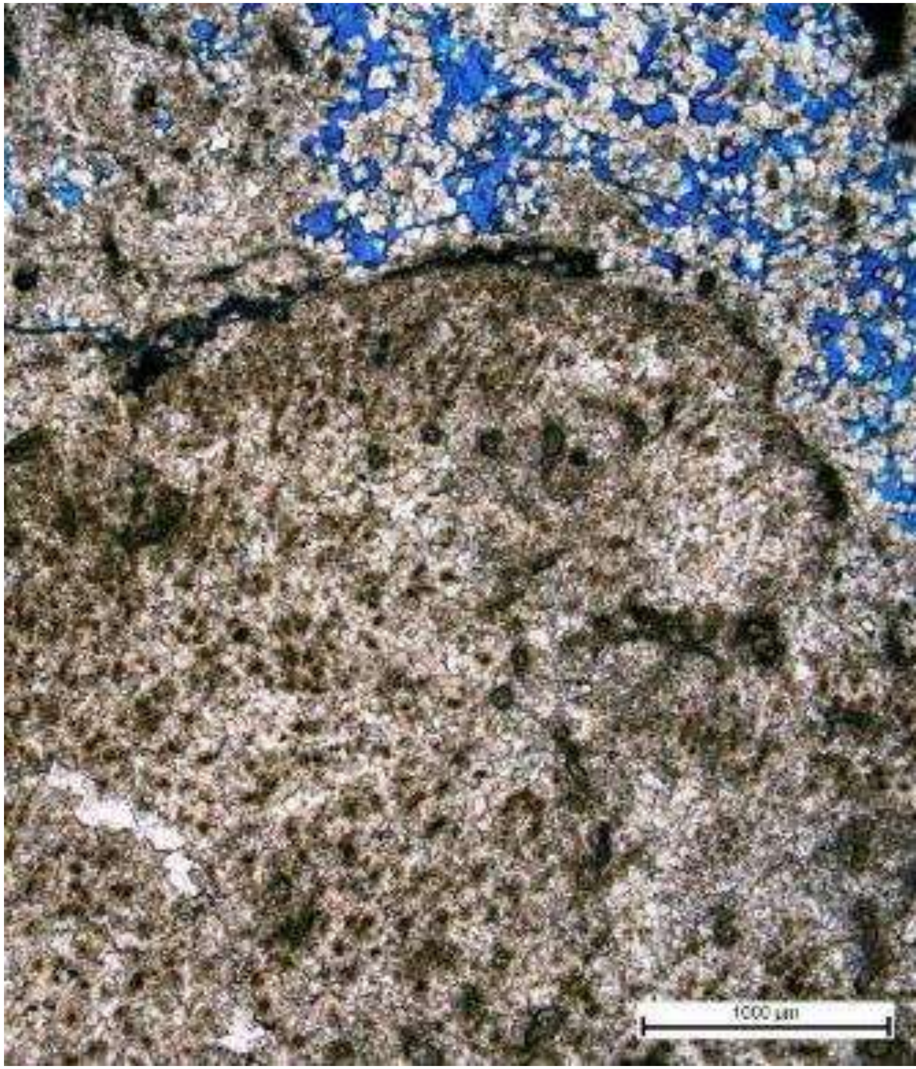




Argyll 30/24-26: columnar microbialites, equivalent to Trow Point Bed of NE England at top of Ca1 (Zechsteinkalk), which here is 25 cm thick. Thumb-nail for scale. Remarkable continuity of 10 cm thick bed over 1000 km of basin floor, = 100 m reef.

POROSITY: INTERCRYSTALLINE FROM REFLUX DOLOMITISATION
by seawater / evaporated seawater

|---- 1 cm ----|

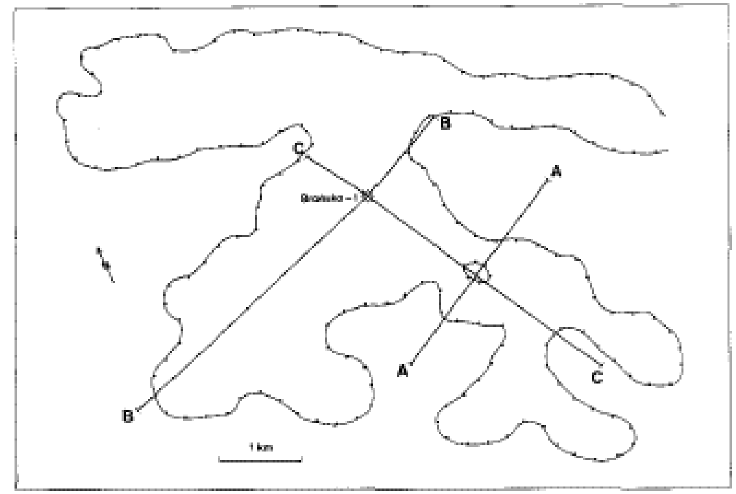


Ford Fm (Ca1b) reef-core facies – mottled vuggy dolomite with suggestion of former colonial organisms in thin-section. $\delta^{13}C$ 6.3 ‰, $\delta^{18}O$ -1.2 *‰.*

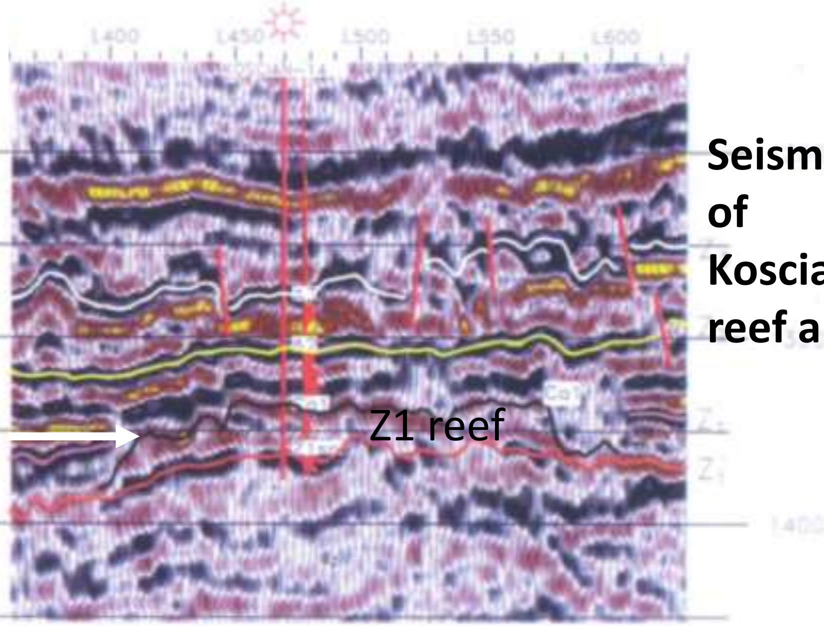
REEFAL RESERVOIRS

(Dyjaczynski, Peryt et al. 2001)

Wolsztyn Ridge
central Polish Basin
Ca1b reef sitting directly on Carboniferous ridge



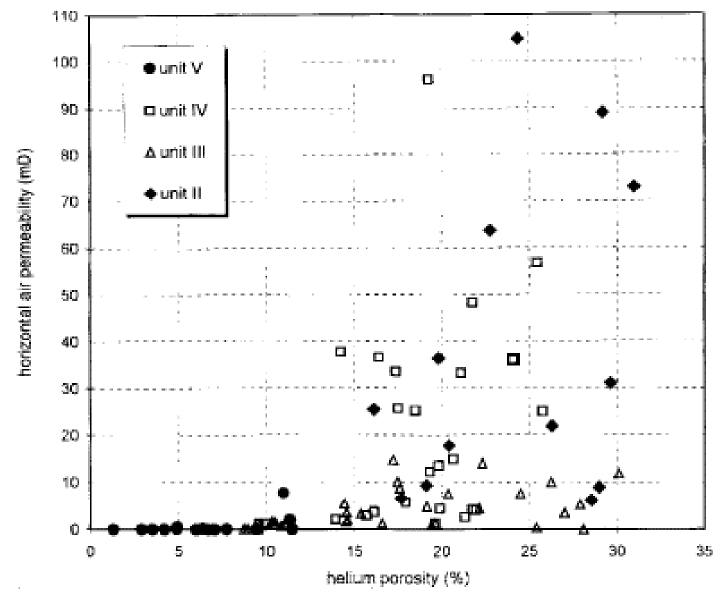
Outline of Bronsko reef complex



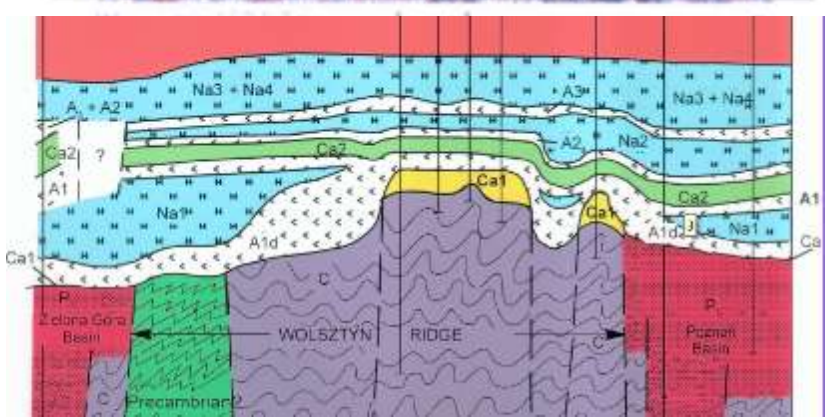
Z1 reef

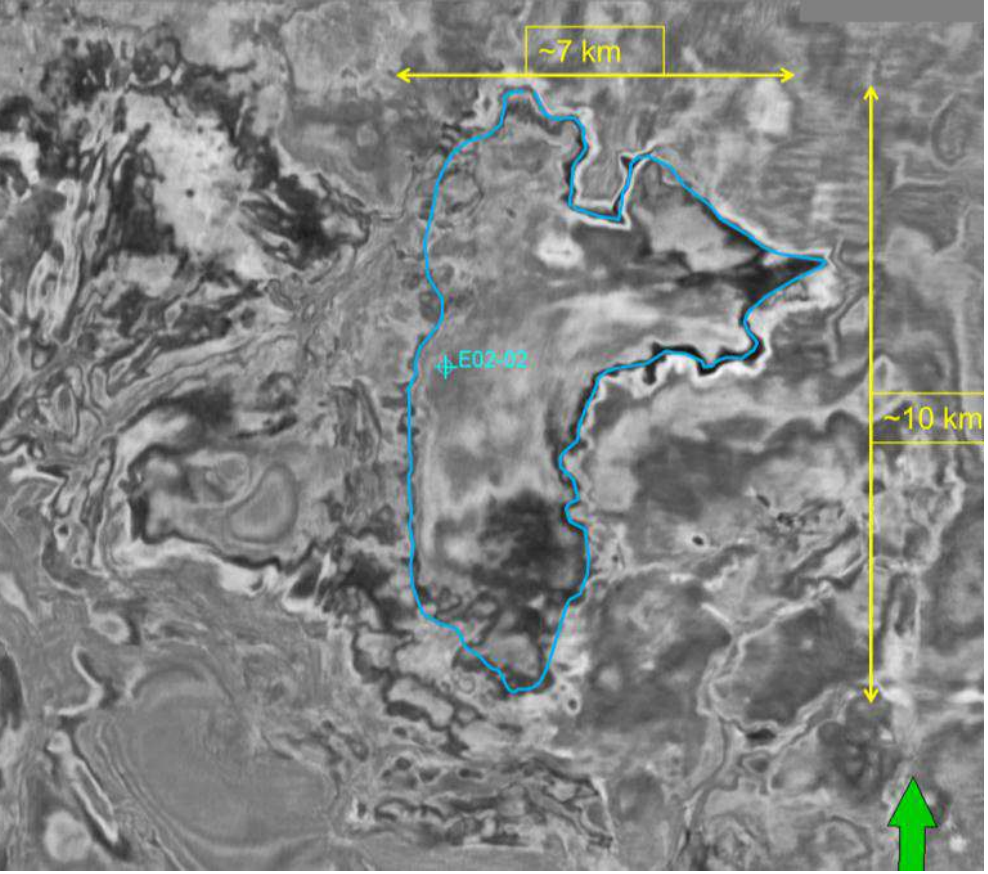
Z1 reef

Seismic of Koscian reef area

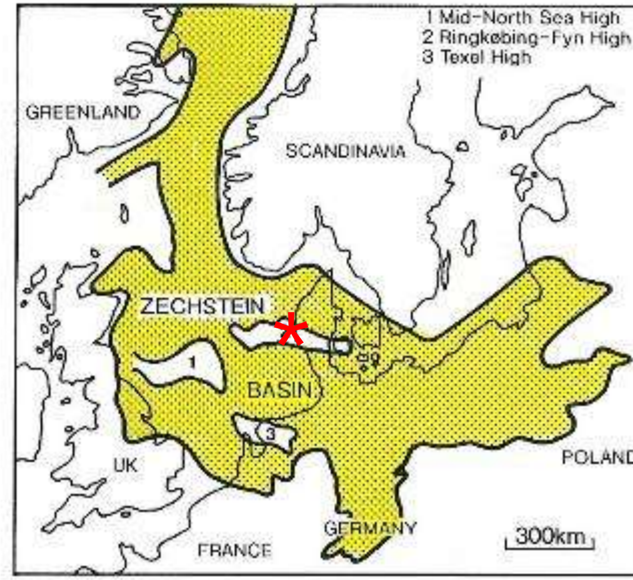


Best poroperm in reef-core facies



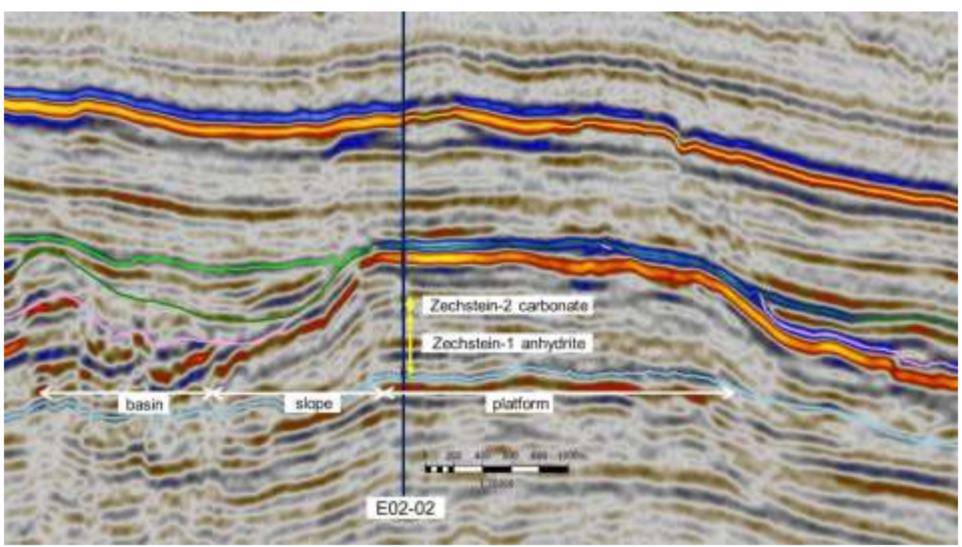


REEFAL RESERVOIRS



RECENT DISCOVERIES NORTH SEA

Time-slice map flattened on base Zechstein showing the outline of a Z2C isolated carbonate platform on the southern side of the Mid-North Sea High (Jaarsma et al. 2014).



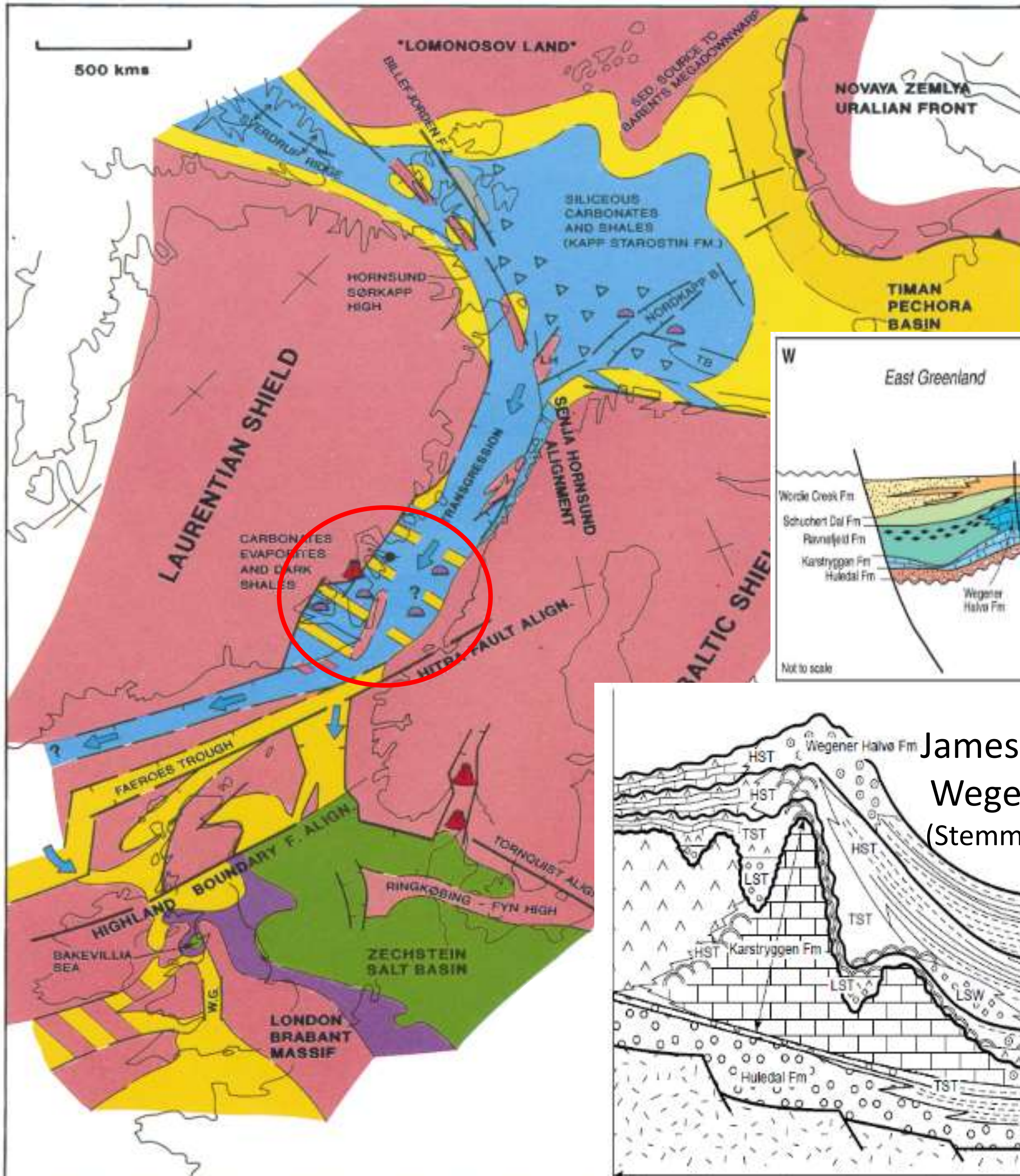
East-West seismic cross-section through well E02-02 near the margin of the platform. Isolated buildups controlled by pre-existing Carboniferous topographic highs.

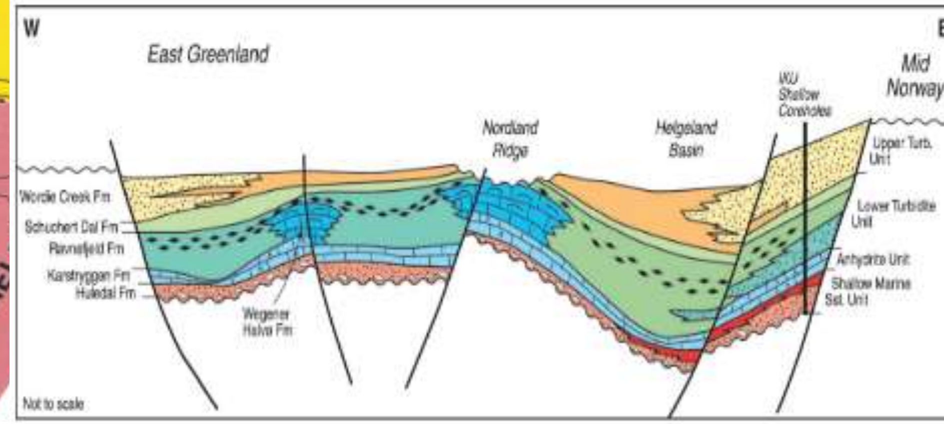
TARGET:

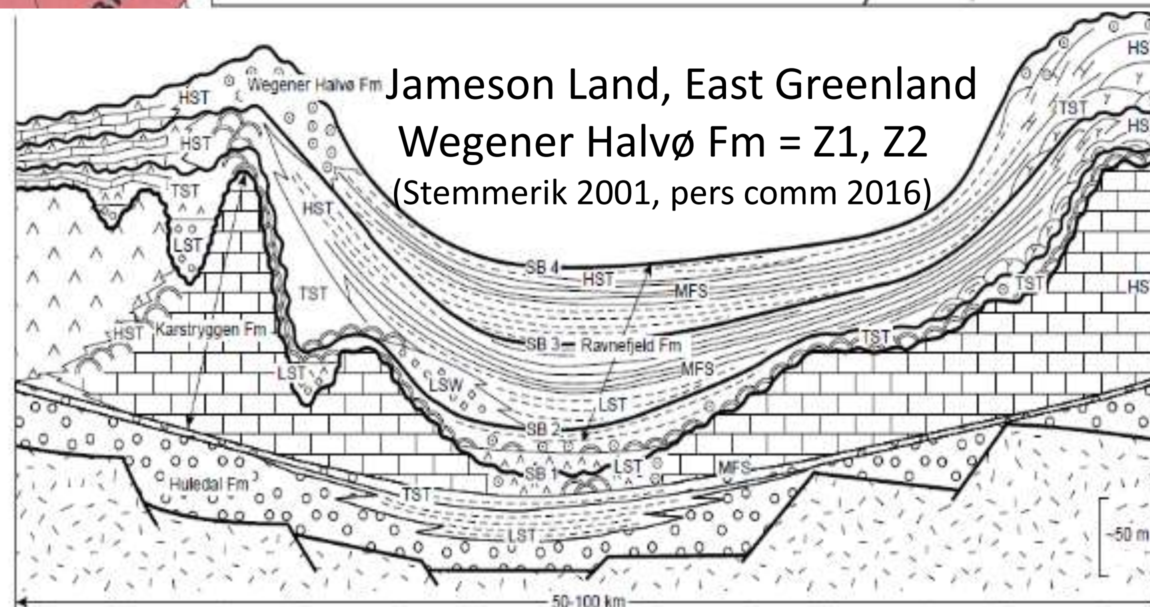
Buildups and oolite bodies at platform margin.

AND FARTHER NORTH… MORE BUILDUPS:

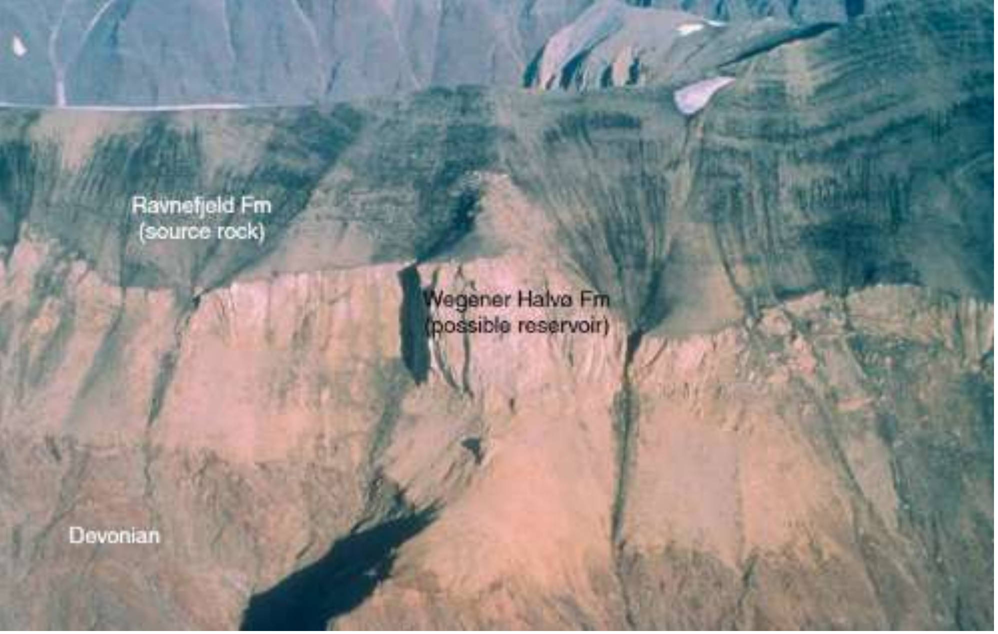
NW Europe-Greenland in the Kazanian (255 Ma) from Dore (1992) and Bugge et al (2002).

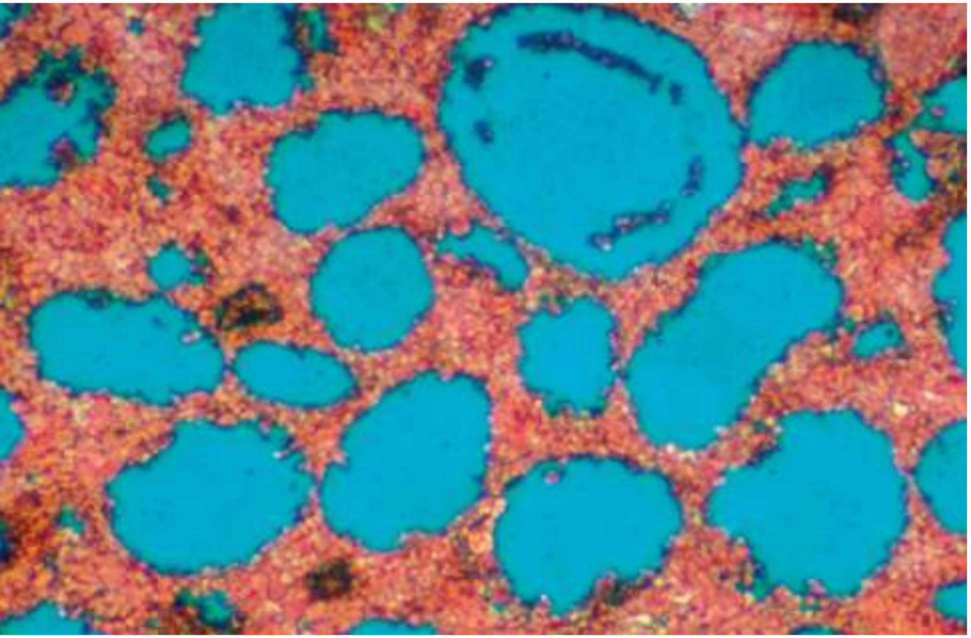


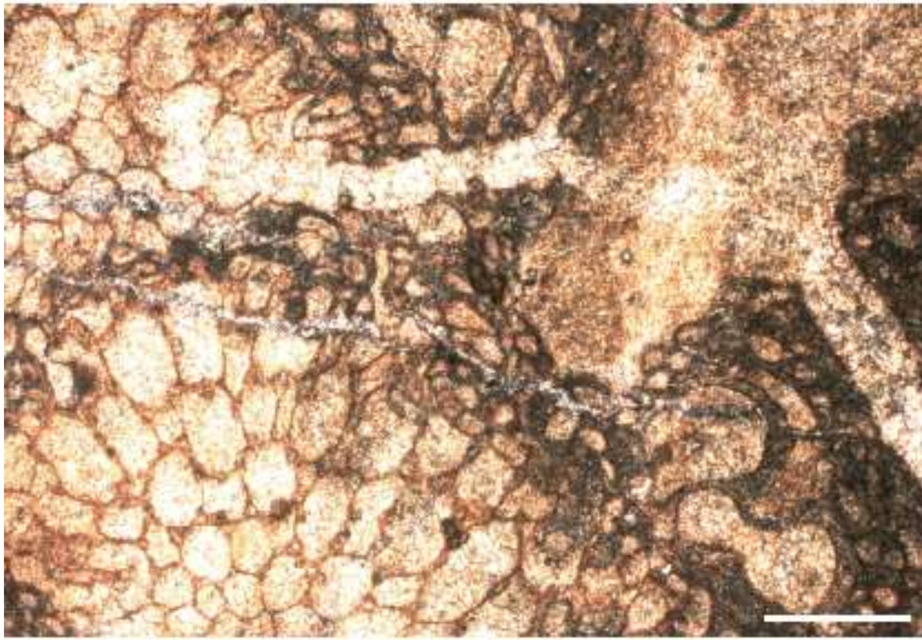




Jameson Land, East Greenland
Wegener Halvø Fm = Z1, Z2
(Stemmerik 2001, pers comm 2016)

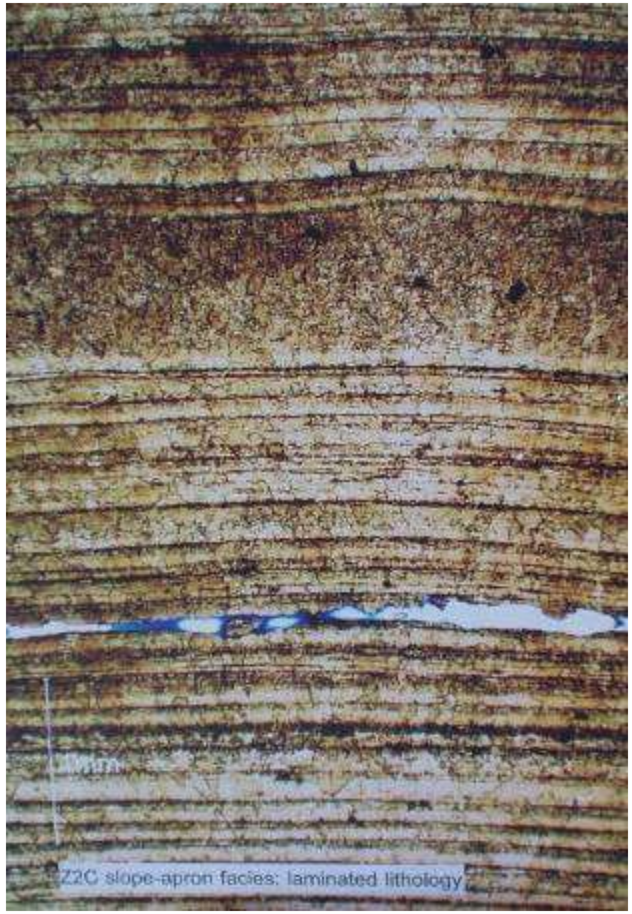






Wegener Halvø Fm: buildups and flank facies with bryozoans, microbes, bivalves, flank facies. Buildups exposed and karstified. Also oolites. Close to basinal source rocks. Scholle et al.

SLOPE FACIES RESERVOIRS: cores from offshore NE England and Polish sub-basin

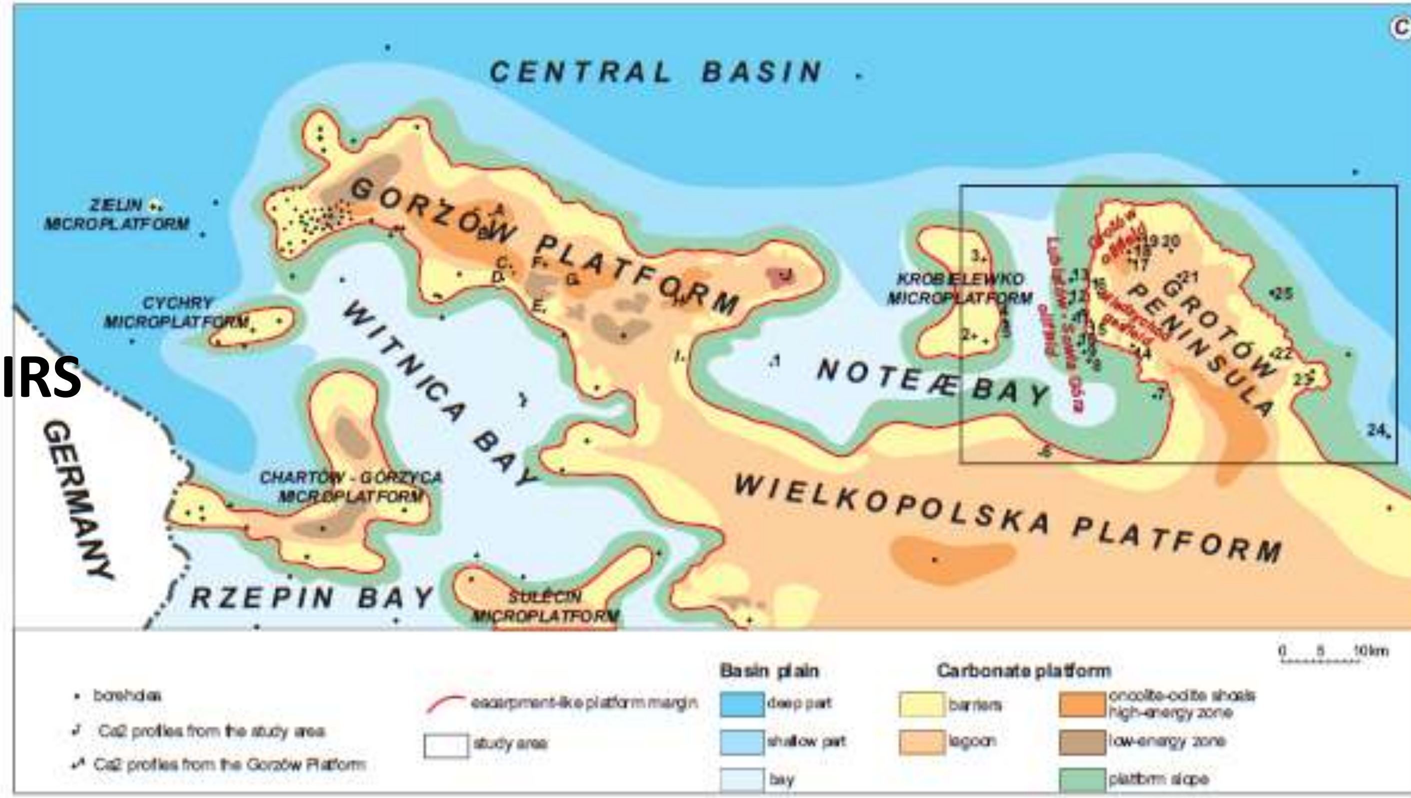


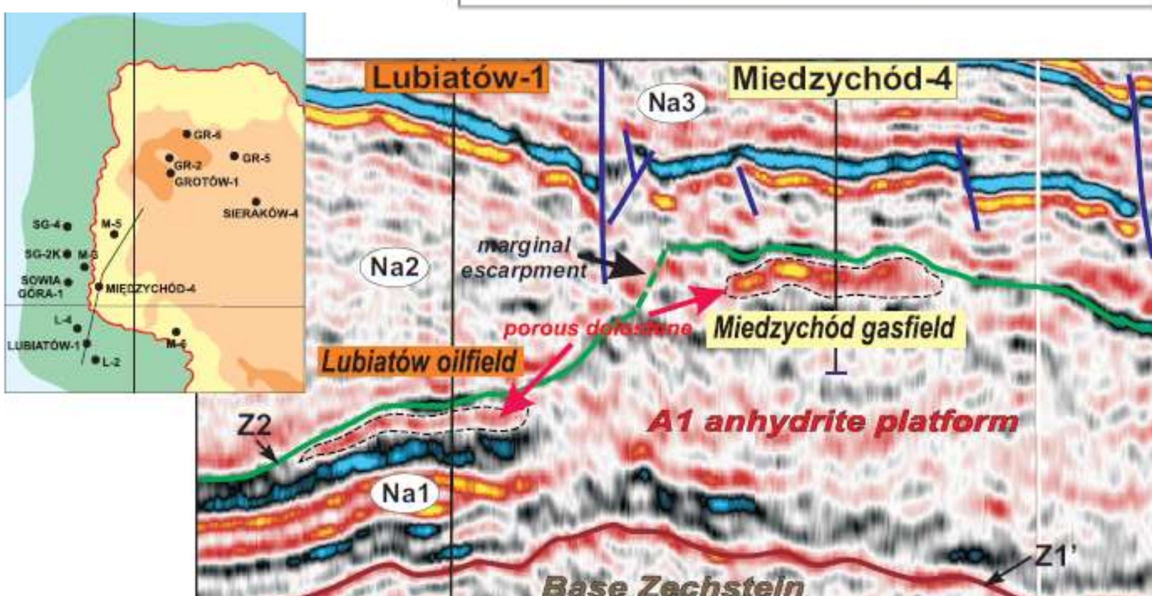
Laminites, turbidites, slumps, bioturbated lime mudstones
Reservoir controls: porous zones in coarse resedimented units, plus microporosity and fracturing of tight facies,
BUT loss of porosity through dedolomitisation.
Slope facies are also the source rock.

SLOPE FACIES IN THE FIELD

Upper slope facies: slumps, channels, debrites
Lower slope facies: turbidites, laminites.

SLOPE RESERVOIRS
Poland Sub-basin

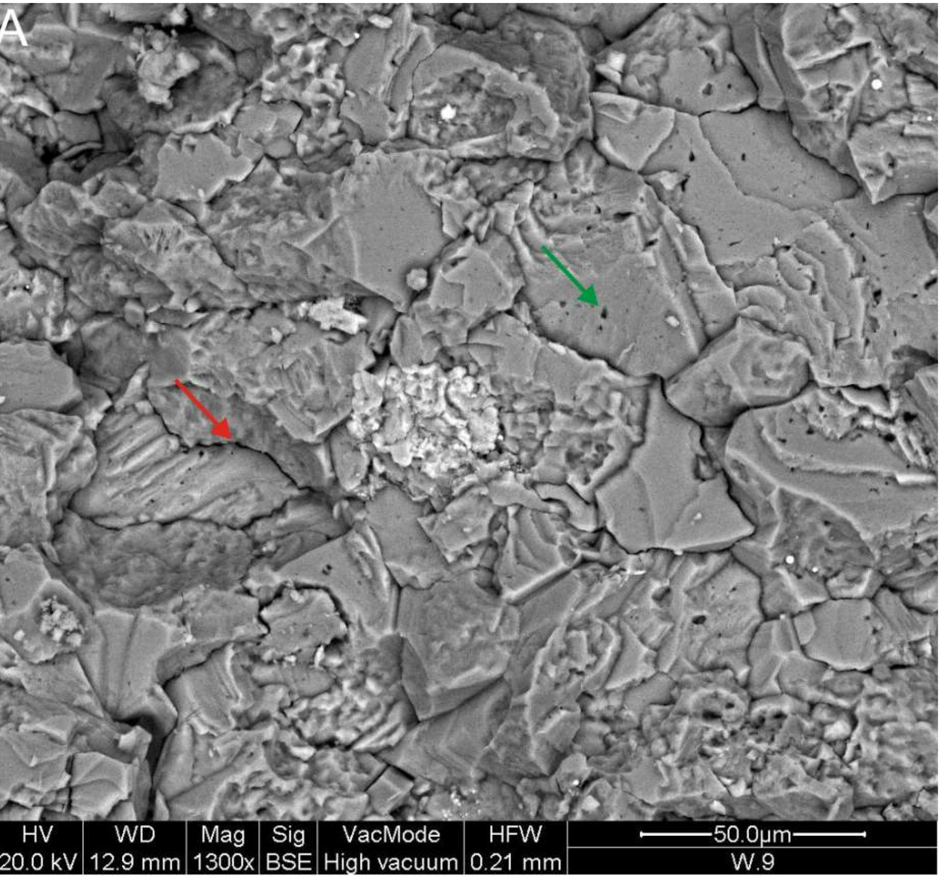


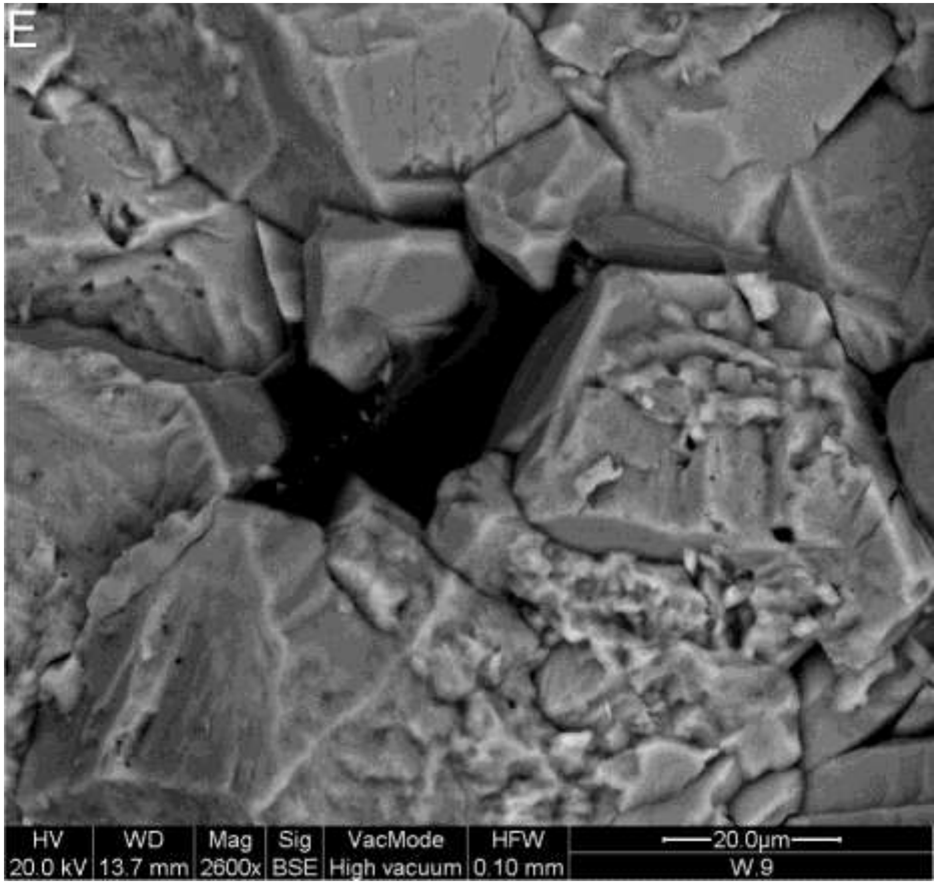


Main Dolomite of Grotow (Slovakiewicz & Mikolajewski 2009).

Reservoirs in shelf oolite and slope breccias and turbidites.

MICRO- NANO- POROSITY IN SLOPE FACIES:





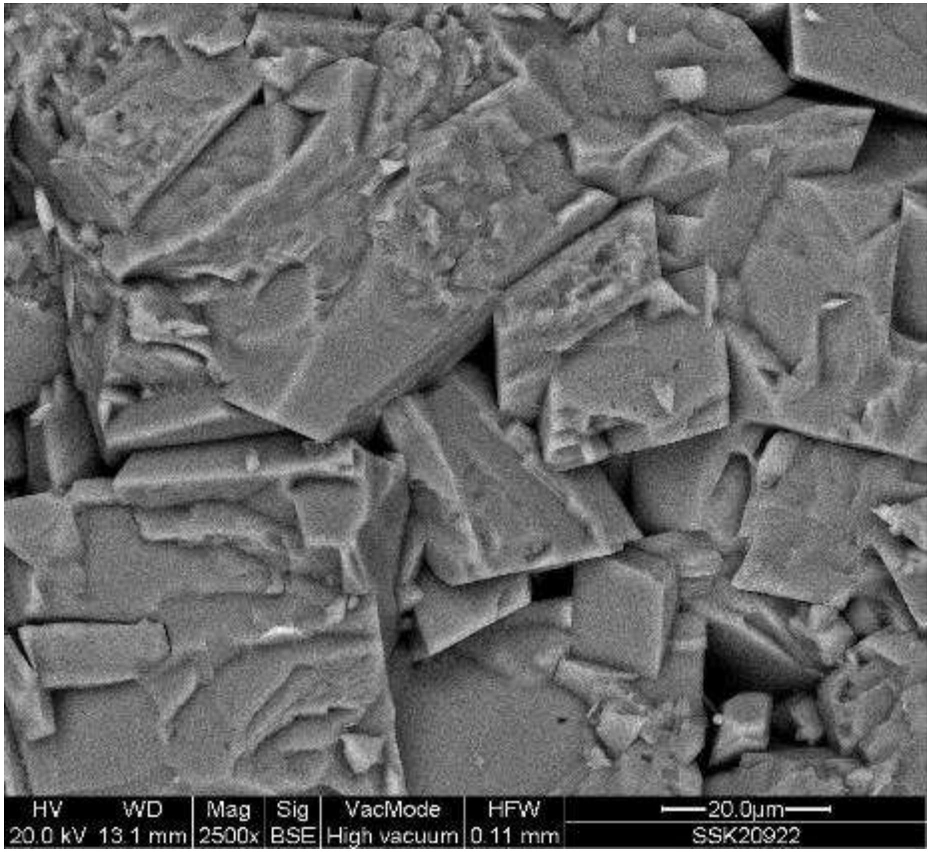
Inter-crystal/particle pores in calcite-dominated facies.

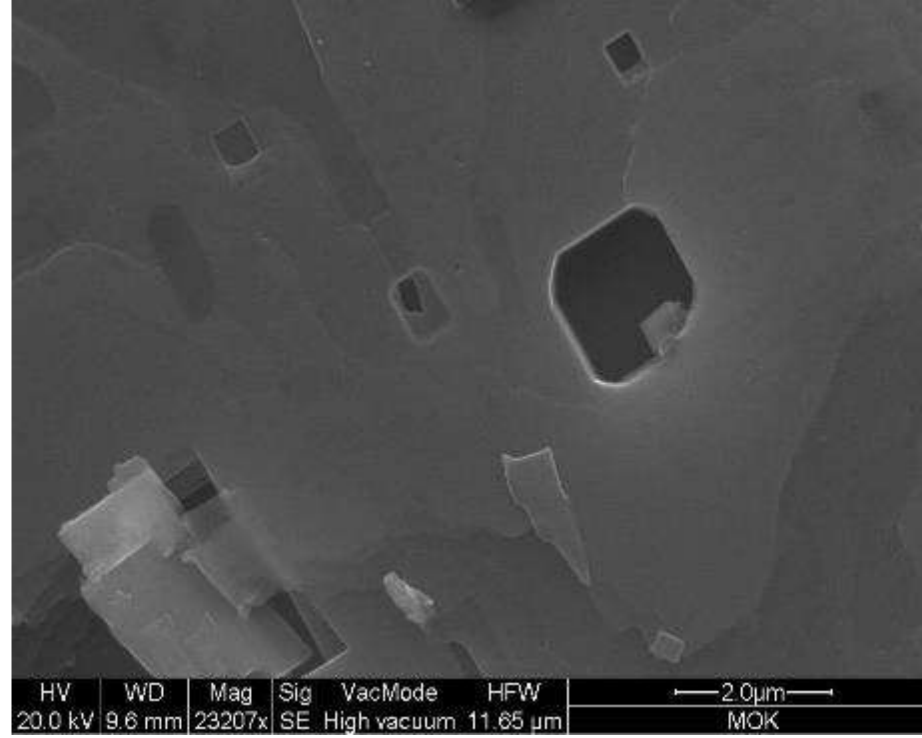
A) Irregular, embayed to curved crystal boundaries (red arrow) common pores. Note also intra-crystal pores (green arrow);

E) Bitumen (dark area in the centre) hosted in a large inter-crystal pore.

Slowakiewicz, Perri & Tucker (Jour Petroleum Geology, 2016)

MICRO- NANO- POROSITY IN SLOPE FACIES:

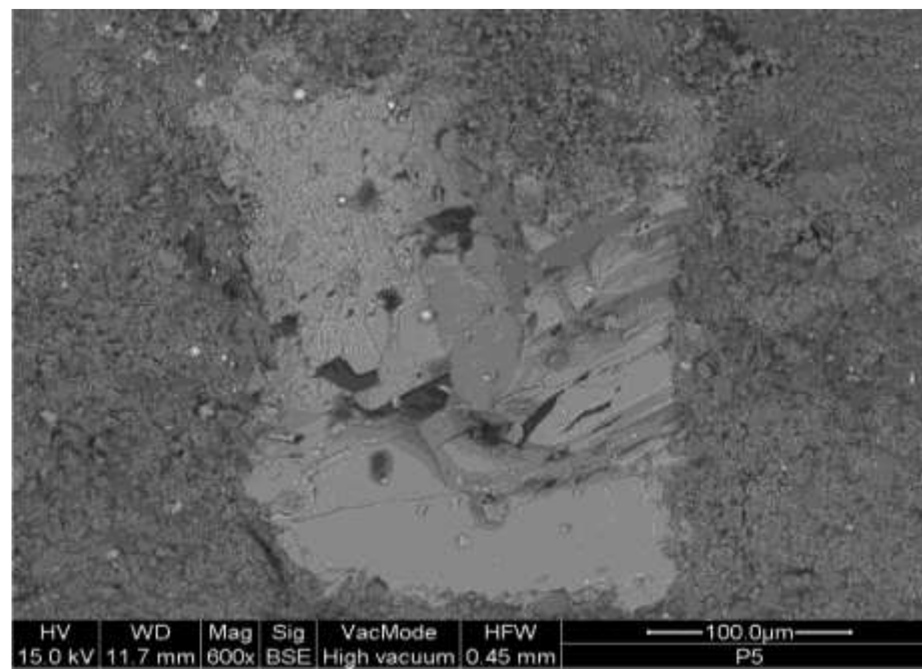




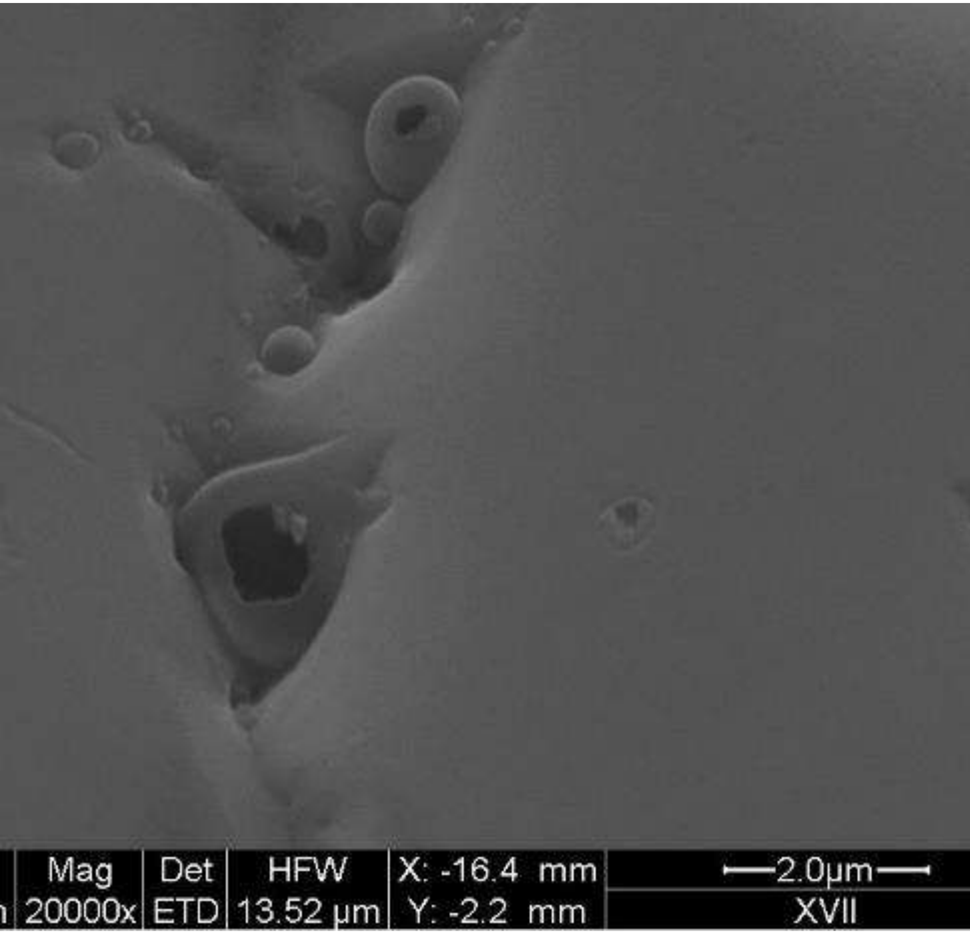
Above L: Intercrystal pores in laminated dolomite mudstone. Egton High Moor. Depth 1373 m.

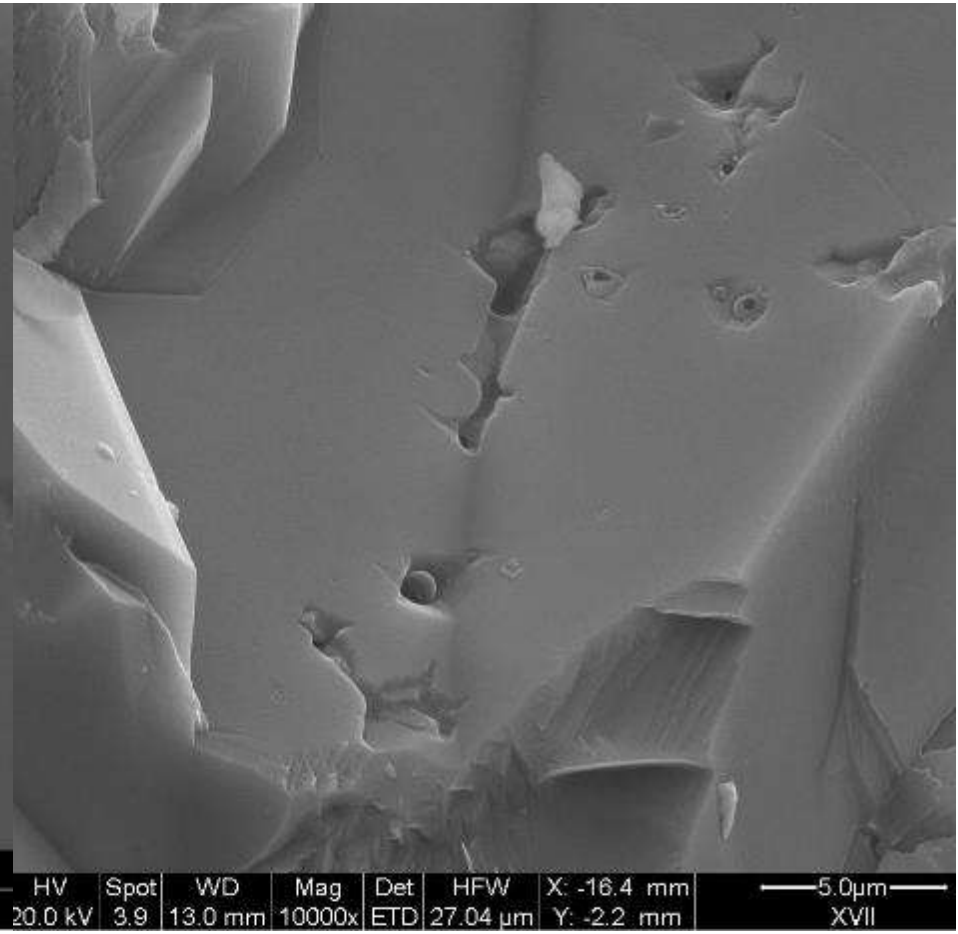
Above R: Calcite spar with intra-crystal pores, irregular to polyhedral cavities. Depth 3324 m.

Right: Intracrystal pores in anhydrite containing bitumen. Well Petrykozy-4K. Depth 2822 m.



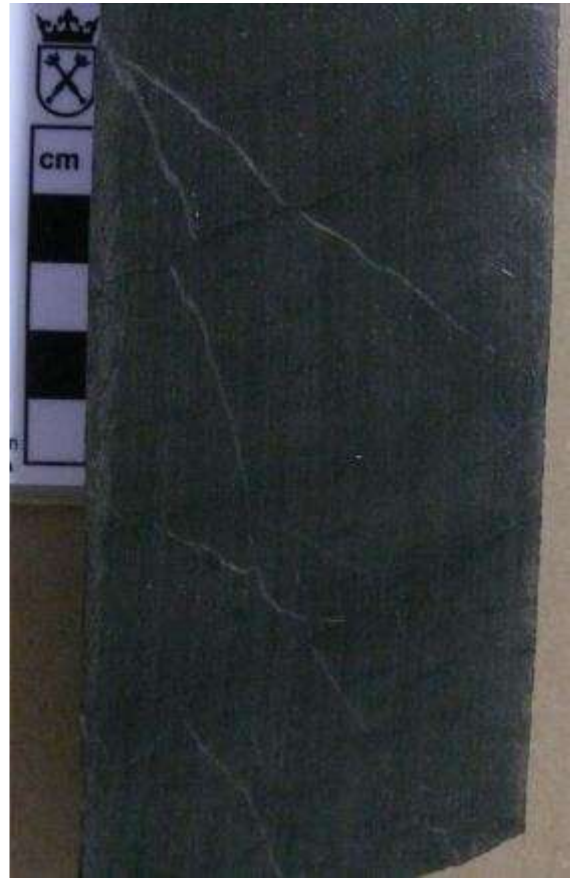
OIL DROPLETS IN MICROCAVITIES IN SLOPE FACIES



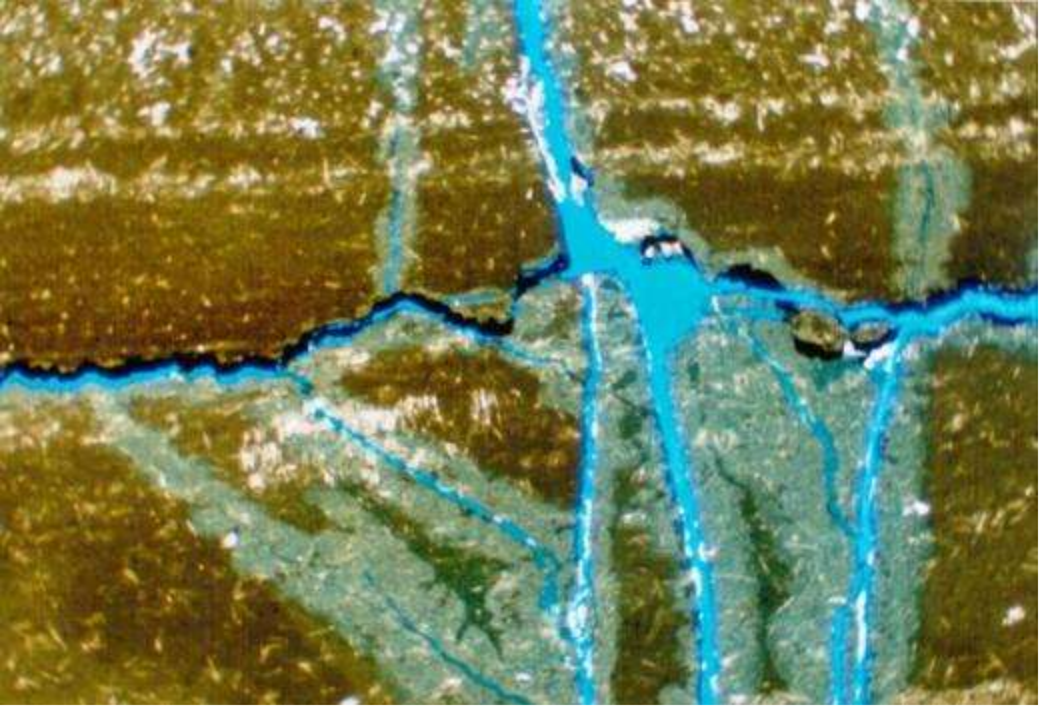


Intracrystal pores containing oil / bitumen remnants (spheres).
Laminated lime mudstone, slope facies. Poland Well WK-8, depth 3109 m.
Slowakiewicz, Perri & Tucker (2016).

FRACTURES IN SLOPE FACIES



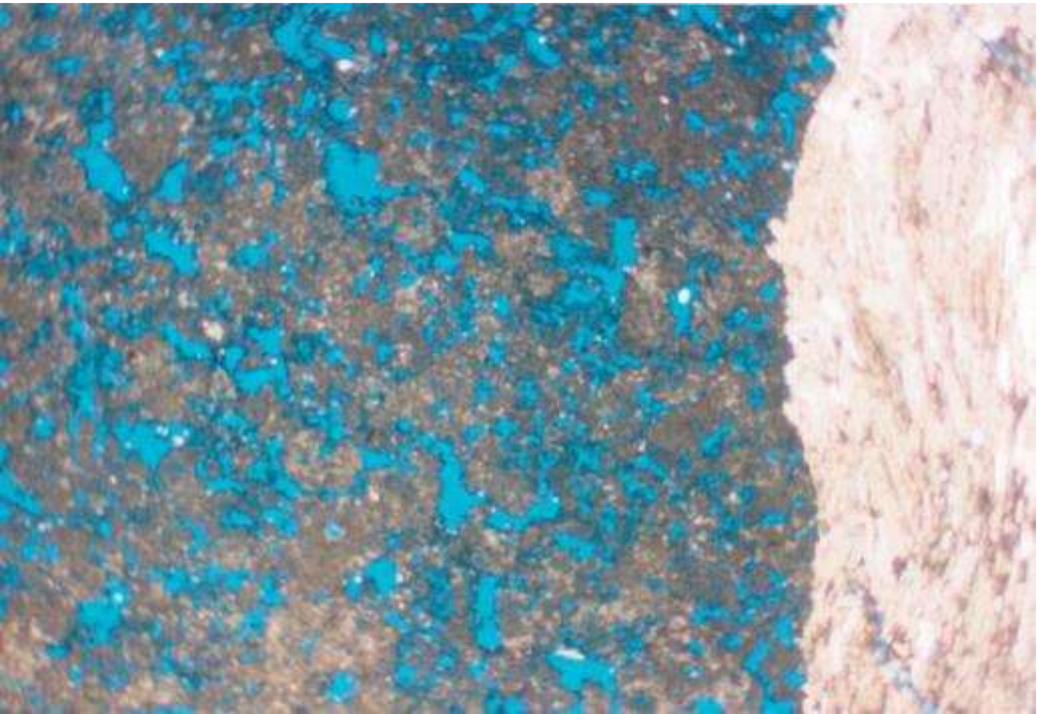
Z2 Slope facies, depth 2590 m. Polish sub-basin.
Fractures: some filled, some open, some offset, brecciated zone + vugs.



FRACTURES AS LOCATIONS OF BURIAL DISSOLUTION

Microporosity developed along fractures;
bitumen in stylolites.

Subsurface Netherlands,
depth 2430 m.



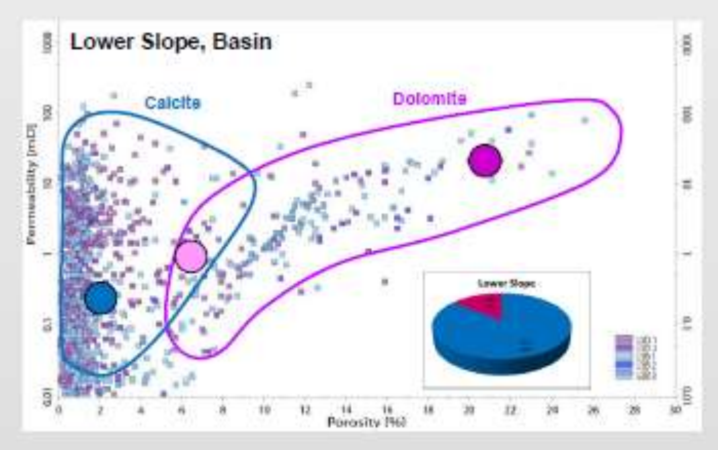
FRACTURES VERSUS MATRIX

Fracture filled with anhydrite cement, whereas matrix retains its original high intergranular porosity.

Fluid flow concentrated in fractures so they are cemented up.

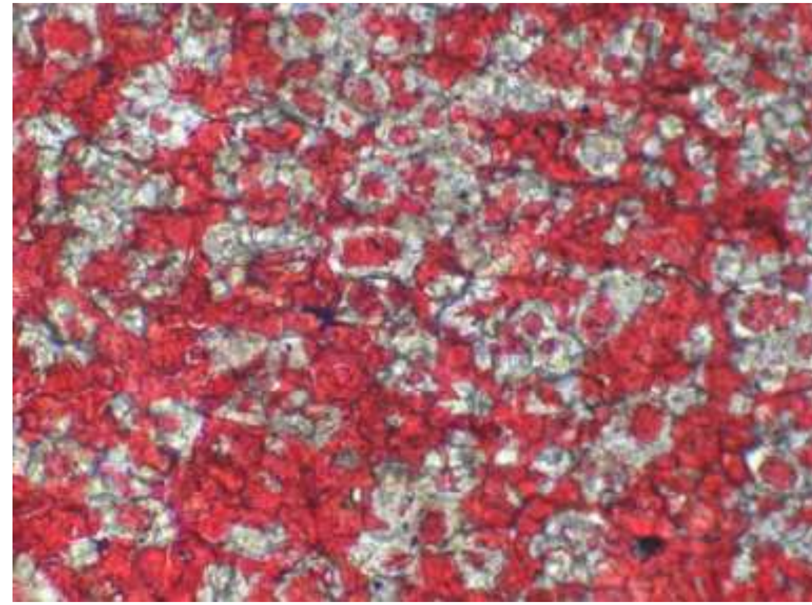
Subsurface Netherlands,
depth 2450 m.

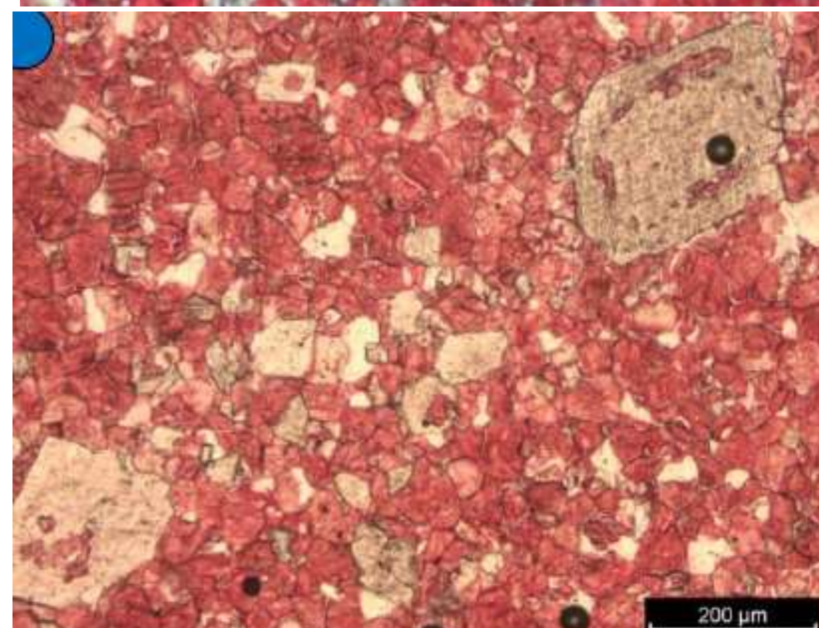
SLOPE FACIES RESERVOIRS: another factor to consider is dedolomitisation



Reduced porosity through dedolomitisation

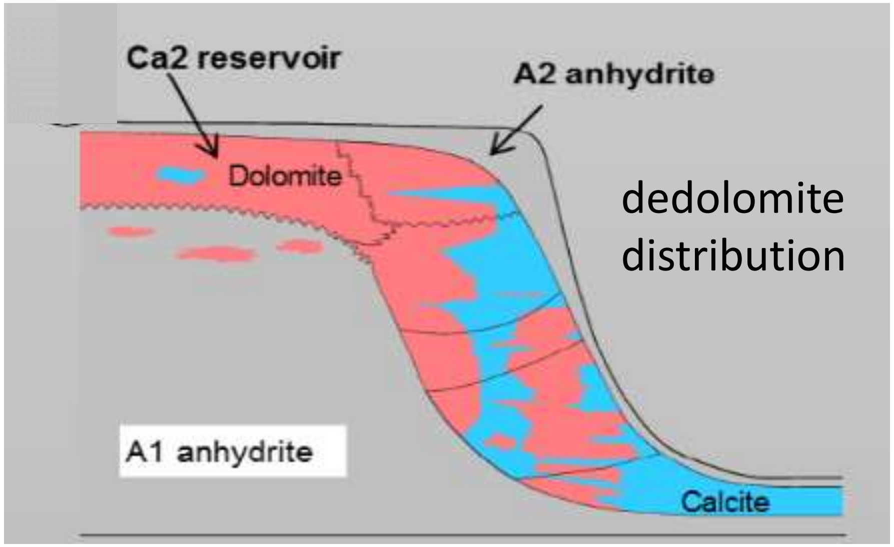
calcite v dolomite poroperm





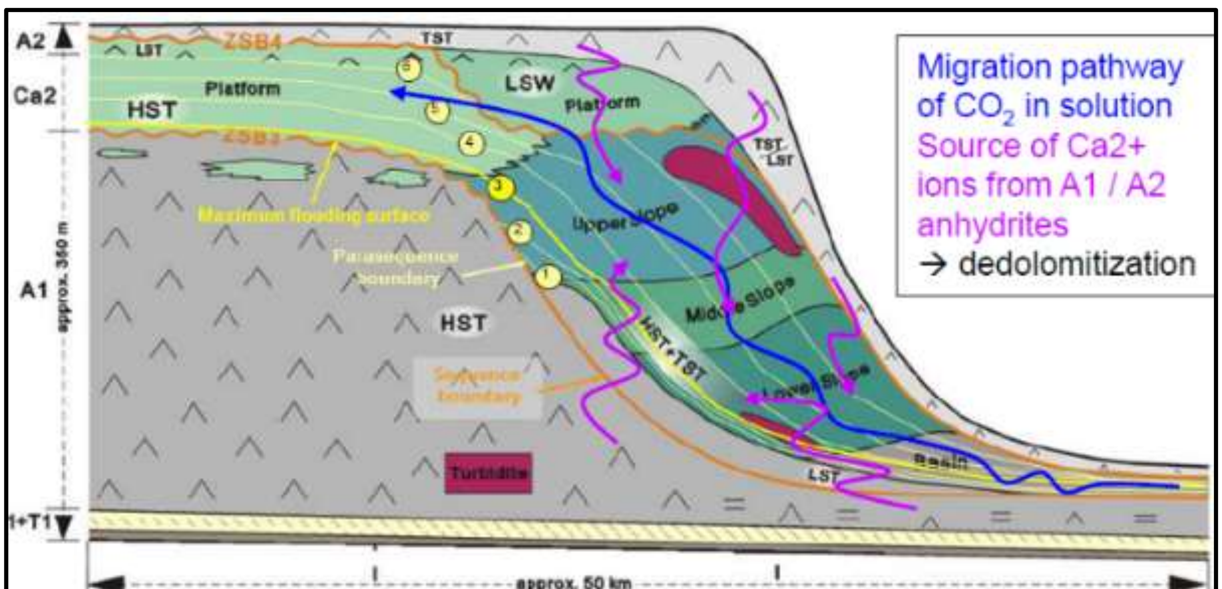
From Schoenherr et al. (S&D, 2014)

DEDOLOMITISATION DURING MODERATE BURIAL: associated with gypsum dehydration to anhydrite



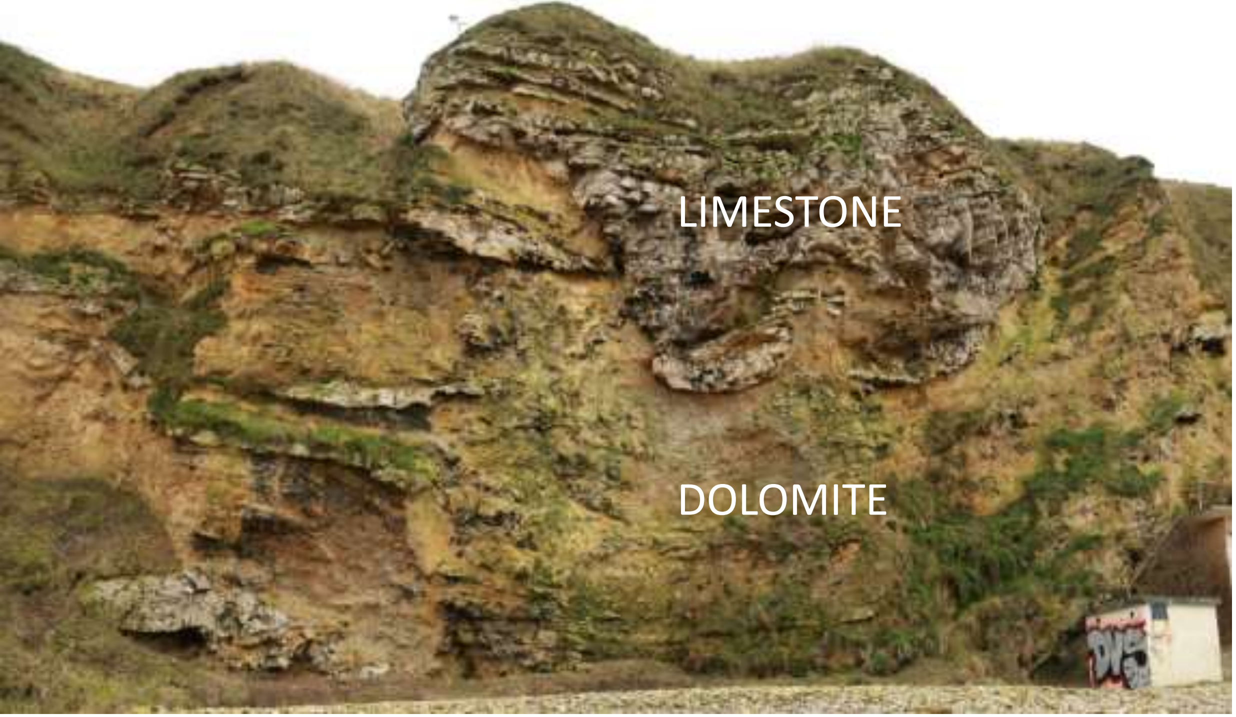
In German Sub-basin, Zechstein not uplifted, totally buried to 5 km since deposition.

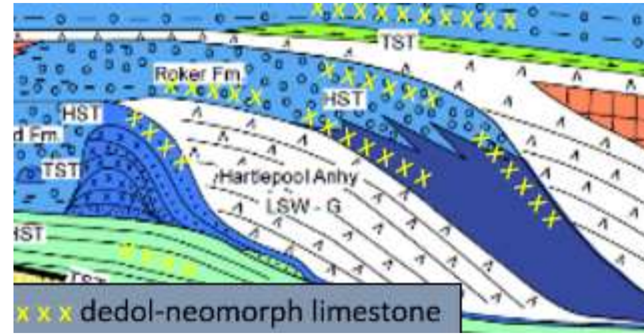
Dedolomites /secondary limestones mainly in Ca2 slope facies, some in platform.
Formed through fluids migrating out of evaporites and organic-rich sediments.
From Schoenherr et al. (2014).



Model for subsurface dedolomitisation: related to gypsum – anhydrite dehydration releasing much water and Ca^{2+}; CO_2 from organic matter decomposition also driving the process.

DEDOLOMITE / SECONDARY LIMESTONE AT OUTCROP IN NE ENGLAND



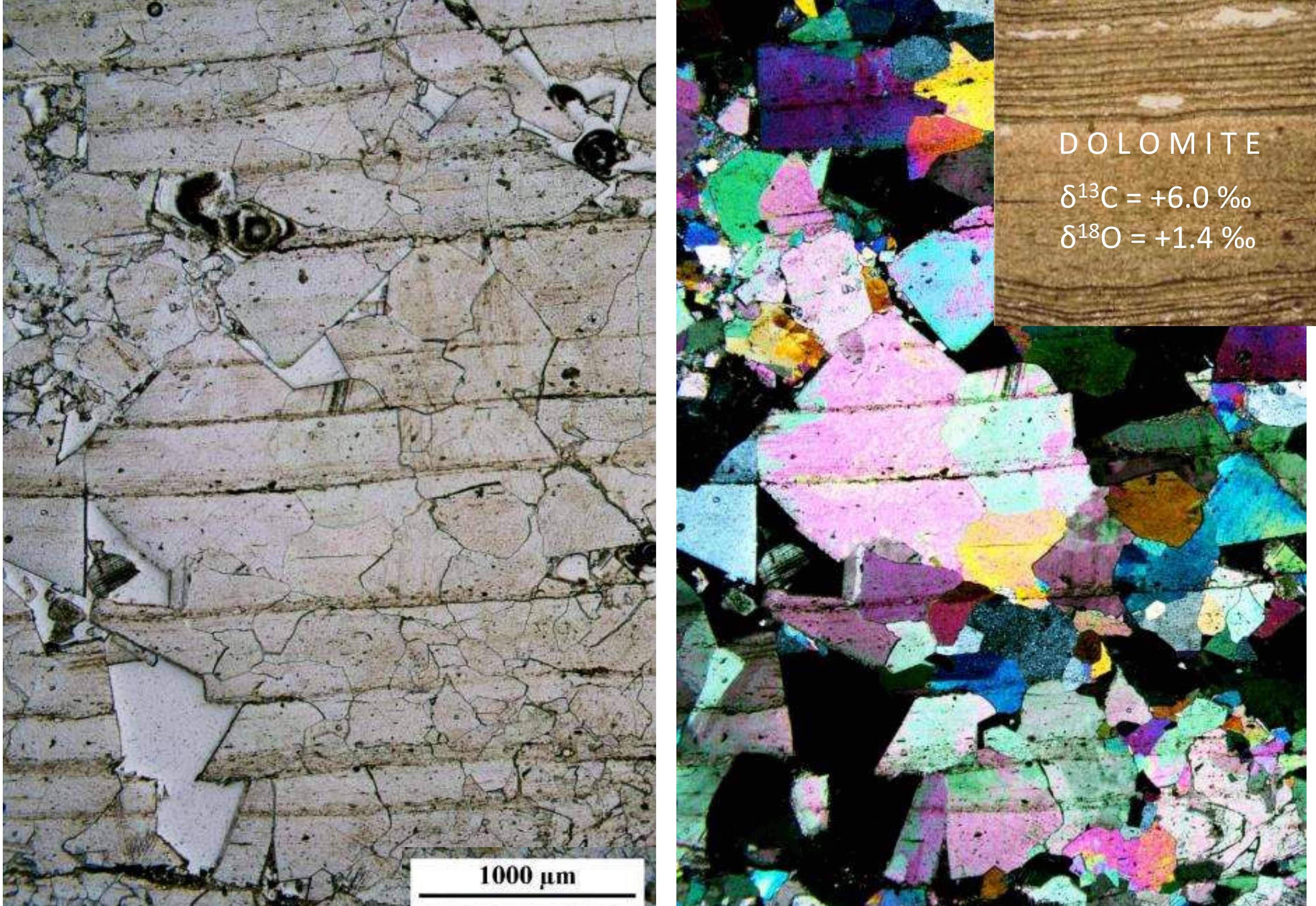


Often close to evaporite units

Grey limestone in coarser-grained lenses in upper slope facies.

Dark-grey to black organic-rich laminated limestone in lower slope facies (= Sapropelic Marker in well logs). Units with thicker-turbidites (buff) largely remain as dolomite.

SECONDARY LIMESTONE / DEDOLOMITE in Ca2 Roker Fm. NE England: following facies.



Calcitised slope laminites, Roker Fm., NE England. PPL & XP. $\delta^{13}C$ = 5.8 ‰, $\delta^{18}O$ = -4.0 ‰.
Secondary limestone - dedolomite

MODERATE BURIAL: DEDOLOMITISATION-NEOMORPHISM

A spectrum from NEOMORPHOSED LIMESTONE THROUGH TO DEDOLOMITE - related to gypsum dehydration releasing Ca^{2+} ions, water and CO_2 from organic matter decomposition.

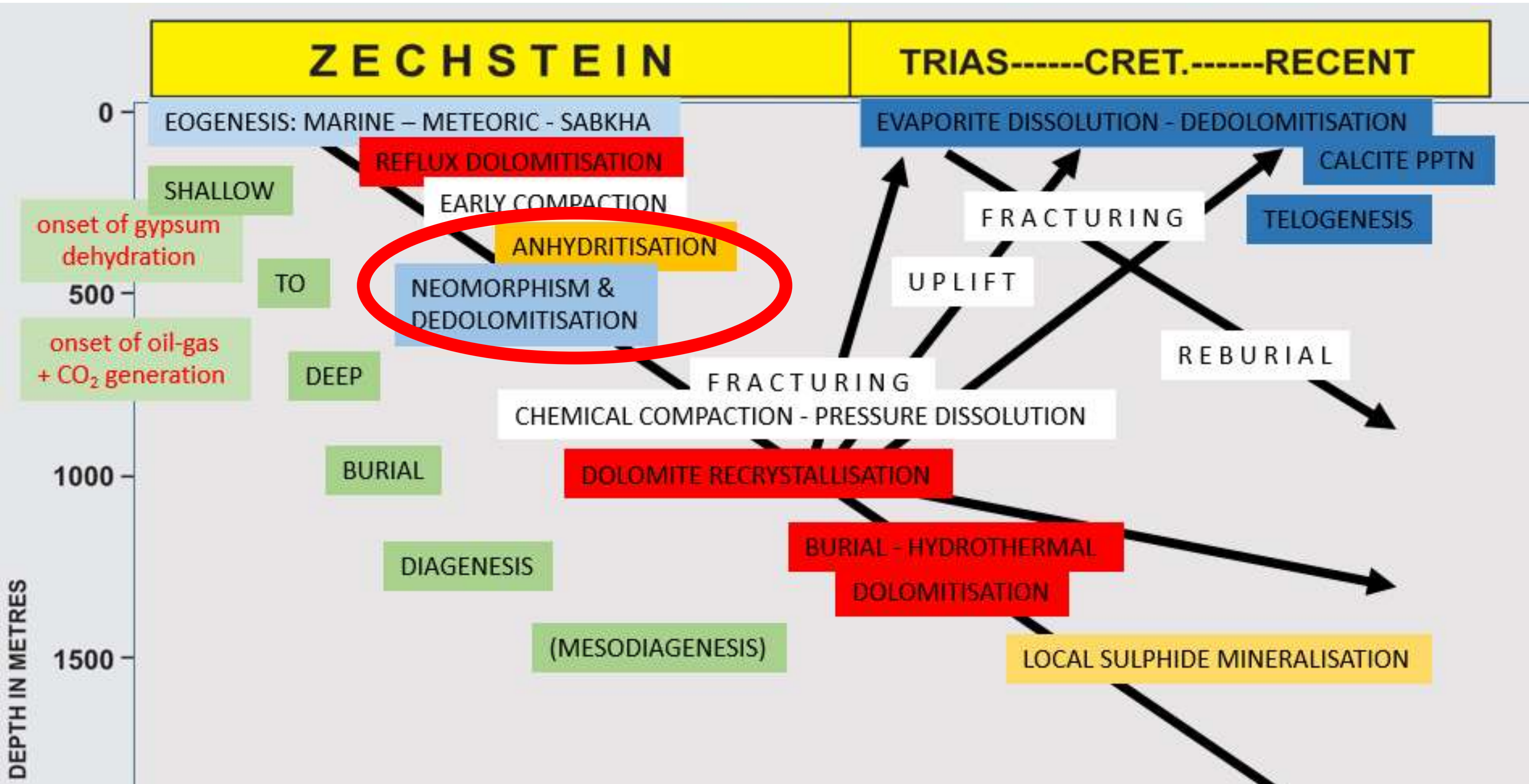


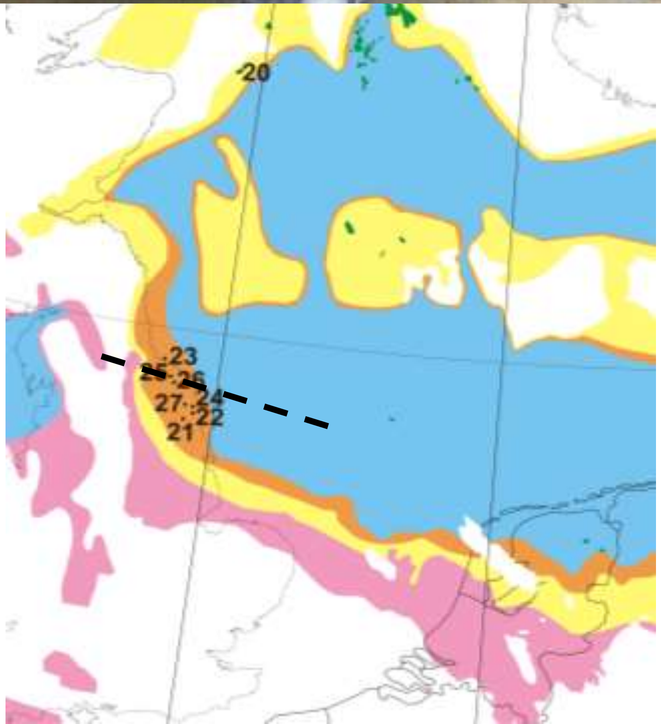
Figure Tucker 2016

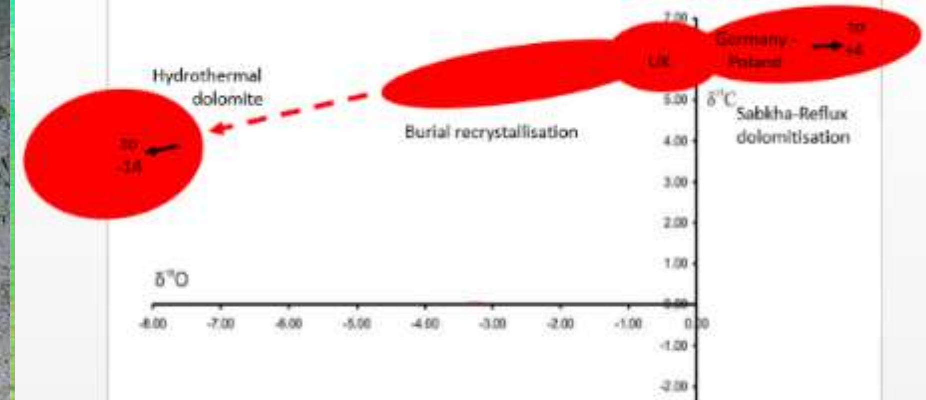
HYDROTHERMAL-HYPOGENE BRECCIA RESERVOIRS

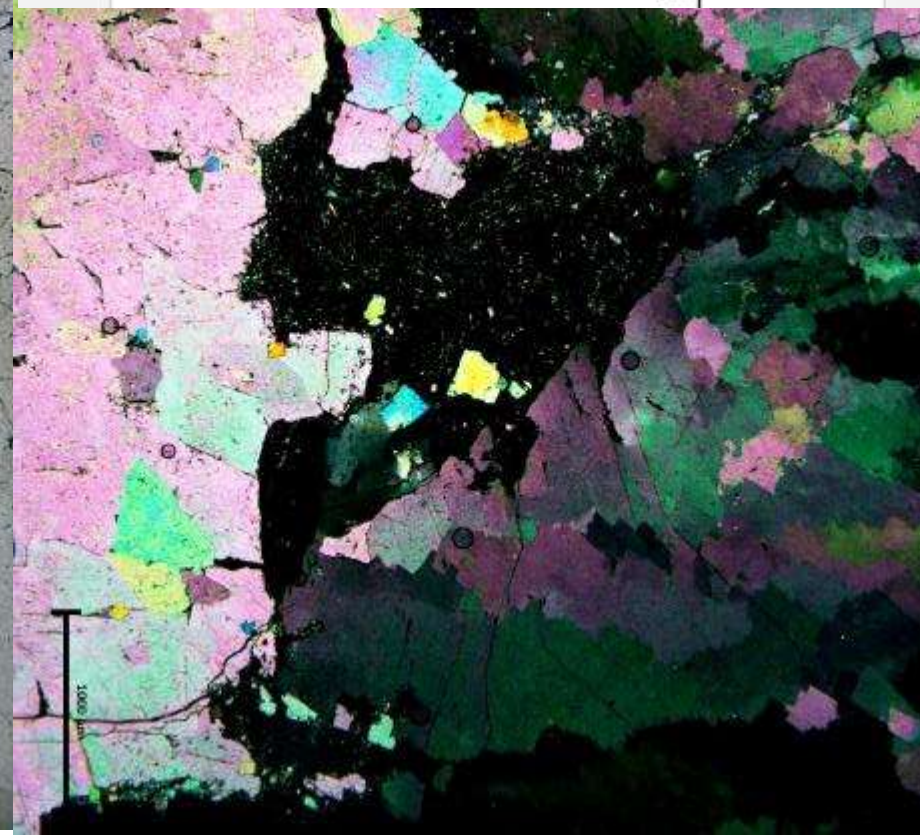
Lockton-2a, Yorkshire, NE England: a 1970s gas reservoir with many fractures and faults, and mineralisation.

Highly-fractured slope facies with dolomite fracture fills. Lockton-2.

From an area of extra-high heat-flow and high VRo in vicinity of major tectonic Lineament in the Cleveland Basin.



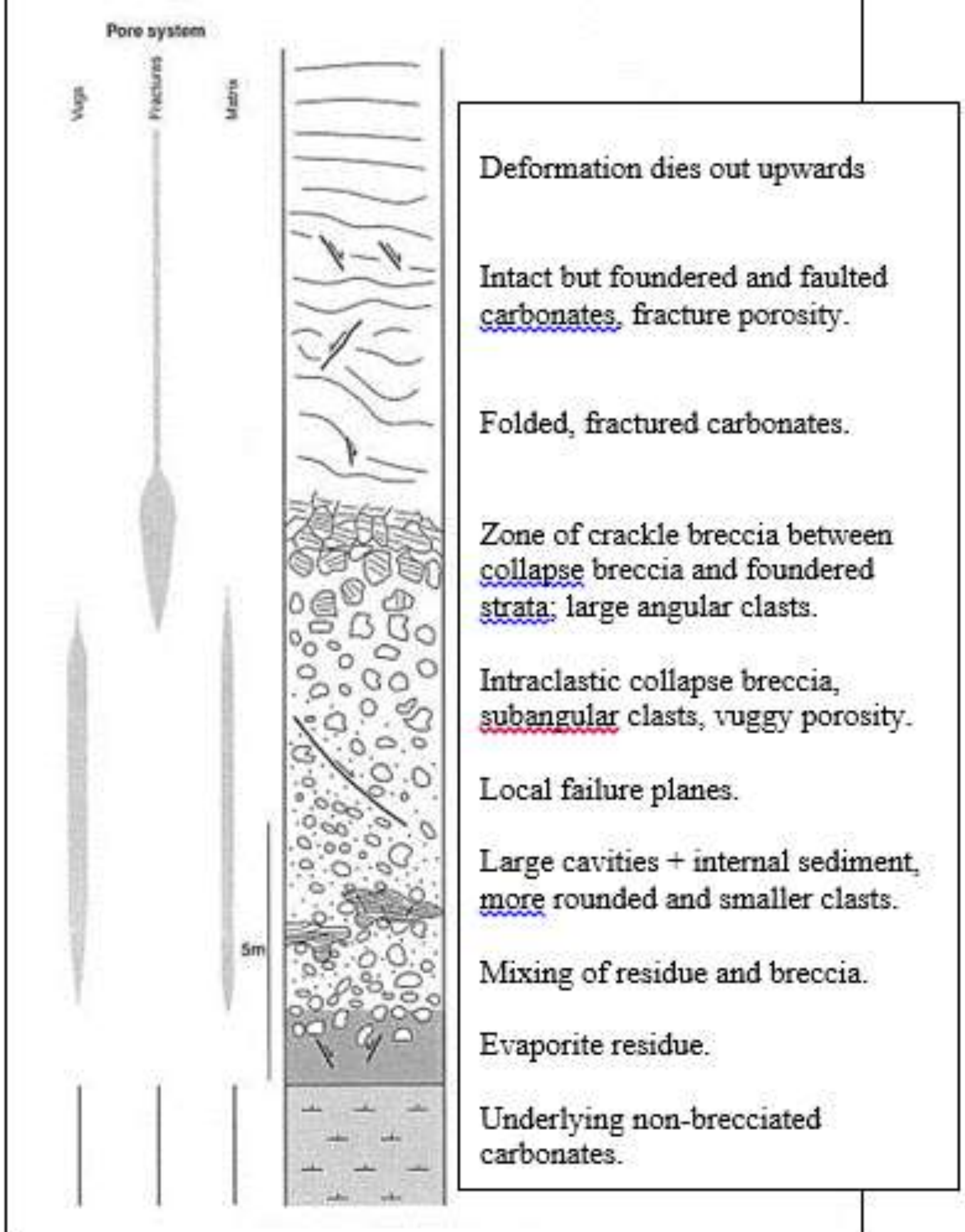




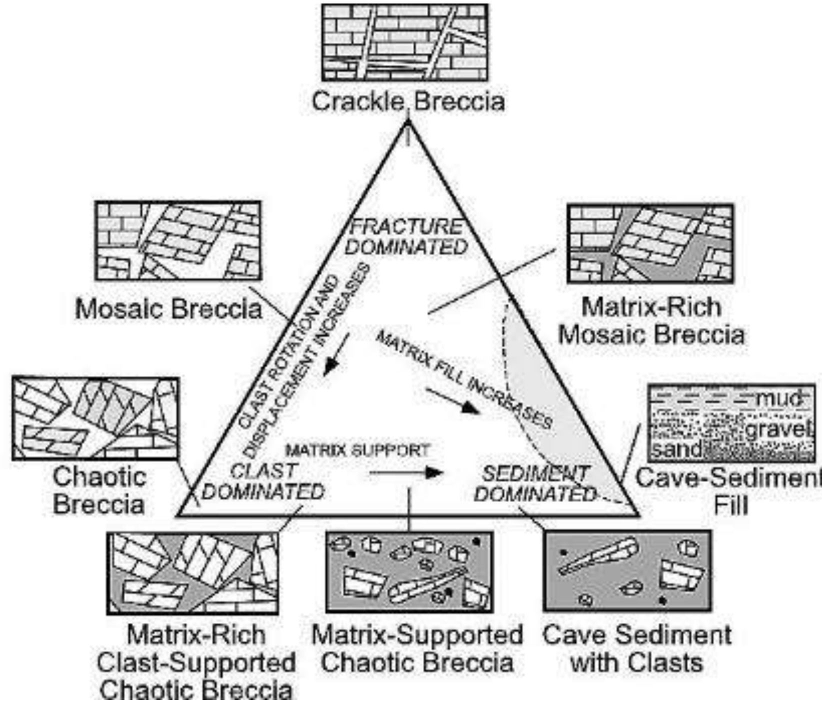
Hydrothermal – deep burial dolomite + bitumen. Scale bar = 1 mm.
Lockton-2a: saddle /baroque dolomite. Isotopes: $\delta^{13}C$ 4.2 ‰, $\delta^{18}O$ -13.95 ‰.

ZECHSTEIN BRECCIAS

1) Evaporite dissolution
2) Limestone karst



Evaporite collapse breccia: internal stratigraphy (from Gutteridge & Tucker).



Classification of cave breccias and sediment fills (Loucks et al. 2004).

OFTEN DIFFICULT TO TELL DIFFERENCE BETWEEN THESE BRECCIA TYPES IN CORE
CONTEXT IMPORTANT

BRECCIAS: 30/24-26 Argyll. Zechstein carbonate (~30 m) thick.

Argyll 30/24-26 depth 9158’ and 9165’.
Collapse breccia likely from dissolution of A1.
Note differences in amount of matrix and some streaked out clasts. Variable matrix.

MAJOR OIL RESERVOIR (actually first in North Sea)

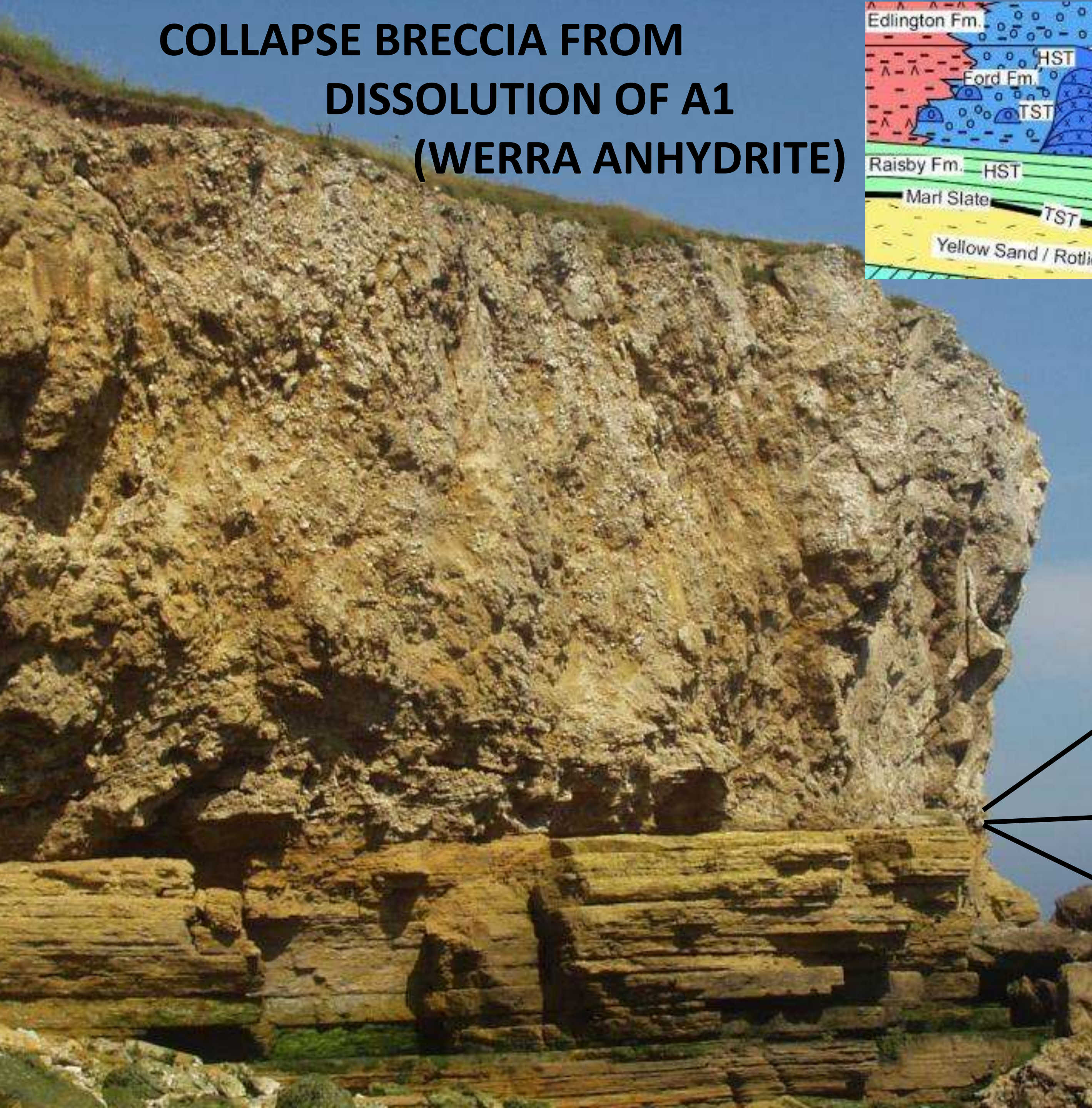
BRECCIAS: 14/19-C41 (Claymore) – Zechstein carbonate (35 m thick)

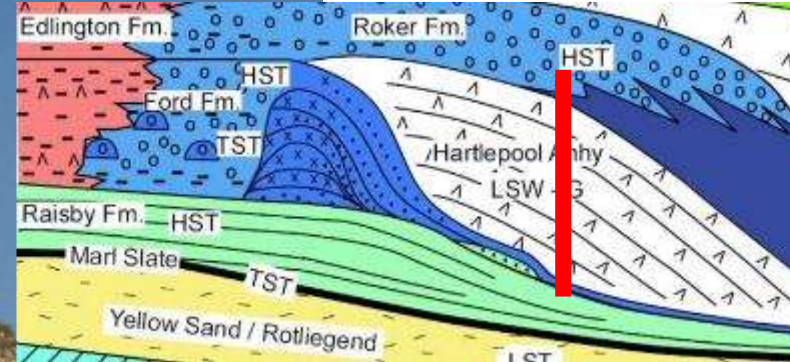
LEFT: Breccia with reddish colour, some laminated internal sediment, calcite spar-filled cavities. Probably palaeokarstic (limestone dissolution) breccia, top of Ca2, depth 10324'.
RIGHT: Higher up, clay-matrix breccia = collapsed brecciated Ca3 after dissolution of A2 evaps. Claymore area was a structural high in the basin, but not so deep.

PALAEOKARST BRECCIA

Palaeokarstic surface with reworked breccia of limestone clasts within Zechsteinkalk, between Ca1a (ZS1) and Ca1b (ZS2) at Zechstein sequence boundary 2 (ZSB2)
(Seesen, Harz, Germany, last week).

COLLAPSE BRECCIA FROM DISSOLUTION OF A1 (WERRA ANHYDRITE)





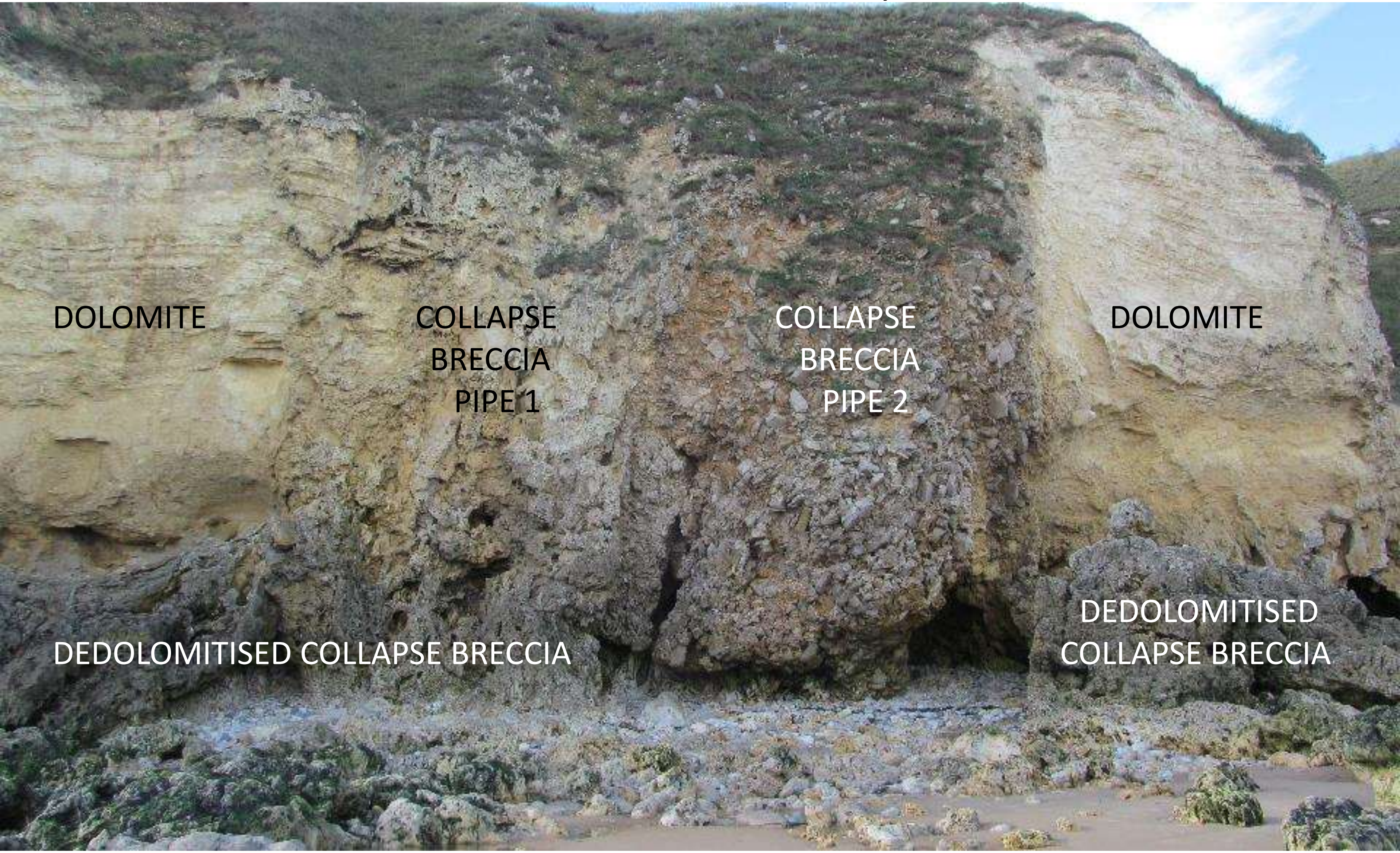
Collapse brecciated Ca2 (Hauptdolomit, Roker Fm) 15 m thick, stratiform breccia.

5 cm residue = 150 m anhydrite A1, 5 km offshore, east.

10 cm Ca1b basin facies = 100 m reef 5 km to west.

Ca1a = Raisby Fm. Zechsteinkalk

EVAPORITE DISSOLUTION-COLLAPSE BRECCIATION, and DEDOLOMITISATION



Hartlepool Anhydrite (A1) residue 25 m below beach.
2 types of collapse breccia a) stratiform (dedolomitised), b) pipes, later.

Clast of collapse breccia (dedolomitised) which is coated, within a collapse breccia. Dissolved out clasts originally dolomite. Tynemouth, NE England. Slab 15 cm across.

EVAPORITE COLLAPSE BRECCIA

with laminated sediment, deposited in a cavern in dissolving anhydrite.

Residue (10 cm clay) of 150 m anhydrite (A1, Werra).

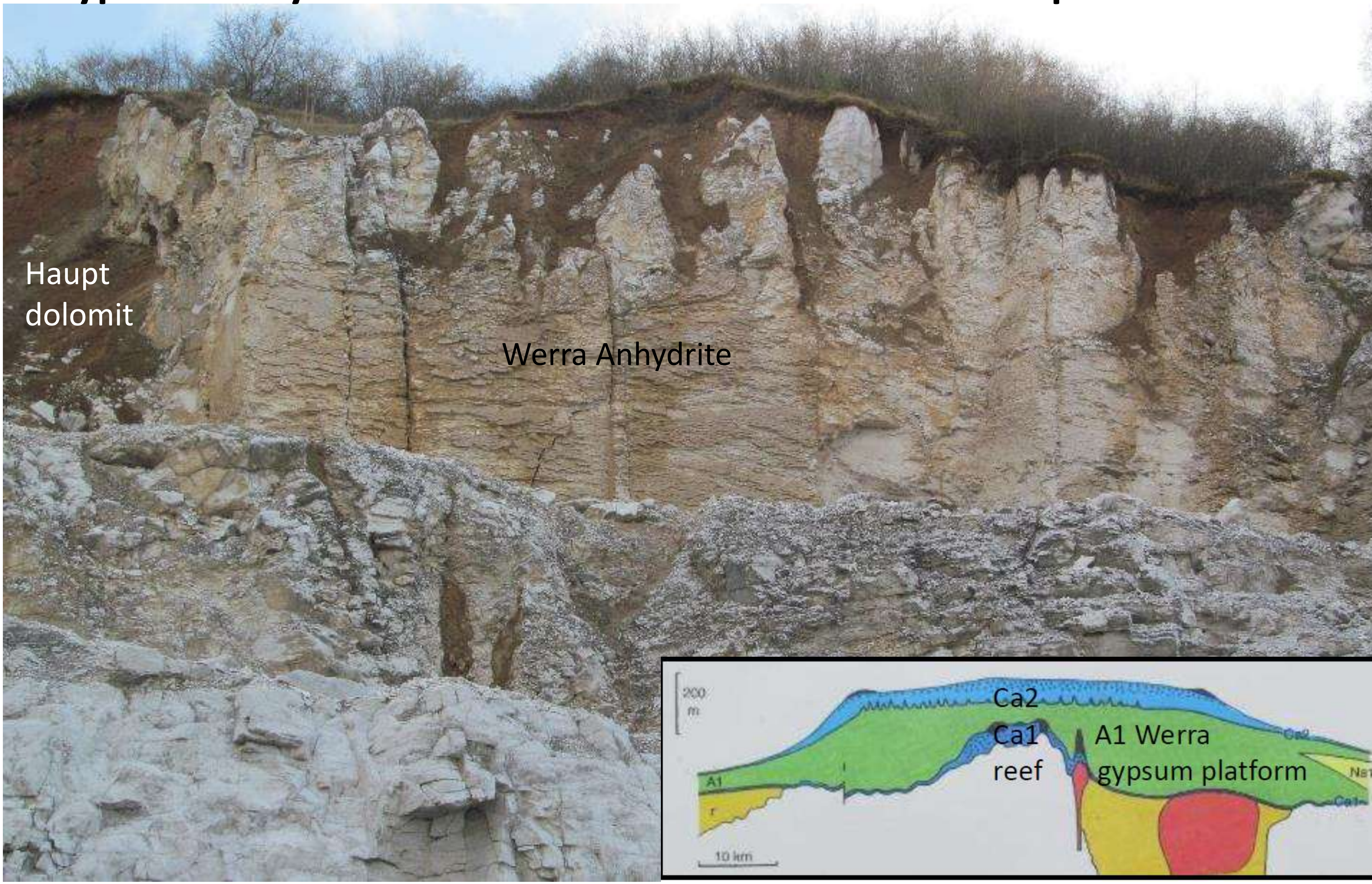
Top surface of basinal Ca1b facies
(10 cm thick microbialite = 100 m reef 5 km to west)

BEDDED SEDIMENT WITHIN COLLAPSE BRECCIA

ABOVE: Laminated sediment, graded laminae, synsed fault, small collapse feature.

RIGHT: Laminated sediment with clast of breccia, deposited within cavern in collapsing carbonate, cut by vertical sediment dyke. Clasts dissolved out were dolomite clasts. NE England.

Gypsum-anhydrite dissolution and formation of collapse breccias



Scharzfeld, Harzgebirge. Werra Anhydrite, dissolution surface with Hauptdolomit (Ca2) above.

Gypsum-anhydrite dissolution and formation of collapse breccias

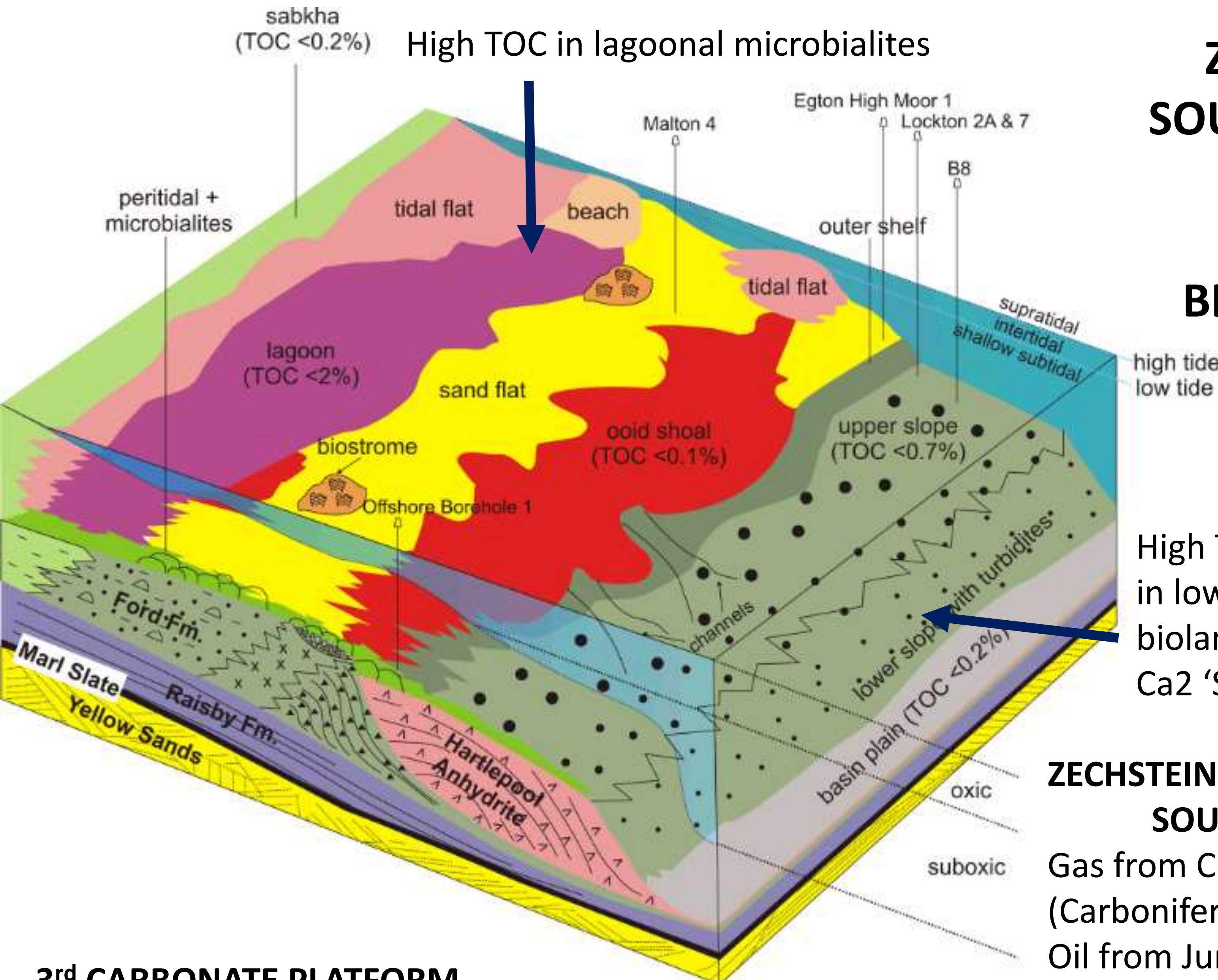
Blocks of brown collapse brecciated Ca2 (Rauchwacke) forming scree.

Collapse brecciated Ca2 (Rauchwacke), Walkenried Monastery, Harzgebirge, Germany

ZECHSTEIN SOURCE ROCKS

TOCs & BIOMARKERS

High TOC in lagoonal microbialites



High TOC (up to 2%) in lower slope biolaminites, e.g. Ca2 'Stink Dolomite'.

3rd CARBONATE PLATFORM
Depositional model for Roker Fm

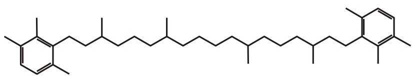
(Slovakiewicz, Tucker, Perri, Mawson AAPG Bull 2013)

ZECHSTEIN HYDROCARBONS SOURCE ROCKS:
Gas from Coal Measures (Carboniferous),
Oil from Jurassic, even Devonian,
but also Zechstein itself: so **Zechstein self-sourcing.**

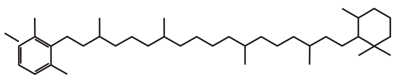
BIOMARKERS INDICATIVE OF MICROBES

Green sulphur bacteria

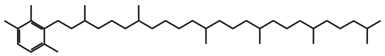
isorenieratane



ß-isorenieratane

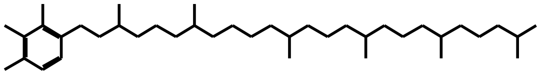


chlorobactane



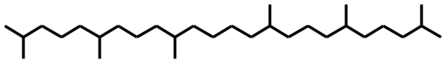
Purple sulphur bacteria

okenane

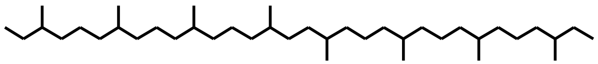


Archaea

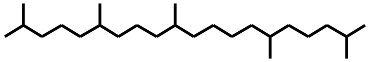
squalane



biphytane

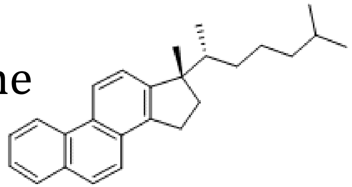


PMI



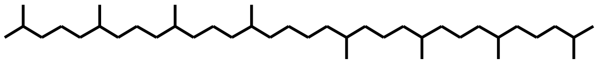
Eukaryotes (esp algae)

sterane



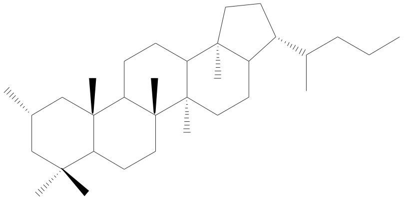
Anaerobic bacteria

lycopane



Cyanobacteria

2-methylhopanes

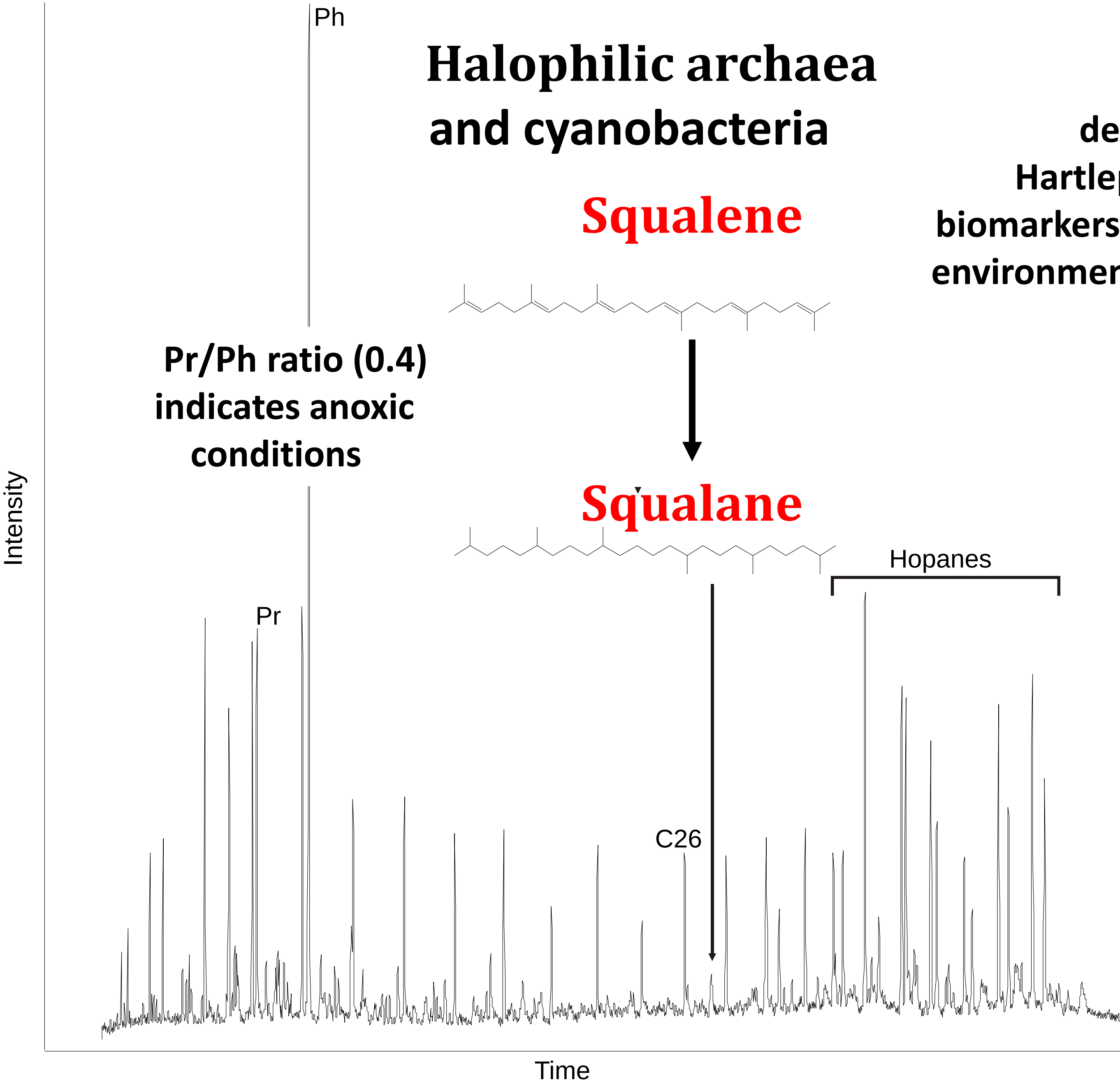


Terrestrial organic matter indicated by certain hopanes and tricyclic terpanoids

INTERTIDAL-SABKHA MICROBIAL FACIES

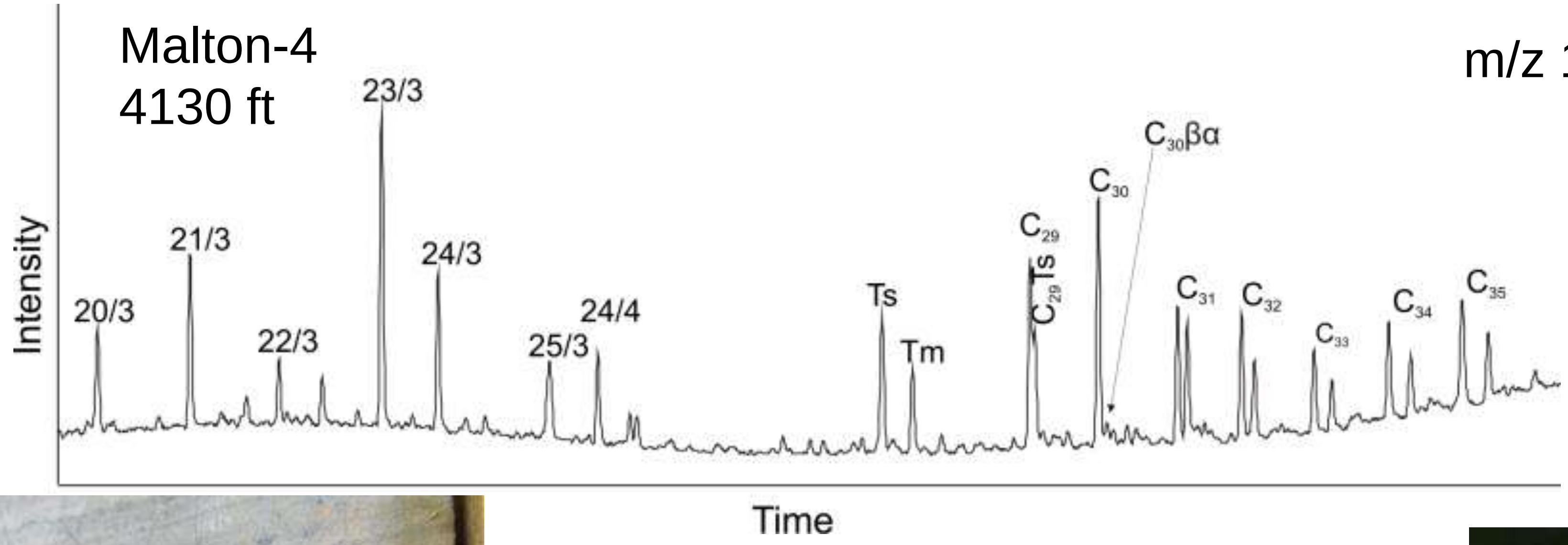
Halophilic archaea and cyanobacteria

Pr/Ph ratio (0.4) indicates anoxic conditions



Offshore Borehole 1
depth 1049ft (319.7 m)
Hartlepool Anhydrite (Z1A)
biomarkers indicate hypersaline environment and extremophiles (archaea).

EVIDENCE OF A TERRESTRIAL PLANT CONTRIBUTION



Malton-4 - western margin of the Zechstein Basin in Yorkshire, lagoonal – microbial facies.

Biomarkers: tricyclic C23 and tetracyclic terpanes C24 (and ratio C23/C24) indicate contribution from terrestrial plant material.

Hopanes indicate cyanobacteria.

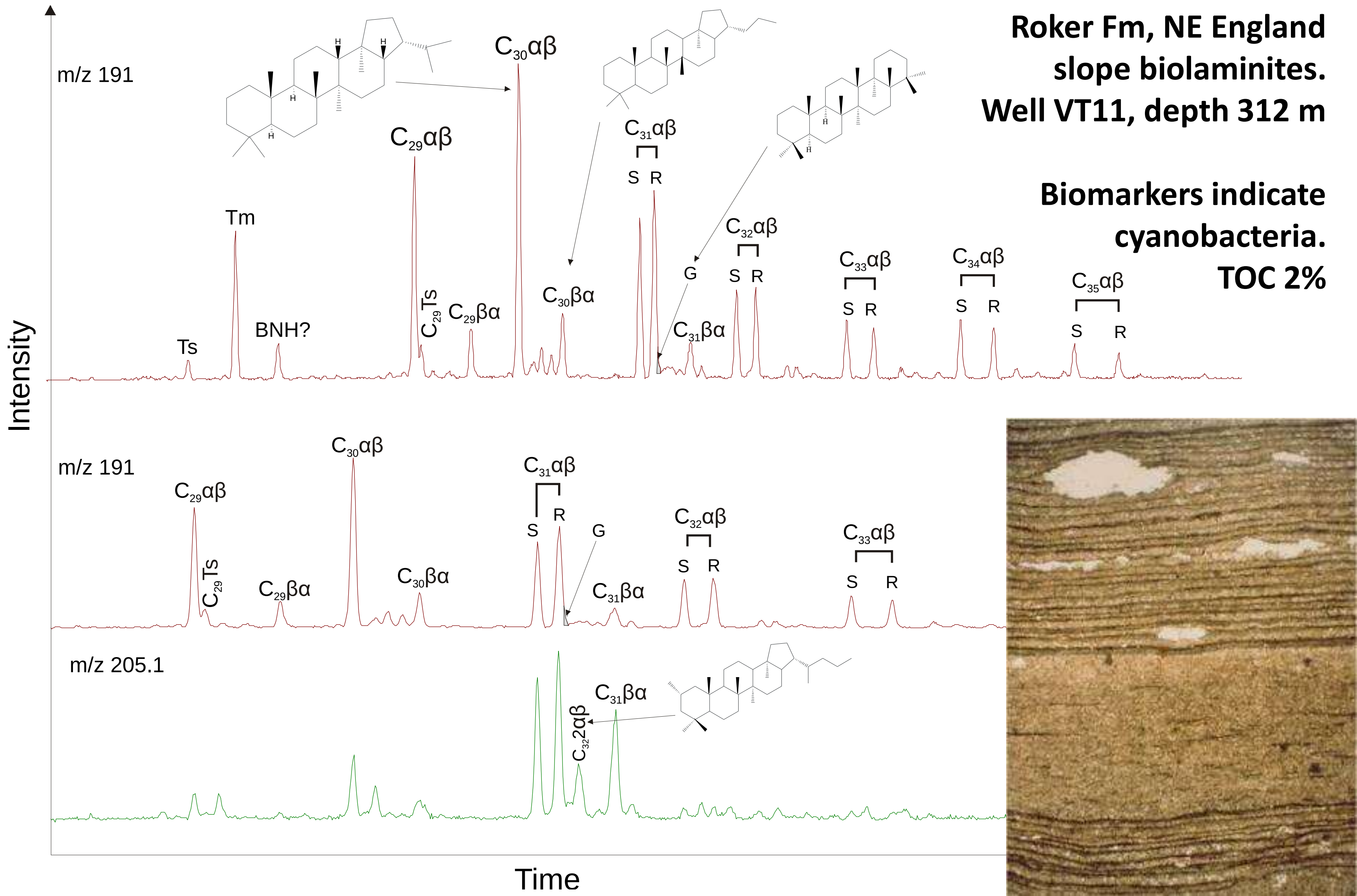
Fossil plants occur in Roker Fm.
shallow-water facies at outcrop.

SLOPE BIOLAMINITE FACIES

Hopanes & 2-methylhopanes

Roker Fm, NE England
slope biolaminites.
Well VT11, depth 312 m

Biomarkers indicate
cyanobacteria.
TOC 2%

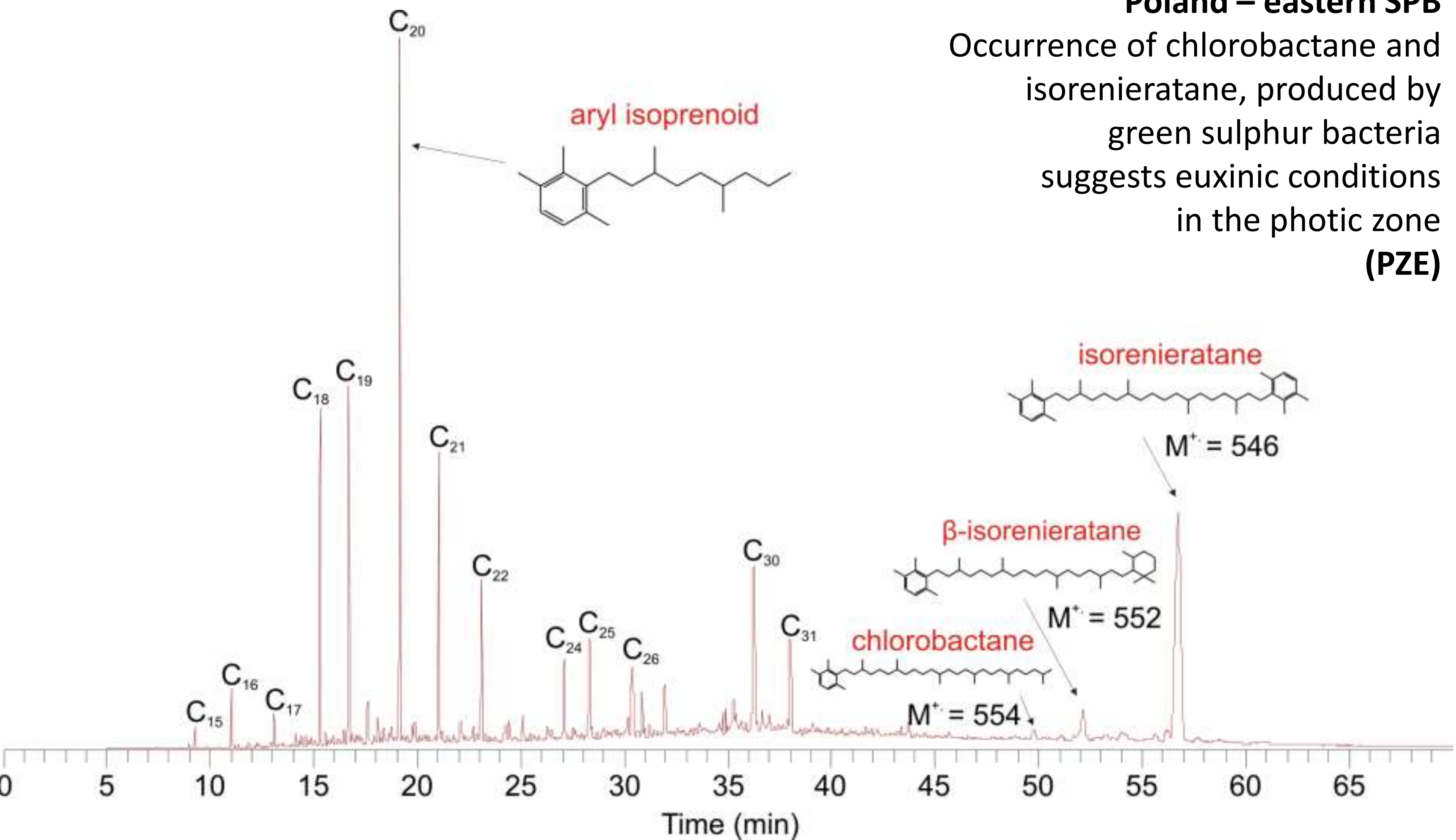


EVIDENCE OF EUXINIA

Isorenieratane and its derivatives

m/z 133+134

Błotno-3 (3348.15 m) Toe-of-slope apron
Poland – eastern SPB
Occurrence of chlorobactane and isorenieratane, produced by green sulphur bacteria suggests euxinic conditions in the photic zone **(PZE)**

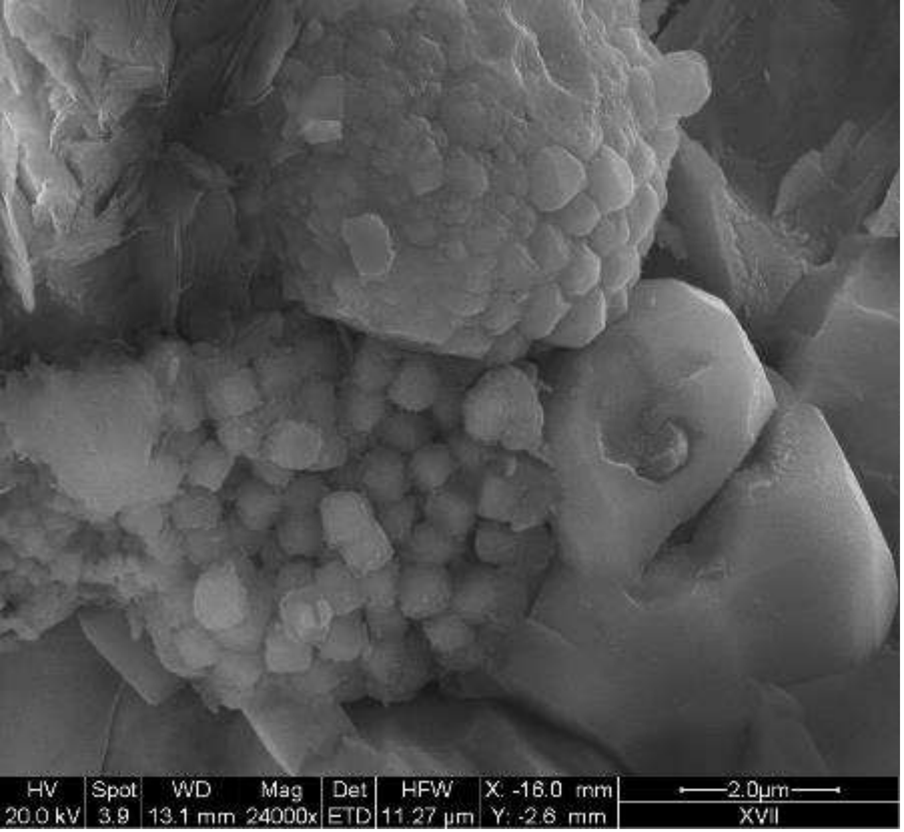


EVIDENCE OF EUXINIA

Slope facies Poland

Well WK-8

Slowakiewicz, Perri & Tucker 2016

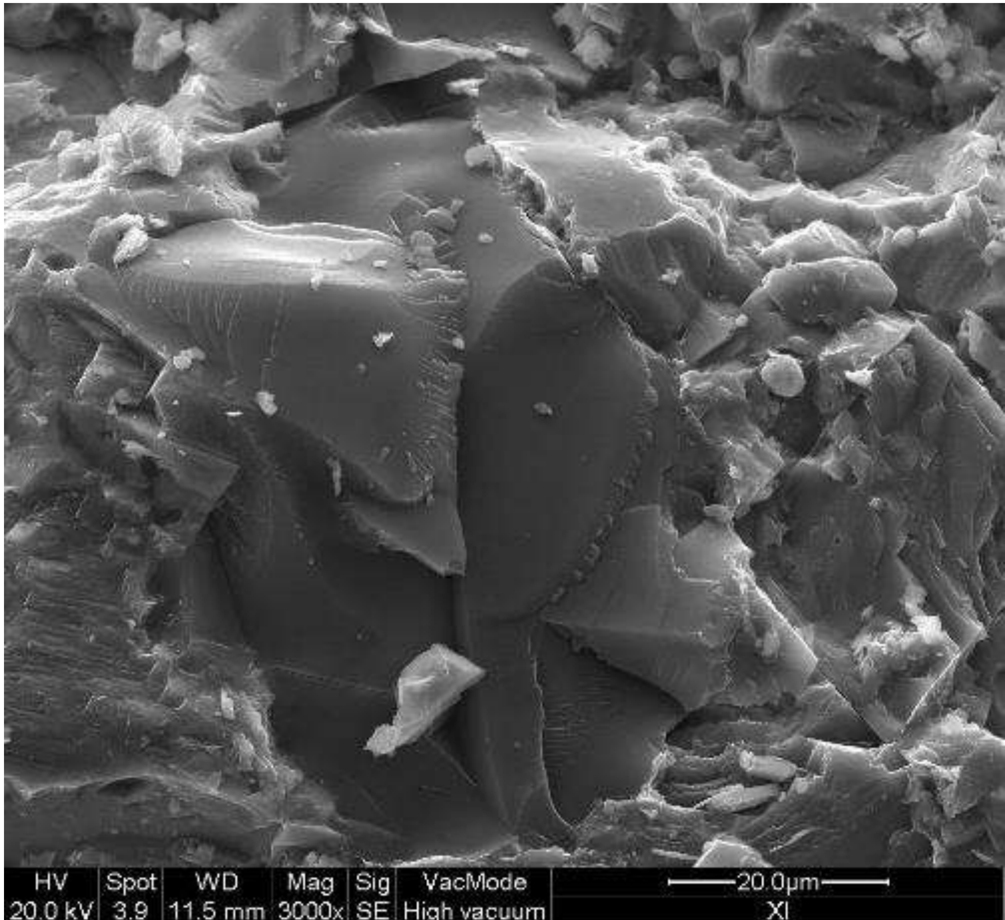


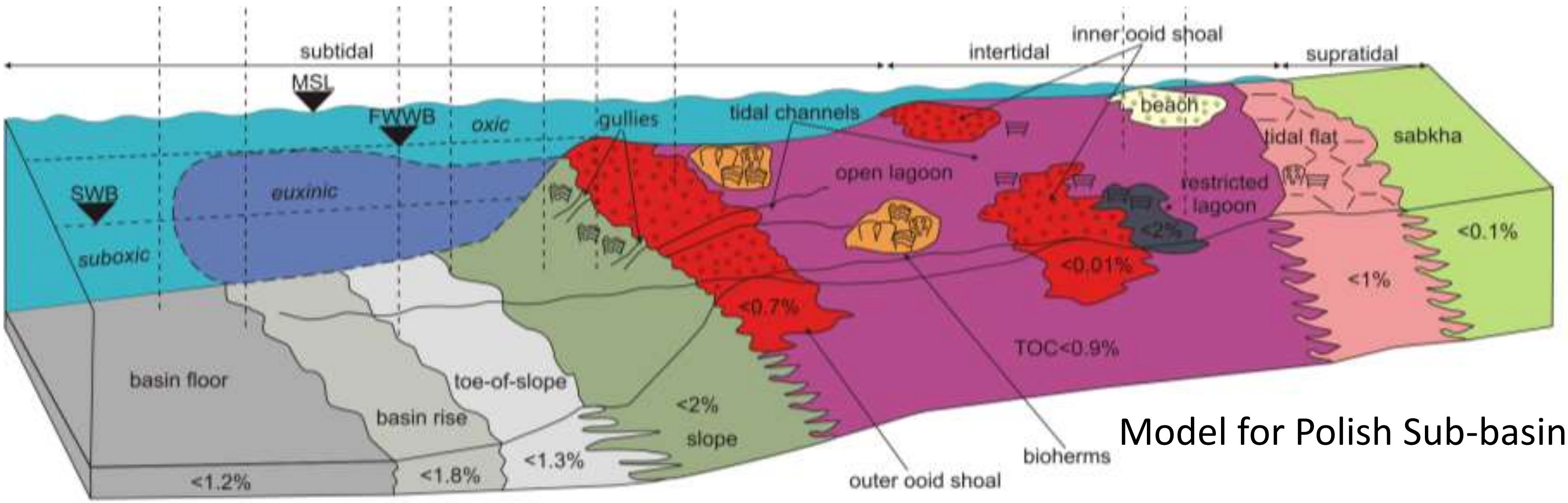
Microcrystals of framboidal pyrite

Sulphate reducing bacteria:
SO_4^{2-}+ OM → HS^- + H_2S + HCO_3^-

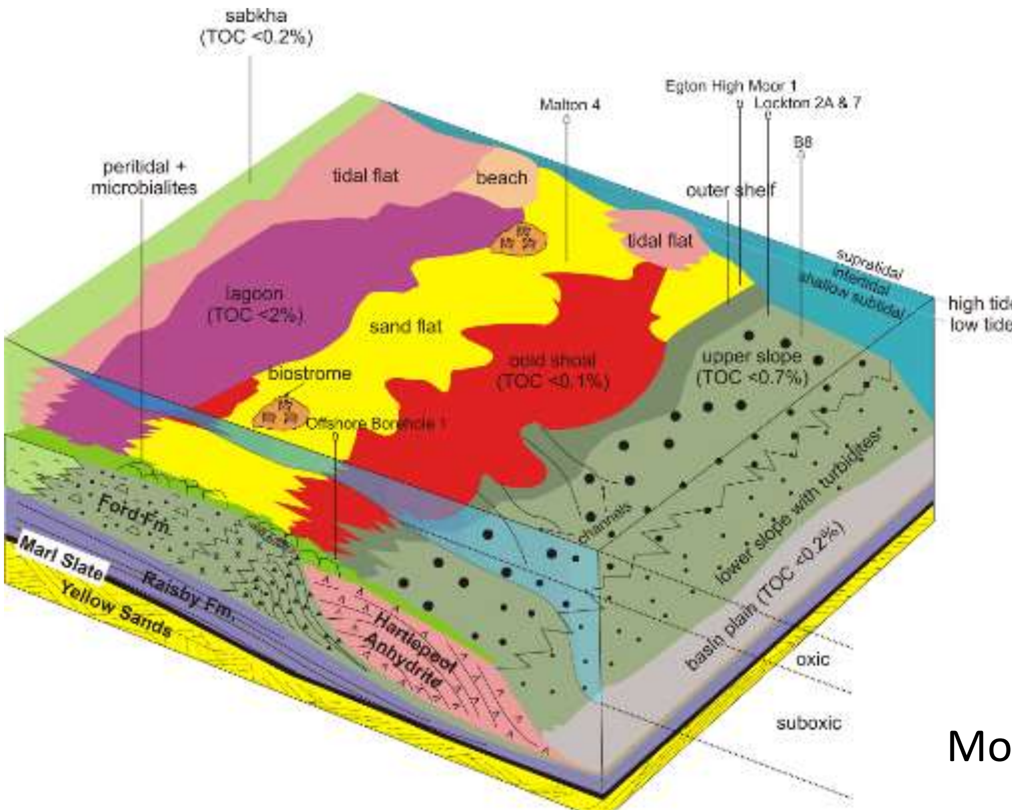
but green sulphur bacteria (anaerobic and photosynthetic) also involved in precipitation of pyrite and sulphur:
$H_2S + CO_2 \rightarrow CH_2O + H_2O + 2S$
$FeS + H_2S \rightarrow FeS_2 + H_2$

Native sulphur microcrystals





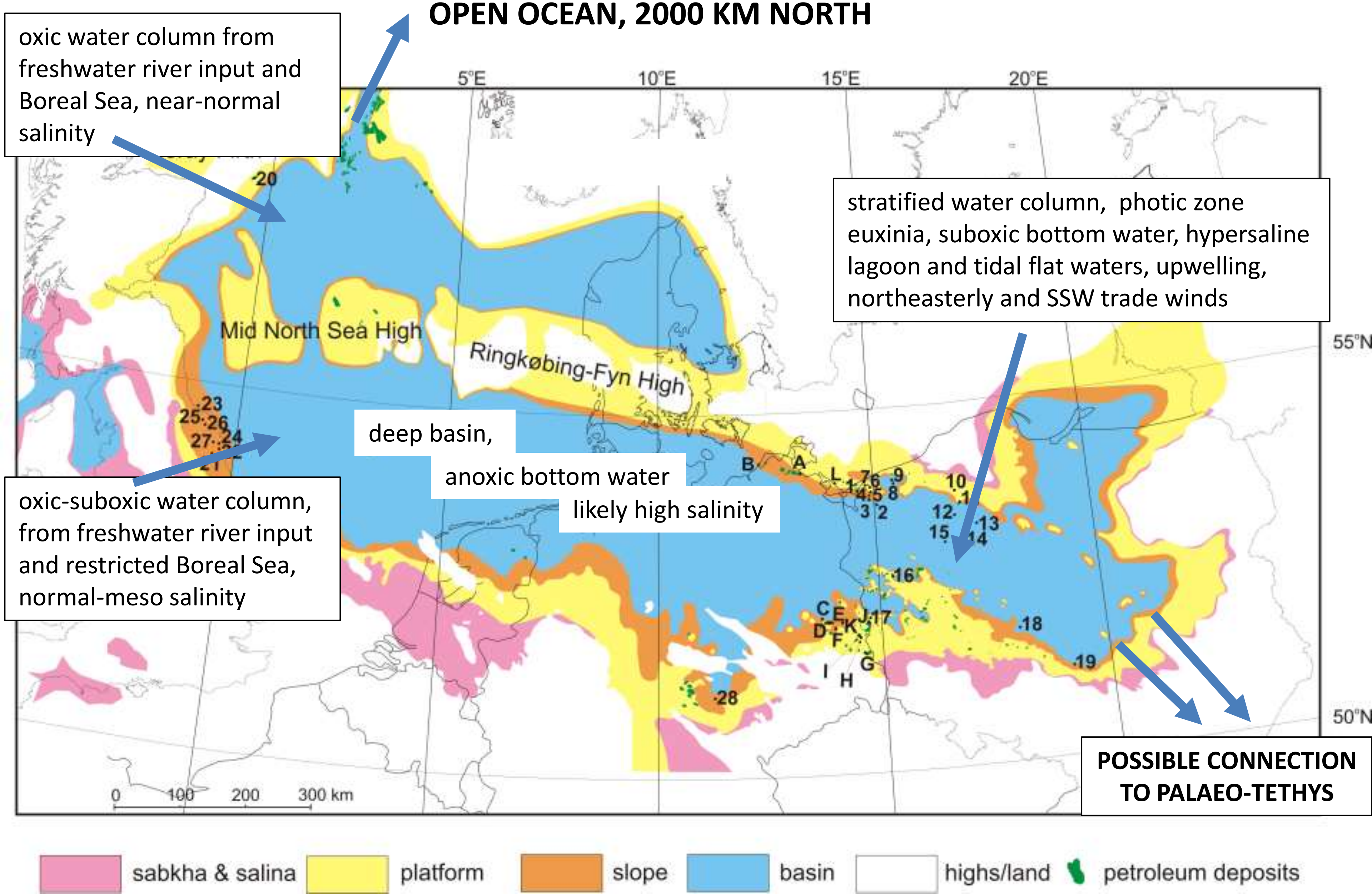
Model for Polish Sub-basin



Depositional models for Zechstein source rocks:
formed within anoxic lagoons
and
where photic zone euxinia developed above slope, mostly in eastern part of basin.
Slowakiewicz, Tucker et al. (2013; 2015).

Model for Anglo-Dutch sub-basin

OPEN OCEAN, 2000 KM NORTH



Stable isotopes (C and O) support variations in organic productivity, circulation and redox. Source rocks formed in restricted lagoons and in slope facies where PZE above.

CONCLUSIONS

The 4-systems tract sequence stratigraphic model with SB after FSST fits the data well.

Basin-wide evaporites are all lowstand facies and their deposition involves a disconnect from the open ocean;
their successions may have their own internal sub-sequence stratigraphy.

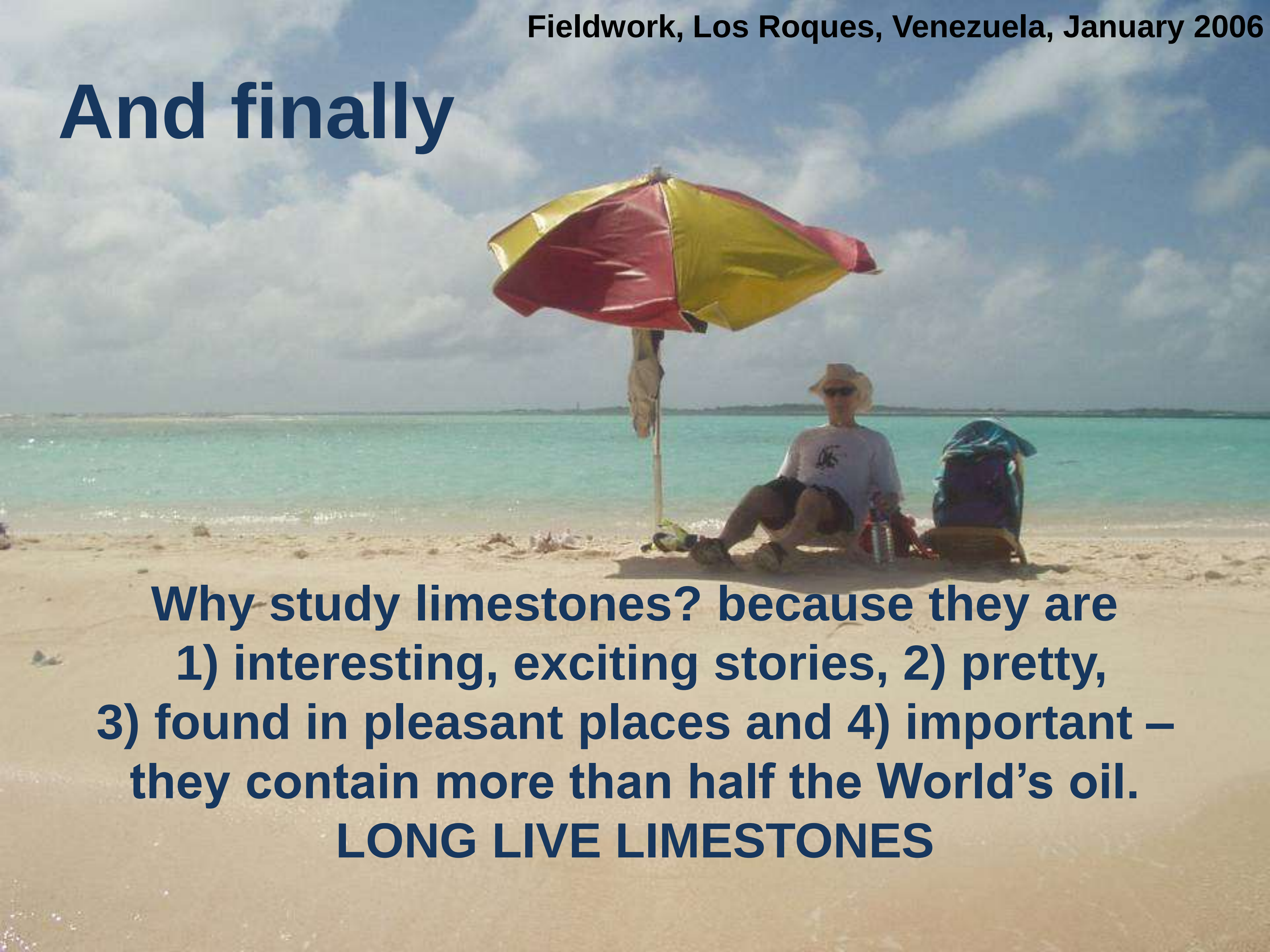
Whole range of reservoir types but presence of fractures significant.

Breccia is a common reservoir type but often difficult to be sure of origin from core material.

Biomarkers indicate variations across the basin in terms of redox; best potential source rocks in the slope and restricted lagoon facies.

Fieldwork, Los Roques, Venezuela, January 2006

And finally



Why study limestones? because they are 1) interesting, exciting stories, 2) pretty, 3) found in pleasant places and 4) important – they contain more than half the World's oil.

LONG LIVE LIMESTONES

THANK YOU

A convenient stop in the desert during fieldwork in Qatar