Microbial Carbonate Reservoirs of the Argyll and Auk Fields Reinterpreted in a Sequence Stratigraphic Context*

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Abstract

The shift of focus to basin margin areas, prompted by the UK 29th Licensing Round, has led to re-evaluation of the Palaeozoic, including the Zechstein. The Zechstein reservoir interval in the Northern Permian Basin (NPB) is encompassed by the Halibut Carbonate Formation, equivalent to the entire Z1 (highstand and lowstand systems tracts) and lower part of the Z2 (highstand systems tract) cycles of the Southern Permian Basin (SPB). However, previously, little attempt has been made to extend the SPB sequence stratigraphic understanding into the NPB. The Zechstein is a major reservoir in the Argyll and Auk fields. Historically, opinions have varied as to the interpretation of the Zechstein reservoir facies in these fields. Some former interpretations suggest deposition on a shallow carbonate shelf, with the main reservoir consisting of peritidal stromatolites. However, after re-examined of the core from these fields within the context of a regional study, it has been concluded that deposition took place in a basinal position. The main reservoir of the Auk and Argyll fields is interpreted as a lowstand deposit. Its microbial nature is a reflection of the hypersalinity that characterised lowstand deposition in the Zechstein. This microbial facies can be recognised regionally and is present under thick Zechstein salt (again indicative of a basin centre position) in a well in the northern part of the Central Graben, where the upwards change to microbial facies is abrupt and associated with the immediate cessation of clastic input, indicating a major change in basin hydrology. Analogous lowstand carbonates are similarly recorded in the centre of the SPB, developed offshore from anhydrite platforms. A possible small scale modern analogue is Great Salt Lake, Utah, where microbialites cover >1200 km^2 of the lake floor. This study shows that it is possible to extend a unified Zechstein sequence stratigraphic model across both the SPB and NPB. This has shed new light on the depositional architecture of the Zechstein system, leading to revised interpretations of the origin and distribution of microbial reservoir facies. Additionally, it highlights the dangers of only considering highstand depositional models when searching for reservoir analogues. Recent results from the 38/02-1Z exploration well are interpreted in the light of this new sequence stratigraphic study, resulting in further insights into the palaeogeography of early Zechstein deposition.

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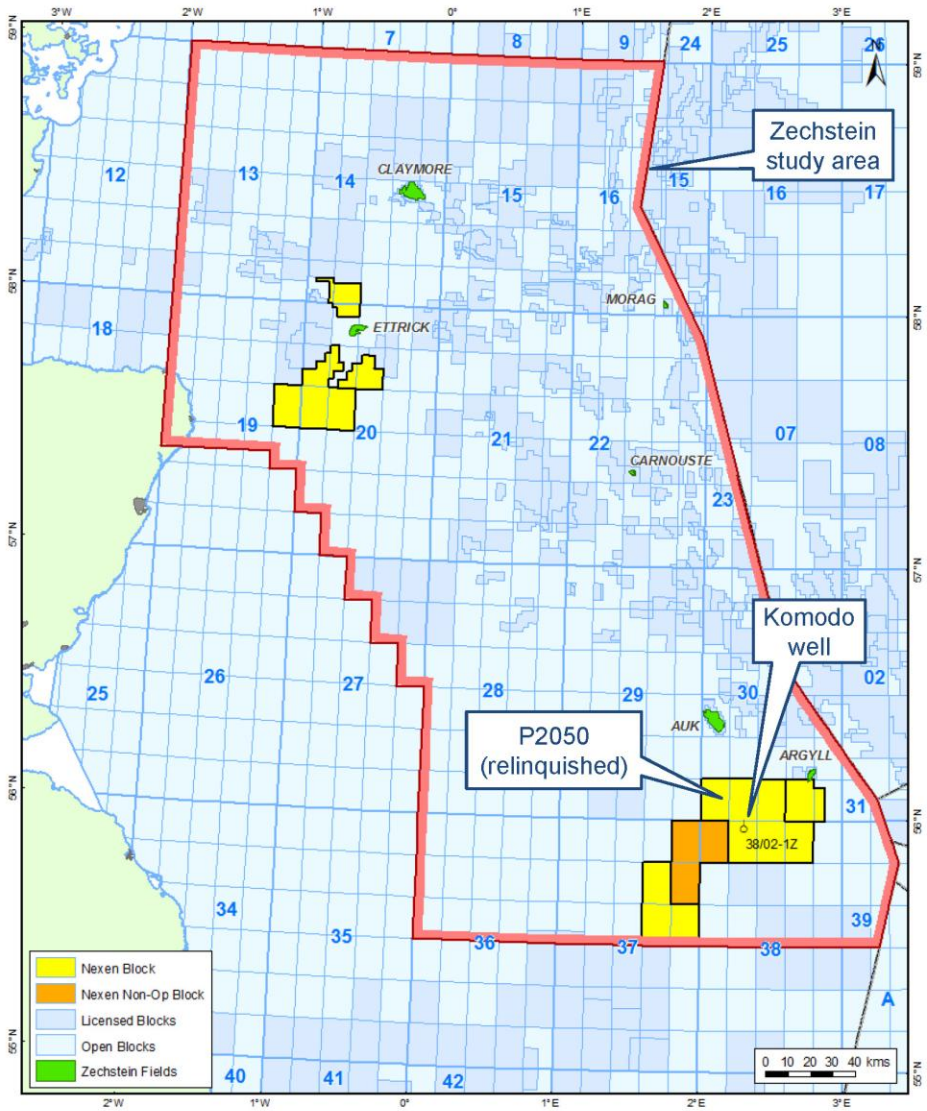
Key Messages



Zechstein specific:

The Zechstein of the Auk and Argyll fields includes a previously unrecognised Z1 lowstand systems tract that can be widely recognised in the Northern Permian Basin

General:

Given the same data set, it is possible to produce very different depositional models, with potentially major implications for hydrocarbon exploration and development

Presenter's notes: In 2016 Nexen drilled the Komodo well in the P2050 license in the southern Central Graben with dual Zechstein and Rotliegend targets. Initially we thought the Zechstein succession in Komodo would be like that in the nearby Auk & Argyll fields, the most significant Zechstein discoveries in the NPB. Note the Argyll is now called Alma. However, a combination of in-house work and core based observation made by Geospatial Research Limited as part of a Zechstein multi-client study made us change our minds about the depositional setting of the Zechstein in the area. This presentation documents the story behind this change in interpretation.

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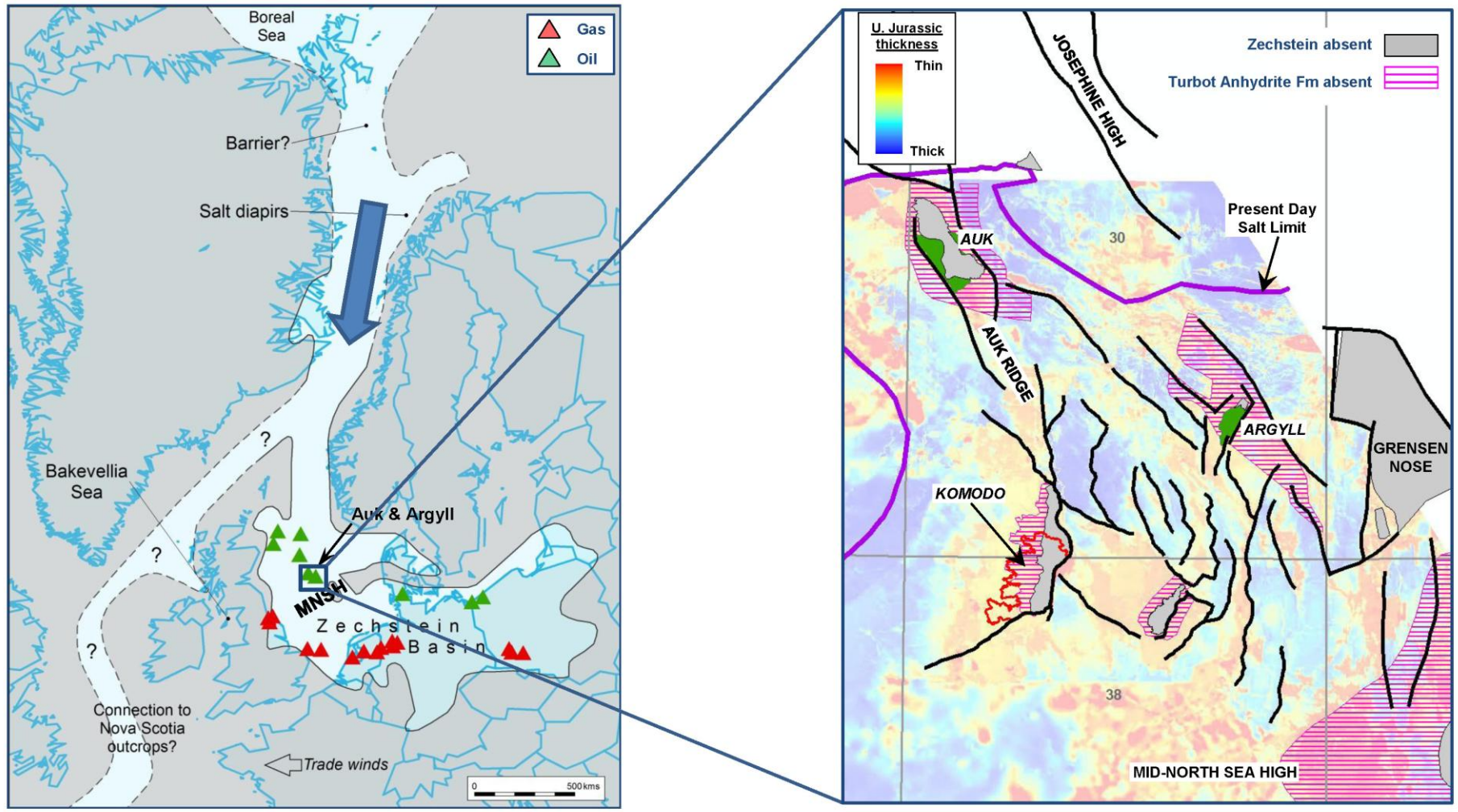
The key messages of this talk is are:

- that the microbial reservoirs of the Auk and Argyll fields are part of a Z1 lowstand systems tract that can be widely recognised in the Northern Permian Basin, not the Z1 highstand systems tract as previously suggested in publications about these fields
- depositional models are not unique and it is possible to come up with very different models based on largely the same dataset, with potentially major implications for exploration and development

Zechstein Basin Palaeogeography



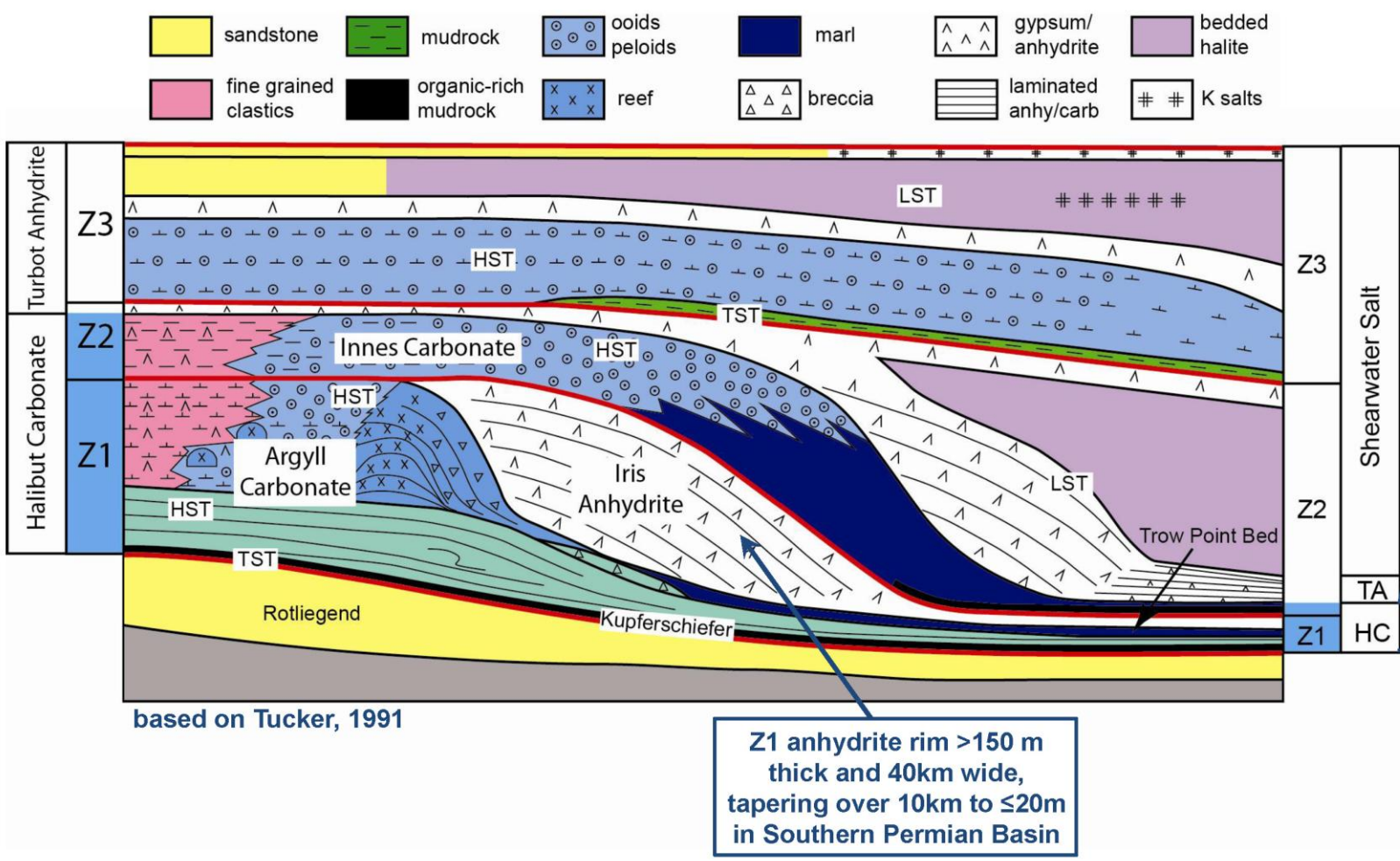
based on Taylor (1986)

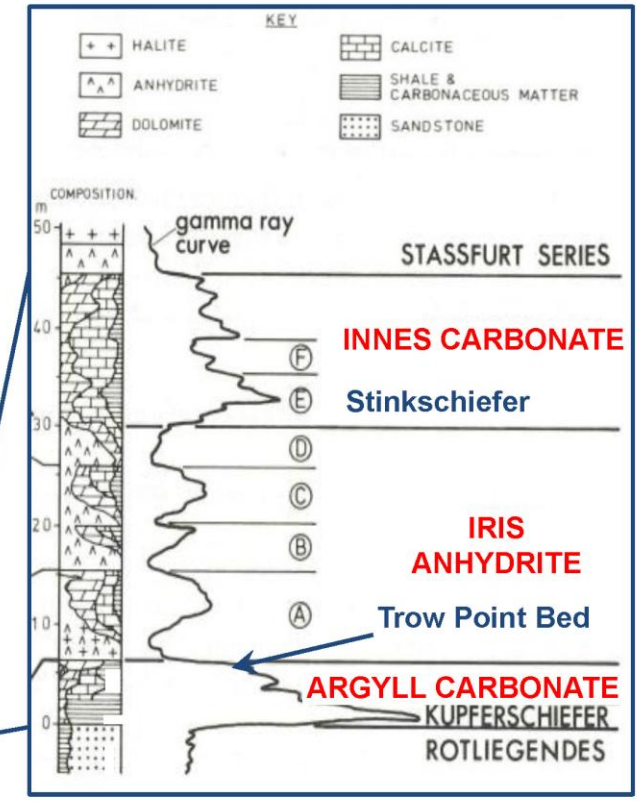
Presenter's notes: The Zechstein Sea formed in the Late Permian when an intra-cratonic depression was catastrophically flooded by the Boreal Ocean to several 100 ms water depth. The basin was divided into southern and northern parts by the mid-North Sea High. Since the only connection from the southern basin to the wider ocean system was via the northern basin we presume that both basins experienced the same sea level history. Thus, the much better understood southern basin is considered a strong analogue for its northern counterpart.

Zooming in, this map of Upper Jurassic thickness highlights the Mesozoic faulting that formed the Argyll and Auk structures and resulted in the creation of reservoir quality within the Zechstein. The highs are highlighted by the hot colours on the underlying map of Upper Jurassic thickness. Mesozoic uplift resulted in the total removal of the Zechstein over parts of both fields (grey areas) and the dissolution of anhydrite over a wider area (pink hatched areas). The Komodo prospect lies on a southern extension of the Auk Ridge.

Southern Permian Basin Analogue

Lower Zechstein architecture in Southern Permian Basin





Z1/Z2 basinal log signature in Southern Permian Basin (Taylor, 1980)

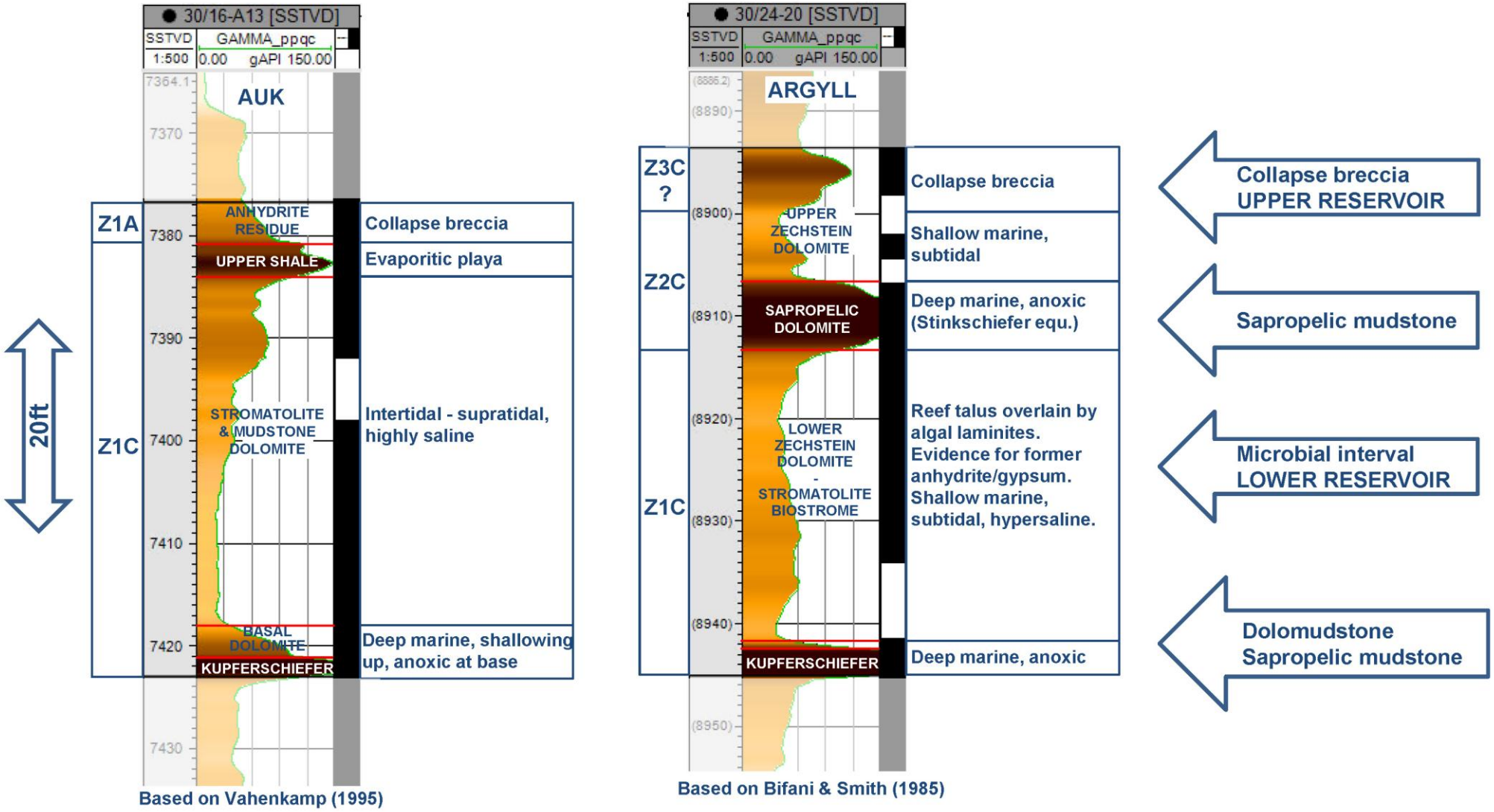
Presenter's notes: The architecture of the lower part of the Zechstein in the SPB is illustrated here. The succession consists of a number of basinwide cycles, named Z1, Z2 etc consisting of carbonate highstand and evaporite lowstand systems tracts. The majority of the topography was filled during the first two cycles. We expect the same general organisation in the northern basin, where the lower, more carbonate dominated, interval is called the Halibut Carbonate Formation. The upper evaporite dominated interval is called either the Turbot Anhydrite or Shearwater Salt formations. The Halibut Carbonate has 3 member, the Argyll, Iris and Innes that correlate with the Z1 carbonate, Z1 anhydrite and Z2 carbonate respectively.

(Presenter's notes continued on next slide.)

(Presenter's notes continued from previous slide.)

The gamma signature of the condensed basinal succession looks like this in the southern basin. At the base is the high gamma Kupferschiefer sapropelic mudstone which becomes less prominent or absent around the basin margins, either due to facies change or non-deposition. Above this is a condensed Z1 carbonate unit topped by the Trow Point Bed, which consists of small columnar stomatolites and/or oncoides, which is widely present outboard of the Z1 platform in the southern basin. The low gamma basinal Z1 lowstand deposits consist of alternations of anhydrite and laminated carbonate, in some cases the carbonate being dominant. Above this is another high gamma sapropelic interval referred to as the Stinkschiefer which marks the base of the Z2 carbonate. In NPB terminology these units would be named as shown here. Note that much of the Iris Anhydrite would not actually be anhydrite in a basin centre setting in this scenario.

Auk and Argyll Zechstein Published Interpretations



Presenter's notes: This slide shows the successions in the Argyll and Auk fields based on published information. The key points are:

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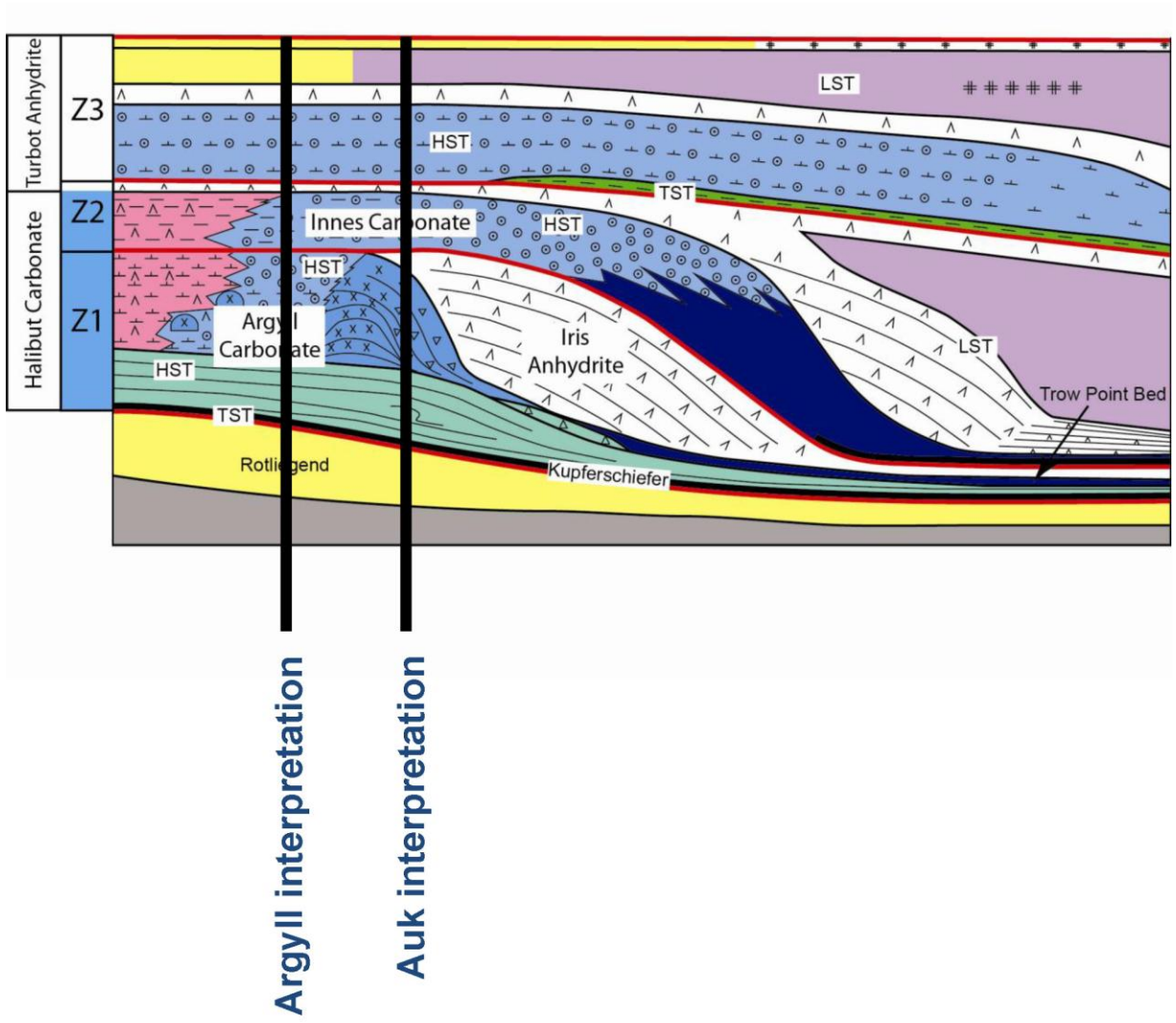
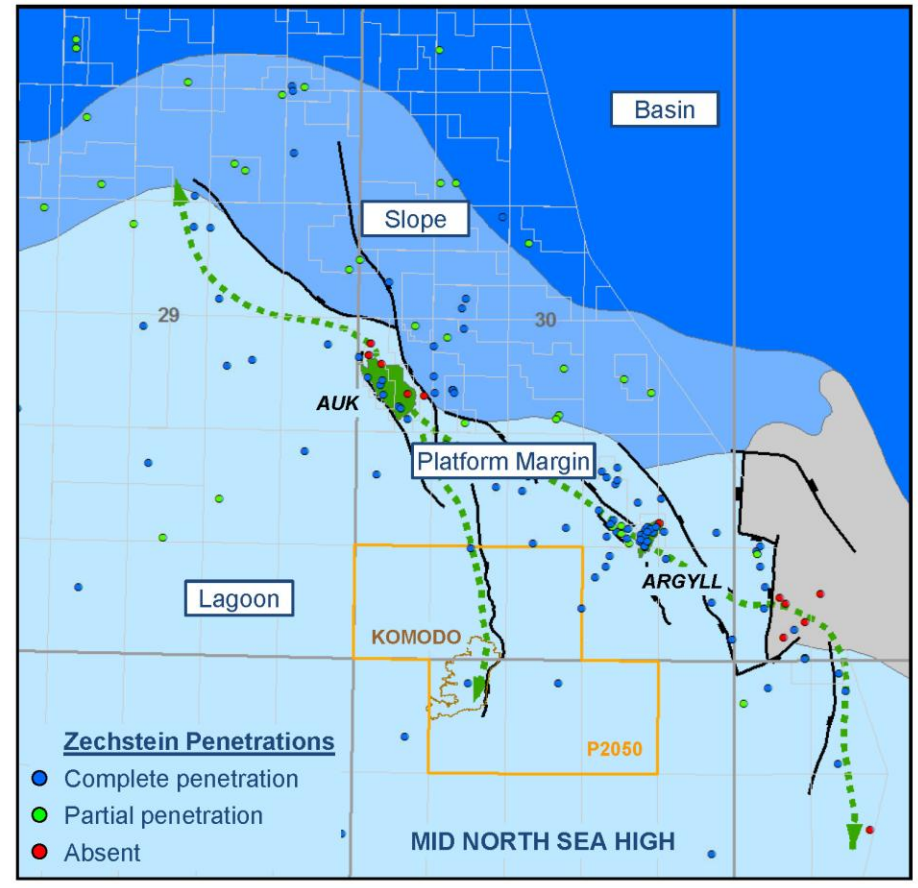
- at the base there is a well developed Kupferschiefer overlain by thin dolomudstone, interpreted as basinal
- this is abruptly overlain by a microbial interval, which forms the lower reservoir unit, interpreted as peritidal to shallow marine
- above is another high gamma sapropelic dolomite, and
- the succession is capped by a collapse breccias which comprises the upper reservoir unit.

Both authors agree that the microbial unit belongs to the Z1 highstand carbonate, but differ in their interpretations of the upper interval. The Argyll interpretation has the sapropelic dolomite at the base of the Z2 carbonate and correlated to the Stinkschiefer of the southern basin. In this interpretation the Z1 lowstand is missing. In the Auk interpretation the sapropelic unit was interpreted as a local playa deposit on the platform top, with the residue of the Z1 lowstand evaporite above.

Original Depositional Model

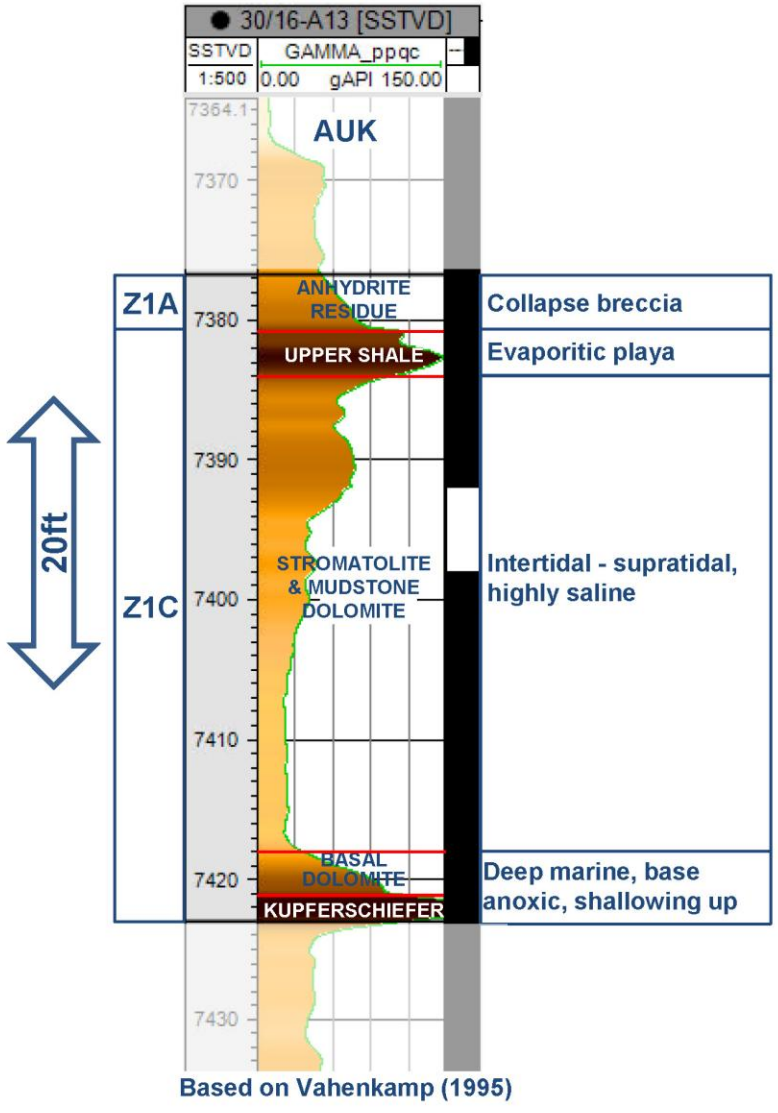


Original depositional model

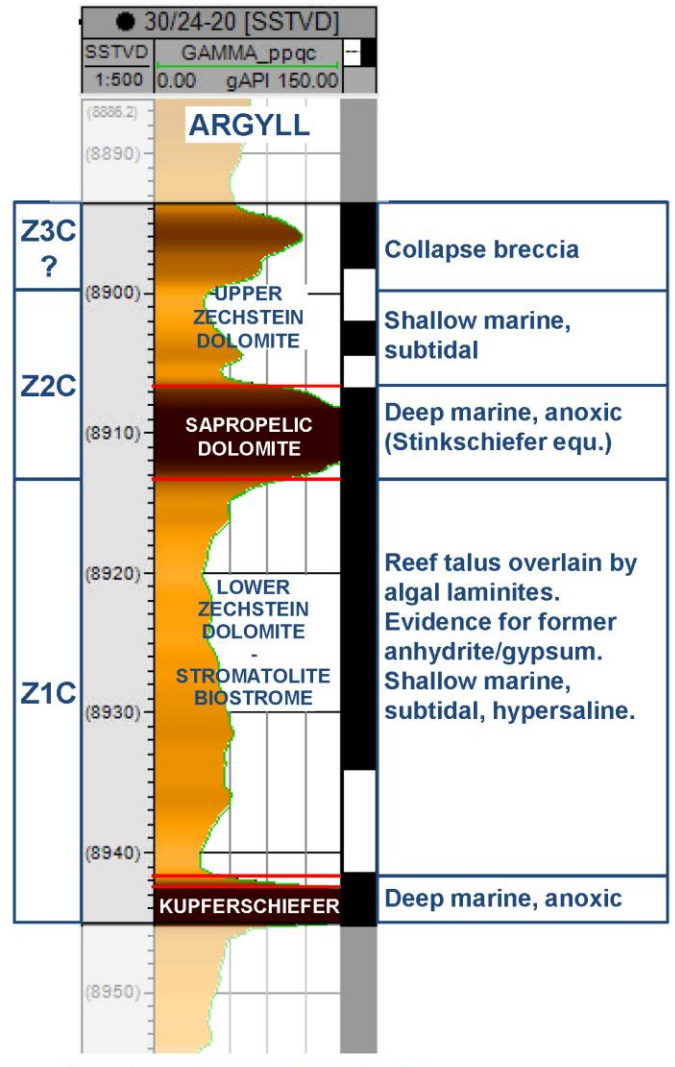


Presenter's notes: These interpretations place Auk and Argyll in the locations shown here on our cartoon cross section. Based on this we initially interpreted the palaeogeography to look like this during deposition of the Halibut Carbonate Fm. The model infers an underpinning basement high that formed the shelf margin, which became reactivated in the Mesozoic. Hence, there was a shelf margin belt of relatively shallow water where peritidal microbial facies could develop with a deeper shelf lagoon to the SW. It was argued that since the Komodo Prospect was on an extension of the Auk Ridge, it was also a relative high during Zechstein deposition, so a succession similar to that seen in Auk and Argyll could be expected. We now think that there was a fundamental flaw in our understanding of the stratigraphy of the Auk and Argyll fields.

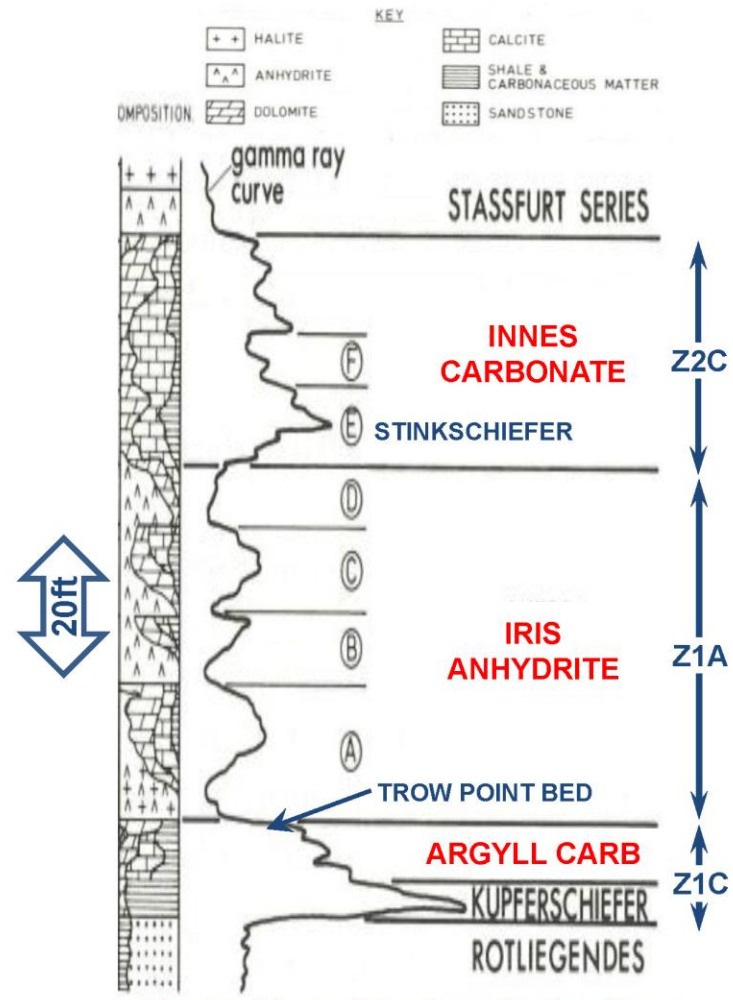
Southern Permian Basin Analogue



Based on Vahenkamp (1995)



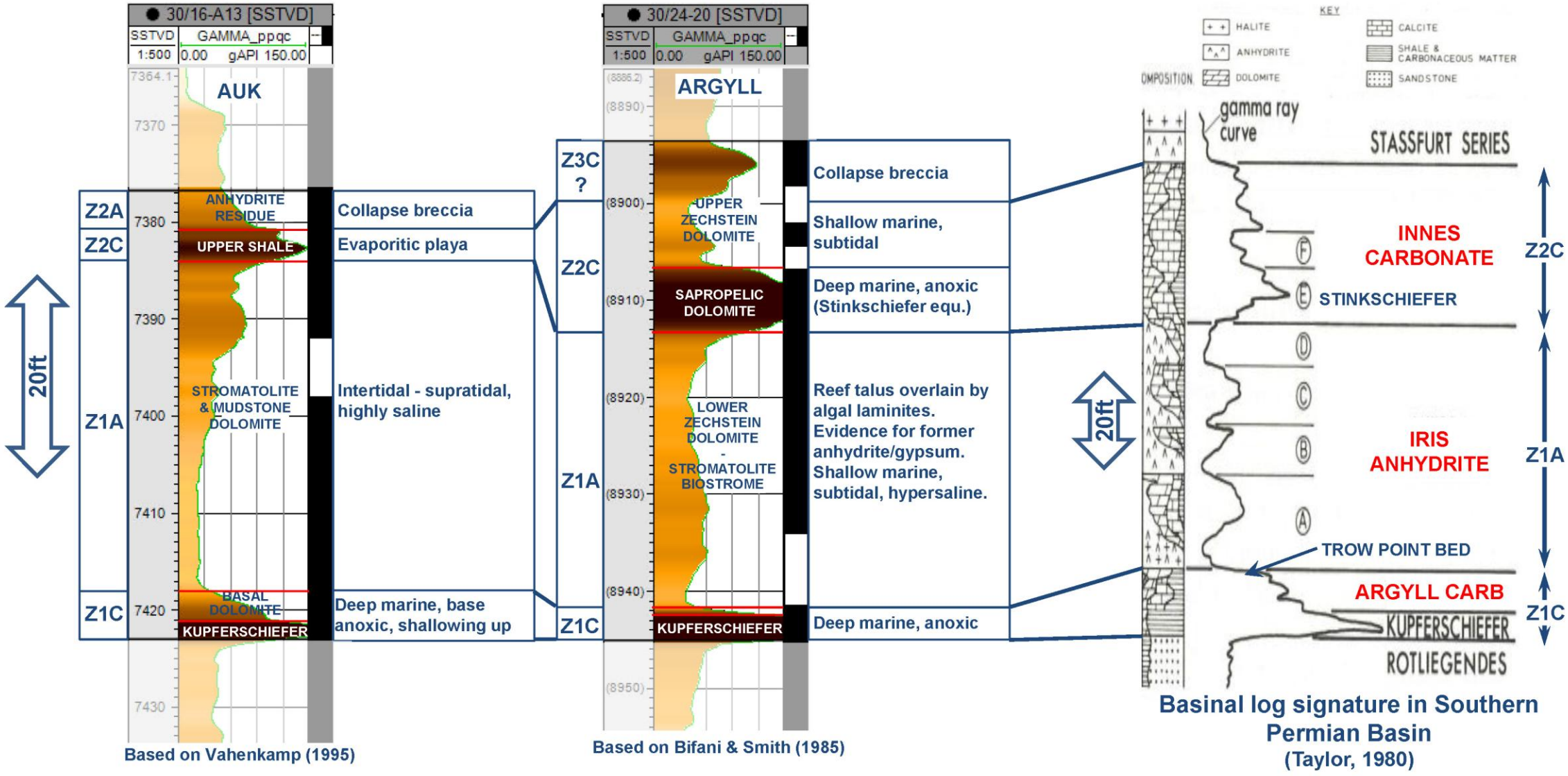
Based on Bifani & Smith (1985)



Basinal log signature in Southern Permian Basin
(Taylor, 1980)

Presenter's notes: If you compare Argyll and Auk wells to the basinal succession of the southern basin there are some notable similarities, although the succession is approximately 3x thicker in the southern basin. In particular, the character of the Z1 carbonate compared to the Kupferschiefer and Basal Dolomite, the low gamma character of the overlying unit and the ramp up in gamma to an upper sapropelic unit.

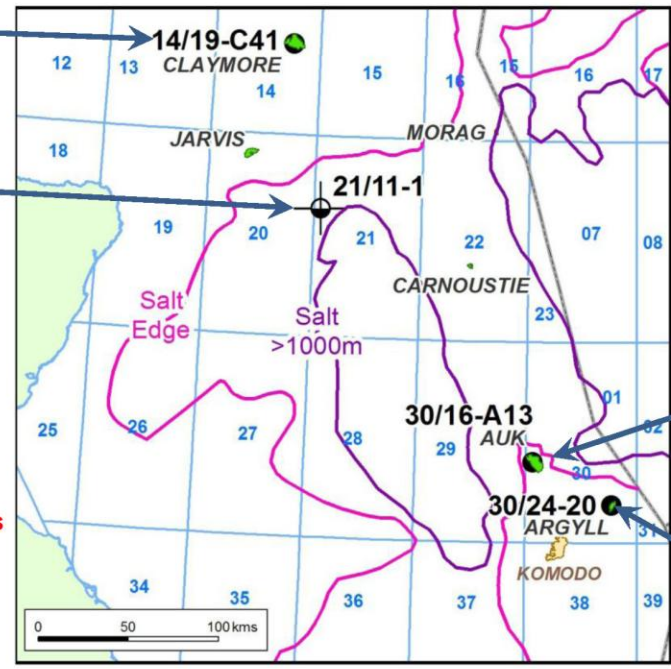
Southern Permian Basin Analogue

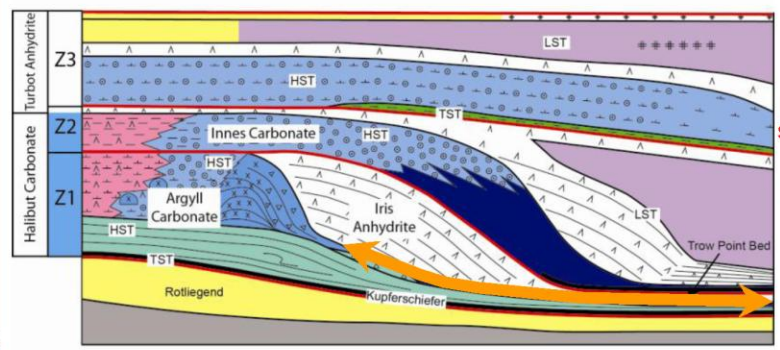


Presenter's notes: We now interpret the microbial unit to be associated with the Z1 lowstand, rather than the highstand, making it equivalent to the Iris Anhydrite Member, and the subsequent sapropelic unit to be equivalent to the Stinkschiefer.

We will now look at the evidence supporting this interpretation.

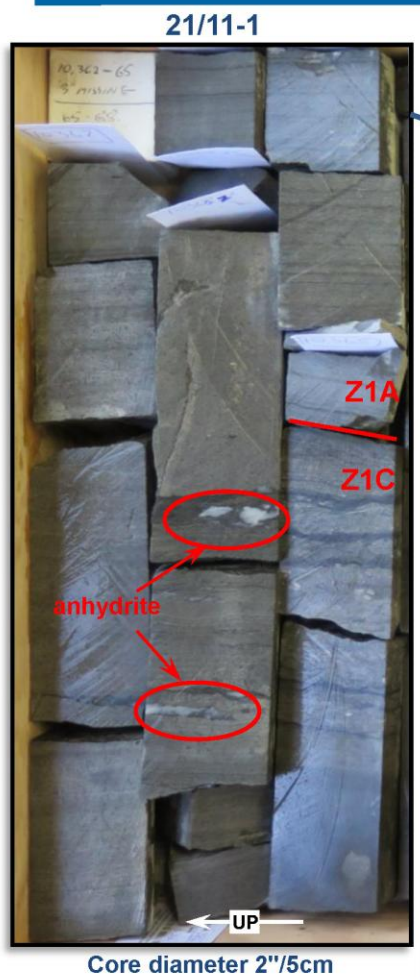
Trow Point Bed Equivalent Identified in NPB

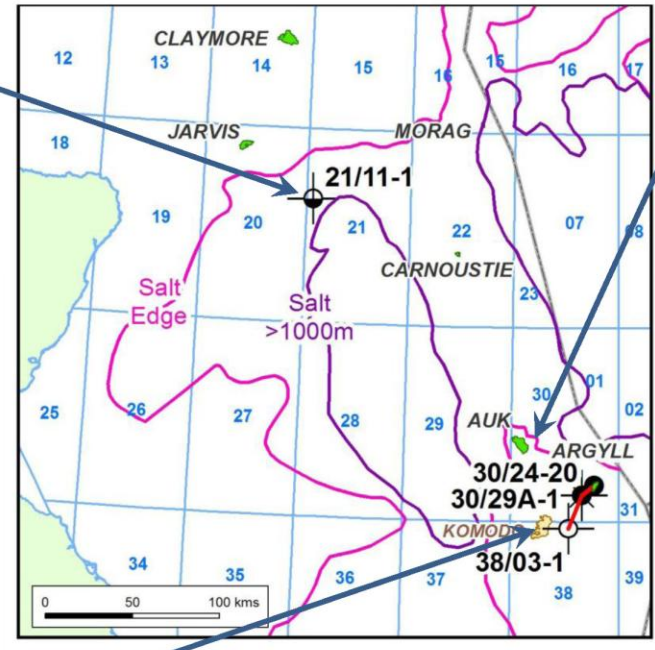


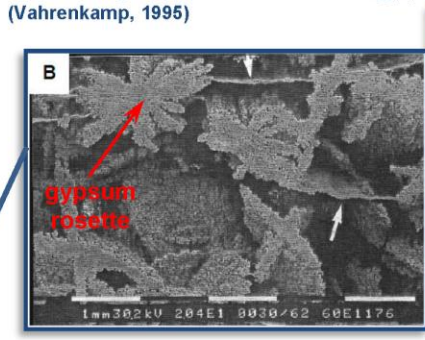


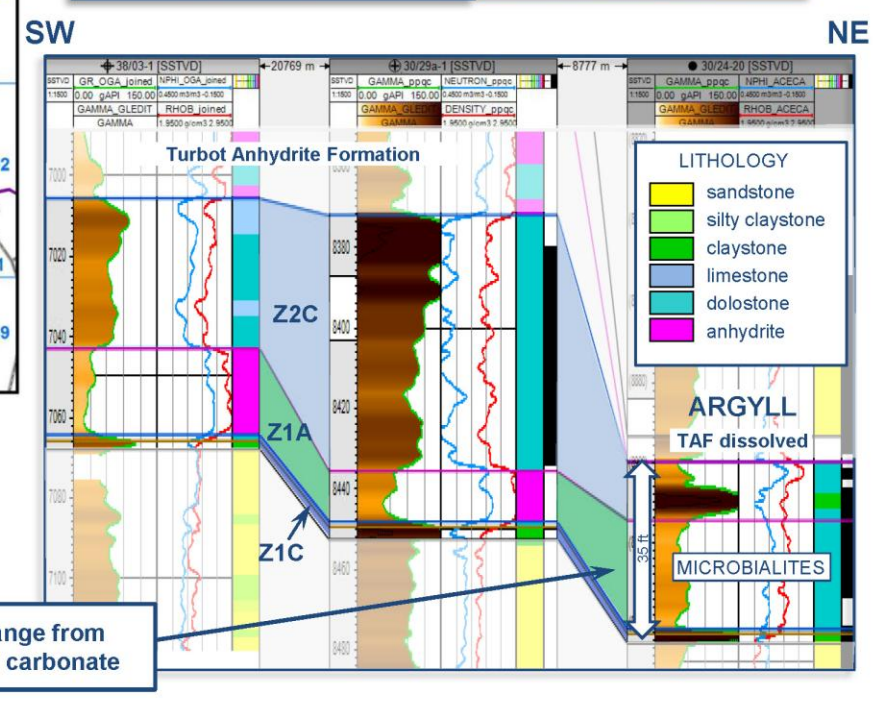
Presenter's notes: We recognise an equivalent of the Trow Point Bed throughout the northern basin, marking the boundary between Z1 highstand and lowstand deposits. It is illustrated here in 4 wells from widely spaced locations shown on the map, the pink and purple lines show the location of the later salt basin and hence the basin centre. The Argyll well is the most proximal and has columnar stromatolites of similar dimension to those described from outcrops of the Trow Point Bed in NE England. In the other wells a thin bed of poorly preserved oncoids is present similar to that described from the centre of the southern basin. Note the abrupt change to laminated facies above the Trow Point Bed in all of these wells, indicating a sudden change in basin hydrology.

Association of Anhydrite with Microbialite









Presenter's notes: We are saying that the microbialite interval is equivalent to the lowstand evaporite. So what evidence is there that the microbialites in the NPB are associated with anhydrite? Well, there is quite a lot of evidence and it comes in a variety of forms.

Lateral equivalents of the microbial unit still retain anhydrite and in some cases the unit is wholly anhydritic, as seen in this well correlation to the SW of Argyll. In basin centre wells anhydrite nodules are invariably observed.

(Presenter's notes continued on next slide.)

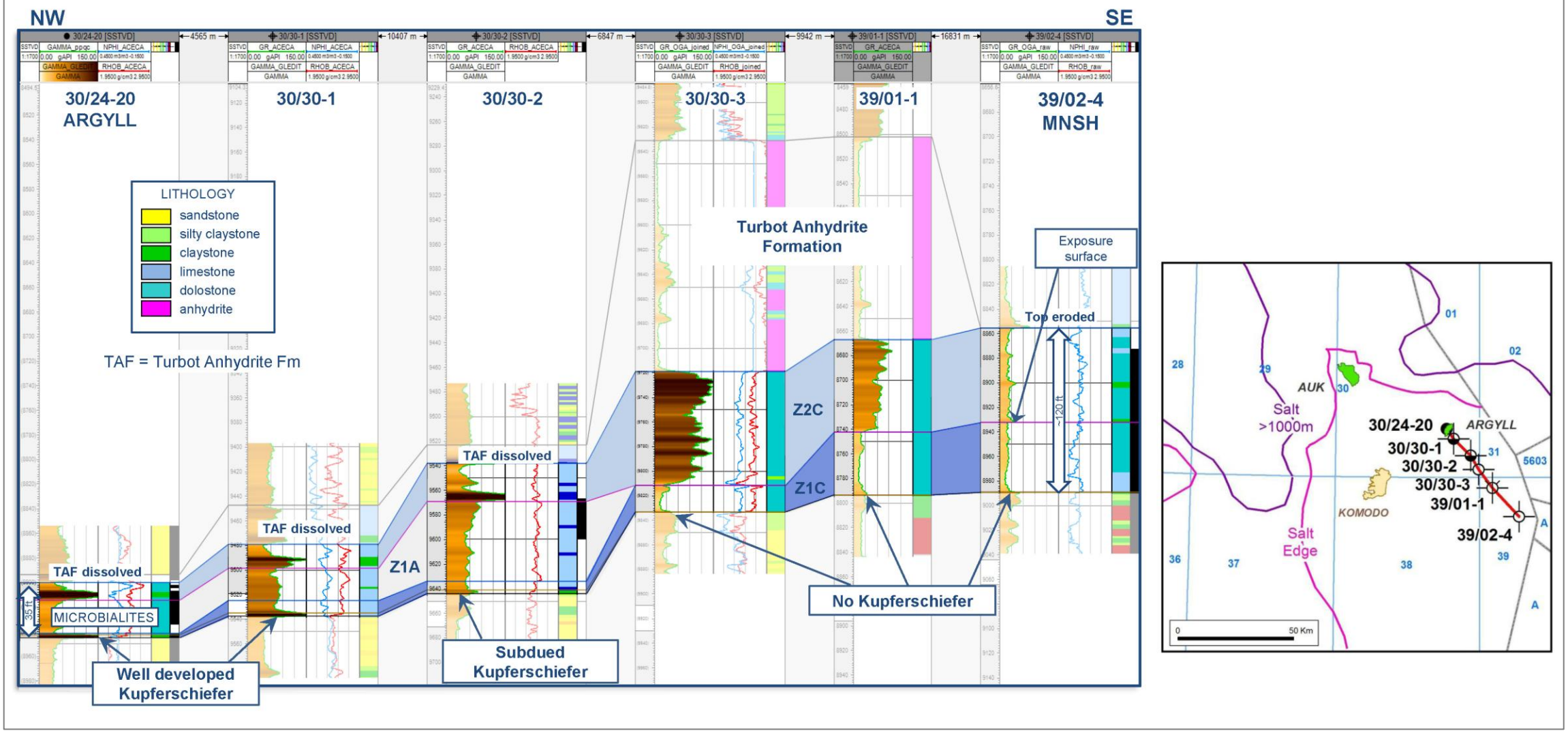
(Presenter's notes continued from previous slide.)

In wells that have been affected by dissolution monomict breccias are present within the microbial interval, which we suggest are evaporite dissolution breccias, rather than karsts as previously suggested.

Vahrenkamp showed that dolomudstones present within the microbial interval of the Auk Field originally consisted of carbonate/gypsum mush, illustrated in these pore cast and CL images. Note the gypsum rosettes and the darker areas that are replaced gypsum crystals.

Consequently, there is little doubt that evaporites were an important original feature of the microbial unit, even if those evaporites are no longer preserved.

Basin Scale Geometry



Presenter's notes: Finally, the large scale basin geometry shows that the platform margin was located to the south of the Argyll Field on the MNSH. This arrow indicates where the cross section lies on our cartoon cross section. The most proximal well consists of 120 ft of clean, shallow water carbonates, confirmed by core. In the Argyll well the equivalent interval is only 35 ft thick and contains common deep water facies. Additionally, the Kupferschiefer can be seen becoming less prominent in a proximal direction. It is difficult to reconcile these observations with shallow water, highstand deposition at the Argyll location during formation of the microbial interval. The easiest explanation is that the microbial interval was deposited during a lowstand in the basin, which is shown here as a wedge that butts out against the Z1 platform. The other conclusion we can draw from this is Zechstein deposition at Argyll was not substantially influences by a precursor to the present structure. Consequently, our assumption that the Komodo Prospect would be a copy of Auk and Argyll because of its structural position was flawed.

Basin Scale Geometry

NW

30/24-20 [SSTVD] — 4565 m — 30/30-1 [SSTVD] — 10407 m — 30/30-2 [SSTVD] — 6847 m — 30/30-3 [SSTVD] — 9942 m — 39/01-1 [SSTVD] — 16831 m — 39/

30/24-20 ARGYLL

30/30-1

30/30-2

30/30-3

39/01-1

LITHOLOGY
- sandstone
- silty claystone
- claystone
- limestone
- dolostone
- anhydrite

TAF = Turbot Anhydrite Fm

Turbot Anhydrite Formation

Exposure surface

Top eroded

~120 ft

Z2C

Z1C

Z1A

TAF dissolved

TAF dissolved

TAF dissolved

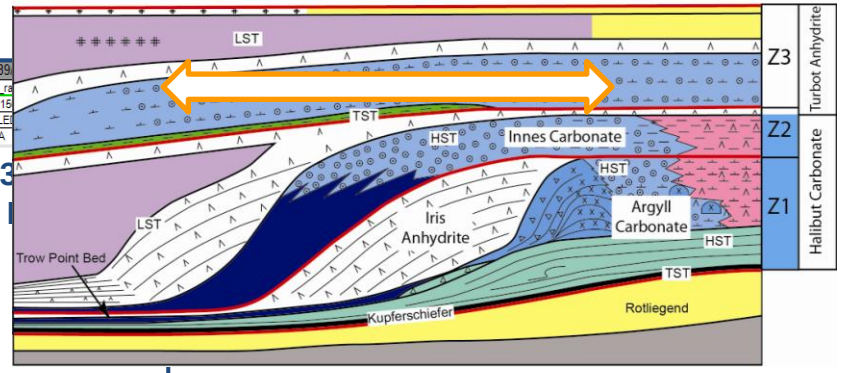
35 ft

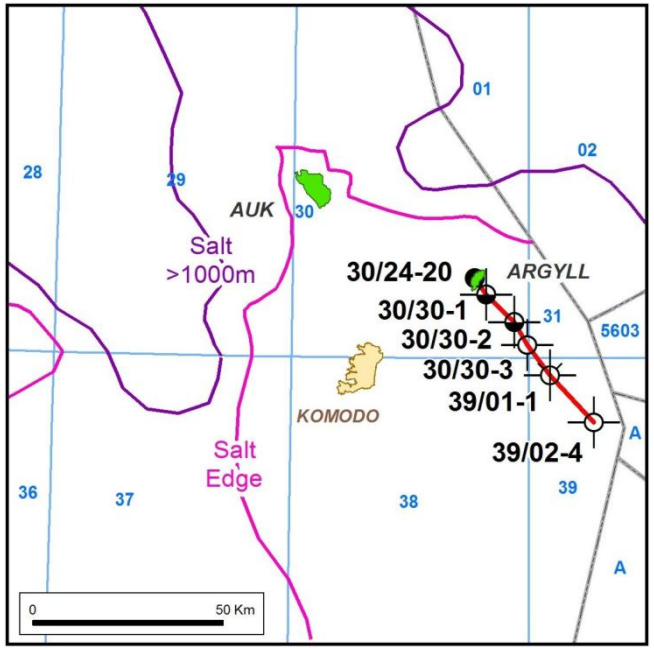
MICROBIALITES

Well developed Kupferschiefer

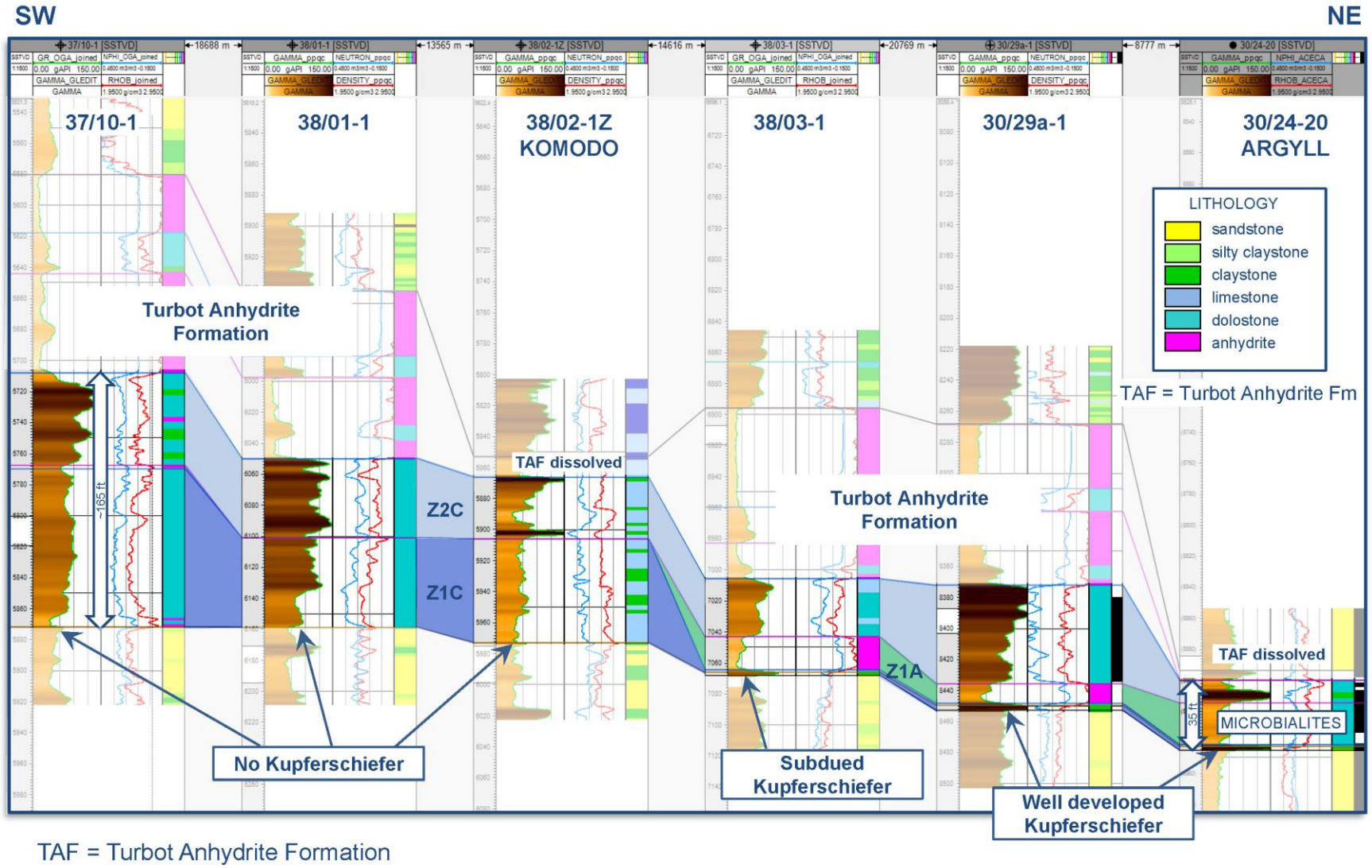
Subdued Kupferschiefer

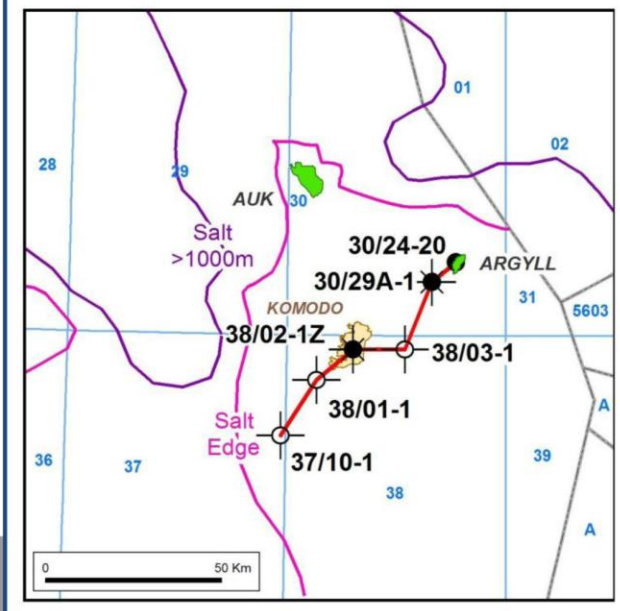
No Kupferschiefer





Komodo Interpretation Post-drill



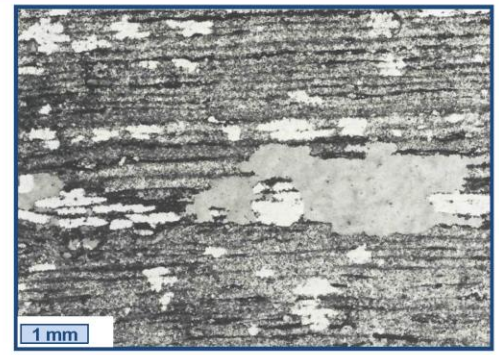


Presenter's notes: This is supported by the results of the Komodo well. Other than the fact that the upper anhydrite has been removed, the Komodo well has more in common with the wells to the SW, which we interpret as slope facies because of the relatively elevated gamma ray signature, than to the basinal wells to the NE. The Z1 lowstand anhydrite, laterally equivalent and up-dip of the Argyll microbial reservoir, butts out against the slope of the Z1 slope.

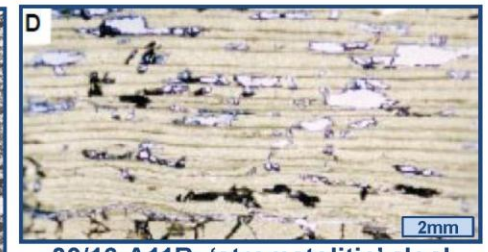
This raises questions regarding the depositional environment of the microbialites.

Subaqueous Origin of Z1 Microbialites

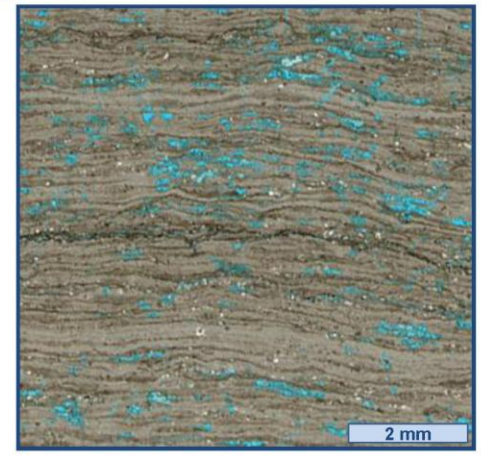
- Analogy with time equivalent deposits in the SPB suggests that the NPB must have been flooded during the Z1 lowstand, although water levels were likely highly unstable
- Microbialites lack desiccation features
- Widespread uniformity in microbial facies
- □Stromatolitic□ facies from Auk looks similar to deep water, basinal laminated carbonates from the Middle Carbonate Member of the Z1 Anhydrite, Denmark



SPB basin centre mm-bedded carbonate mudstones, Middle Carbonate Member, Z1 Anhydrite, Denmark (Clark , 1980)



30/16-A11B: 'stromatolitic' algal laminae (Vahrenkamp, 1995)



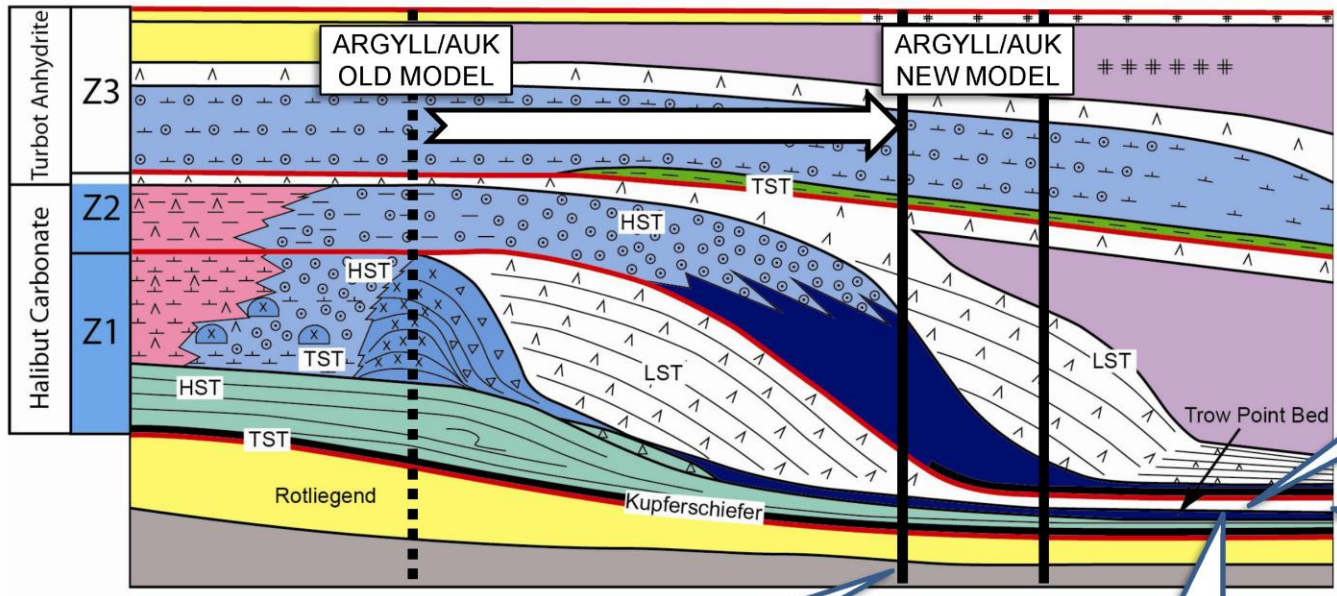
14/19-B2: Z1 lowstand laminated facies

Presenter's notes: The geometry of the Z1 evaporite platforms in the SPB requires that for much of the time the centre of the SPB contained 100's m water, although water levels were likely highly unstable. This implies that the NPB was similarly flooded during the Z1 lowstand, although water depth may have been less. This is supported by various lines of evidence.

This is a fairly typical thin section image of the Z1 microbialites. Sedimentary structures supporting emergence, such as bird's eye vugs, mud cracks, teepees and rip-up clasts, are absent, something noted by the Argyll authors. This and the widespread uniformity of this facies suggest a subaqueous origin.
'Stromatolitic ' facies from Auk look similar to laminated carbonates from the Middle Carbonate Member of the Z1 Anydrite in Denmark, interpreted to be of deep water origin.

All this points to subaqueous deposition, but at what water depth is uncertain. Examples like Great Salt Lake illustrate that extensive subaqueous formation of microbialites in hypersaline conditions is possible, although I am not suggesting this as a direct analogue. More work is required to fully understand the depositional setting of this facies.

Revised Zechstein Understanding Summary



A Z1 lowstand system tract analogous to that of the Southern Permian Basin is present throughout the Northern Permian Basin

Abrupt change from basinal mudstones to laminated microbialites explained in terms of switch from highstand to lowstand deposition

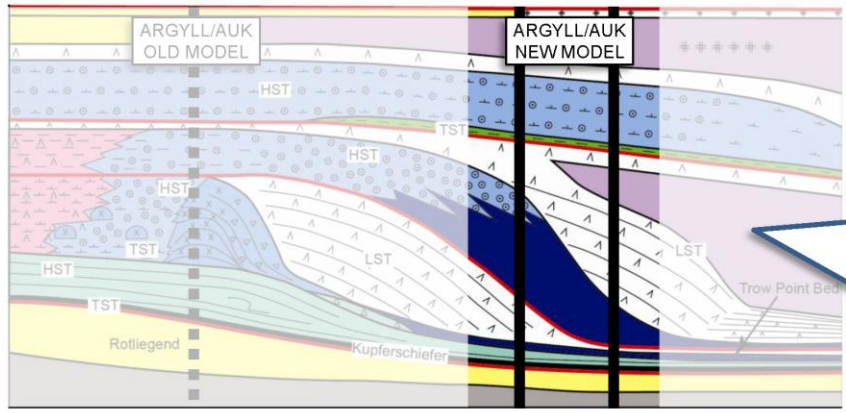
Argyll & Auk are in a basinal position with the microbial unit representing the Z1 lowstand systems tract

An equivalent to the Trow Point Bed is widely present in the Northern Permian Basin

Presenter's notes: In summary:

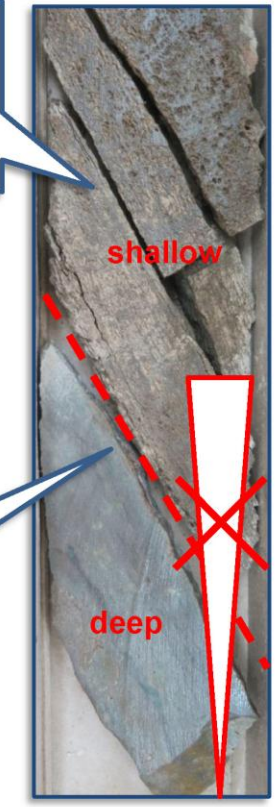
- We now interpret the Auk and Argyll fields to be in a basinal position during Zechtein deposition, with the microbial unit representing the Z1 lowstand systems tract.
- This lowstand systems tract is analogous to that of the Southern Permian Basin and is present throughout the northern basin. The microbialites are likely subaqueous in origin, but water depth is uncertain. We are not the first to came to this conclusion. Our interpretation is in agreement with that of Taylor published in the 2nd edition of Introduction to the Petroleum Geology of the North Sea, which seems to have been largely forgotten because the Zechstein chapter has changed in content in subsequent editions of the book, although it is expressed our ideas in more sequence stratigraphic terms.
- A previously unrecognised equivalent to the Trow Point Bed is widely present in the Northern Permian Basin, highlighting the similarity between the northern and southern basins
- The abrupt change from basinal mudstones to laminated microbialites commented on by previous authors has been explained in terms of a change from highstand to lowstand deposition.

Same Data, Two Models – Why?



Depositional models for small areas of a basin have to make sense in terms of the sequence stratigraphic architecture of the basin as a whole and the geometrical constrains that imposes

The rocks are important and the details matter



An abrupt change from deep to shallow water deposition cannot be described as a shallowing upward succession

Analogues need to be understood and leveraged to their maximum

Important details in original publications are often lost in transcription to databases compiled from public domain data

The Trow Point Bed—a deposit of Upper Permian marine oncoids, peloids and columnar stromatolites in the Zechstein of NE England

D.B. Smith

SUMMARY An extensive thin bed of oncoids, peloids and columnar stromatolites occurs at the top of the Cycle 1 carbonate of the English Zechstein sequence in NE England, here termed the Trow Point Bed, it lies on the lower part of the basin-margin slope, basinward of a linear shelf-edge reef in the Ford Formation. The bed is generally 0.05–0.20 m thick but locally ranges to 0.60 m, it rests on an uneven surface that has a local relief of up to 15 m and slopes exceeding 35° in places. It contains a sparse marine fauna of foraminifera, ostracods and bivalves; there are only a few traces of current action and sorting, and terrigenous sediment nowhere comprises more than 5% of the bed.

The Trow Point Bed is generally similar to deposits described at a comparable stratigraphical position in Germany and Poland and although environmental indications are partly mutually contradictory, it seems likely that the bed accumulated in oxic conditions on the basin floor under water perhaps 25–100 m deep.

Stratigraphy and distribution

The Trow Point Bed is an extraordinarily extensive thin dolomitized bed of oncoids, peloids and subsidiary columnar stromatolites at the top of the Cycle 1 carbonate of the Zechstein sequence in NE England (Fig. 1) it ranges from 1 m to more than 20 m above the base of the EZ 1 carbonate according to the stratigraphic level of an underlying slide plane (see Smith 1970b). The bed lies on the lower part of the basin margin slope, entirely basinward of a linear shelf-edge reef in the Ford Formation; it has not been recognized within 3 km of the foot of the reef wall.

Oncoids at this stratigraphical position in the English Zechstein sequence have been recognized (Smith & Francis 1967, plate 13A; Magrave 1975, 1978; unpublished National Coal Board records) in the cores of several National Coal Board offshore boreholes (see Fig. 2 for distribution); elsewhere oncoids at a similar stratigraphical position have been reported from cored boreholes in the southern North Sea (Taylor & Colter 1975), northern Germany (Fachtbauer 1968; Richter-Bernburg 1982) and Poland (Peryt & Peryt 1975 and other authors).

On land in NE England the oncoid bed is exposed for about 1 km in coastal cliffs between Trow Point (NZ 386 667) and Frenchman's Bay, South Shields, and less continuously for a further 0.3 km to the SE (Smith 1970a, p. 76); farther north it has been reported in Marden Quarry near Cullercoats (Land 1974, p. 110). Trow Point has been chosen as the type locality because the bed is readily accessible there and displays most of its typical range of variation; it differs at Trow Point from most of its offshore provings, however, in that it has been partly or wholly dedolomitized during or after dissolution of the overlying Hartlepool Anhydrite.

Thickness and field relationships

The Trow Point Bed is unusually varied in thickness. At outcrop it is most commonly 0.05–0.20 m, but ranges locally to 0.60 m, it is absent from or not readily recognizable over perhaps 5–10% of its outcrop. This variation in thickness is closely related to the hummocky character of the top of the underlying slide sequence (Smith 1970b, fig. 8), the bed being thickest and most uniform in the hollows and thinning sharply against and over the steepest and tallest slide blocks and other eminences (Fig. 3); in places it clings to primary slopes of 40° or more. Variation in thickness appears to be less sharp offshore, presumably because there the bed rests on more distal (less hummocky) parts of the slide sequence. Some variations in the thickness partly result from stylolitization.

In the South Shields area the base of the Trow Point Bed has a medium-scale primary relief of at least 15 m, partly because of drape over slide blocks but mainly because of the irregularity of the underlying slide plane. Its base is also uneven in detail and in offshore boreholes B2 and B8 it features cracks up to 8 cm deep and 1 cm across that are partly filled with sediment of the bed itself; in a surface exposure (3941 6602) 1.1 km SE of Trow Point the surface bears a 3–8 cm pattern of grooves resembling desiccation cracks. Cracks

From Harwood, G.M. & Smith, D.B. (eds), 1986, *The English Zechstein and Related Topics*, Geological Society Special Publication No. 22, pp. 113–125. 113

Presenter's notes: Our original and updated models are very different despite relying on largely the same data set. It is useful to reflect on what drove the change in interpretation.

- The rocks are important and the details matter. The updated model is strongly influenced by a fresh and unbiased re-evaluation of the core data.
- For instance, shallow facies abruptly above deep facies does not constitute a shallowing upwards succession, as this transition has a times been reported. In a shallowing upward succession all the intermediary steps between the deepest and the shallowest must be present. This has important implications for the geometry of the depositional system.
- Analogues need to be understood and leveraged to their maximum and we think some similarities between the Northern and Southern Permian basins have been either missed or misinterpreted in the past.
- We have found the detail present in original publications invaluable and it is often these details that are lost in transcription to commercially available databases.
- Depositional models for small areas have to make sense in terms of the overall sequence stratigraphic architecture of a basin and the geometrical constrains that imposes. Focusing on a small area and doing 'postage stamp' geology without the regional overview can be dangerous.

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