A Coastal Barrier-Spit System: An Alternative Depositional Model for the Kudu Gas Field, Namibia*

Roger Swart[1]

Search and Discovery Article #20451 (2018)**
Posted December 24, 2018

*Adapted from oral presentation given at 2018 International Conference and Exhibition, Cape Town, South Africa, November 4-7, 2018
 DOI:10.1306/20451Swart2018

[1]BlackGold Geosciences CC, Windhoek, Namibia (rogerswart@afol.com.na)

Abstract

The 1.3tcf Kudu gas field located in SW Namibia has long been considered a coastal aeolian deposit that is interbedded with lava flows. The evidence for this is based largely on steep dips (22-24 degrees) recorded in dip meter logs, the presence of anhydrite and well sorted grains. In the actual core the dips are however not readily apparent. In the core there is evidence for marine bioturbation at certain levels and there are associated marine units with fossils. The presence of these marine fossils has given rise to some uncertainty in the aeolian interpretation, but no reasonable alternative has previously been proposed.

Recent field work in the well exposed Namibe Basin of SW Angola has identified a possible alternative analogue for Kudu. In the marine Maastrichtian interval, a unit occurs with steep cross beds but is clearly shallow marine. The marine nature is given by the presence of abundant shark teeth and other marine fossils. The maximum observed thickness is about 10-12m, the same order of magnitude as the 8m thick, steeply dipping unit in the core.

Recently, a portion of the Troll Field has been reinterpreted as a barrier-spit system. This is a well sorted, well stratified system with dips poorly preserved in the core. Thickness of the spit portion is about 4m.

It has been shown that longshore drift systems have been active in Angola since the Albian and are still strongly active on the Namibian coast today. It is highly likely that the Kudu sands may be a product of a coastal spit system. This model will help explain the steep cross beds, the presence of anhydrite, texture, close association with other marine sediments, and the north-

south elongation of the reservoir. This has implications for future exploration for similar reservoirs to Kudu on the Namibian margin.

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A coastal-barrier spit system:
An alternative depositional model for the Kudu gas reservoir, Namibia

Roger Swart

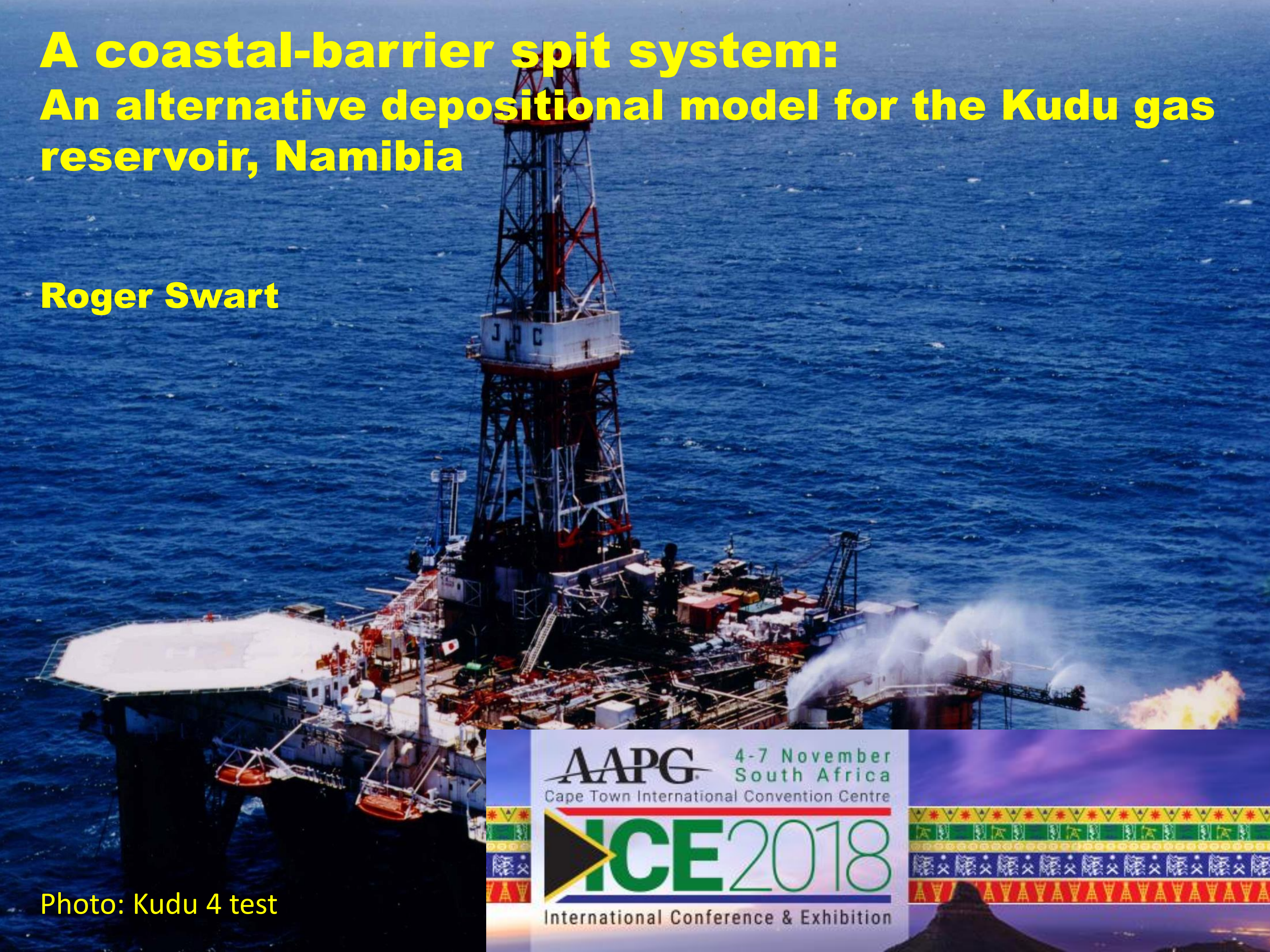


Photo: Kudu 4 test

Talk outline

- Background
- Current sedimentological interpretation
- What are the issues?
- One alternative
- Summary

Some background – drilling history

- Originally discovered in 1973/74 by a Regent-Chevron-Soekor consortium

> considerable debate on the merits of drilling ahead. Soekor and Swakor, however; felt strongly that the stratigraphy and hydrocarbon potential at deeper levels should be tested despite the lack of any demonstrable trap, and serendipitously, gas was encountered beneath horizon P2 at 4400 m below sea level. Further drilling to a total depth of 4452.5 mbKB (metres below kelly bushing) established that the reservoir consists of two main sandstone bodies of 52 m (4426 to 4278 mbKB) and 24 m (4317 to 4341 mbKB) thickness separated by a basalt and underlain by a succession of basalt and non-marine sandstone. The calculated average sandstone porosity

McLachlan, 1990

- 1987-1988 Kudu 2 & 3 drilled by SWAKOR (now Namcor)
  - Kudu 2 ok, but not tested
  - Kudu 3, flowed at 38 million standard cubic feet/day
  - Several wells drilled since with varying success

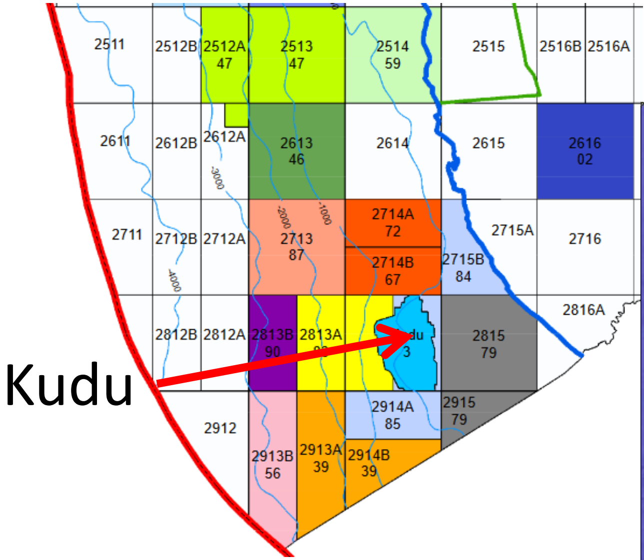
Well information

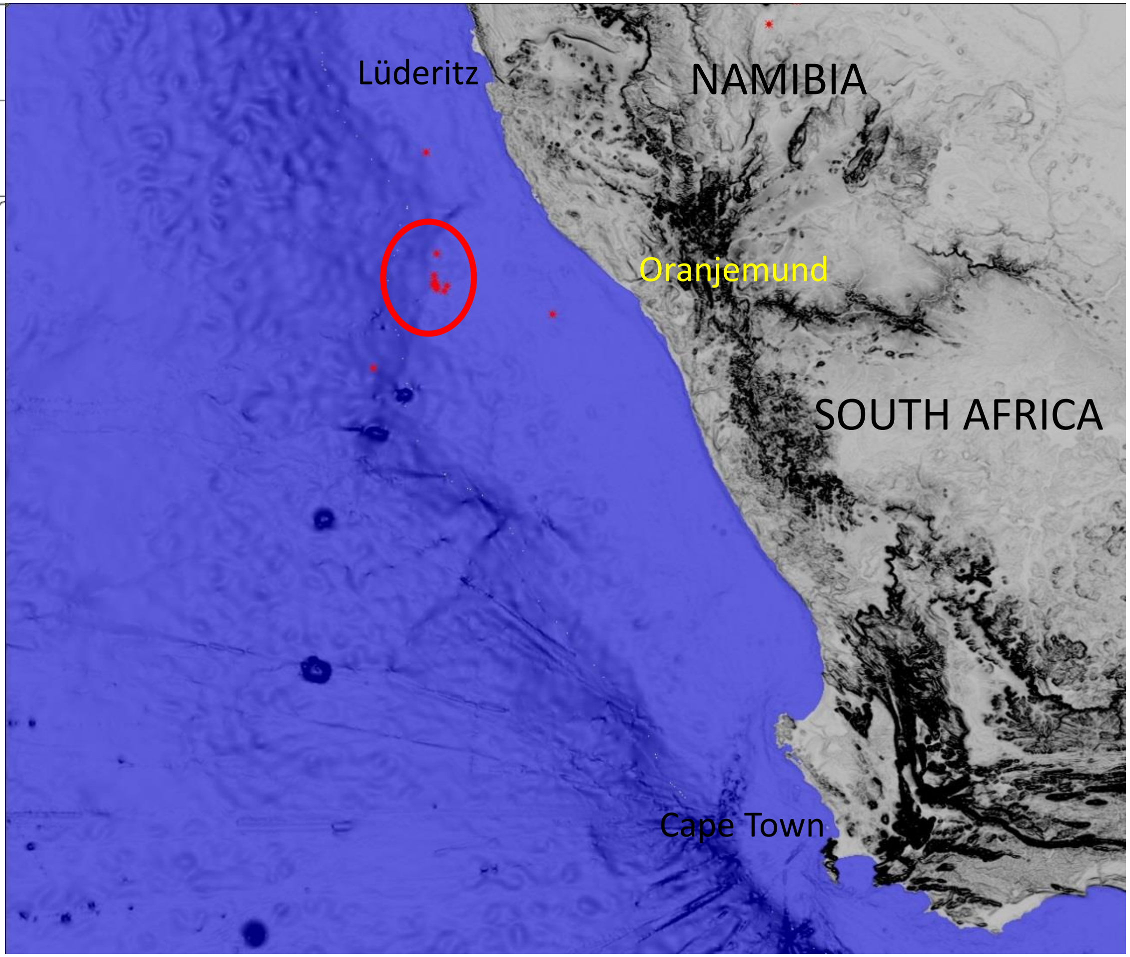
- Wells in c. 170m water depth
- 130km to closest landfall
- 170km west of Orange river mouth
- Reservoir c. 4,400-4,500m below sea level
  - c. 30-60m thick

- 96% methane (CH_4)
- Small amounts of condensate (liquids)
- Low CO_2 and H_2S
- High temperature (154^{o}C) and high pressure (7400psi in reservoir)

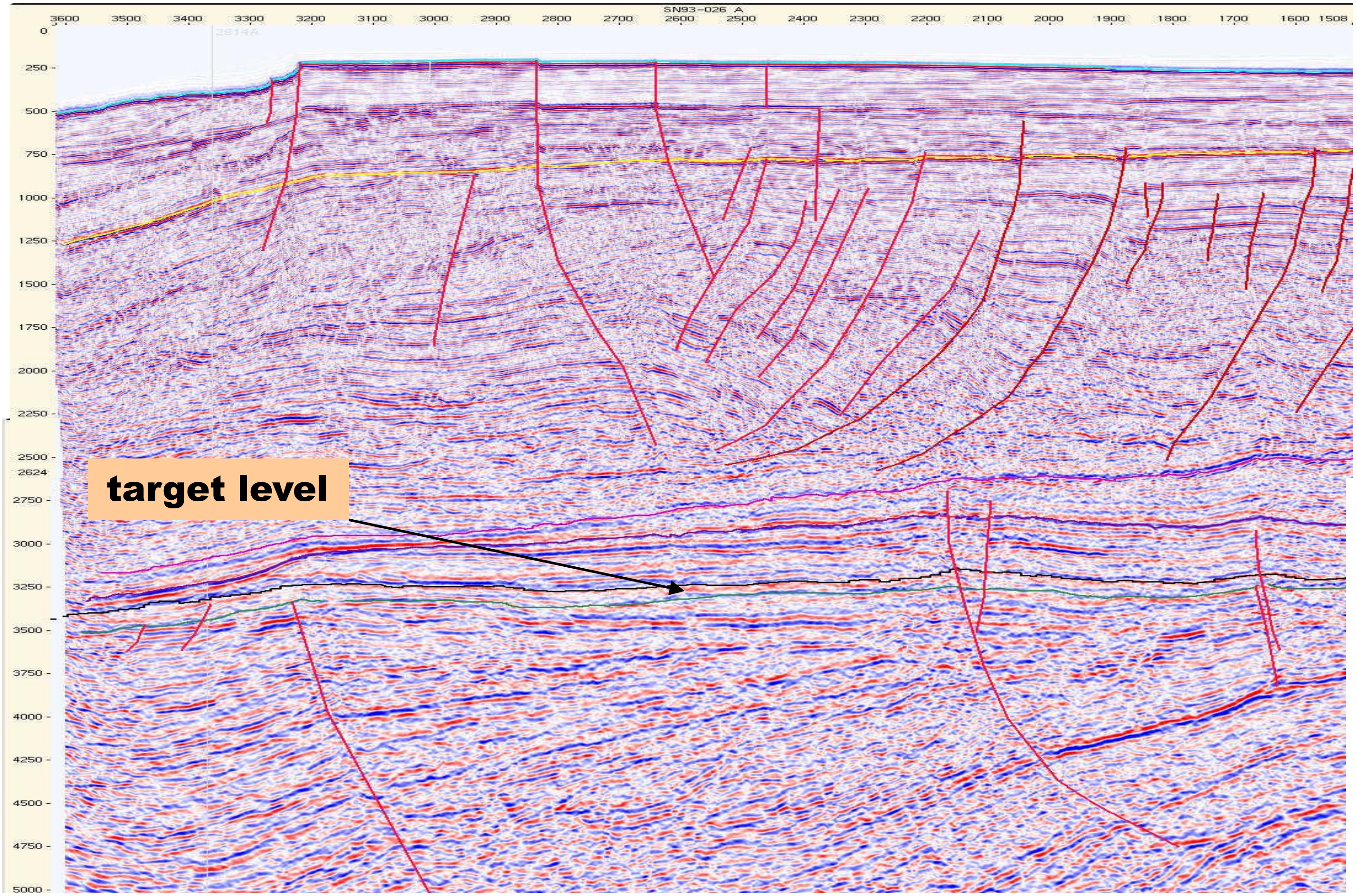
- Reserves?? 1.3 tcf GIIP?

Location


Kudu
2511
2512B
2512A 47
2513 47
2514 59
2515
2516B
2516A
2611
2612B
2612A
2613 46
2614
2615
2616 02
2711
2712B
2712A
2713 87
2714A 72
2714B 67
2715A
2715B 84
2716
2812B
2812A
2813B 90
2813A
2815 79
2816A
2912
2913B 56
2913A 39
2914A 85
2914B 39
2915 79


Lüderitz
NAMIBIA
Oranjemund
SOUTH AFRICA
Cape Town

A bit of seismic



- Reservoir sands interbedded with basalt (sdr's??)
- Faulting above reservoir
- Both a challenge for drilling, seismic acquisition & interpretation

CURRENT SEDIMENTOLOGICAL INTERPRETATION

Communs geol. Surv. Namibia, 6 (1990), 9-23

The stratigraphy and sedimentology of the reservoir interval of the Kudu 9A-2 and 9A-3 boreholes

H. de V. Wickens and I.R. McLachlan
Soekor, P.O. Box 307, Parow 7500, South Africa

The studied intervals of the boreholes can be divided into two major parts (Fig. 1):

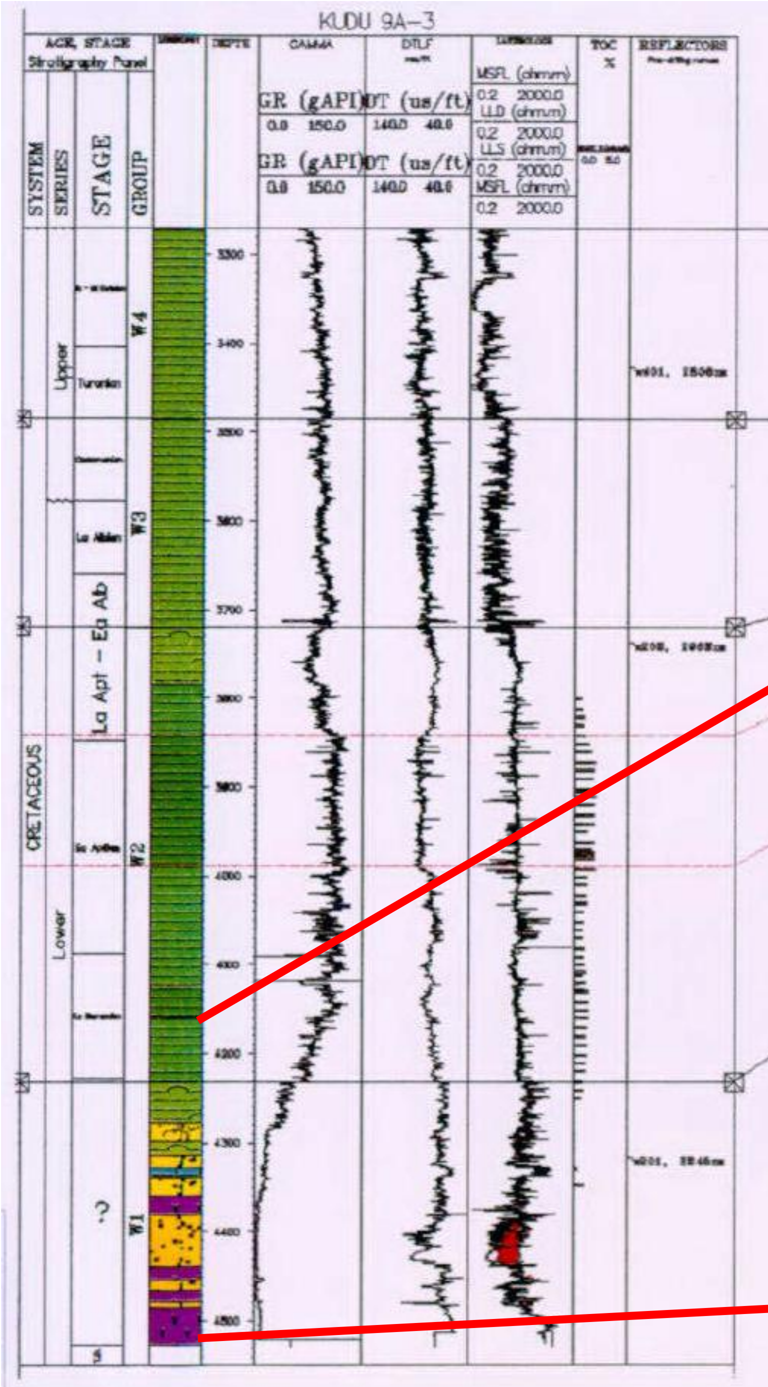
Zone of interest

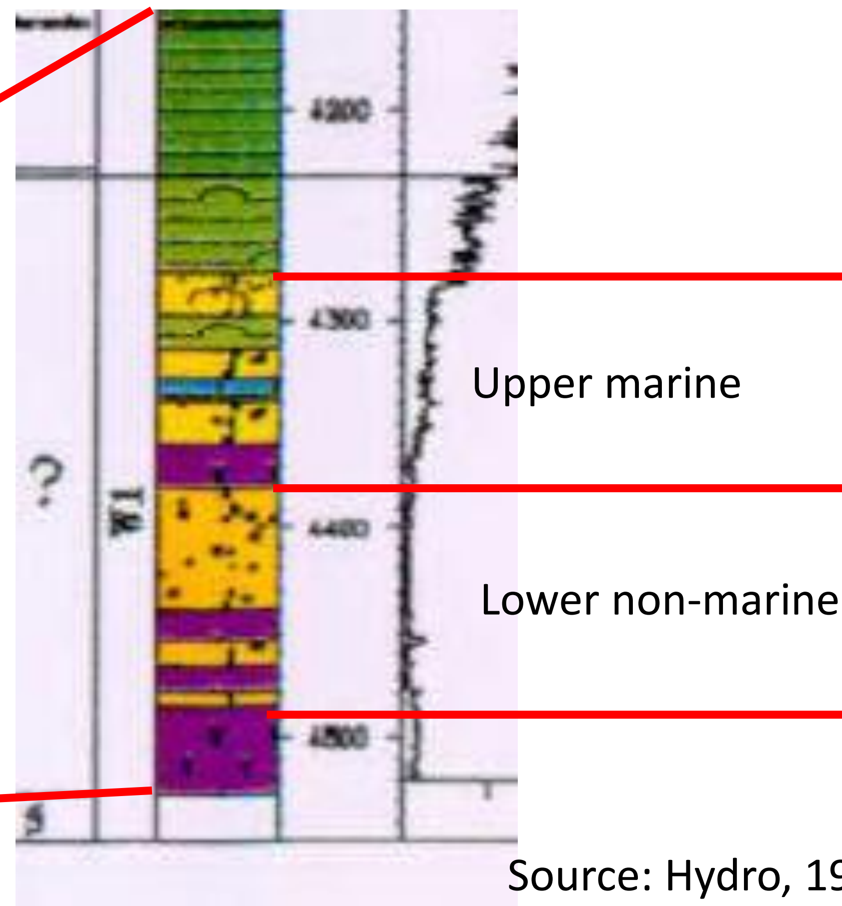
- a Lower Non-Marine Unit incorporating the whole of the Lower Gas Sand of Kudu 9A-3 and possibly part of the Lower Gas Sand of Kudu 9A-2. This unit includes basalt, anhydritic aeolian sandstone and volcaniclastic sandstone;

- an Upper Marine Unit incorporating the Upper Gas Sand of both wells and possibly part of the Lower Gas Sand of Kudu 9A-2. It also includes limestones and volcaniclastic sandstones.

Major source of information on the sedimentological interpretation of Kudu

Kudu 3





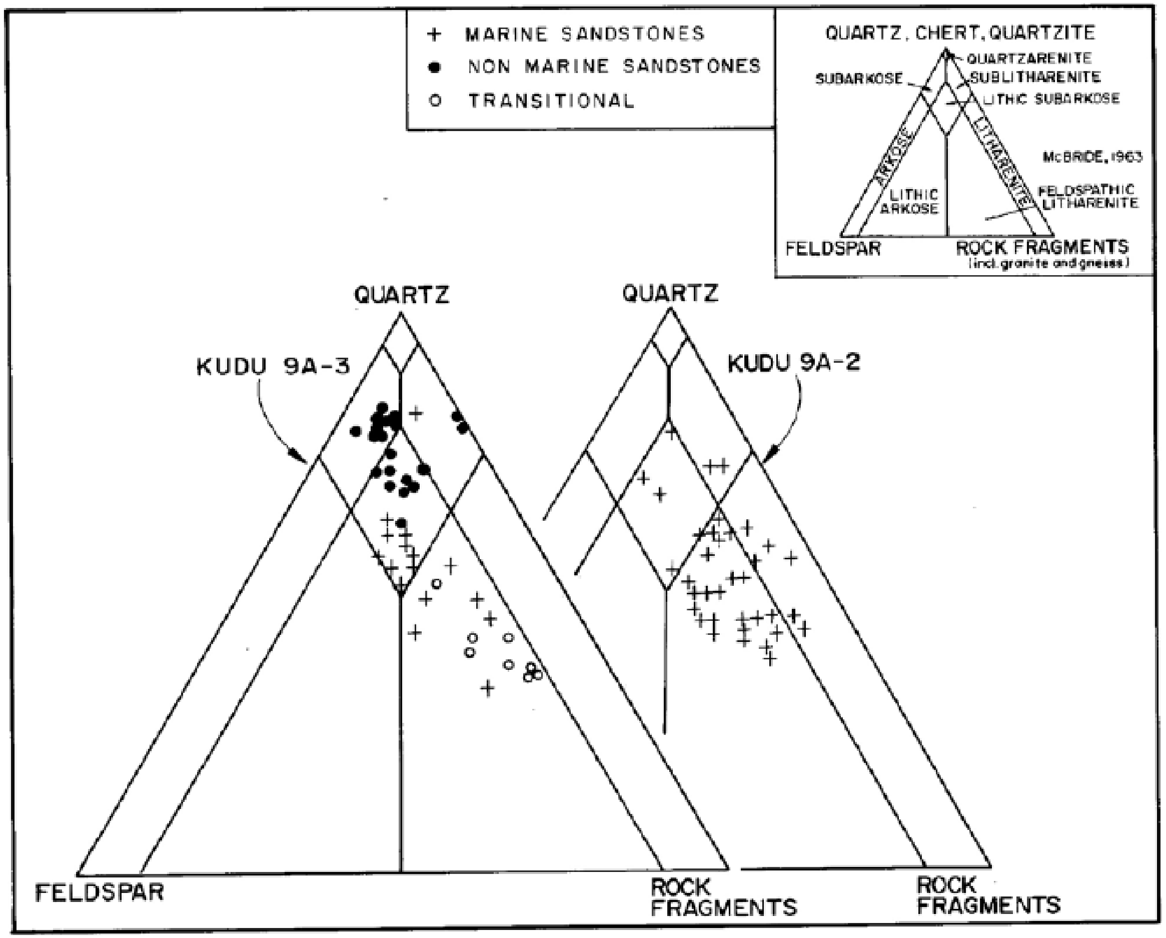
Source: Hydro, 1998

Facies 3: Anhydritic (aeolian) sandstone (correlation units B, D)

This facies is confined to the Lower Non-Marine Unit of the boreholes (Fig. I) and constitutes the bulk of the Lower Gas Sand of Kudu 9A-3. The total thickness of the anhydritic facies in this borehole is 73 m and there are, in addition, thin sandstones of similar appearance within the underlying basalt (e.g. the thin gas-bearing sandstone at 4478 m to 4482.50 m in Kudu 9A-3). It

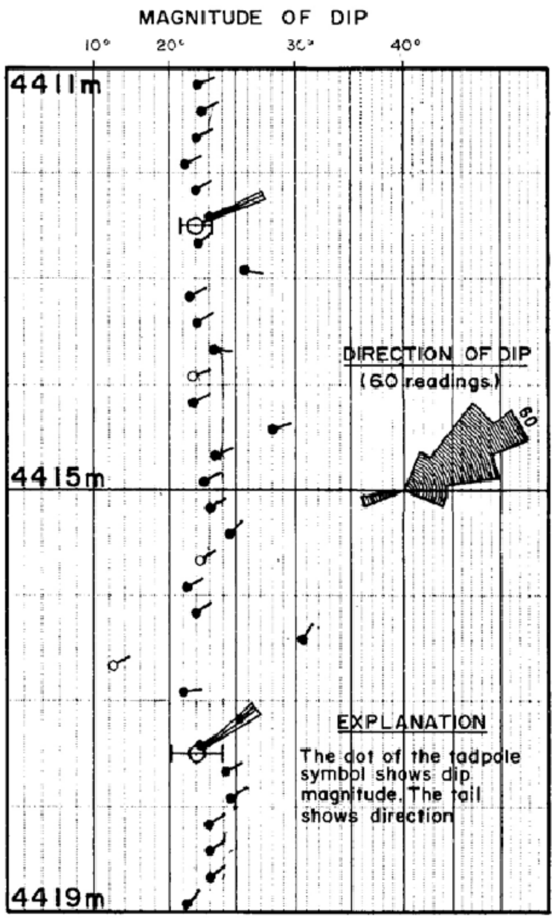
- Fine to medium grained
- Well sorted, well rounded
- Light grey to white
- Vertically elongated anhydrite nodules; may be in clusters
- Large scale cross stratification from dip logs
- bulk of Lower Gas sand in Kudu-3 is interpreted as aeolian
- more thin sandstones lower down that are interbedded with basalt

- Sub-arkosic to lithic subarkosic

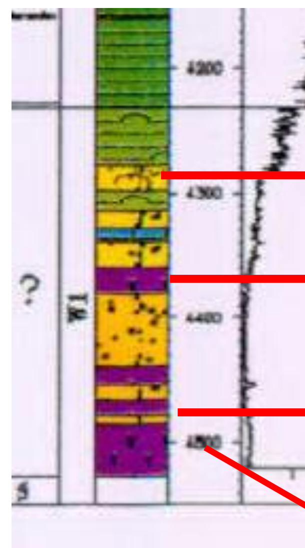


From Marot, 1990

• Bedding planes difficult to recognise in core

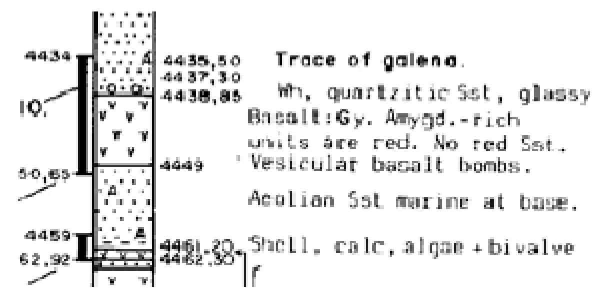


- Dipmeter log is the main source of information on the cross bedding
- Large scale, high angle cross stratification

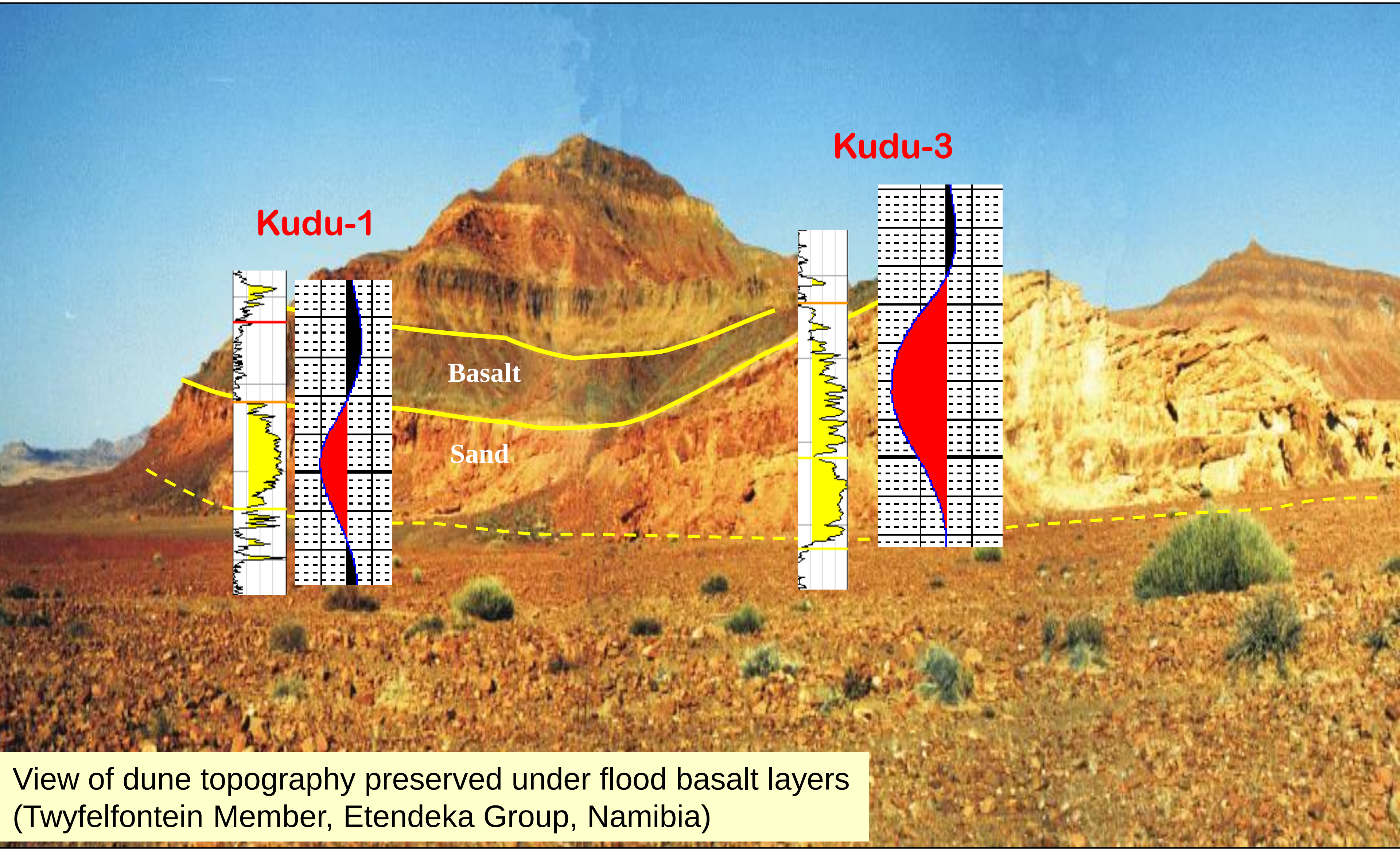


Upper marine

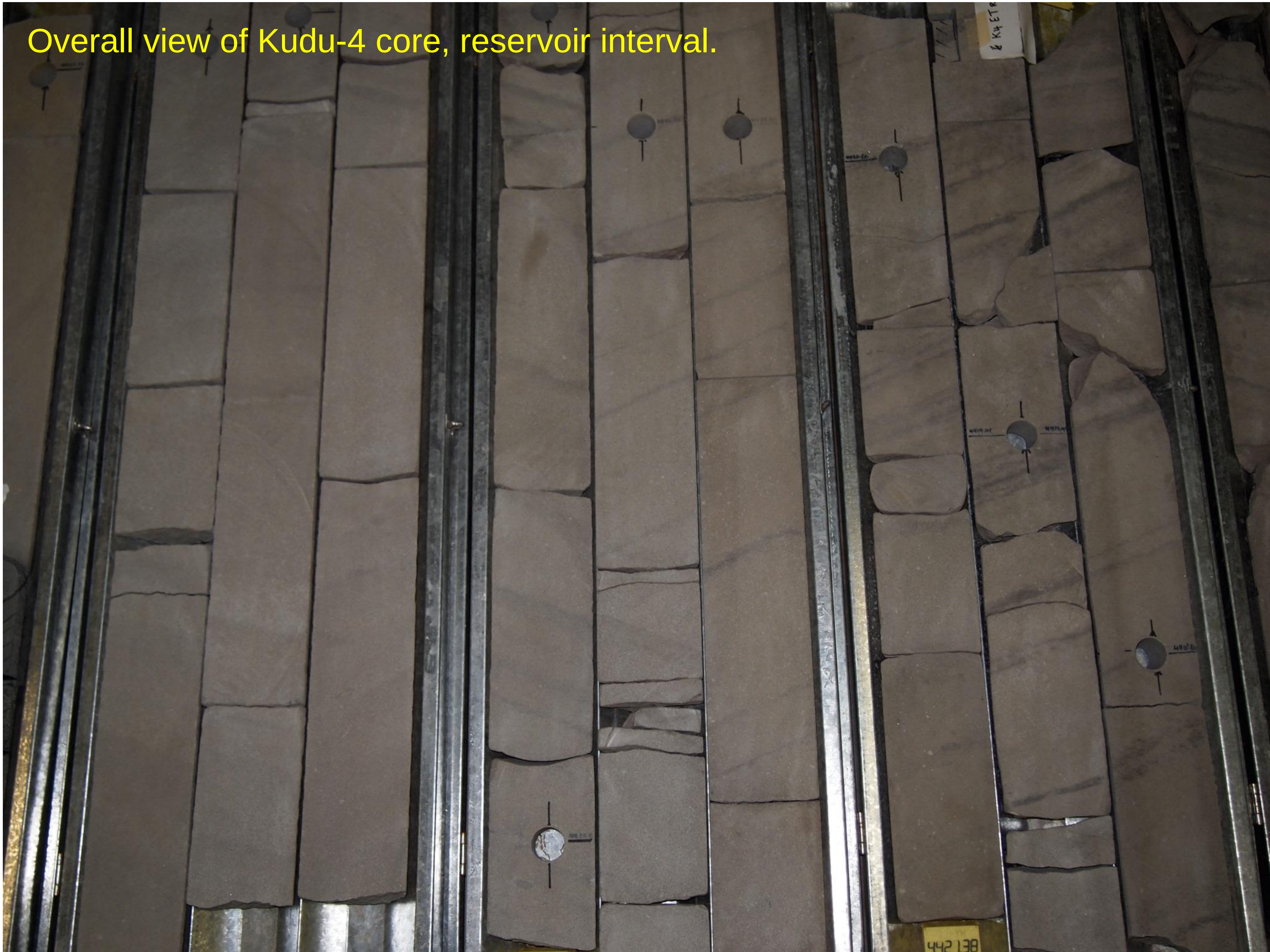
Lower non-marine



The aeolian interpretation led to the Early Cretaceous lower Etendeka Group in the Huab area being used as an analogue for Kudu



View of dune topography preserved under flood basalt layers (Twyfelfontein Member, Etendeka Group, Namibia)



Overall view of Kudu-4 core, reservoir interval.

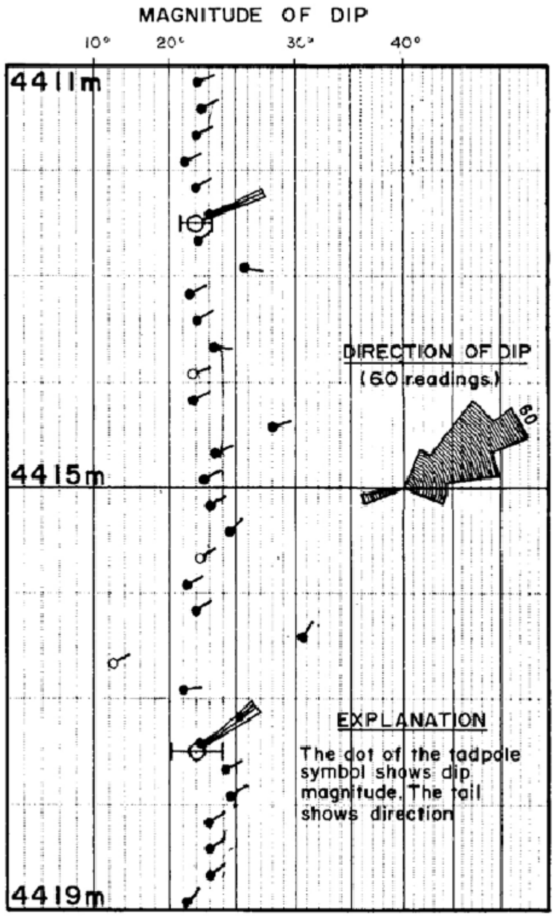
Summary of previous work

“*The massive nature of the sandstones and the presence of high-angle cross-bedding, anhydrite and well-sorted and well-rounded sand grains, suggest an aeolian origin, perhaps in a coastal dune complex*.”

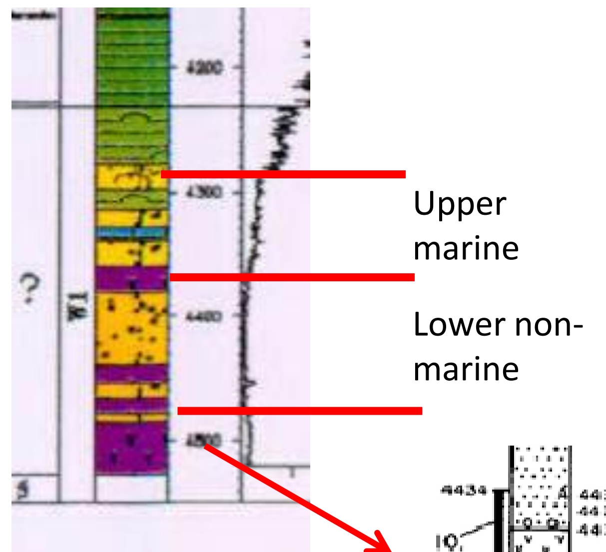
Wickens & McLachlan, 1990

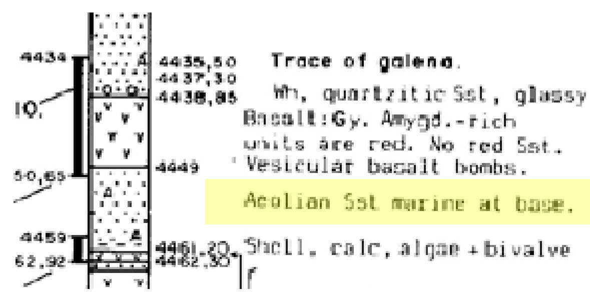
So what are the issues with this interpretation?

- Bedding planes difficult to recognise in core



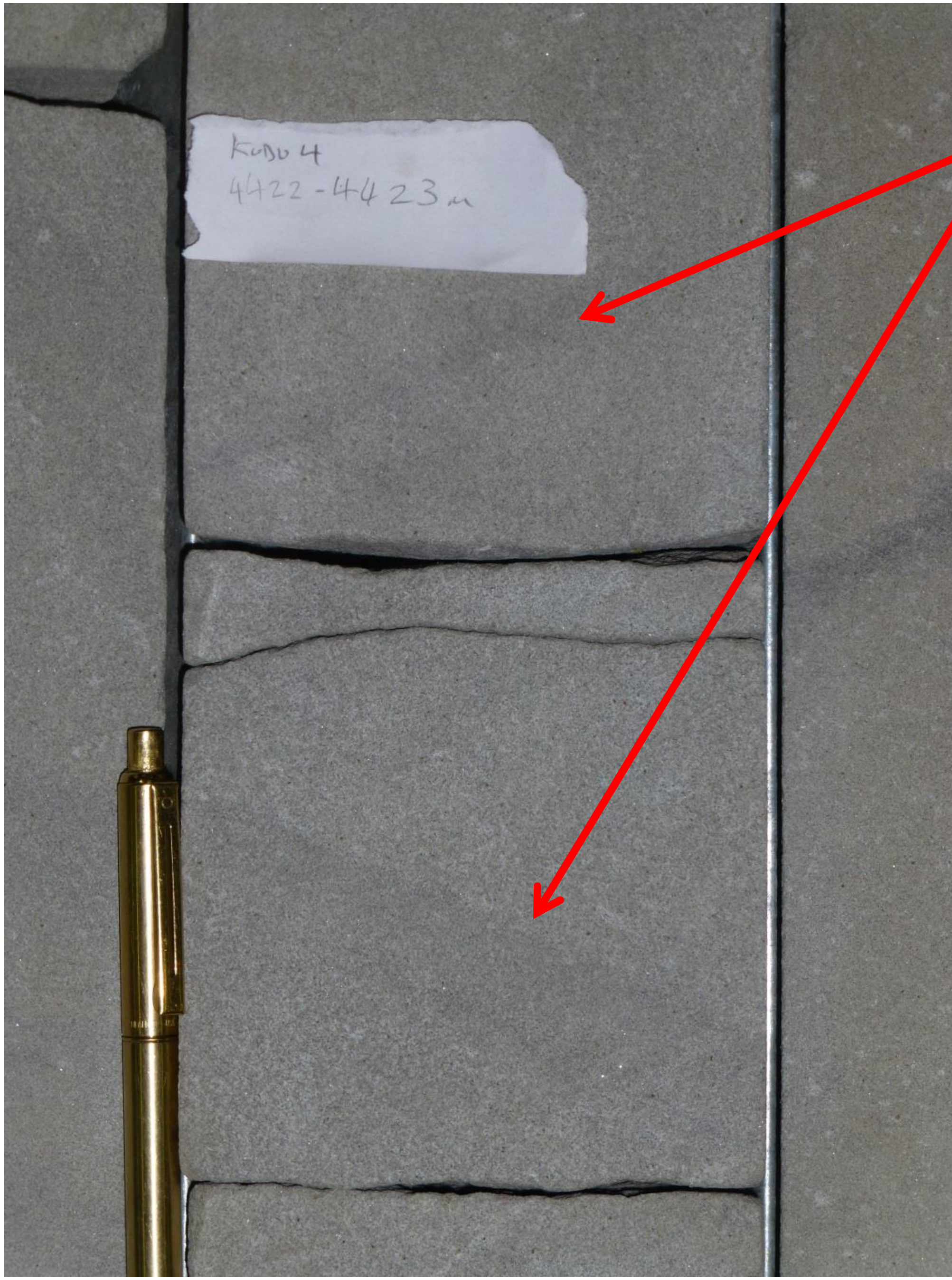
- Dipmeter log is the main source of information on the cross bedding
- Large scale, high angle cross stratification





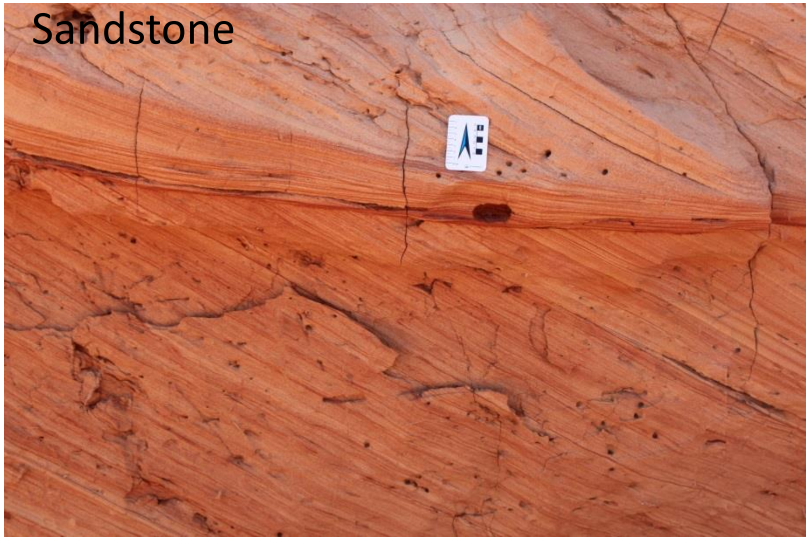
- Shelly marine debris at base of non-marine unit
  - Alarm bell??

- Wispy lamination – marine?
- but not aeolian….

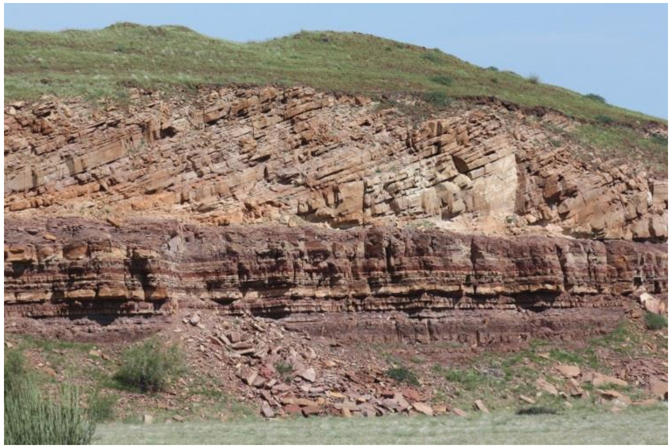


Kudu-4
Interpreted aeolian cross bedding

Compare this with aeolian cross bedding in Miocene Tsondab Fm Sandstone

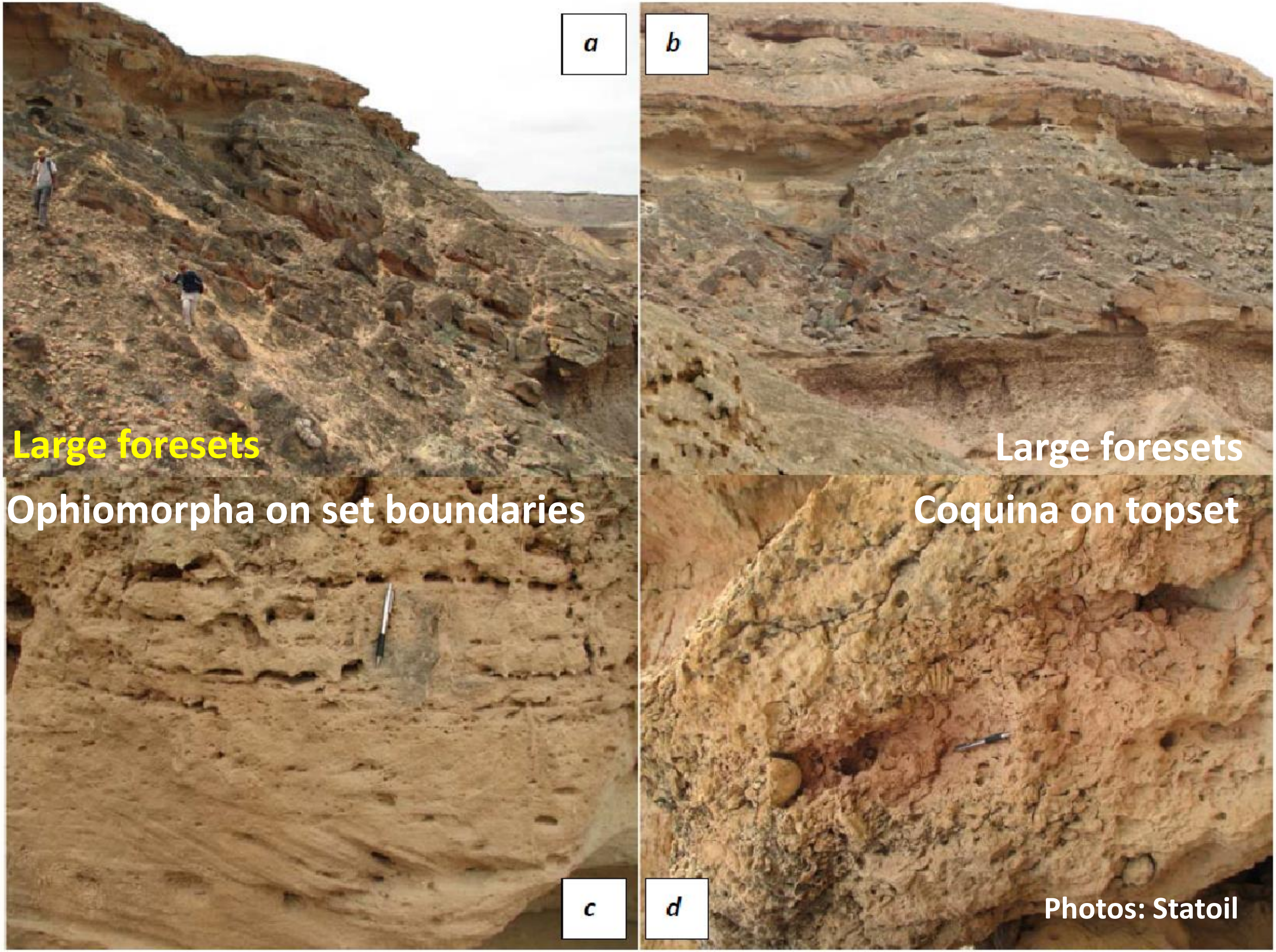


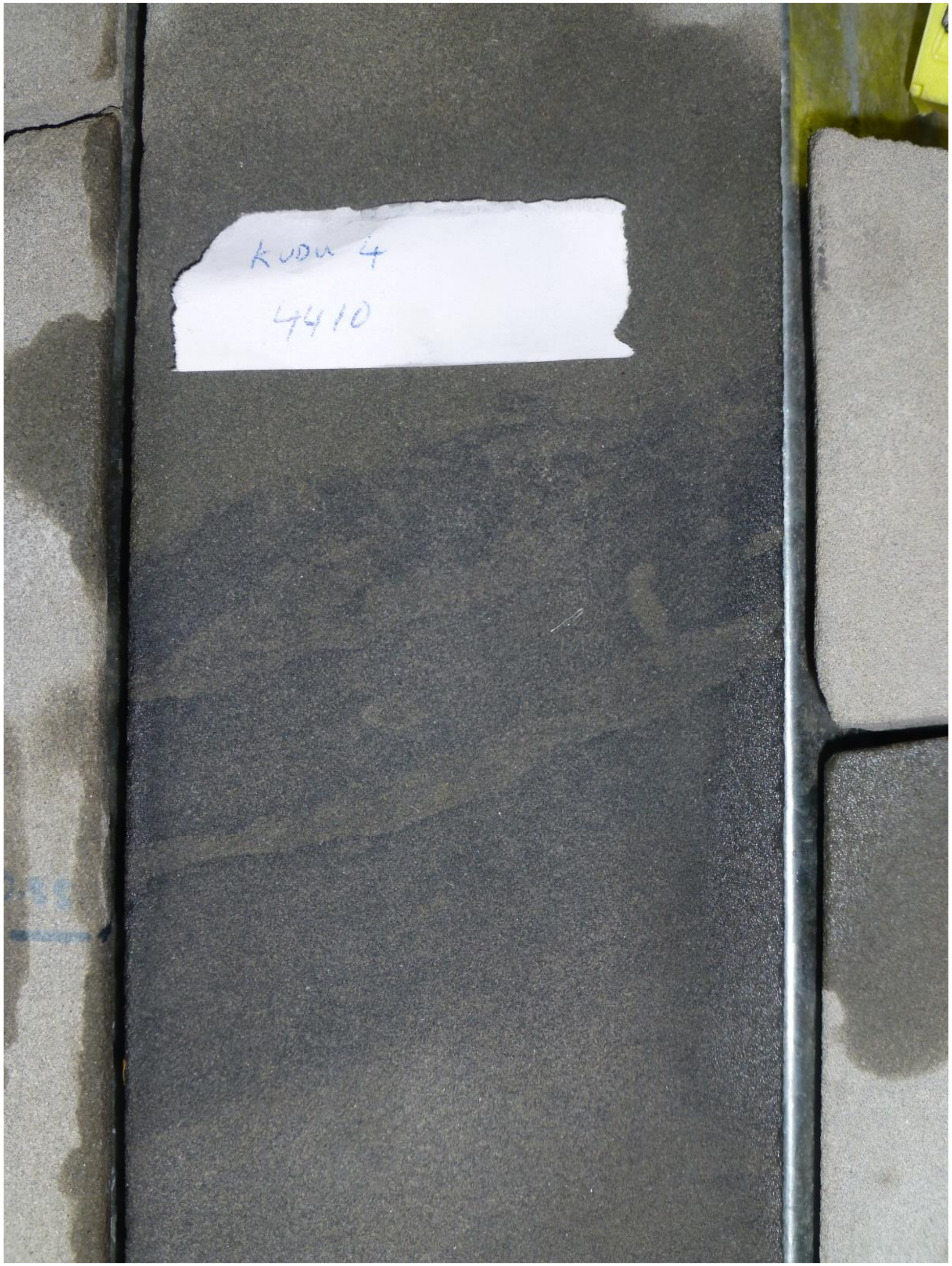
Or Twyfelfontein Mbr (Etendeka Group)



What alternative settings are there that explain marine looking character?

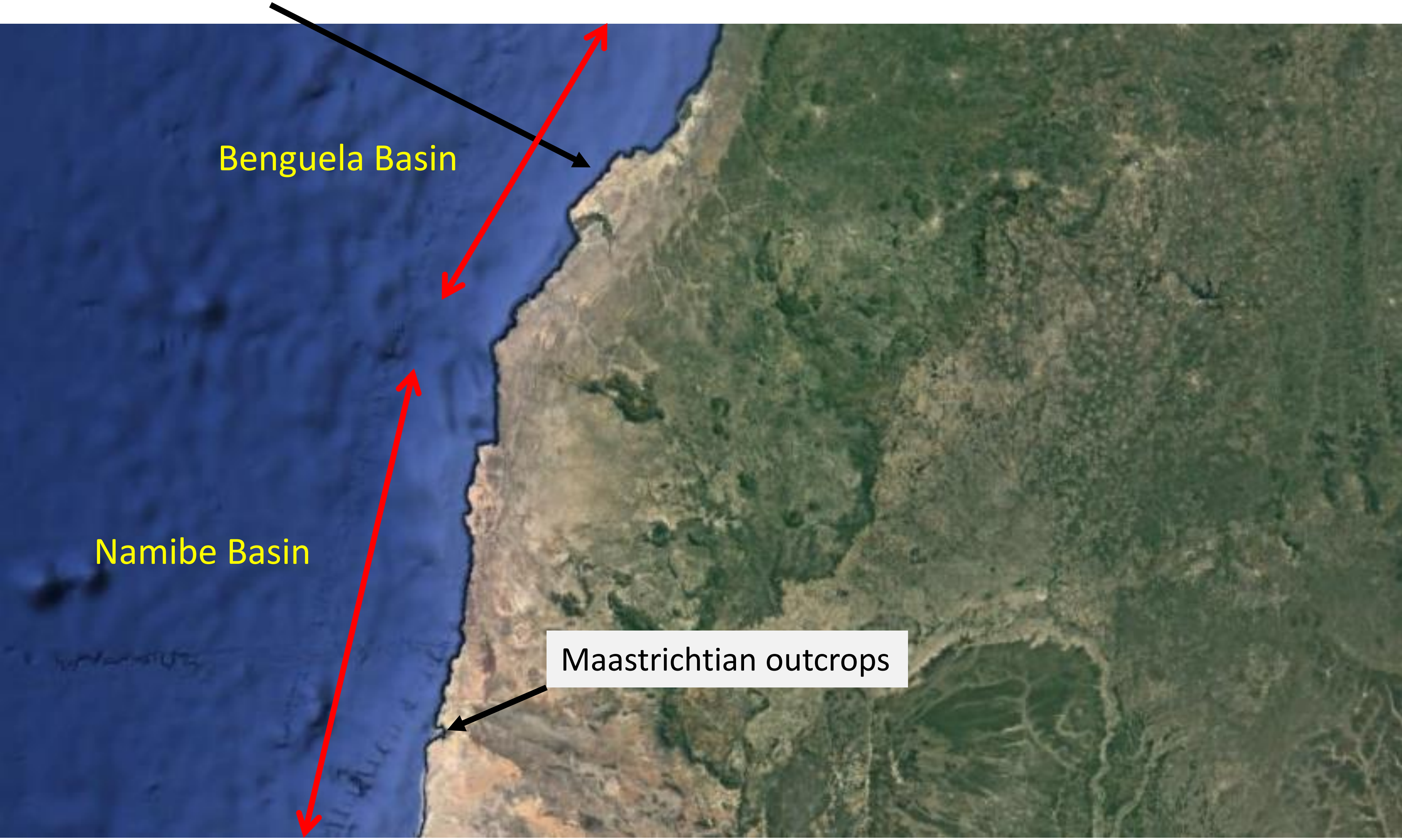
In Bero River, same beds associated with marine fossils - shark teeth, mososaurus tusks


a
b
Large foresets
Large foresets
Ophiomorpha on set boundaries
Coquina on topset
c
d
Photos: Statoil



And in the Kudu core we have burrows that resemble ophiomorpha.

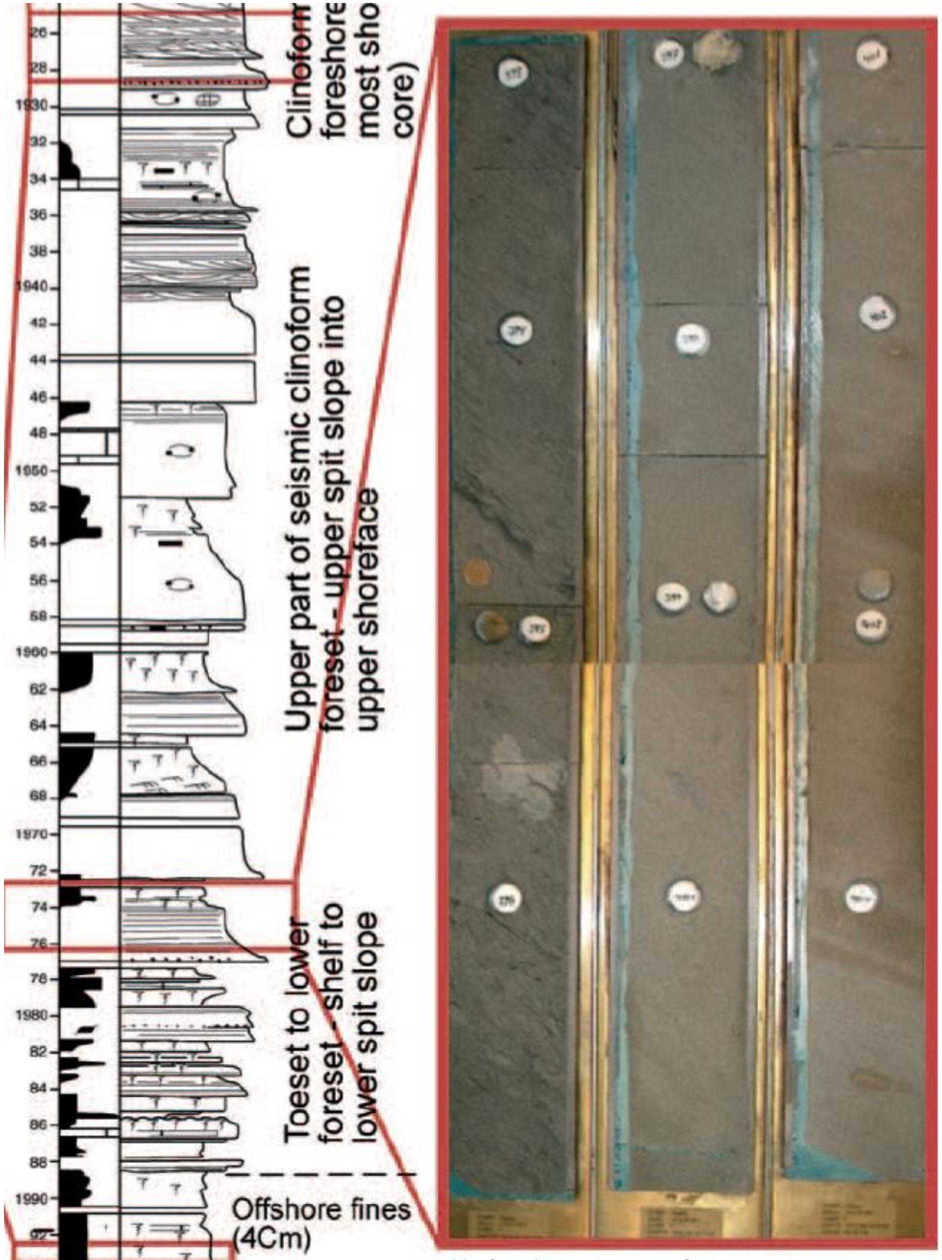
Also have major systems like this in Albian in Benguela Basin (c.110Ma).
Quesne *et al.*, 2009; Dinis *et al.*, 2016



Troll Field, Norway

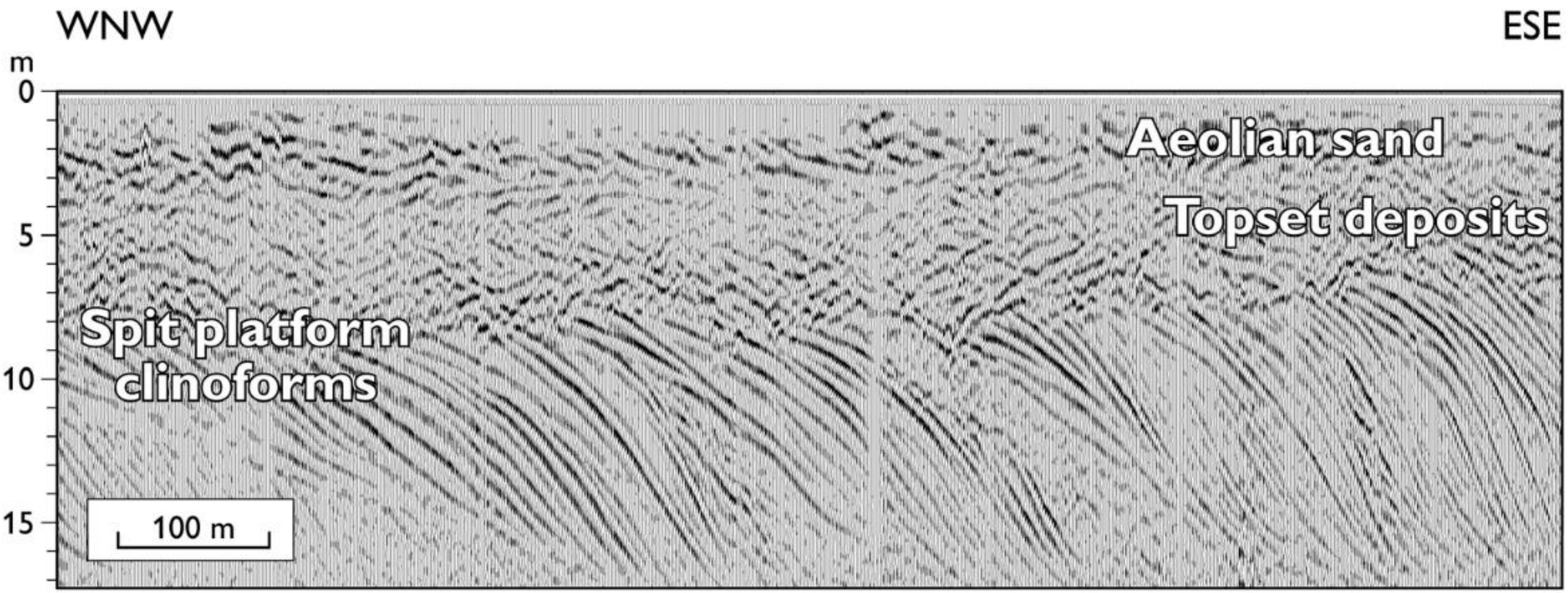
- One of largest gas fields in world
- Described by Dreyer *et al*., 2005
- In part interpreted as a barrier-spit system
  - Well sorted, well stratified
  - High proportion of rounded to sub-rounded quartz grains
  - Ophiomorpha burrows in places

Troll **Kudu**



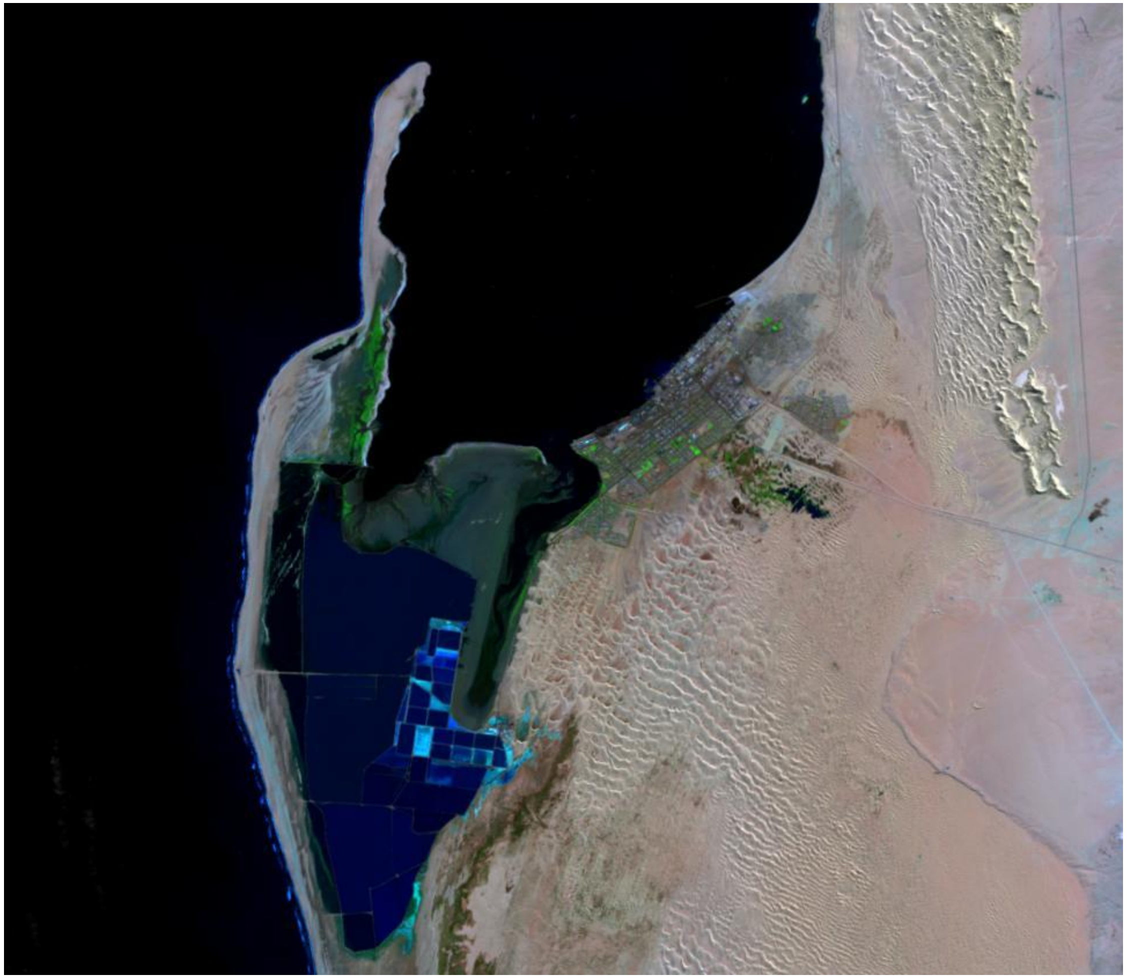
Troll field data from Dreyer *et al.*, 2005

- A GPR look at a modern spit system

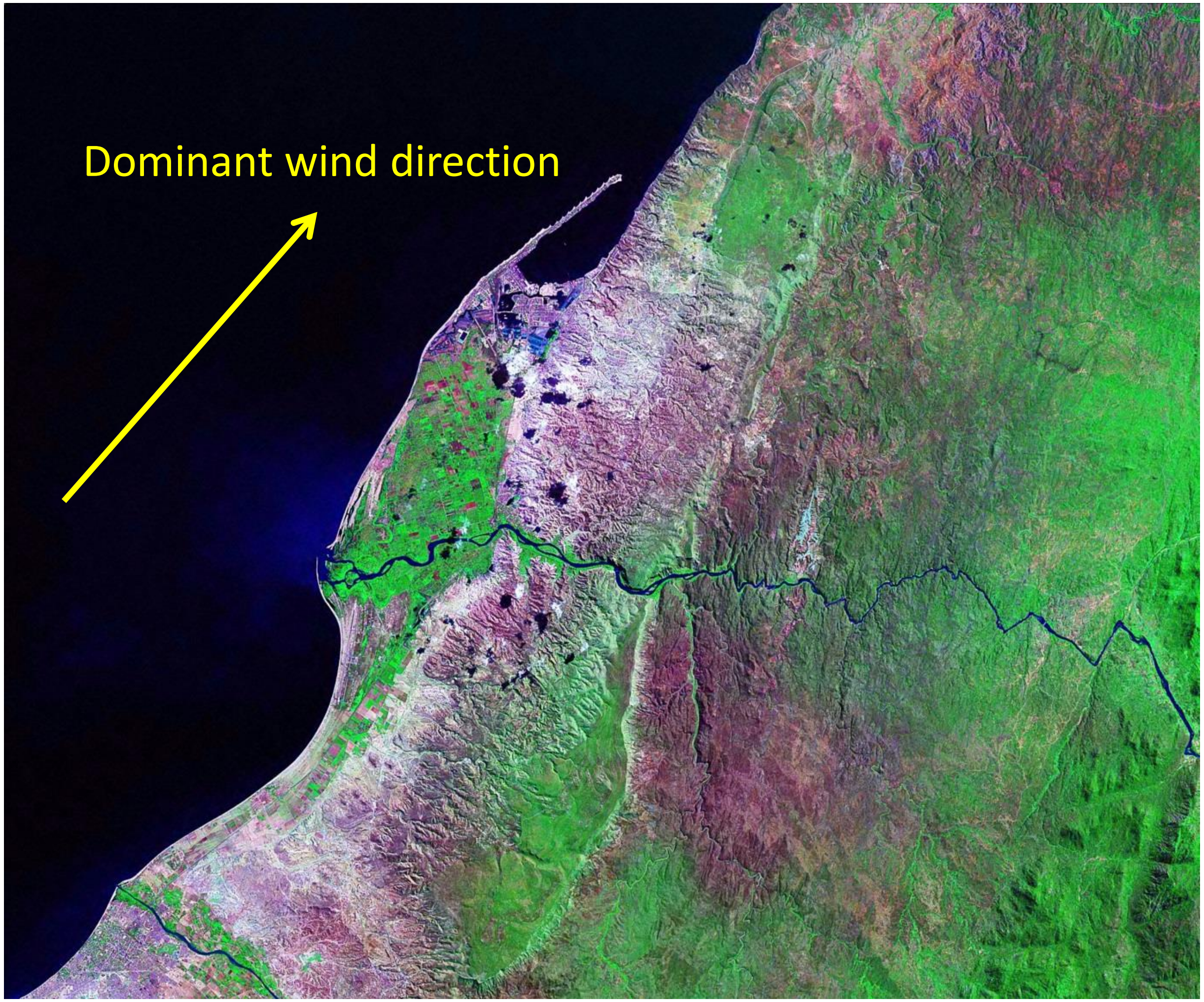


Johannessen & Nielsen, 2009

Evidence suggests that an option for Kudu may be a coastal spit such as Pelican Point today…..



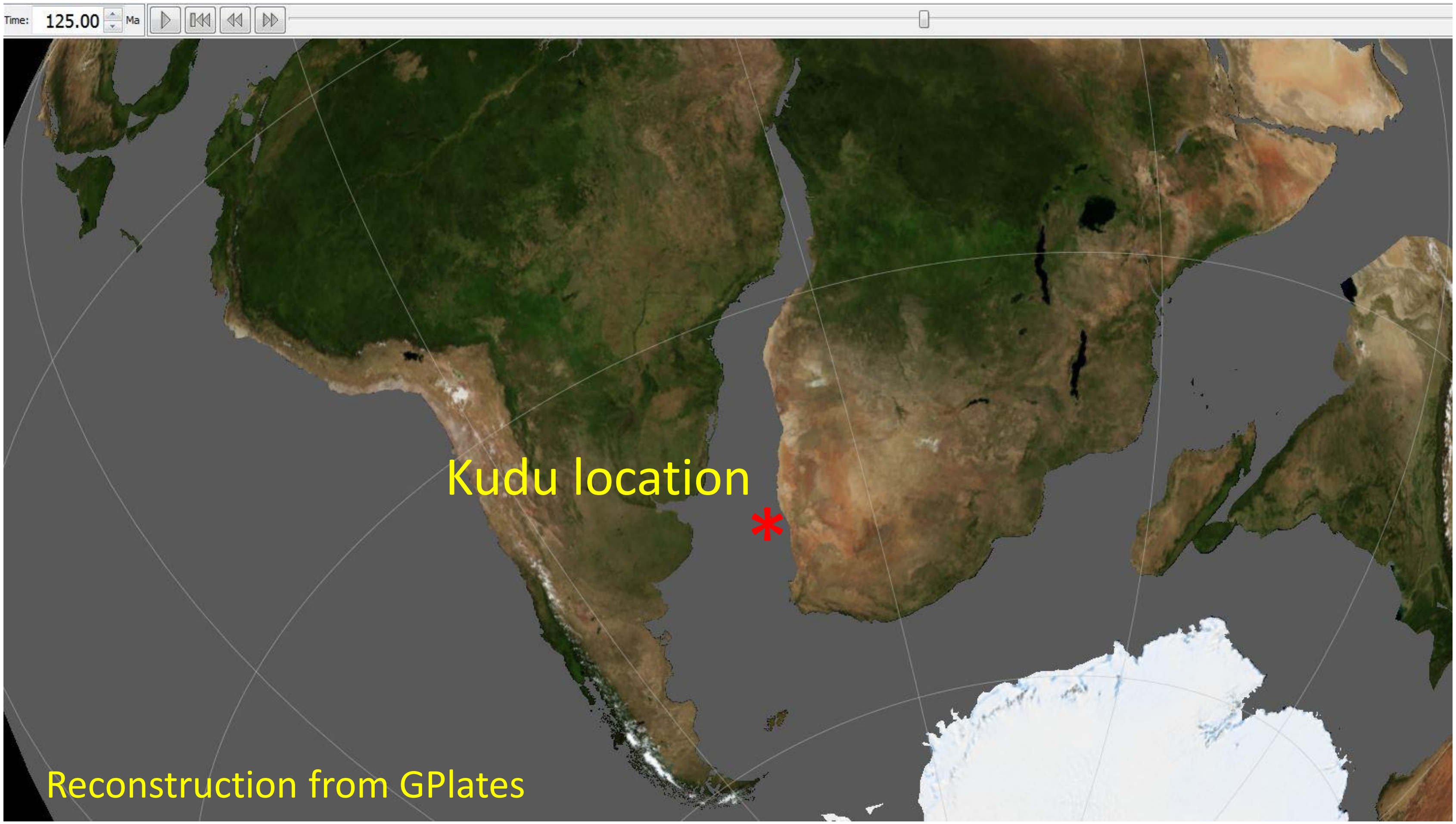
…… but most coastal spits are found downwind of a river input, eg. Lobito, Angola



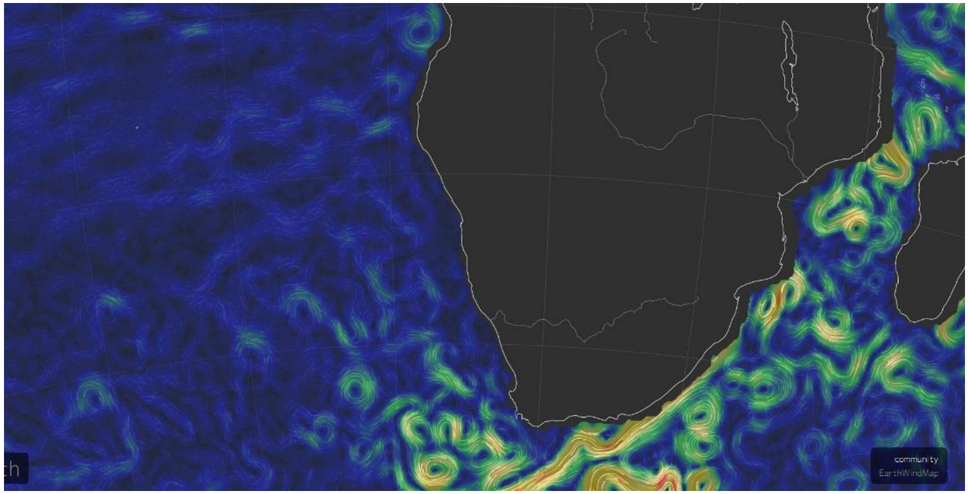
South Atlantic reconstruction 125Ma

What were the currents and wind direction at that time?

- Was the ocean wide enough for current systems to develop?
- Evidence from Angola spits & carbonate platforms is that the wind was from the SW in Albian
- Was the input (i.e. sand supply) point the palaeo-Orange River?

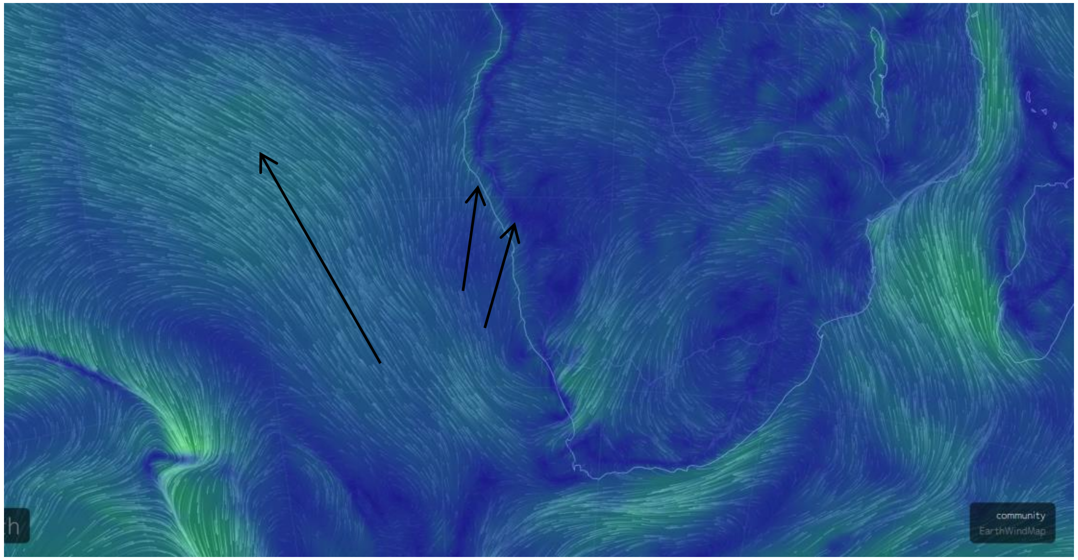


And, at any rate, the main driver for formation of coastal spits is wind, not currents. The Benguela system today is very weak…..



Modelled ocean currents, 8th April 2016
http://earth.nullschool.net/

…. but the winds are persistent and strong

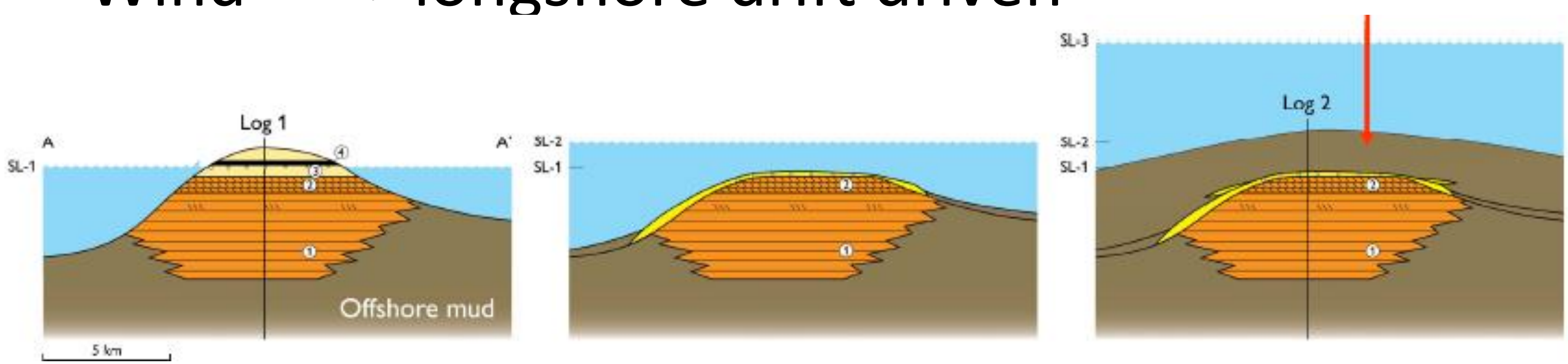


Wind direction

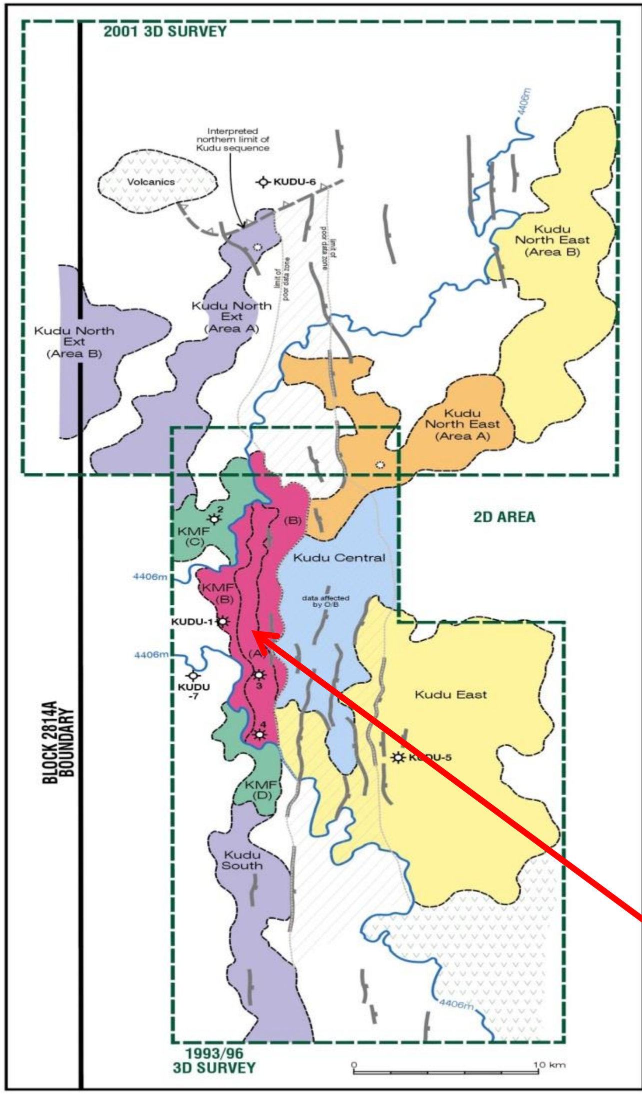
Modelled winds at sea level, 8th April 2016
http://earth.nullschool.net/

Coastal spits - summary

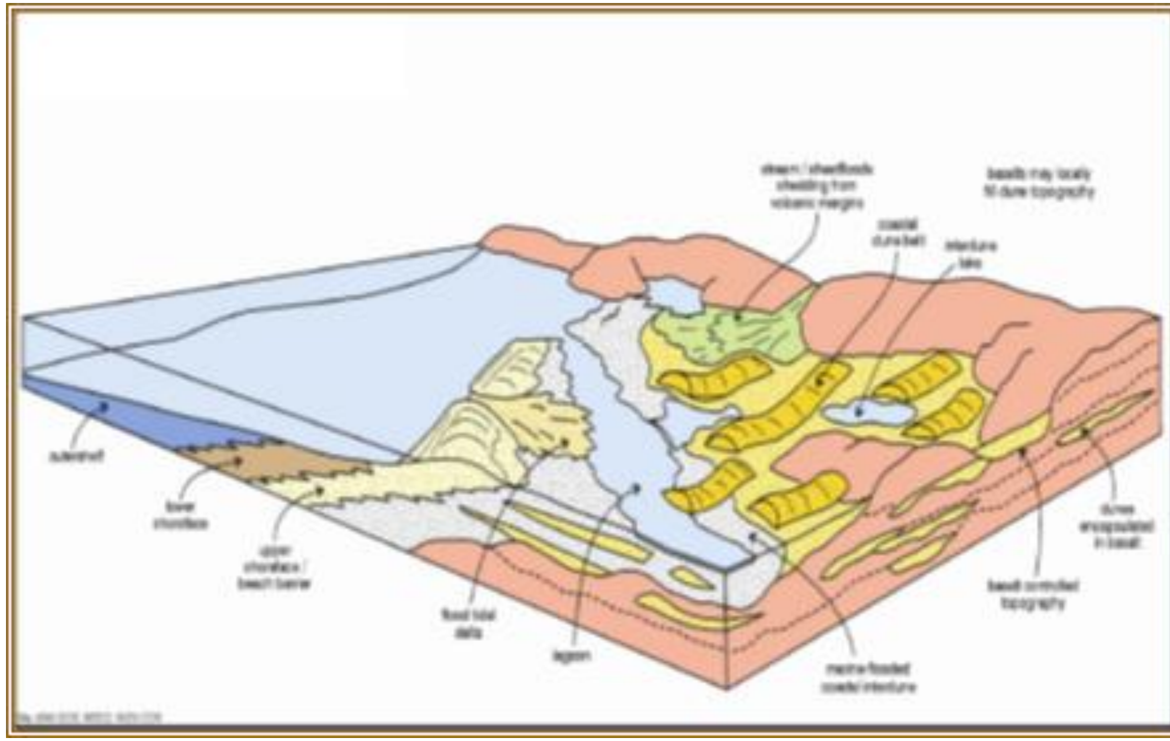
- Not well known in geological record
- Coastal sand spit will be elongate
  - may explain why the major reservoir sands at Kudu that have been discovered so far are elongated N-S
  - Generally encased in mud but in Kudu have volcanics sealing the sand body
- These bodies can be several km^3 in dimension
- Wind ⟶ longshore drift driven



Johannessen & Nielsen, 2009



Source: NamPower after Tullow



In previous interpretations there is acknowledgement that the “sweet zone” in Kudu is a narrow N-S belt. The sedimentological interpretation at the stage of interpretation shown here is evolving towards a coastal spit but the large cross beds are still interpreted as dunes

- Coastal spit model explains
  - Large, steep cross beds
  - Anhydrite cement
  - Texture (grain size, sorting, rounding)
  - Association with marine sediments, fossils & bioturbation
  - N-S elongation of the reservoir

- Need to reassess exploration models for future Kudu’s
- Need to reassess existing reservoir models for efficient recovery of the gas

Reservoir model

- Size
- Connectivity
- Geometry

Need to know what the correct environment is to model the reservoir correctly

THANK YOU

Thanks: Ian sharp (Equinor) for pictures, ideas and references and Graham Pritchard for photos