Hydrocarbon Prospectivity of Offshore Senegal - Unlocking the Door to a New Deepwater Petroleum Province*

Louise Martin[1], Igor Effimoff[2], Joseph Medou[3], and Matthew Laughland[4]

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[1]International Exploration, Hunt Oil Company, Woking, United Kingdom
[2]First Australian Resources Ltd, Houston, TX (Igormoff@aol.com)
[3]Petrosen, Dakar, Senegal
[4]International Exploration, Hunt Oil Company, Dallas, TX

Abstract

The MSGBC Basin remains one of the last few remaining under-explored basins along the west African margin. This study, located offshore Senegal, south of the Dakar peninsula and north of Gambia, identifies all the key components required for a successful petroleum system. In 2007, an extensive 3D seismic program (20502 km) was acquired which highlighted two key parasequences: the pre-Senonian unconformity section consisting of a long-lived carbonate platform of Jurassic to Cenomanian age, and the syn-post Senonian unconformity section which consists mainly of stacked Santonian age fans with multiple stacked amplitudes on seismic and an overlying tertiary succession.

Uplift and subaerial exposure along the platform during the late Cetaceous time led to karstification and erosion that we believe are key to development of fracture-related permeability in the carbonate reservoir. Platform uplift was likely associated with differential rotation induced by the withdrawal of Triassic age salt in the southern MSGBC. The erosion event is marked by the Senonian unconformity, clearly recognizable on seismic by hummocky karstified topography. In contrast, the syn-post Senonian section consists of stacked Santonian age deepwater fans. These fan systems are genetically related to incised-valley canyons, which acted as conduits for down-slope transportation and deposition. We mapped three key canyons within the study area where detailed rock physics and attribute analysis indicate that the turbidites are a mixed lithology of reworked carbonate material and paralic siliciclastic sediments.

3D basin modeling was used to determine the timing of generation and spatial extent of the petroleum kitchen for the Turonian age source shale that was deposited along the west African margin. Onset of generation began during the Maastrichtian and continues through the present-day, and the down-slope turbidites, as well as the karstified carbonate platform, are located either within or adjacent to the present-day kitchen. Drawing on analogues from recent Ghanaian discoveries in late Cretaceous turbidites, this opens up the Senegalese offshore basin as an exciting new deep water province along the Central Atlantic realm.

Selected References

Emery, D. and K. Myers (eds.), 1996, Sequence Stratigraphy: Blackwell Science, Cambridge, Massachusetts, 297 p.

Tucker, M.E., 1985, Shallow-marine carbonate facies and facies models, *in* P.J. Brenchley and B.P.J. Williams, (eds.) Sedimentology; recent developments and applied aspects, p. 147-167.

Reading, H.G. and M. Richards, 1994, Turbidite systems in deep-water basin margins classified by grain size and feeder system: Bulletin of American Association of Petroleum Geologists, v. 78, p. 792-822.

Sellwood, B.W. and P.J. Valdes, 2006, Mesozoic climates; general circulation models and the rock record: Sedimentary Geology, v. 190-1/4, p. 269-287.

Hydrocarbon Prospectivity of Offshore Senegal, Unlocking the Door to a New Deepwater Petroleum Province

AAPG

New Orleans April 2010

Louise Martin[1], Igor Effimoff[2*], Joseph Medou[3] & Matthew Laughland[4]

*Presenter

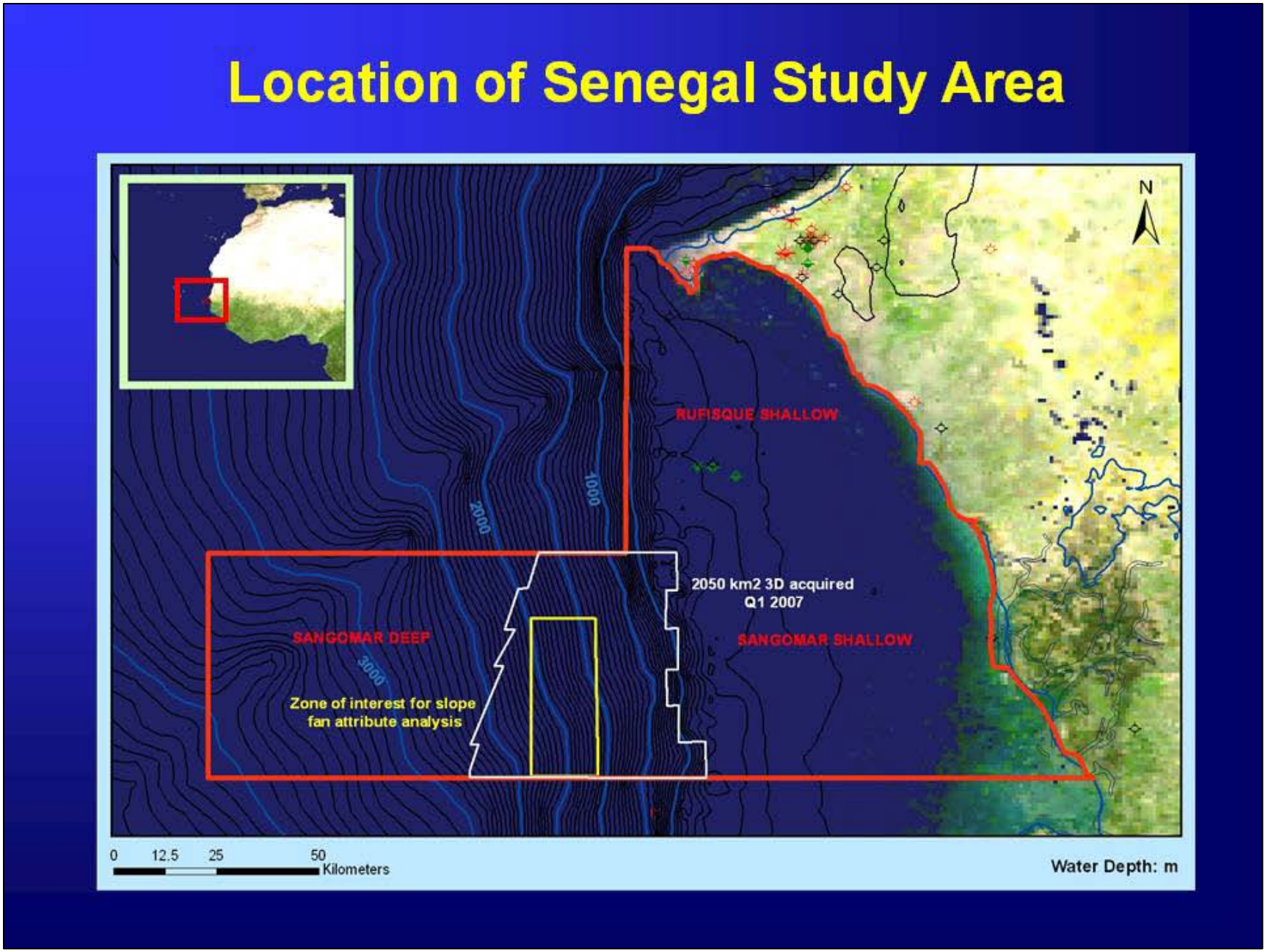
Acknowledgements

Thanks to First Australian Resources & Petrosen for allowing work to be presented.

This presentation is a collaborative effort of geoscientists from FAR, Petrosen and Hunt Oil Company.

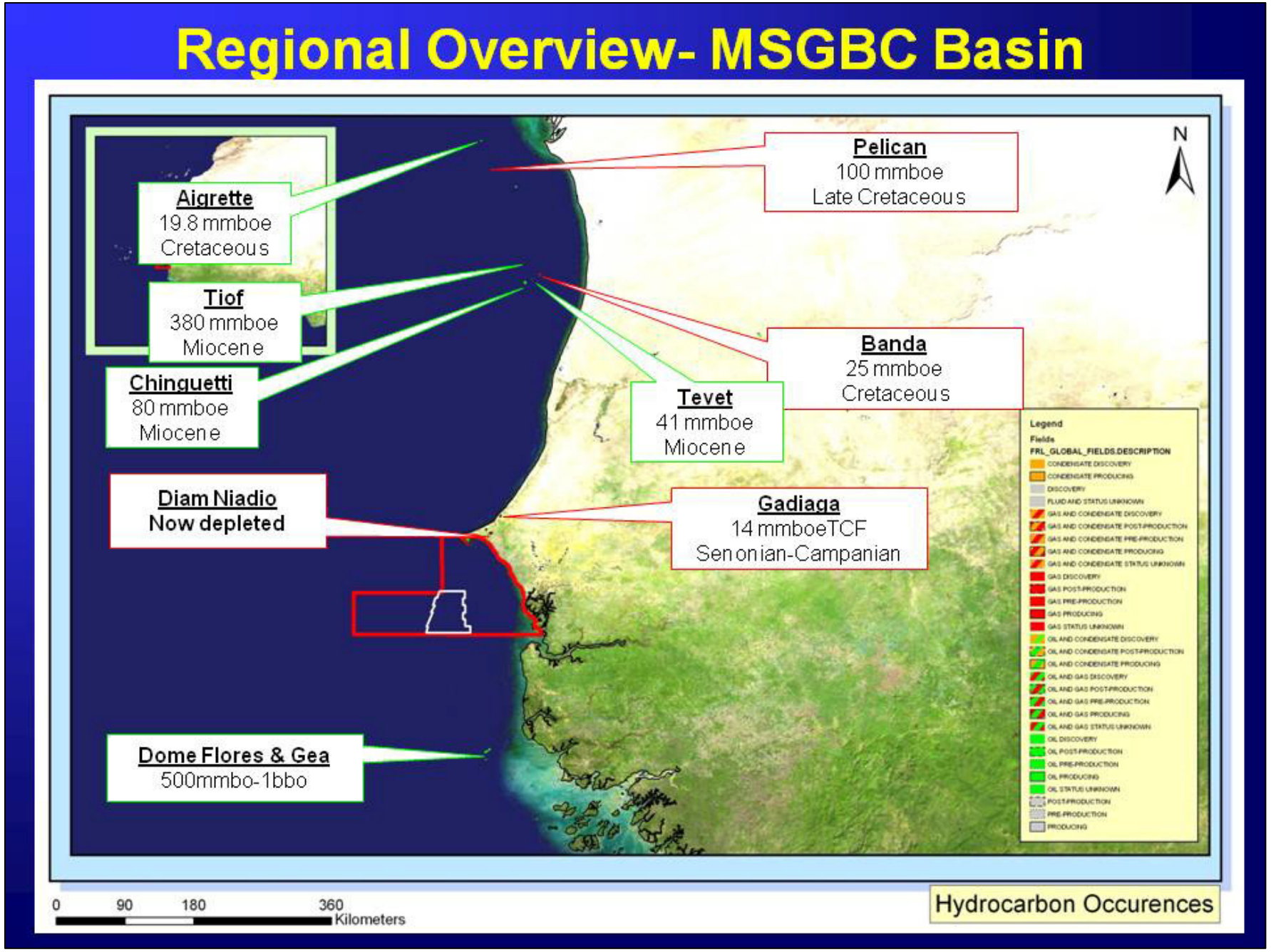
Presentation Overview

1. Location & Regional Geologic Overview
2. Basin Evolution
3. Chronostratigraphy & Geoseismic
4. Depositional Environments & Paleoclimate
5. Seismic Database
6. Seismic interpretation
    - Identified Play systems
7. Source Rocks & Basin Modeling
8. Conclusions



Notes by Presenter: Location of Senegal (small inset map) and offshore study area (large map). Map shows in red outline of study area. White outline shows 2050 sq kms of 3D acquired Q1 2007 and yelllow outline shows the area which was analysed for slope fan attribute analysis. Study area covers about 15,000 sq km.

Regional Overview- MSGBC Basin



Notes by Presenter: Map shows location of SENEGAL (Most western point of Africa—point to Dakar peninsular) You can read the figure straight of slide……also point out reserve figures came from number in 2007/2008. Paleozoic rift basin below with younger Mesozoic rift basin on top.

EVOLUTIONARY STAGES DURING THE OPENING OF THE ATLANTIC OCEAN

Click to View Notes by Presenter

W

E

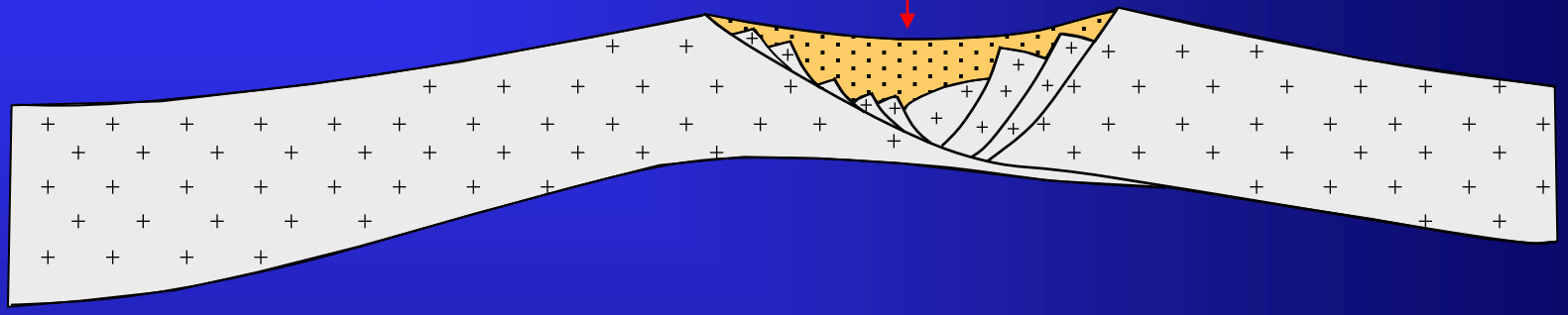
America

Africa

1) RIFT STAGE

(Late Trias – Early Jura)

Continental deposits

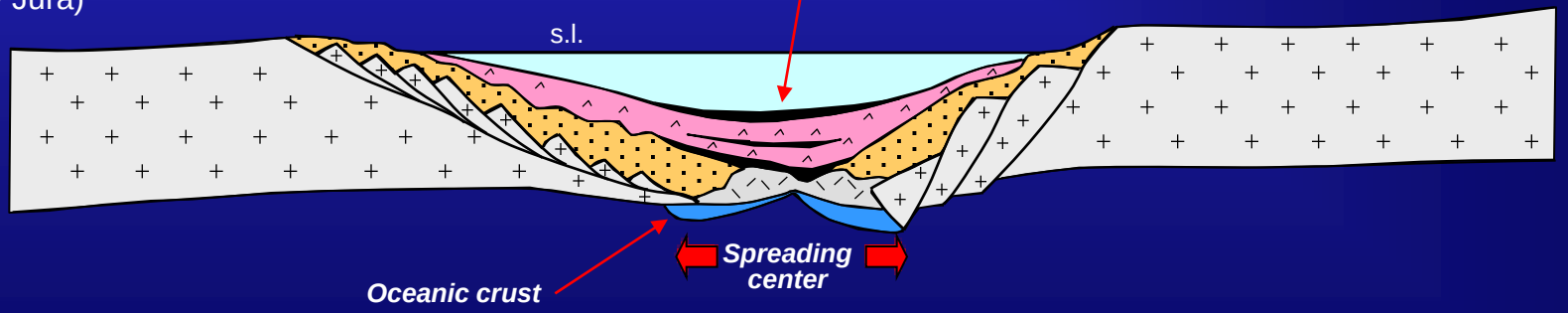


2) PROTO-OCEANIC STAGE

(Early Jura)

Evaporitic and/or anoxic deposits

s.l.



Adapted from Marco (2005)

Notes by Presenter (for previous slide):

1st stage: rifting stage of the Atlantic as America and Africa begin to rift and extend away from one another. This occurred during the late Triassic and Early Jurassic. This saw synrift deposits which were continental in nature.

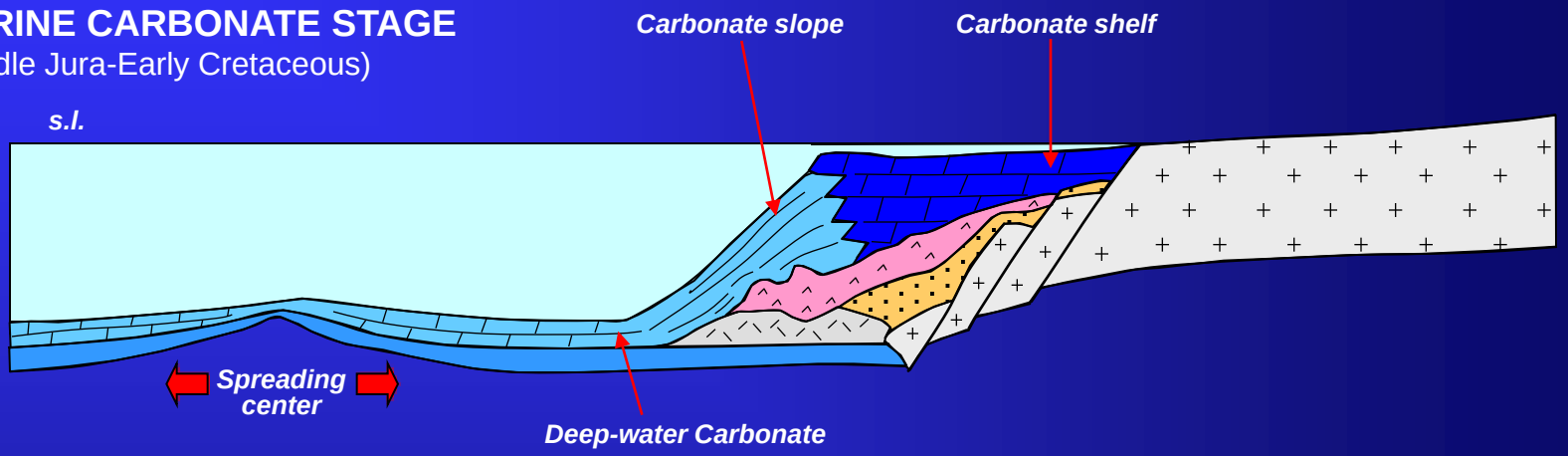
2nd stage: This was the proto-oceanic stage, during the Early Jurassic, This is the true opening of the Atlantic spreading ridge, creating new crust. Rifting continued and saw both a thick evaporitic sequence and in places layers of anoxic deposits.

EVOLUTIONARY STAGES DURING THE OPENING OF THE ATLANTIC OCEAN

Click to View Notes by Presenter

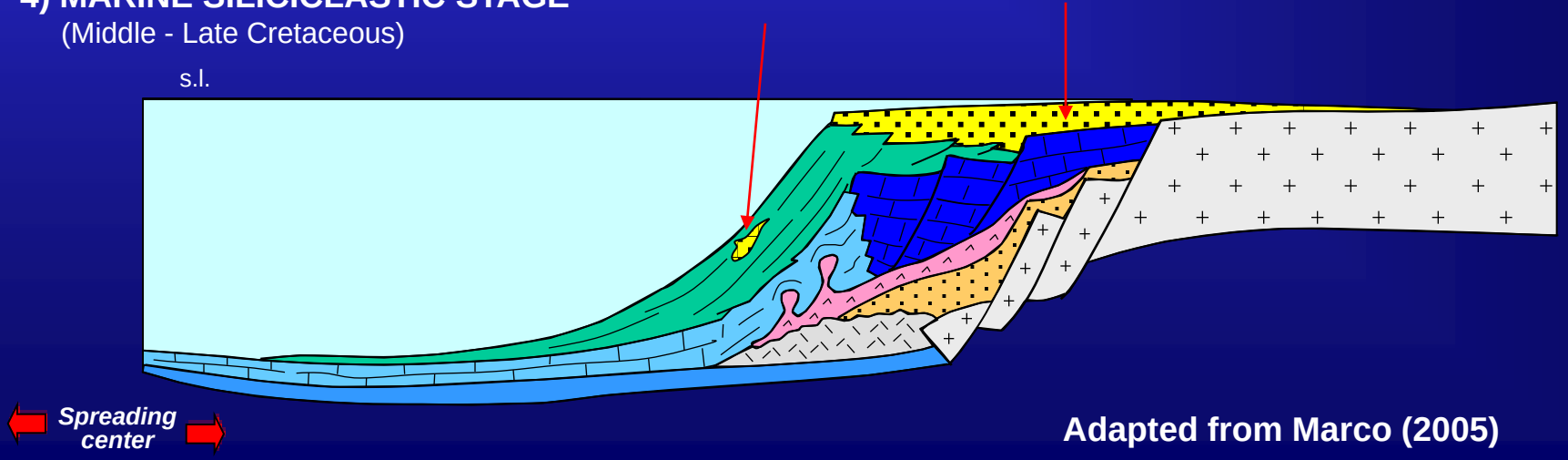
3) MARINE CARBONATE STAGE

(Middle Jura-Early Cretaceous)



4) MARINE SILICICLASTIC STAGE

(Middle - Late Cretaceous)



Adapted from Marco (2005)

Notes by Presenter (for previous slide):

Stage 3 saw the development of a long period of carbonate platform building. This began in the Middle Jurassic and continued well into the Late Cretaceous. Due to differential compaction/rotation, salt movement is observed e.g. Dome Flore etc further south of study area. Many internal geometries can be seen on seismic, indicating more complex progradation and aggradation packages showing that the platform both prograded and regressed through time. Uplift and erosion lead to karstification of the platform edge. This would have enhanced porosity and permeability.

Stage 4. During the Senonian uplift and erosion caused slumping of the platform edge. Salt withdrawal resulted in differential rotation and compaction of the platform. There is Seismic evidence of incised valleys that are clearly depicted., These serve as conduits which reworked carbonate platform sediments and onshore paralic sands are transported down and deposited on the slope and at the base of slope.

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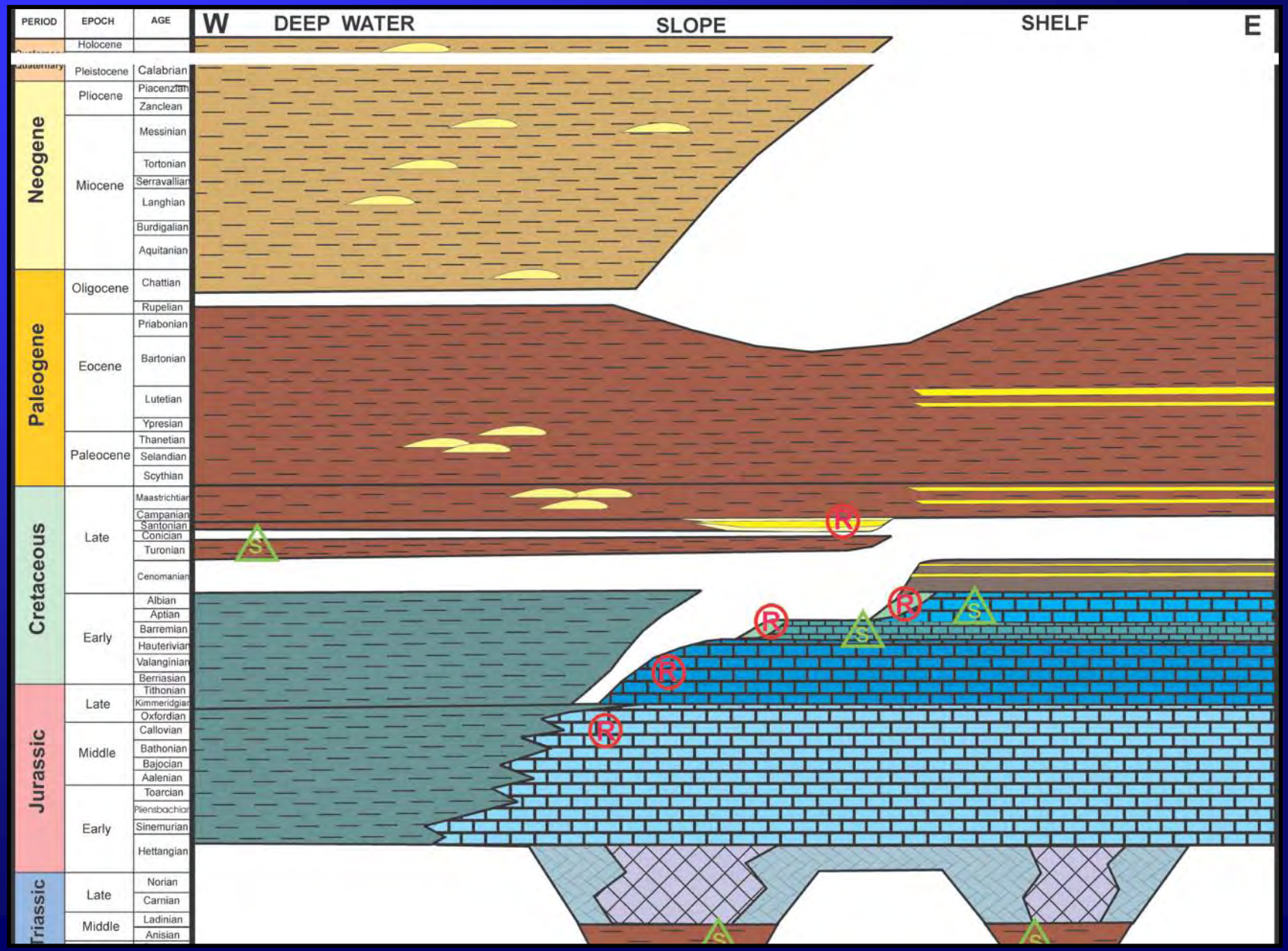
Chronostratigraphy



Notes by Presenter (for previous slide):

COLOURS: GREEN TRIANGLES ARE SOURCES, RED CIRCLES WITH R IS RESERVOIRS

Introduce sources: Proven: Turonian deep marine black shales (Proven by DSDP Wells offshore) Possible: Triassic shales, Albian-Aptian intraformational shales, coals?

Reservoirs: Most likely: Albo-Aptian limestones (karstified….explained in later slide) and Senonian-Santonian slope apron fans. Possible: Neocomian and Jurassic Limestones (too deep?)

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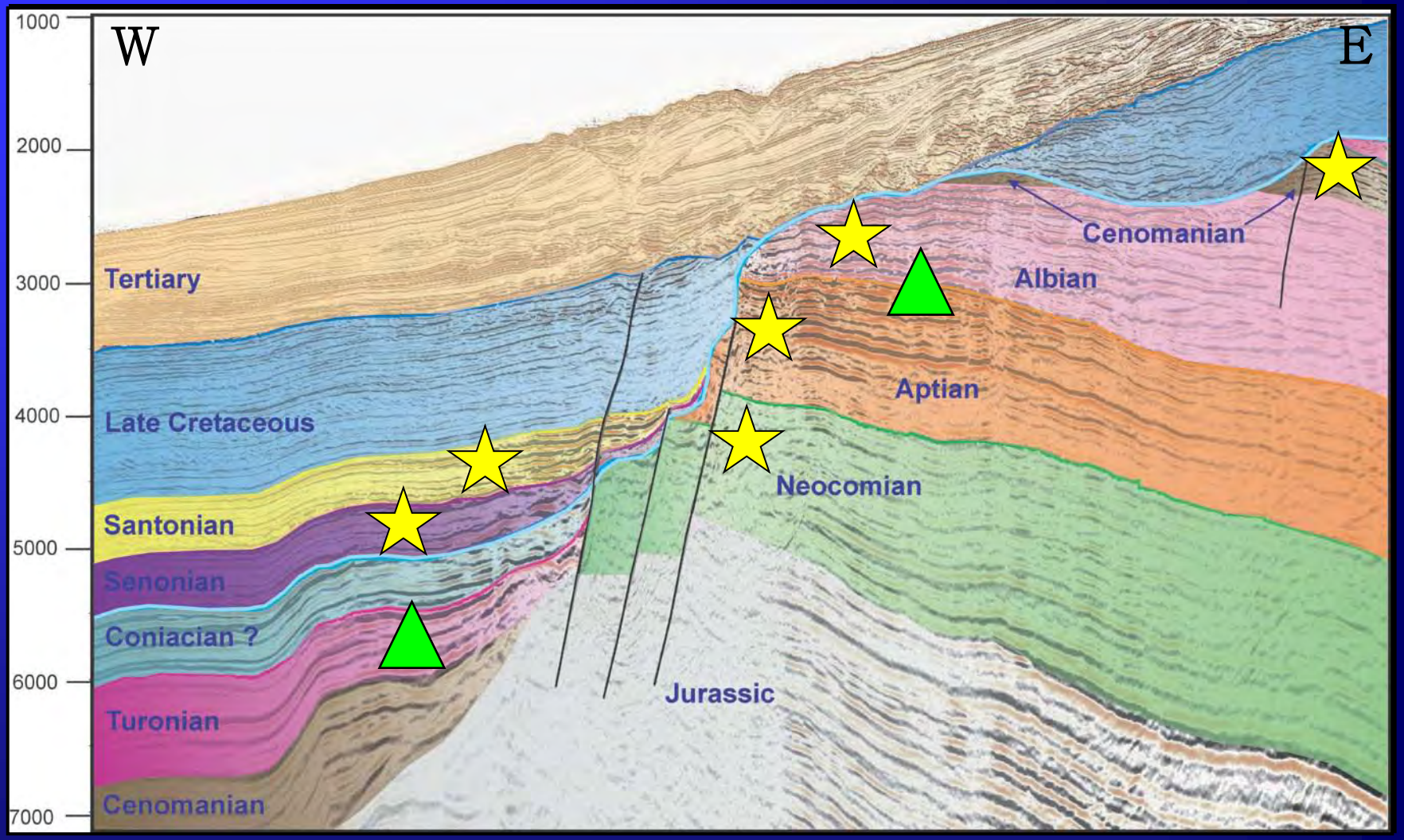
Geoseismic



Two main depositional sequences exist: 1) Carbonate Platform Build up from Jurassic to Cenomanian 2) Senonian unconformity and post Senonian unconformity erosion and slope deposition

Notes by Presenter (for previous slide):

Show blank seismic with interpreted seismic horizons. 1 click of mouse will bring up the interpreted colour fill. Talk to the main units of deposition.

GREEN TRIANGLES are SOURCES

YELLOW STARS are RESERVOIRS

Long lived carbonate platform from the Jurasic to the Late Cretaceous (Cenomanian)

Senonian unconformity marks the end of this and also represents uplift and rotation of the platform (BLUE SEISMI PICTURE)

During this time material was shed off the platform and transported down incised valleys and deposited on he slope. Paralic sands onshore deposited down the slope also.

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Depositional Environments

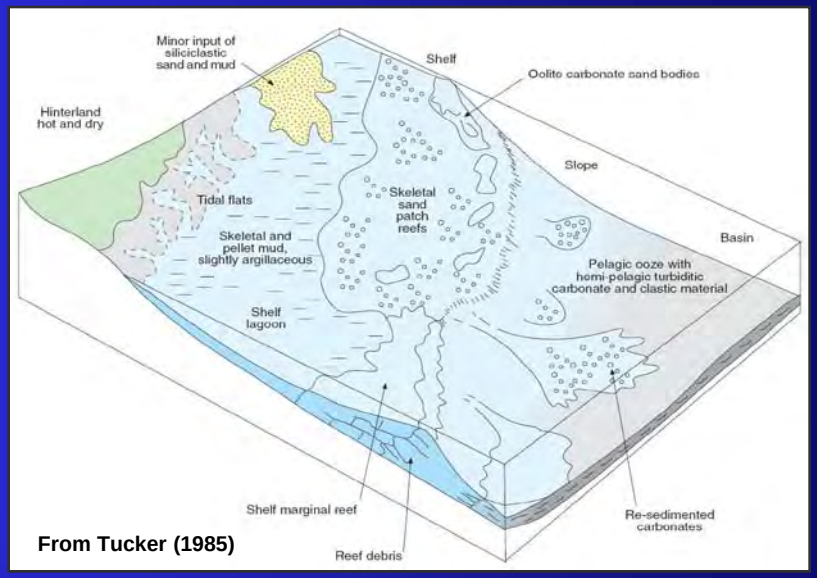
Carbonate Platform

- The carbonate platform deposition began in the Jurassic and continues through the Neocomian, Albian, Aptian and the Cenomanian. From 3D seismic, the last set of aggradational packages are in the Cenomanian.

- Limestone samples from five key wells, range from mudstones to grainstones in Dunhams classification and include peloids, ooids, oncoids, benthonic foraminifera, bivalve fragments, gastropods, echinoderm debris, serpulid worm tubes and skeletal debris.

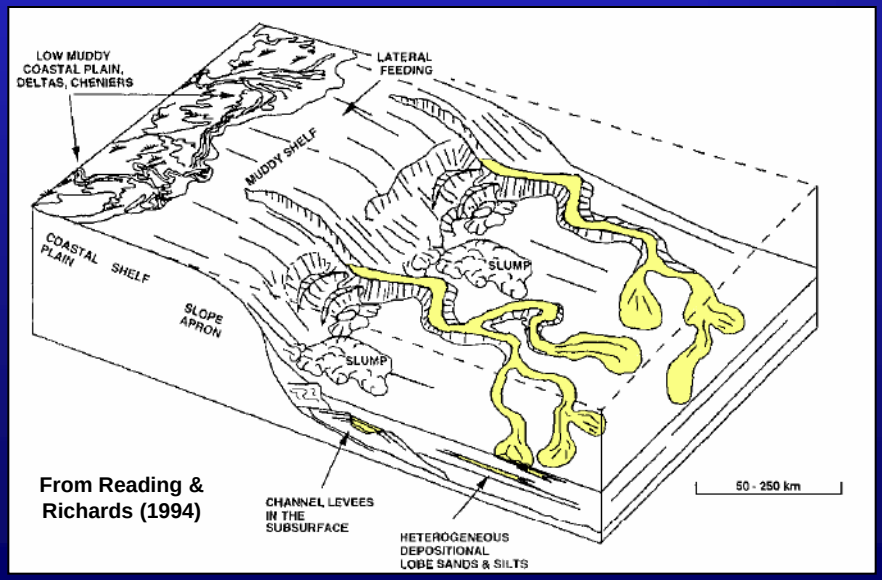
- Thin section work has established the carbonates have been affected by compaction, leaching of skeletal aragonite (forming mouldic pores) and precipitation of calcite cements.

- Porosity and Permeability within these carbonates are the result from secondary diagenesis including vugs and fractures.



From Tucker (1985)

Shelf Apron Fans



From Reading & Richards (1994)

- The timing of the Senonian unconformity was concurrent with exposure of the carbonate platform. This exposure allowed for erosion and incision by sediment by-pass channels. These transported both siliciclastics from onshore and reworked carbonate platform material down slope.

- The geometries of the fans are similar to slope fans in other parts of West Africa e.g. Ghana.

- On 3D seismic these fans are often stacked indicating repetitive influxes of sediment

Notes by Presenter (for previous slide):

CARBONATE PLATFORM

- The carbonate platform deposition began in the Jurassic and continued through the Neocomian, Albian, Aptian and the Cenomanian. From 3D seismic the last set of aggradational packages are in the Cenomanian.
- Limestone samples from five key wells, range from mudstones to grainstones in Dunhams classification and include peloids, ooids, oncoids, benthonic foraminifera, bivalve fragments, gastropods, echinoderm debris, serpulid worm tubes and skeletal debris.
- Thin section work has established the carbonates have been affected by compaction, leaching of skeletal aragonite (forming mouldic pores) and precipitation of calcite cements.
- Porosity and Permeability within these carbonates are the result of secondary diagenesis including vugs and fractures.
- Model used for the depositional enviroment is taken from Tucker 1985

SHELF APRON FANS

- The timing of the Senonian unconformity was concurrent with exposure of the carbonate platform. This exposure allowed for erosion and incision by sediment by-pass channels. These transported both siliciclastics from onshore and reworked carbonate platform material down slope.
- The geometries of the fans are similar to slope fans in other parts of West Africa e.g. Ghana.
- On 3D seismic these fans are often stacked indicating repetitive influxes of sediment.
- Depositional model used loosely is taken from Reading and Richards (1994), however one may difference is that the Senegalese fans contain both reworked carbonate and siliciclastics

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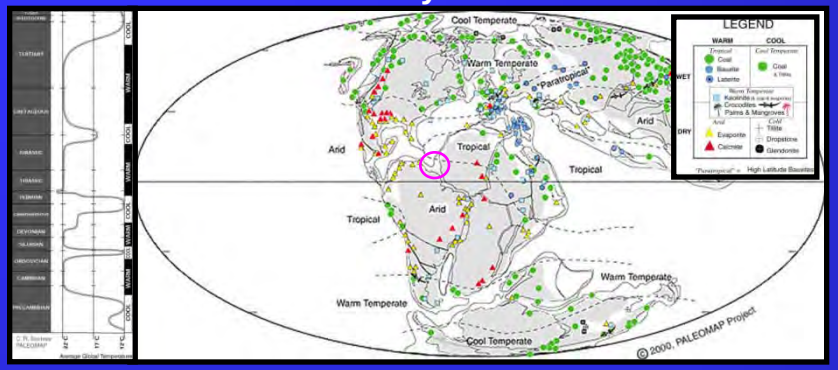
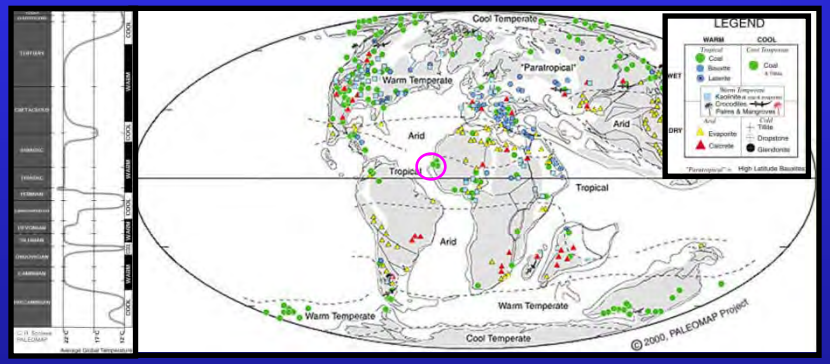
Paleoclimate

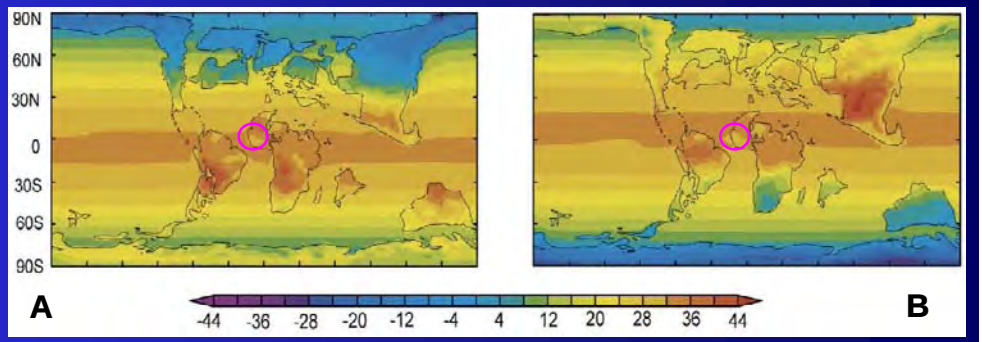
Early Cretaceous



Late Cretaceous

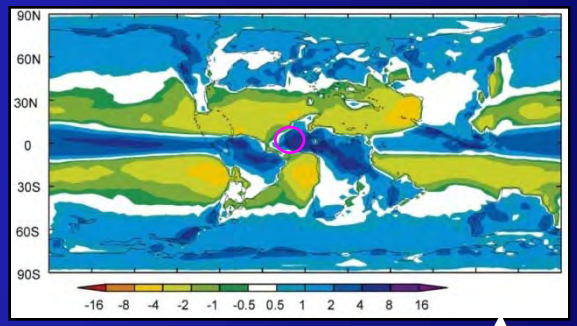


Model simulated Mean seasonal Temperatures



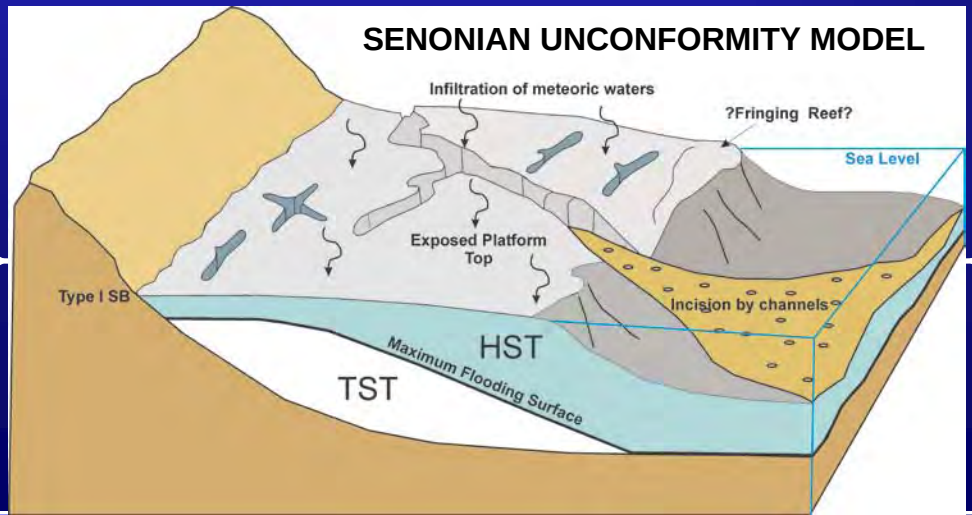
(Sellwood & Valdes, 2006)

Model simulated Precipitation minus evaporation



(Sellwood & Valdes, 2006)

SENONIAN UNCONFORMITY MODEL



(Adapted from Emery & Myers, 1996)

Notes by Presenter (for previous slide):

In order to appreciate the role of the Senonian unconformity, it is importand to understand the Paleoclimate.

Figures on left illustrate the positioning of Senegal during the Early & Late Cretaceous. During the Early Cretaceous, Senegal was in a arid belt and transitioning to a tropical belt during the Late Cretaceous. The Senonian unconformity coincides with the tropical climate period and hence karst conditions are predicted.

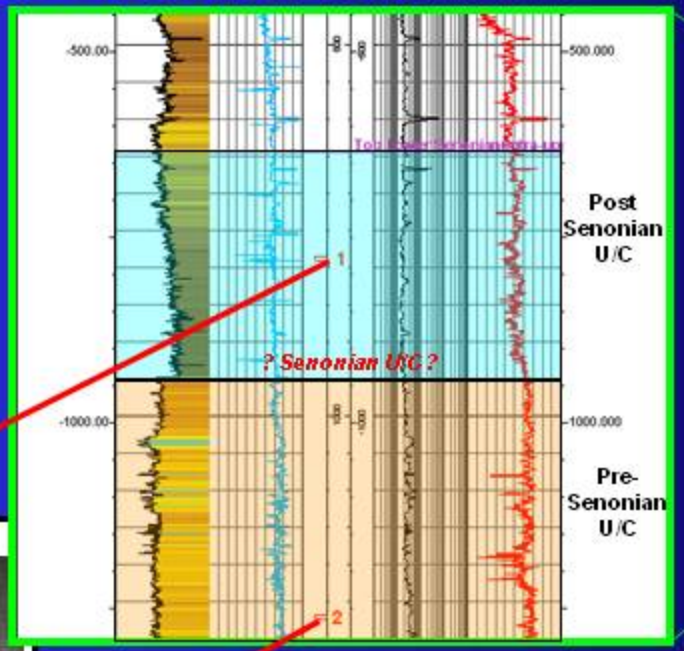
The Cretaceous carbonate platform was differentially rotated in south due to underlying salt withdrawal. This created eastward dipping closure induced fractures due to torsion.

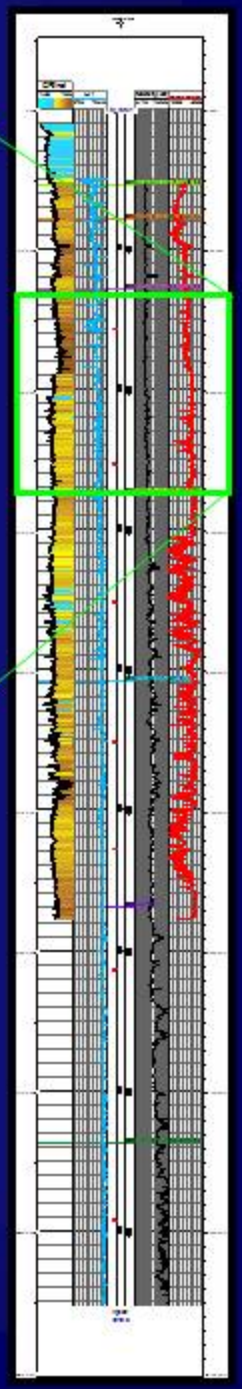
Figures on the right show mean temperatures for the Late Cretaceous and modelled precipitation versus evaporation respectively. These plots aid in showing warm temperatures and high precipitation, both important for karstification to occur, concurrently with the major Senonian unconformity.

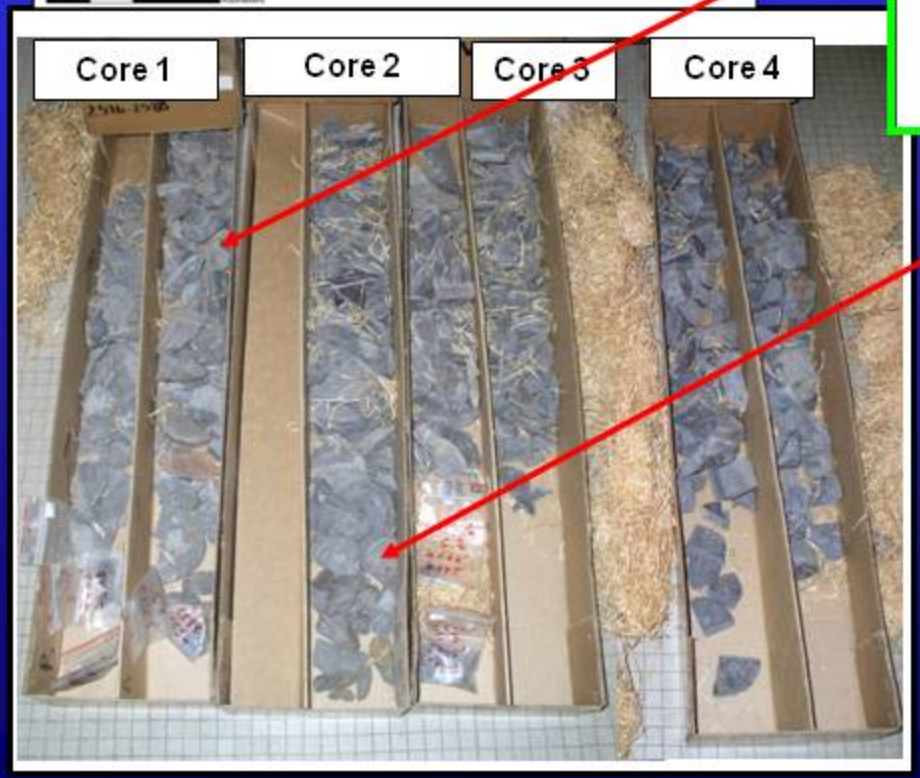
Exposure of the platform allowed for incised channels to form. These acted as sediment bypass and funnels for transporting sediments (both siliciclastic and reworked carbonate detritus) to the platform slope and basin.

Click to View Notes by Presenter

Evidence for Seal







Evidence for a top seal to the Senonian unconformity in the Cap Vert Marine-1 (CVM-1) well. Evidence can also be found in wells on the Rufisque High; RF-2 & DKM-2

Notes by Presenter (for previous slide):

There is good evidence for a top seal for the Senonian unconformity.

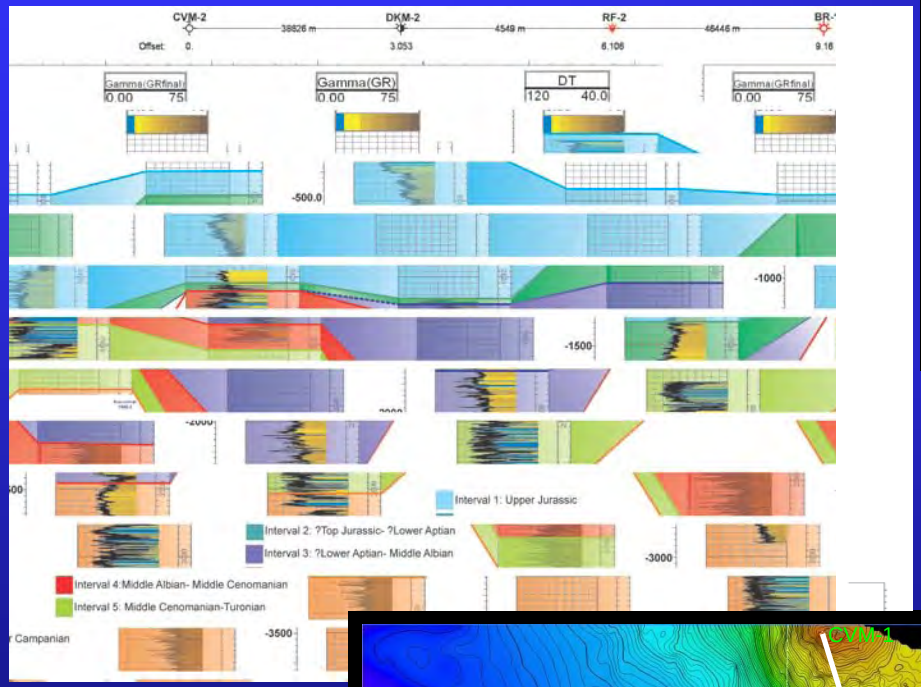
Map shows location of the Cap Vert Marine-1 well. Core logging of the Rufisque2 and Dakar-Marine-2 well show thick shale sequences above the Senonian Unconformity.

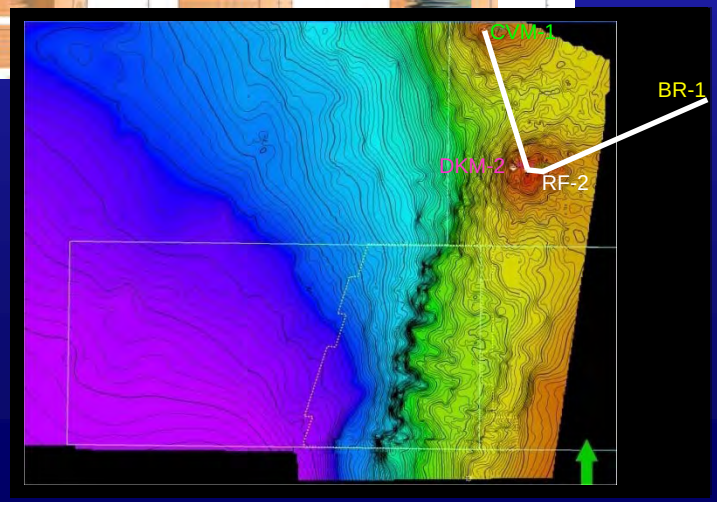
Evidence seen in the cores point to a thick shale section.

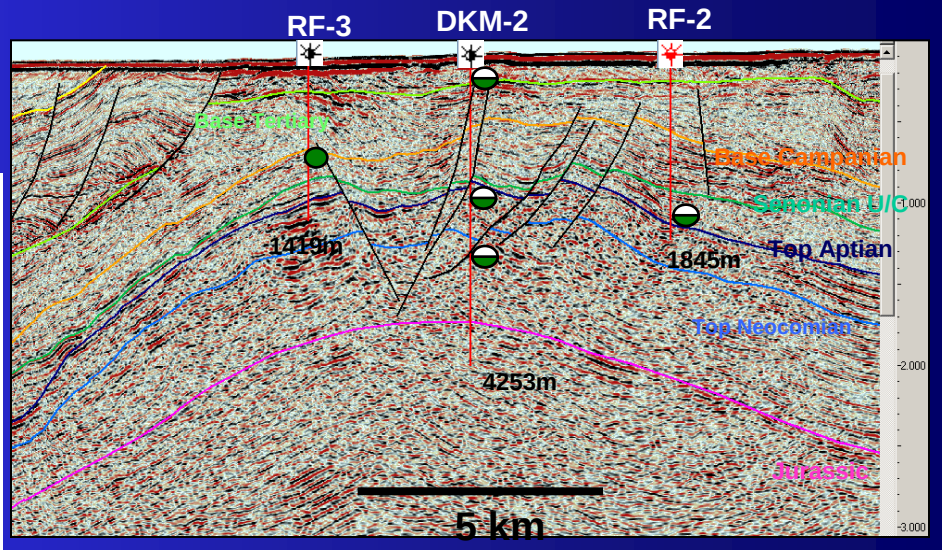
Cores have been damaged and dropped hence the shales are in bits

Rufisque Dome

Seismic Line M84-13 running NW-SE over the Rufisque Dome showing location of two flank wells and one crest of structure well.

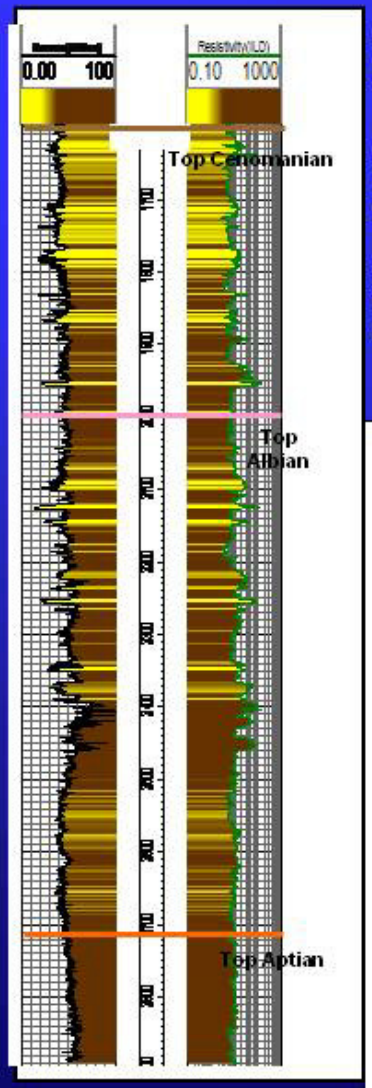




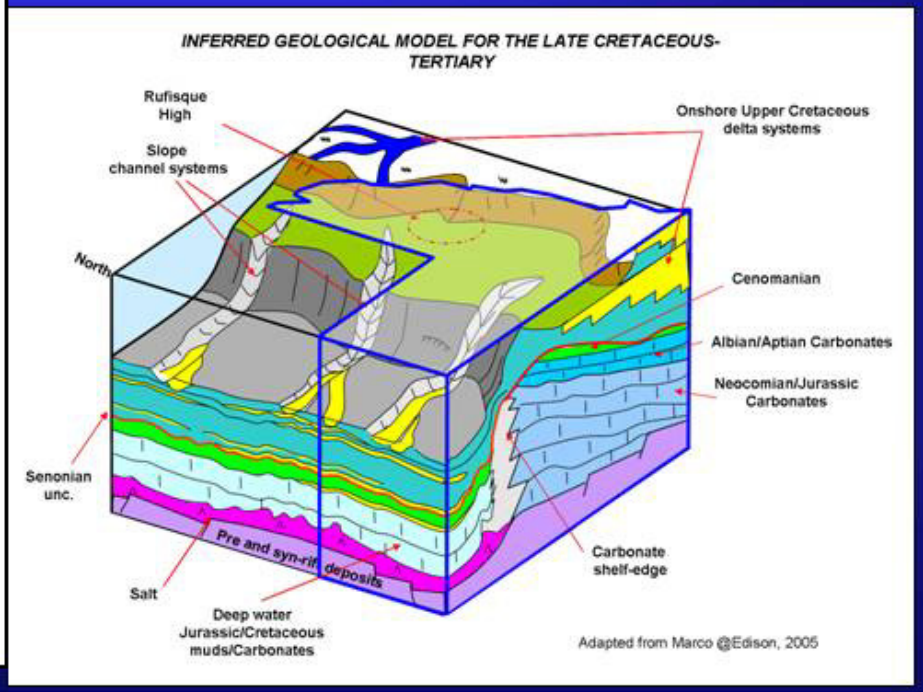


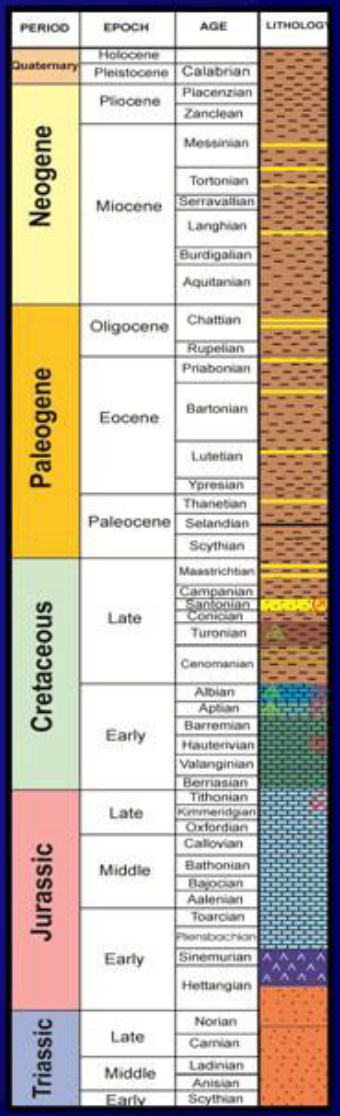
- Rufisque Dome is a igneous upwelling creating a localized high within the License area. The crest of the structure has been tested by RF-1 (not shown) and DKM-2 and two flank wells have also been drilled (RF-2 and RF-3). All three wells have encountered hydrocarbon shows.
- RF-3 tested for oil in Senonian sands (16ft net pay) & RF-2 tested oil in Cretaceous carbonates.
- Fair to good oil shows were encountered in DKM-2 within the Tertiary and Cretaceous aged sections.

Geological Model



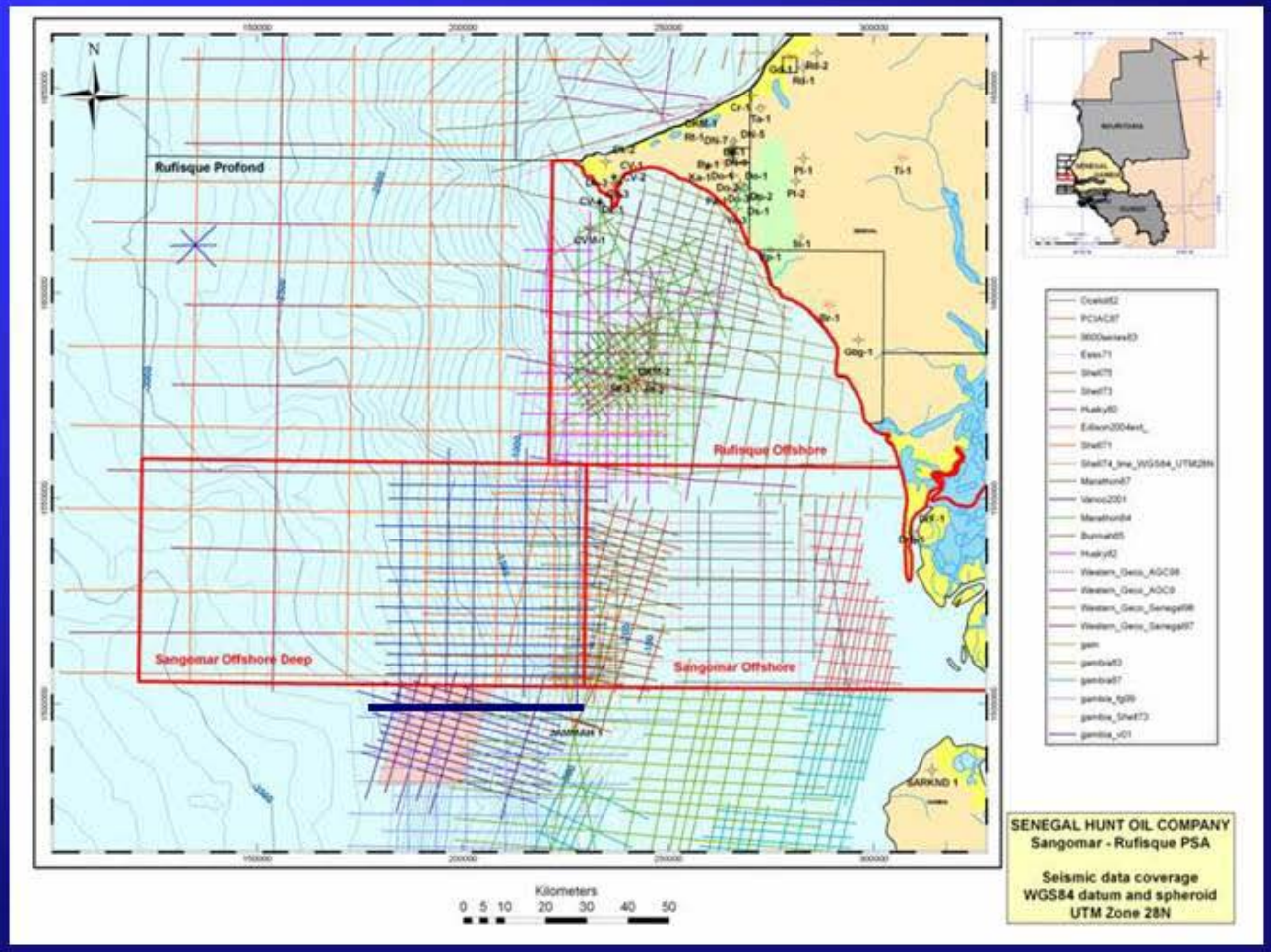
- The Jurassic to Cenomanian is marked with a long lived carbonate platform. Following the Cenomanian, during a period of quiescence, the Turonian source rock was laid down in anoxic deep water.
- Following deposition of the source, the platform was exposed and the carbonates karstified. The period is represented by the Senonian unconformity.
- Post the Senonian unconformity, incised erosional shelf channels transported paralic sands to the upper slope. Stacked seismic amplitude anomalies represent these deposits.





Notes by Presenter: Log curves from CVM-1. Proximal well showing sands in the Early to Late Cretaceous. Inferred Model of the Late Cretaceous to Tertiary. (Adapted from Marco, 2005)

2D Seismic Coverage

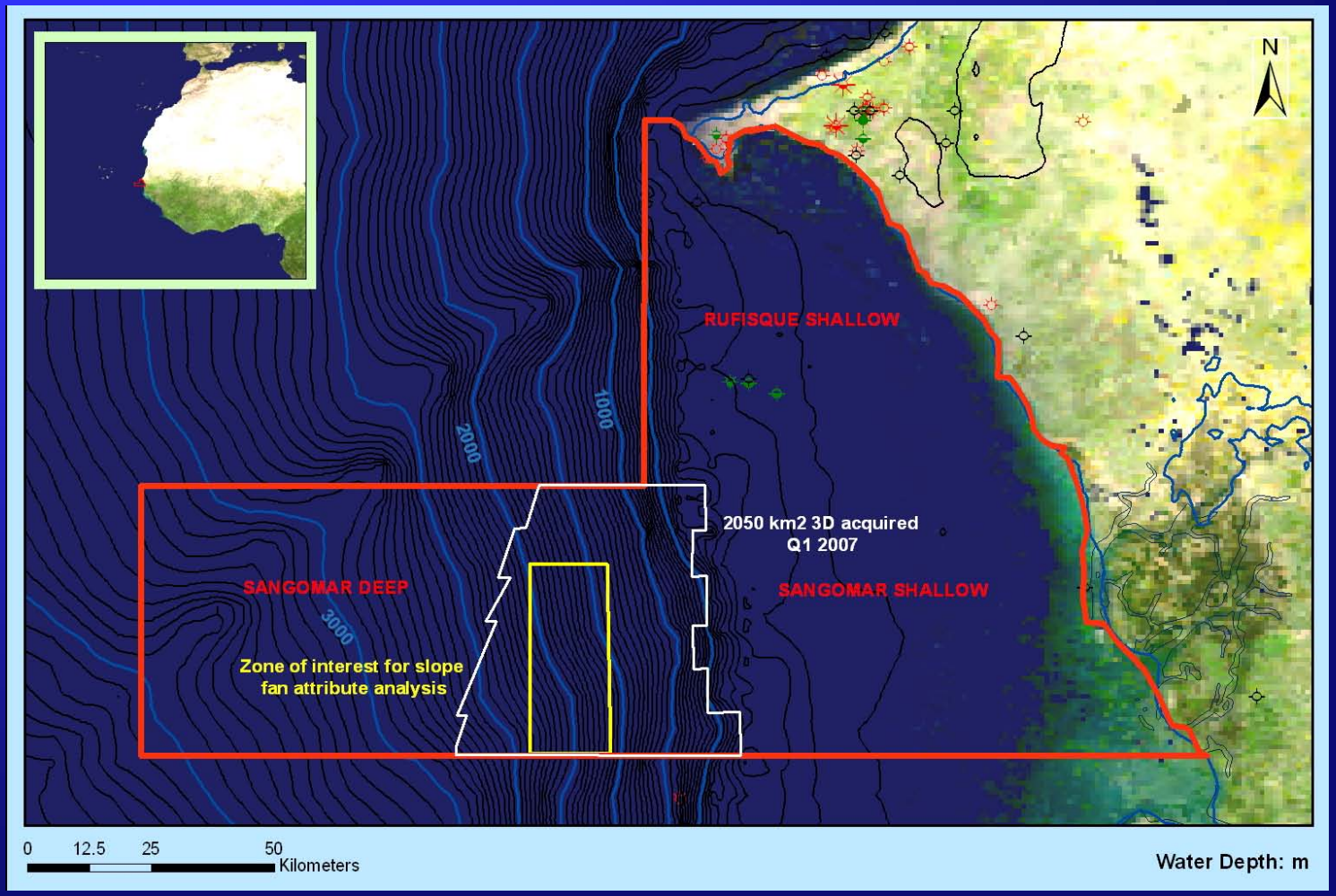


- Predominantly 1970's – 1980's vintage data
- Recent acquisitions by Vanco (2001) and Western Geco (1997)

Notes by Presenter: 2D Seismic coverage mainly 1970s to 1980's data. Data is pretty good but 3D required to determine possible shelf closures and down dip shelf slope apron fan systems.

Click to View Notes by Presenter

2007 3D Seismic Acquisition Program



Notes by Presenter (for previous slide):

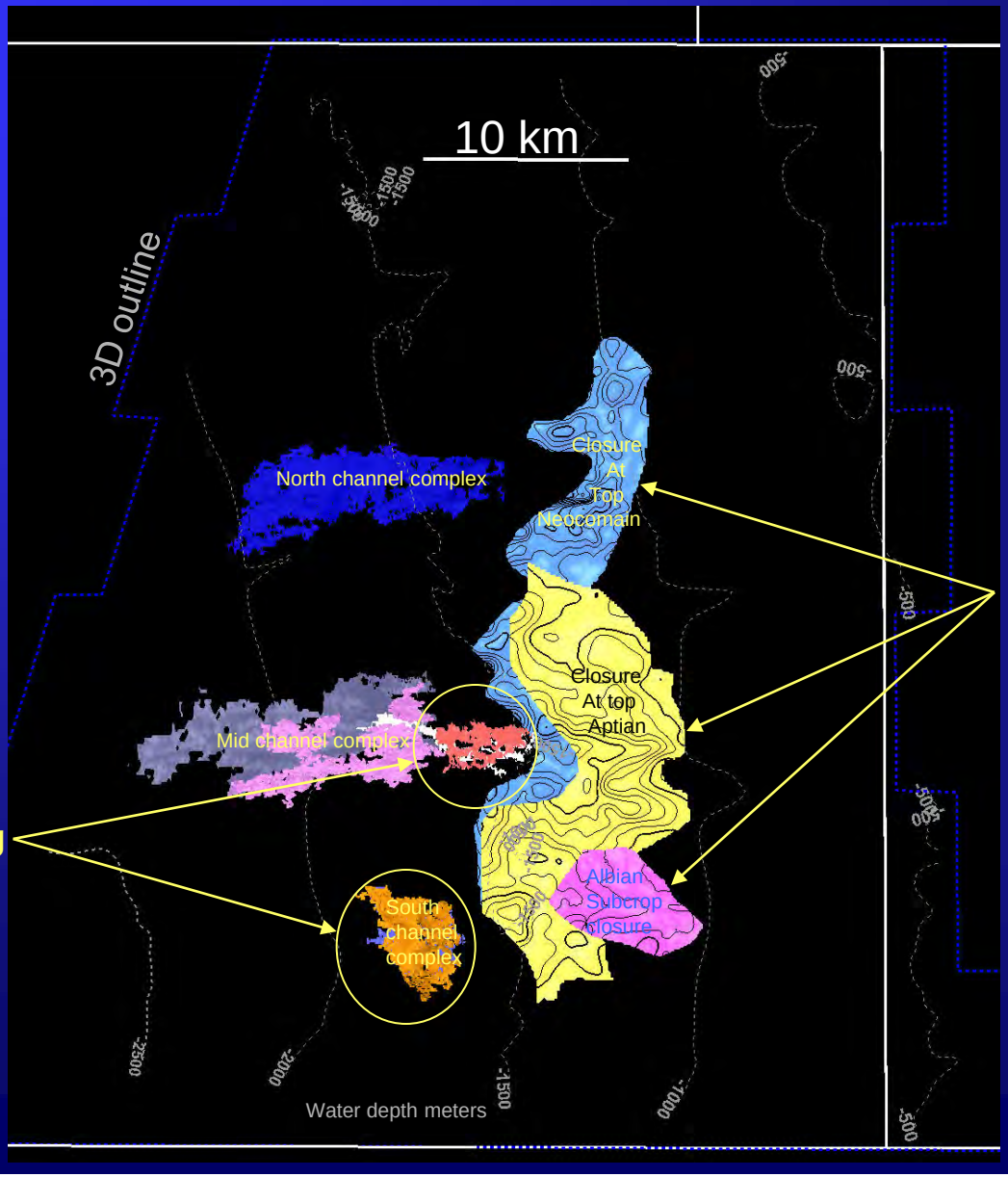
REPEATED SLIDE TO REMIND AUDIENCE OF THE LOCATION OF THE 3D

Location of Senegal (small inset map) and offshore study area (large map). Contours are water depth in meters

Map shows in red outline of study area. White outline shows 2050 sq kms of 3D acquired Q1 2007 and yelllow outline shows the area which was analysed for slope fan attribute analysis.

Senegal – Identified Plays & Leads Summary

Click to View Notes by Presenter



Lower Cretaceous Carbonate Shelf Margin structural closures

Santonian Upper Slope Stacked Fans exhibiting high amplitudes

Notes by Presenter (for previous slide):

Identified plays and leads summary

Start at bottom

CARBONATES

BLUE: Closure at the Neocomian. Carbonate platform edge play

YELLOW: Closure at top Aptian. Carbonate Platform

PINK: Albian Subcrop closure, result of karstic topography

FANS

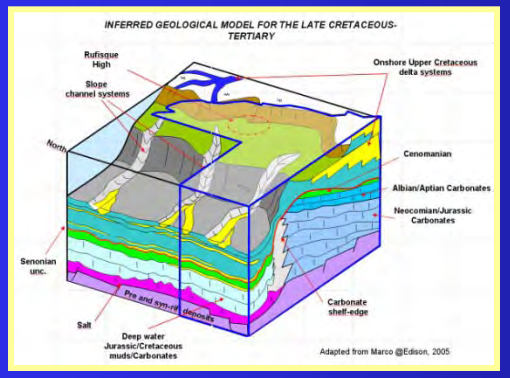
DARK BLUE : Northern Fan. Single unit, Santonian in age

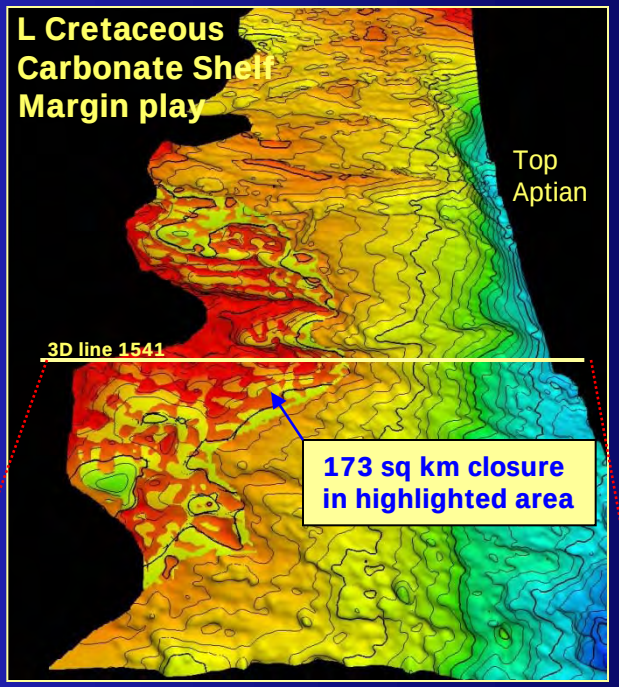
PINK-GREY: Middle Fan: Stacked unit of Santonian Fans

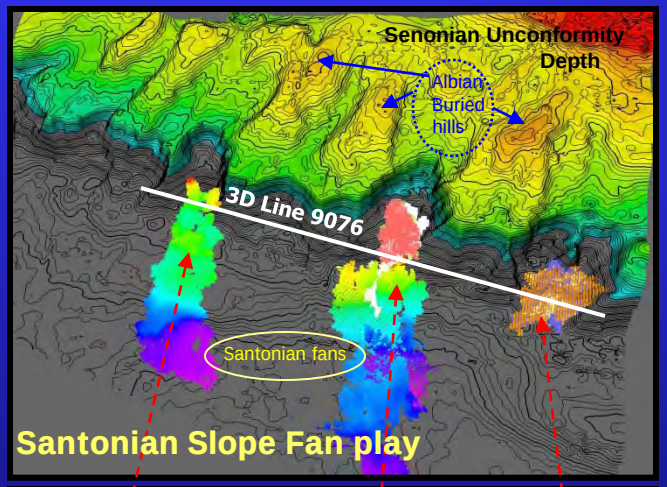
ORANGE: Southern Fan: Stacked unit of Santonian Fans

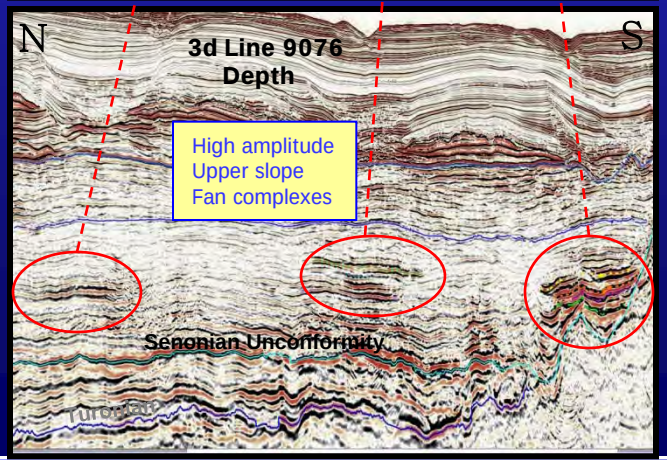
Senegal – Identified Plays & Leads

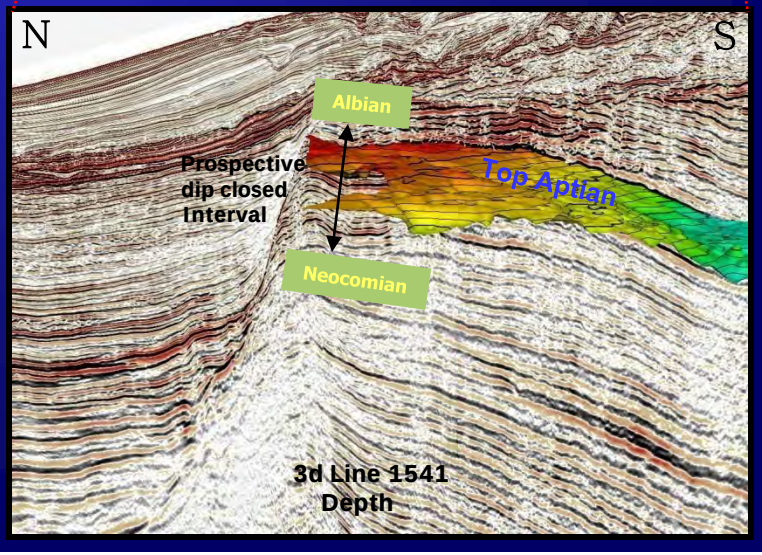
Click to View Notes by Presenter











Notes by Presenter (for previous slide):

Geology model added to remind audience what the shelf looks like. Two parasequence: 1) Long lived carbonate platform 2) Post Senonian Unconformity (erosion/rotation/uplift) of deposited fans.

LEFT FIGURES

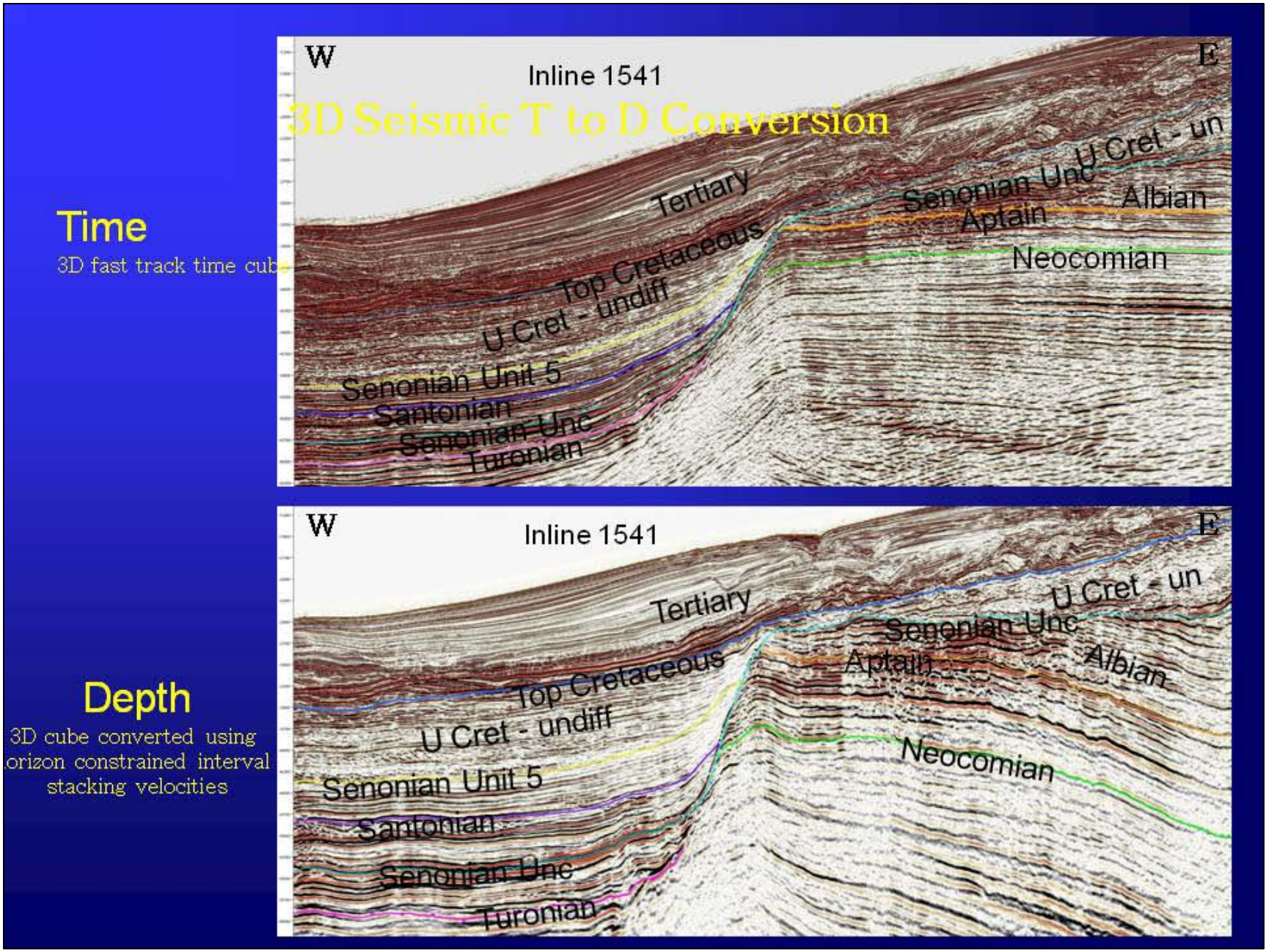
Figure shows the Senonian unconformity grid with the high amplitude fans juxtaposed against the shelf edge. Clearly seen is the cutting nature of these fans and how much incising of the shelf has occurred. The 3D picture shows both the Northern, Middle and Southern Fans (left to right)

The bottom right show the seismic line running parallel with the shelf platform edge. Here we can see the high amplitude upper slope fan complexes.

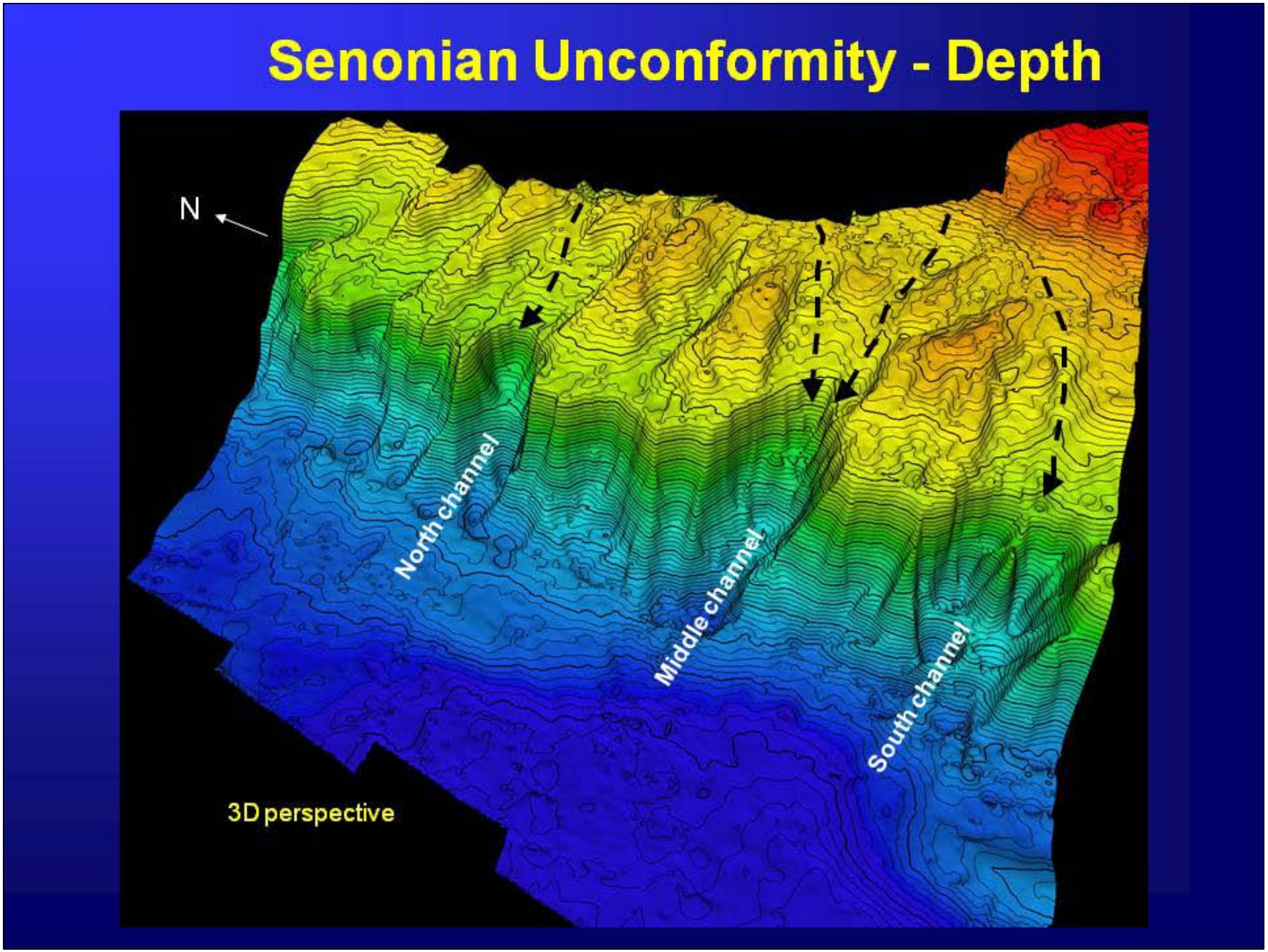
RIGHT FIGURES

Figure show top Aptian depth map with the Aptian closure highlighted. Roughly 173 sq kms.

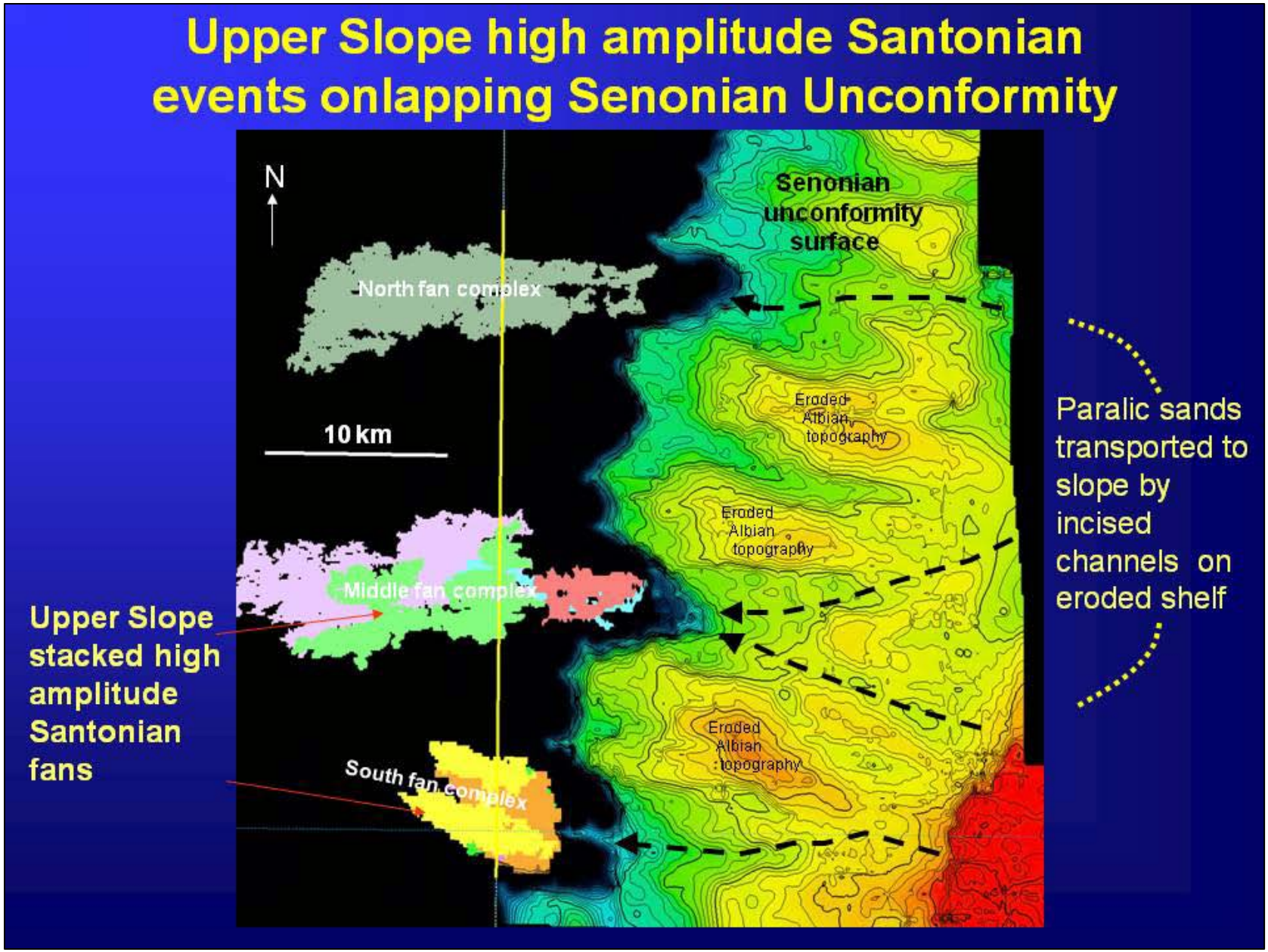
The bottom left shows a 3D seismic line through the carbonate platform, here we can see the prospective dip closed interval between the Aptian and Neocomian.



Notes by Presenter: The depthed volume has more character. The reflectors on the shelf are dipping to the East and internal geometries such as progradations etc can be observed. Mapping of the internal geometries leads us to believe we have seen differential rotation and uplift along this margin.



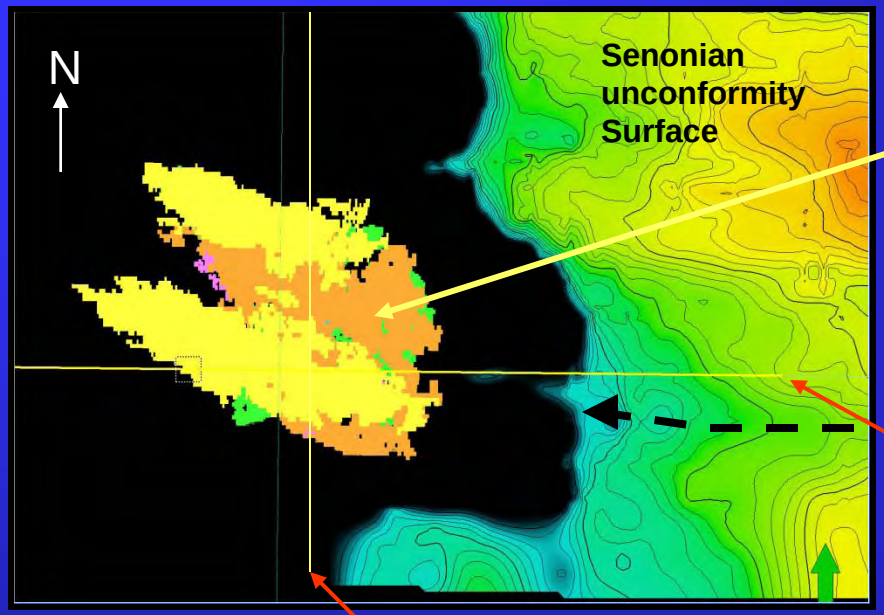
Notes by Presenter: Again here we see the Senonian Unconformity grid this clearly shows the three incised valleys and also has an overall hummocky appearance. This represents the karstic topography at the time of the Senonian Unconformity.



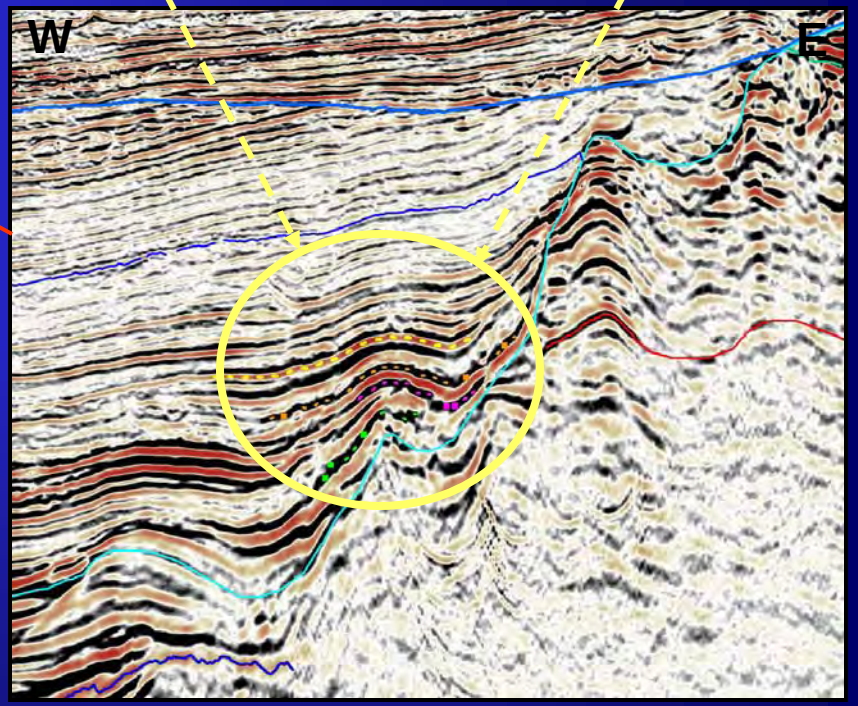
Notes by Presenter: SUMMARY SLIDE SHOWING RELATIONSHIP BETWEEN SHELF EDGE AND FANS. Senonian unconformity grid showing the buried hill of the Albian. Here we can see sediment conduits/paths through this landscape where paralic sand would have been transported to the shelf edge and deposited down slope. The incised channels are observed on seismic and correspond to stacked high amplitude fans.

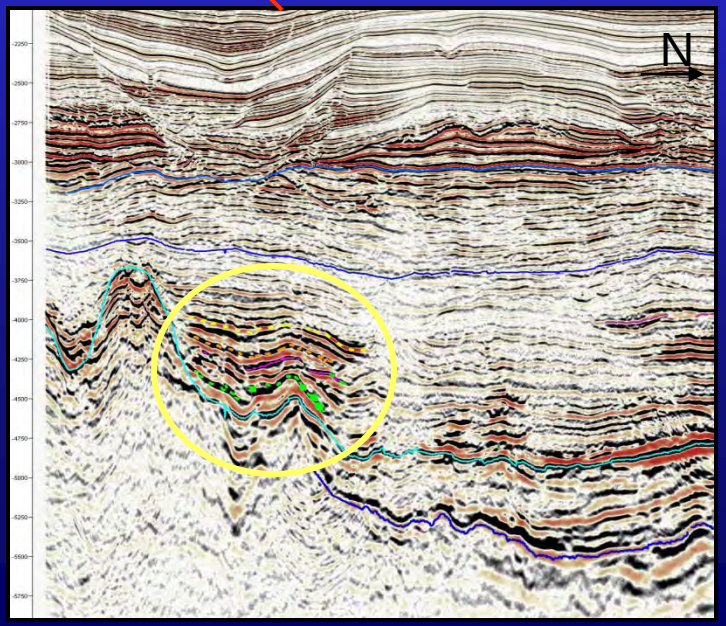
South channel – stacked high amplitude Santonian fans

Click to View Notes by Presenter



Upper slope Santonian fans



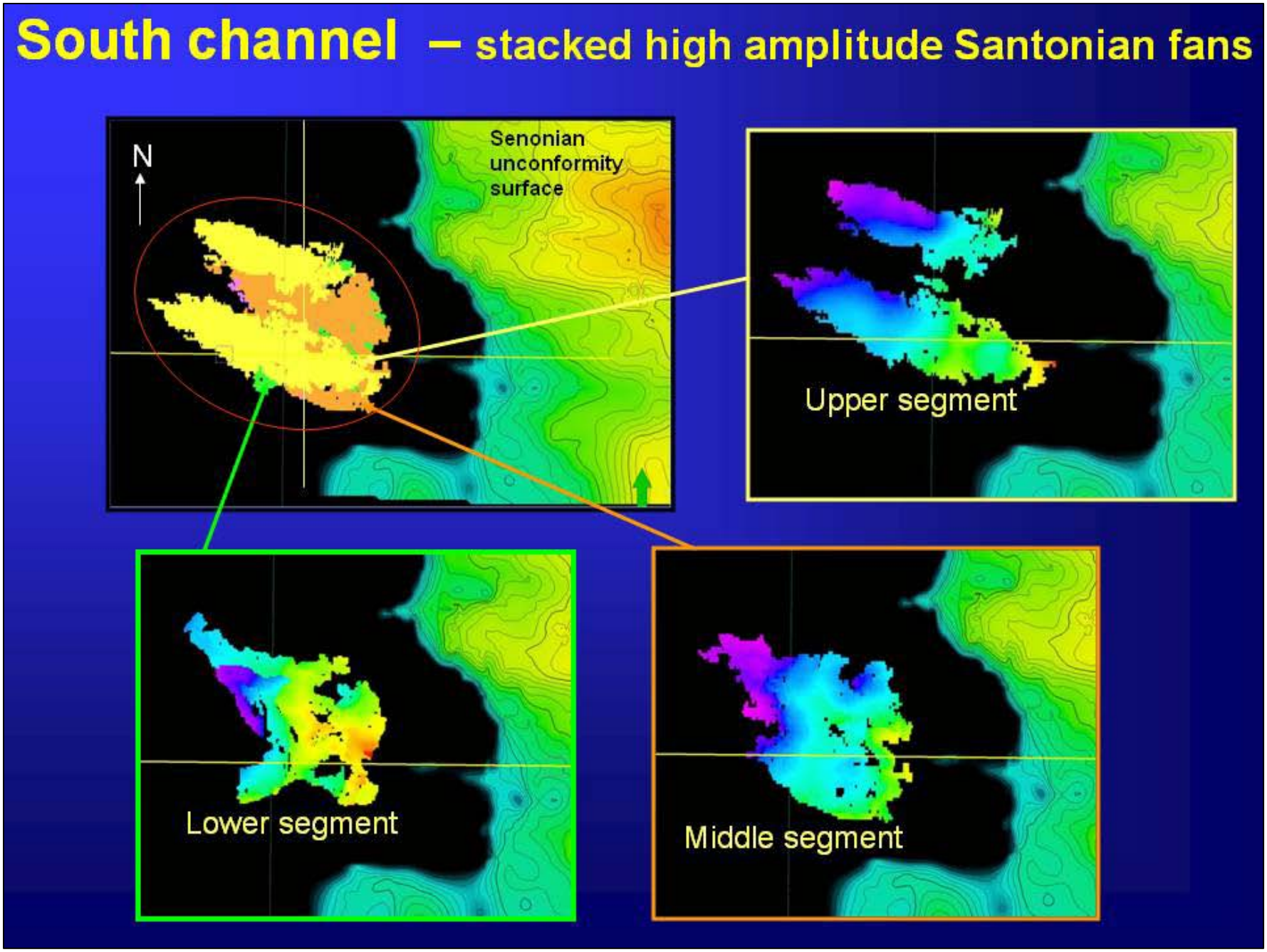


Stacked footprint encompasses +30 km²

Notes by Presenter (for previous slide):

SOUTH CHANNEL IN STUDY AREA.

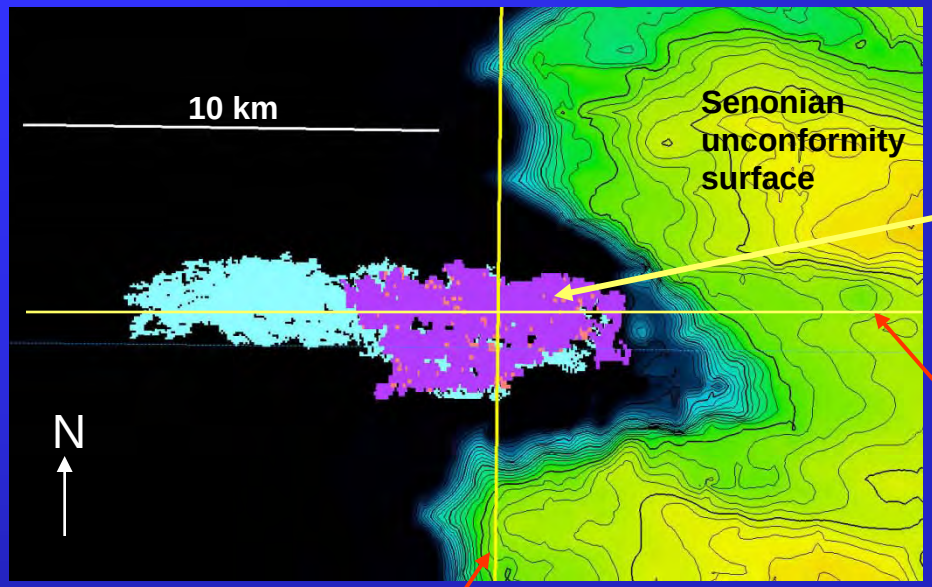
Map shows the footprint of the high amplitudes. This is a stack sequence of around three events. These are Santonian in age and deposited post-senonian U/C and onlap and fill in incised canyons on the platform edge. Sesimic lines show the contained amplitudes within the canyons. Scalloped looking in appearance. Total footprint equals 30 sq kms



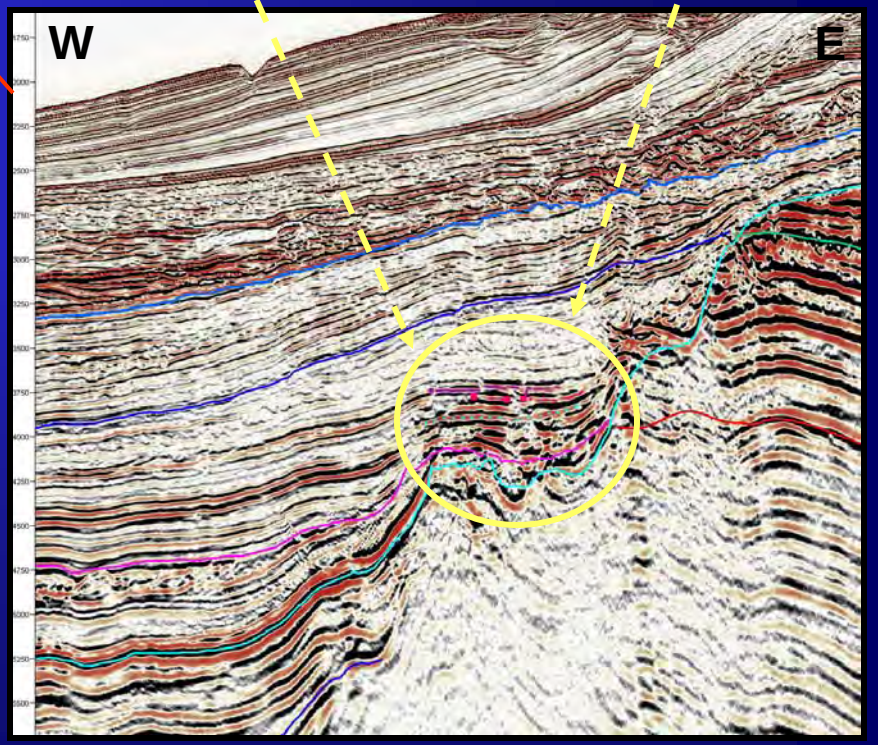
Notes by Presenter: Grid shows the carbonate platform edge and here we can see clearly the incised valley acting as a conduit fro sediment transport. Maps show the amplitude response of each individual sand event. Her we have a stacked fan system of around 3 events.

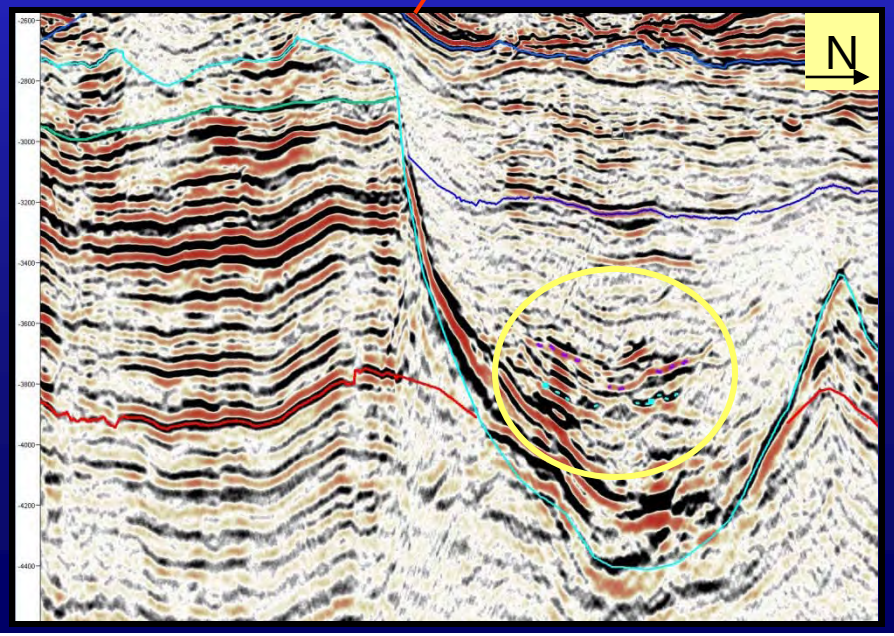
Middle channel – stacked high amplitude Santonian fans

Click to View Notes by Presenter



Upper slope Santonian fans

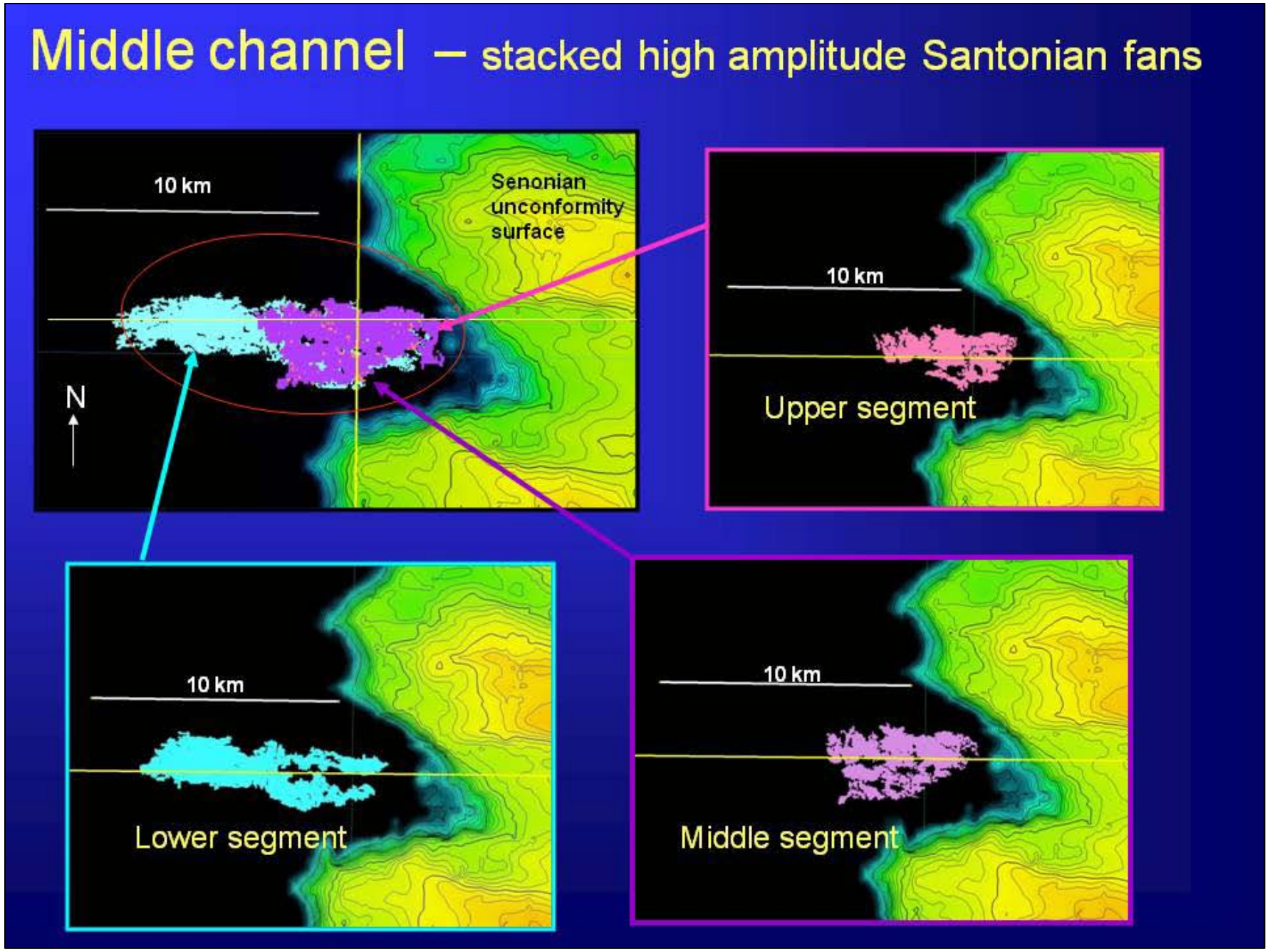




Notes by Presenter (for previous slide):

MIDDLE CHANNEL IN STUDY AREA

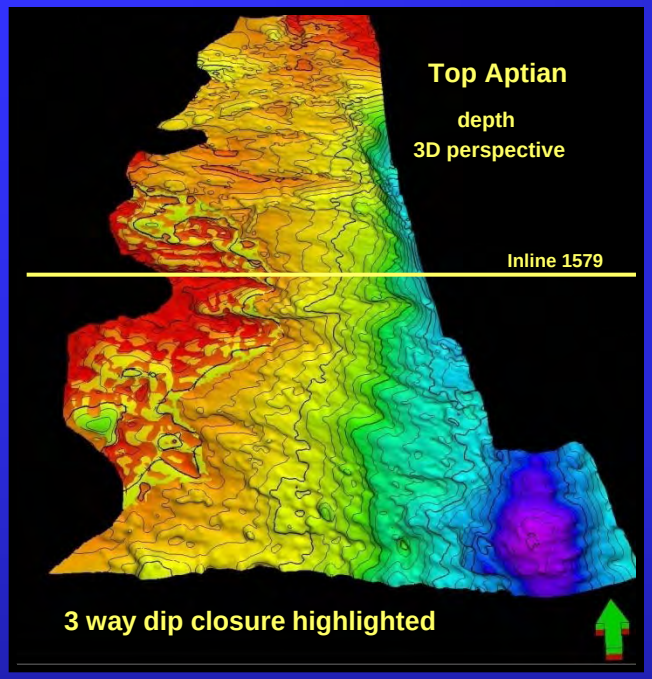
Map shows the footprint of the high amplitudes. This is a stack sequence of around three events. These are Santonian in age and deposited post-senonian U/C and onlap and fill in incised canyons on the platform edge. Sesimic lines show the contained amplitudes within the canyons. Scalloped looking in appearance. Base of this fan is hummocky and looks like a typical scalloped bottom to a fan system.

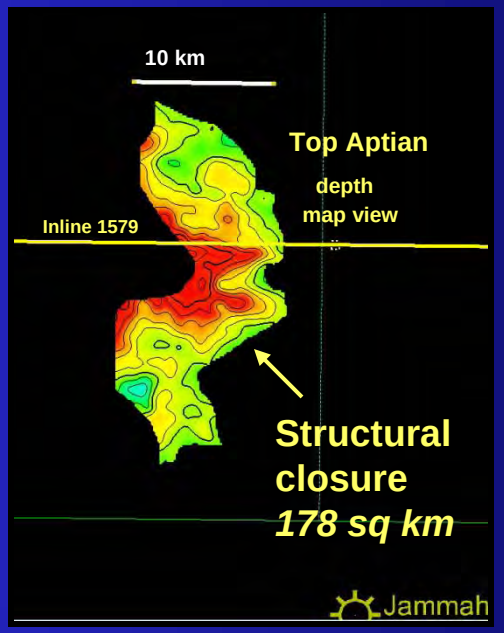


Notes by Presenter: Grid shows the carbonate platform edge and here we can see clearly the incised valley acting as a conduit for sediment transport. Maps show the amplitude response of each individual sand event. Here we have a stacked fan system of around 3 events.

Click to View Notes by Presenter

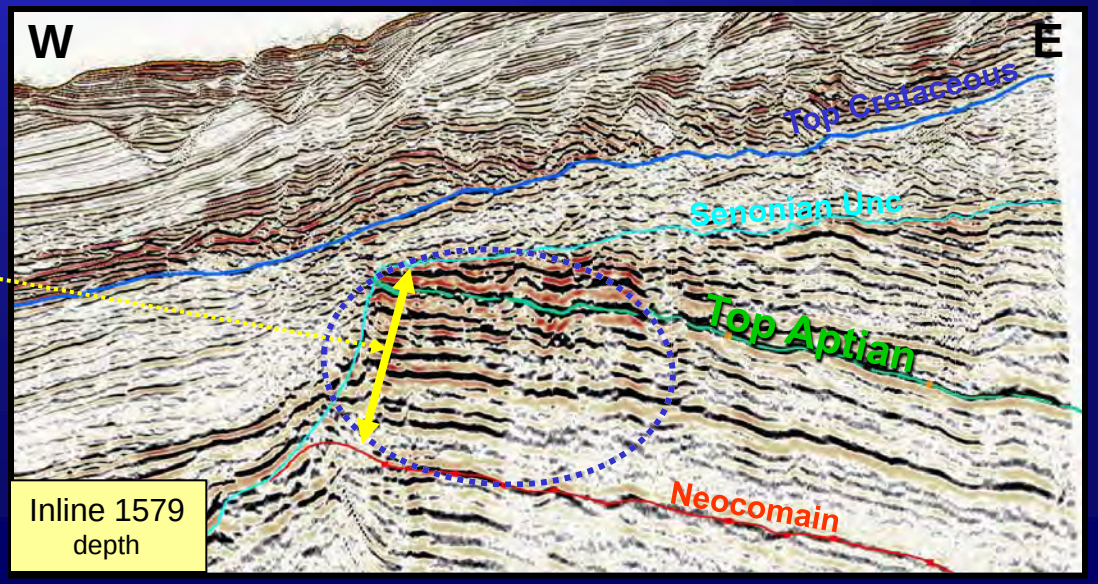
Aptian shelf edge closure





Large dip closed prospective interval

Lower Albian to Neocomian



Notes by Presenter (for previous slide):

Second play type is the Aptian shelf edge closure.

Left map shows Top Aptian depth, with the 3 way dip closed structure highlighted

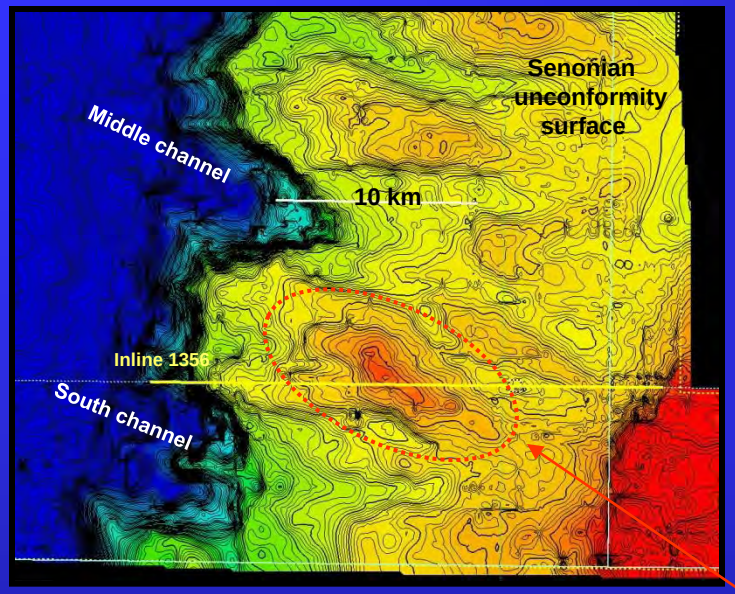
The map to left shows just the closure which is approximately 178 sq kms

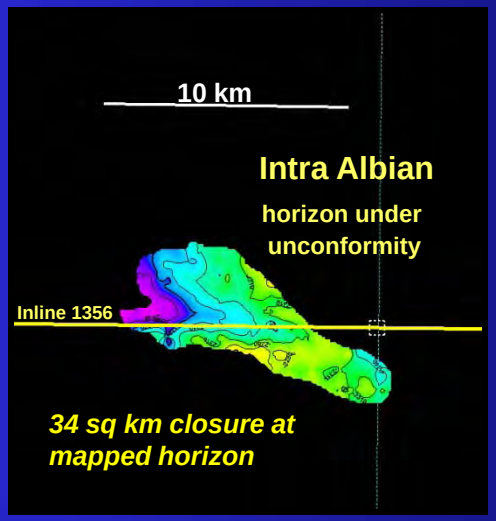
Seismic line shows what the closure looks like in the dip direction. The prospective interval may be from the Neocomian all the way to the Aptian and in places the ALBIAN (EXPLAINED IN NEXT SLIDE)

(POINT OUT THE HORIZONS ON THE SLIDE AKA NEOCOMIAN/APTIAN ETC)

Click to View Notes by Presenter

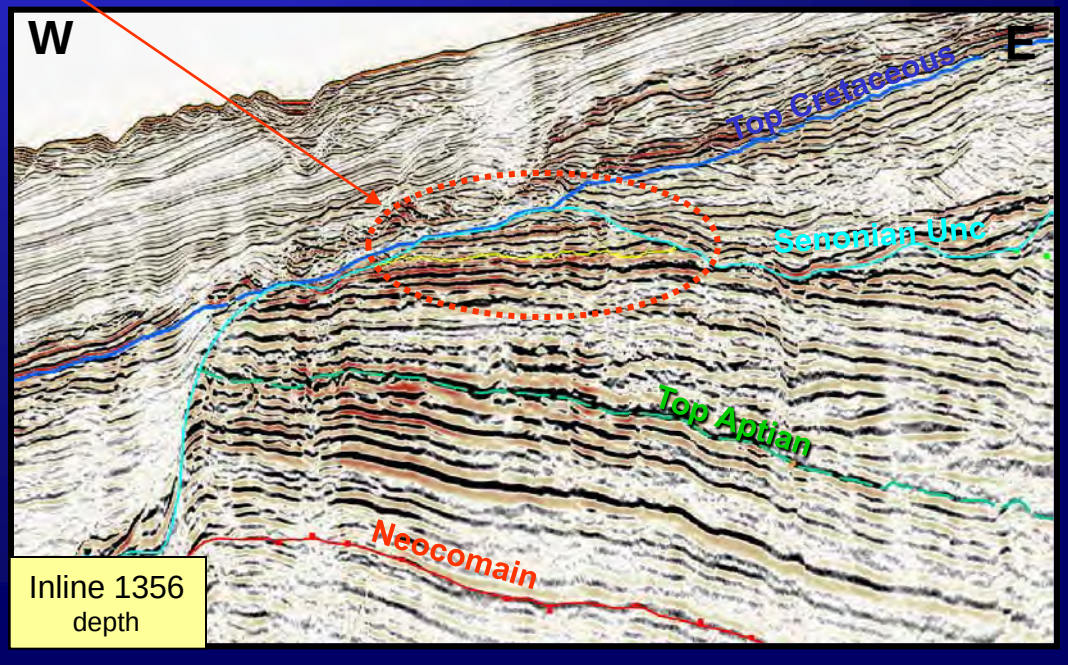
Albian buried hills closures





4 way stratigraphic Albian closure under Senonian unconformity

Albian shelf severely eroded by Senonian unconformity, karstified, then sealed by upper Cretaceous to lower Tertiary shales and marls

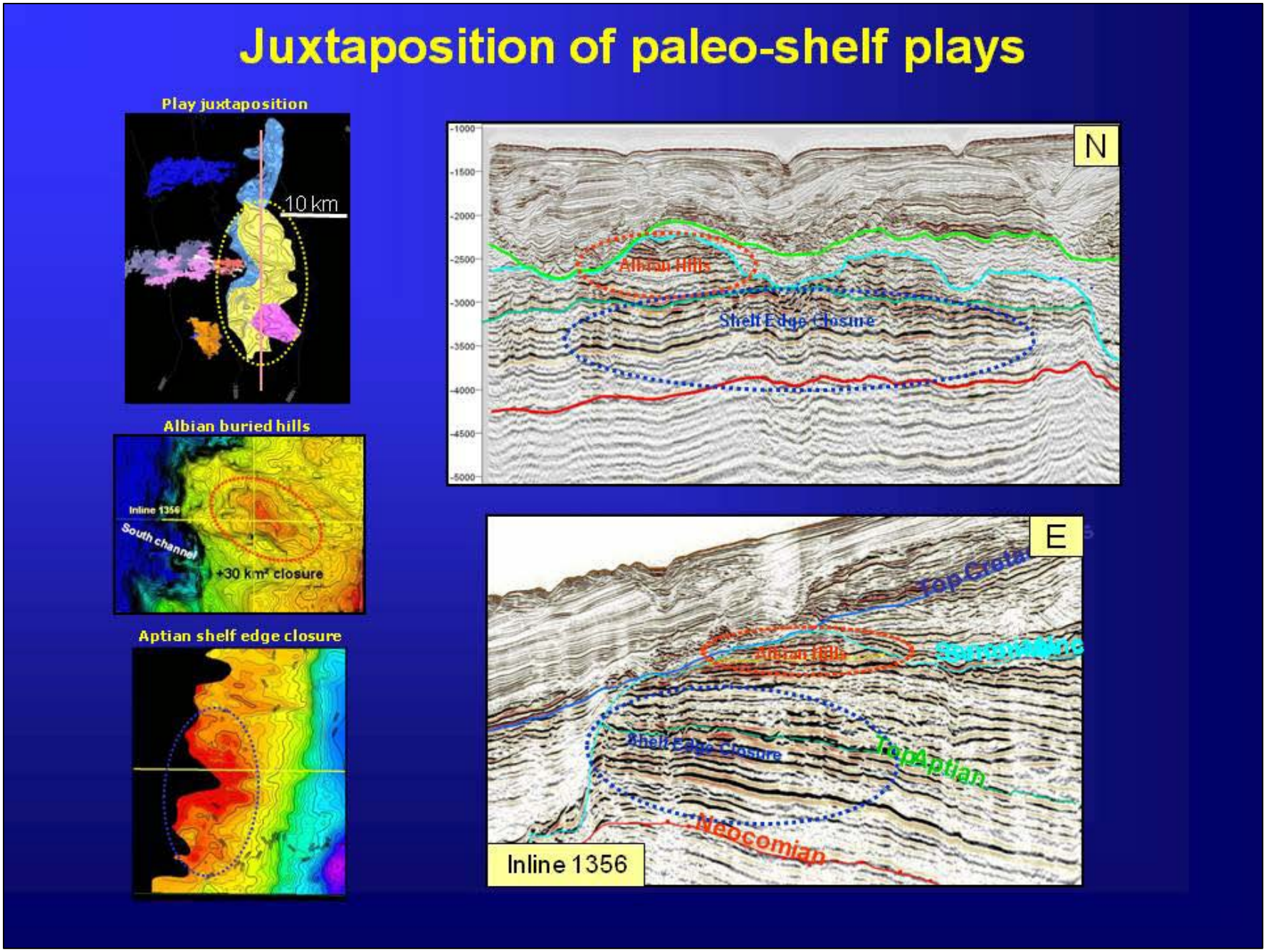


Notes by Presenter (for previous slide):

ALBIAN is non-existant on much of the shelf aka has been eroded by the Senonian unconformity What is left will have been severely karstified and sealed by the Upper Cretaceous lower Tertiary shales……This is the third play type for offshore SENEGAL.

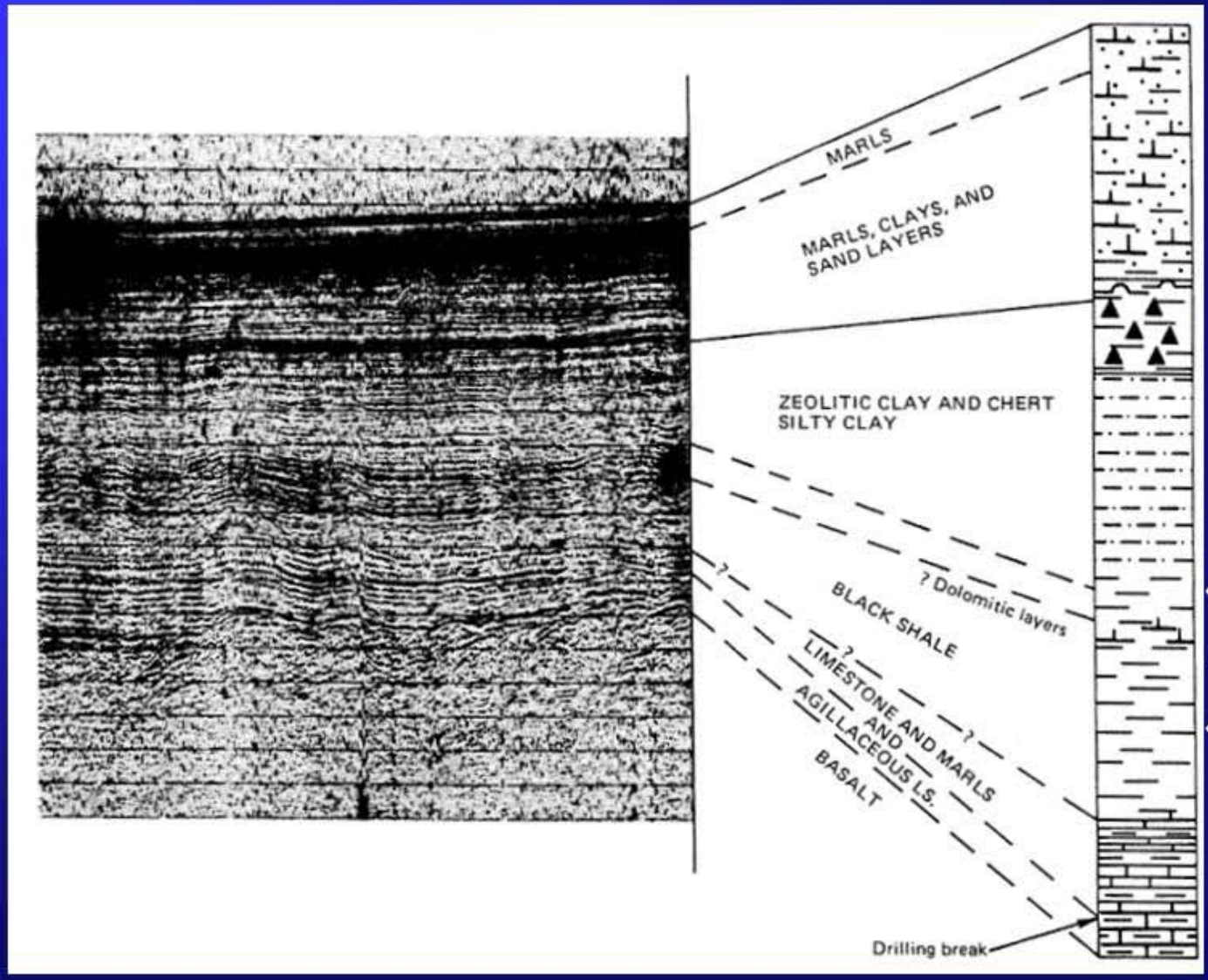
Left map shows Top Albian map- here you can see the karstic topography/ hummocky in appearance. It's a g=four way dip closure structure subcropping the Senonian Unconformity. Total closure is around 34 sq kms.

Seismic- point out the Albian and the Senonian unconformity.



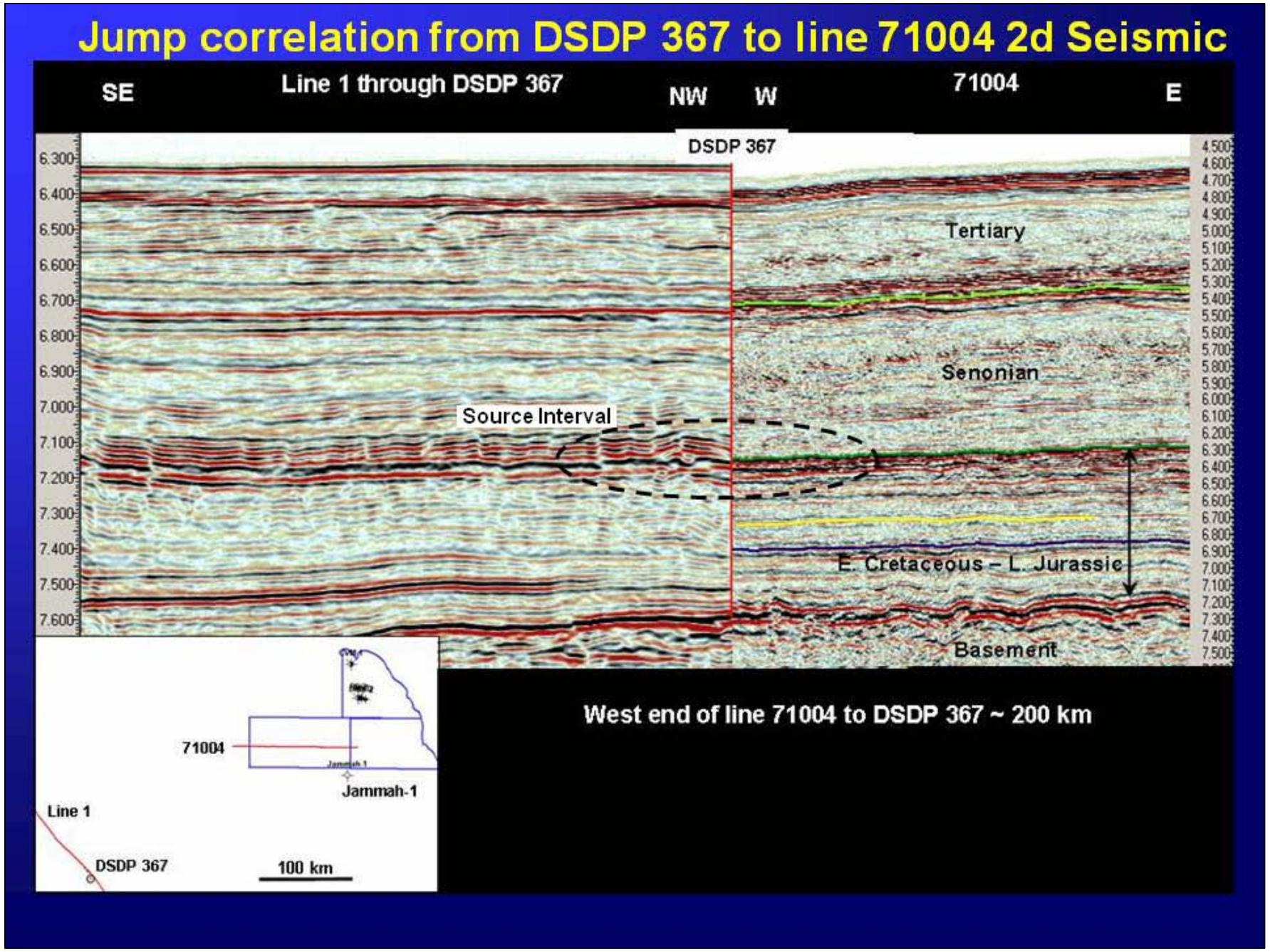
Notes by Presenter: Slide show the relationship of the Albian Buried Hill plays versus the location of the underlying Aptian shelfal closure. Here you can see the Albian and Aptian closure could be tested with one well.

DSDP Site 367 with source interval



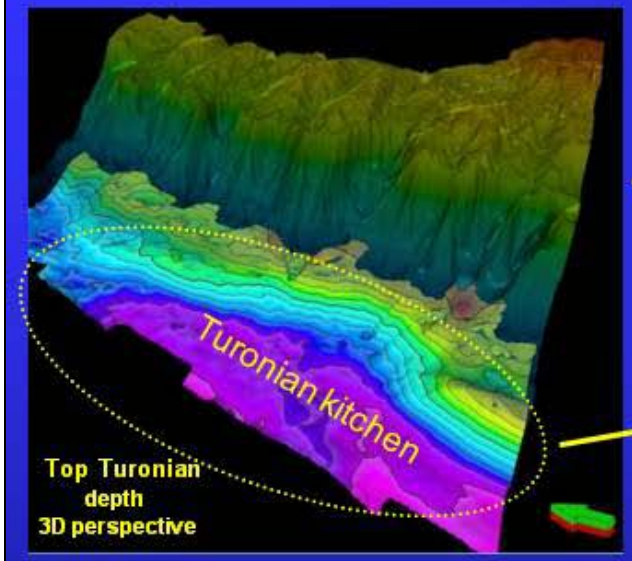
Source: DSDP

Notes by Presenter : Taken from DSDP well offshore Senegal……This well had Turonian Source rock- as is the rest of West Africa. This well was used to jump tie the Turonian source rock into our 2D/3D Seismic Database. SEE NEXT SLIDE FOR EXPLANATION…….Leads in……

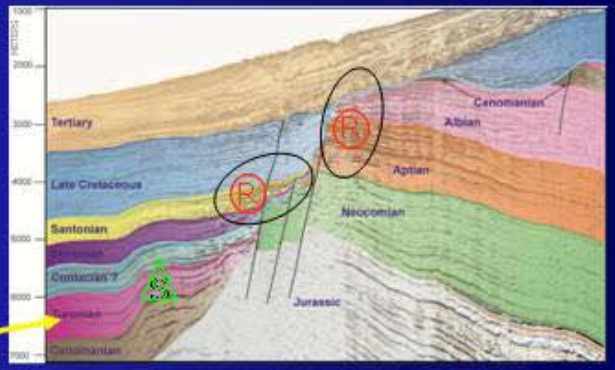


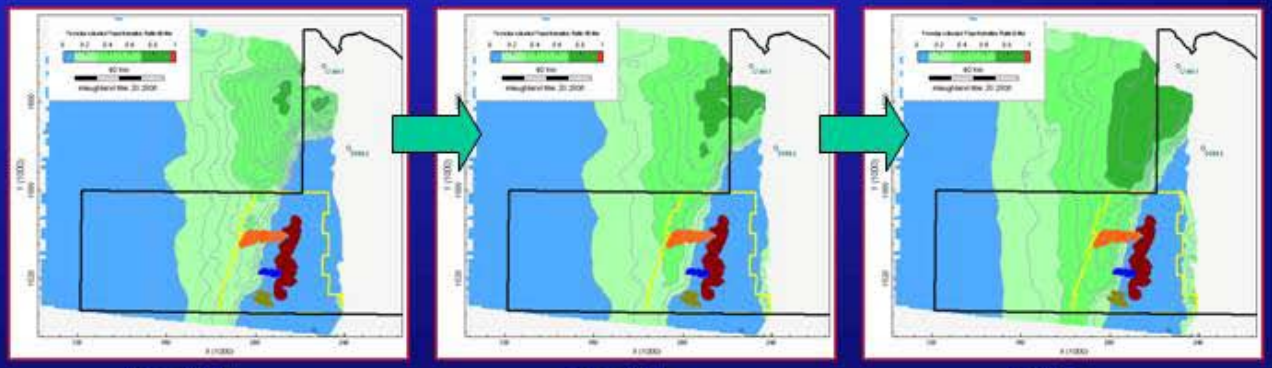
Notes by Presenter: Jump tie between 2D Seismic line within study area and Line one running through DSDP 367 well. Seismically very similar and confident the jump tie is within the Turonian unit. Difficult to tie as no wells penetrate the Turonian in Senegal.

Source Rock & Basin Modelling Summary



Turonian source kitchen
adjacent
to identified plays





60 Ma. 30 Ma. 0 Ma.

Source rock continuously in oil window since late Cretaceous

Notes by Presenter: Basin Modelling points to working Turonian Source Kitchen downdip from the Carbonate shelf. Source rocks have continuously been in the oil window since the late cretaceous

Conclusions

- The offshore geology for the study area can be best described by two parasequences:

  1) A long lived Jurassic-Cenomanian Carbonate Platform followed by

  2) A period of uplift, erosion and karstification when sediments were reworked and deposited down slope which continues to the present day.

- The two play types identified are

  1) Karstified limestone closures

  2) Slope apron debris fans.

- All key parameters for a working play have been identified: source, seal, timing of hydrocarbon migration, trap and reservoir.