A consistent and integrated high-resolution stratigraphic framework for the Sokor Alternances in the R3 East Area, Agadem Basin, Niger

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Abstract

The Palaeocene-Eocene age Sokor Alternances Formation is interpreted as having developed in ephemeral lakes similar to modern-day examples in the East African Rift system. The Alternances is considered the most prolific hydrocarbon-bearing succession in the Agadem Basin. However, there have been few attempts to fully describe its stratigraphy. Previous authors have divided the Alternances into a different number of stratigraphic units using a range of lithostratigraphic and sequence-based nomenclatures. The inconsistency on the different stratigraphic frameworks presents considerable challenges when correlating the Alternances across the basin.

This paper summarises the findings of a study targeted at delivering a detailed and consistent interpretation of the Sokor Alternances stratigraphy. The study sought to integrate a basin-scale seismic stratigraphic framework with more detailed analysis of stacking patterns from well logs.

Three different seismic facies referred to as *stratigraphic units* were recognised across the study area. Depositional stacking pattern analysis made it possible to subdivide these three large-scale units into a high-resolution stratigraphic framework. There is evidence that this stratigraphic framework can be extended across the basin as a consistent regional stratigraphic system. Furthermore, the high-resolution stratigraphic framework demonstrates the importance of the different stratigraphic units on discovery trapping mechanisms.

Background

The Sokor Alternances, also known as the Sokor-1 Formation or simply the 'Alternances', are Palaeocene-Eocene in age and were formed as part of a rift phase within the Agadem Basin in Niger (Zhou *et al.,* 2017). Clastic sediments of the Alternances were developed within an ephemeral lake system where the sands were deposited by fluvial/deltaic distributary channels and mouth bar deltaic complexes (Jilin *et al.,* 2012, Lai *et al.,* 2020 and Genik, 1992). Shales were formed by floodplain and prodelta to lacustrine processes. The Alternances are considered the most prolific proven hydrocarbon-bearing formation within the Agadem Basin.

Figure 1 shows the relative location of the study area and Figure 2 shows the structural and stratigraphic setting. The area of study is focused on the R3 East Area, where in 2018, Savannah Energy drilled five discoveries: Amdigh-1, Eridal-1, Kunama-1, Bushiya-1, and Zomo-1. In 2017, Savannah acquired and processed a PSTM 3D seismic volume on this area and in 2020 reprocessed the volume to a PSDM version. The 3D seismic data along with the well log information from the five discoveries and a dry hole, Ourami-1, drilled by a previous operator, were used to build the stratigraphic framework presented here. It is important to mention that Ourami-1 was drilled on 2D seismic data, and it is just outside the Eridal structural closure. However, Ourami-1 has some oil shows reported within the top sand of the Alternances which indicates the proximity to the oil-water contact of the Eridal oil accumulation.

The structural framework (Figure 2) of the Agadem Basin is controlled by a pulsed trans-tensional regime developed during different stages of the rift evolution within the basin (Ahmed *et al*., 2020). The five discoveries in the R3 East Area were drilled on three-way closures against extensional faults with the structures developed during the latest stages of Cenozoic rifting in the basin dating to late Eocene to Oligocene.

The Alternances were deposited above the Late Cretaceous sand-rich Madama Formation and were succeeded by the shaly Eocene Low Velocity Shale Formation (LVS). The LVS is an important regional top and lateral seal for the hydrocarbon traps within the Alternances (Figure 2).

Internally, the Alternances have been divided into three, four or five units by previous authors *e.g.* Jilin *et al.* (2012) and Lai *et al.* (2020). Following on from the work of previous operators, Savannah Energy (2018) and Wilks *et al*. (2019) divided the Alternances into five stratigraphic units (E1 to E5) based primarily on well log responses. The use of these different stratigraphic frameworks presents some discrepancies when trying to correlate the Alternances between different fields and areas within the basin.

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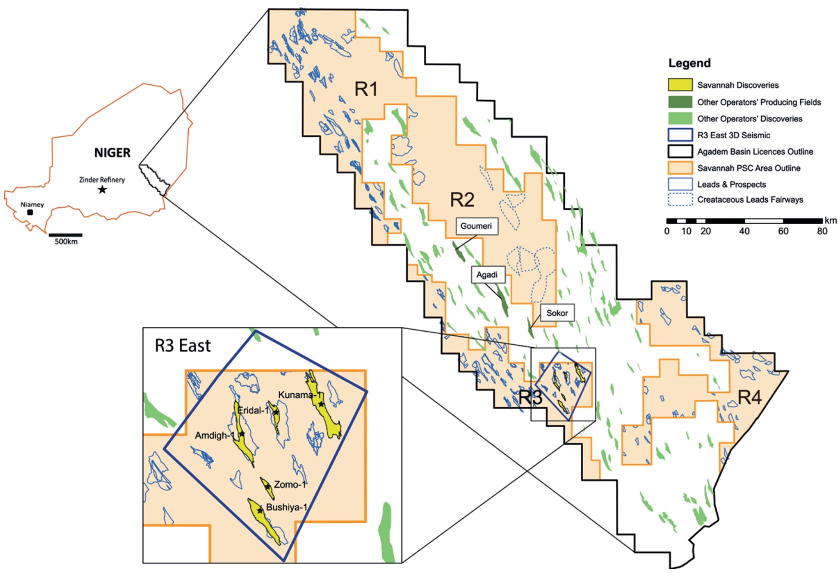

Figure 1 Location of the R3 East study area (in blue) in context of the Agadem Basin.

In order to have a consistent stratigraphic framework, a more comprehensive model was needed. A first pass description of a consistent stratigraphic framework for the Alternances was presented by Rojas *et al*. (2022) in the EAGE Annual Conference and Exhibition in 2022. In this paper, a detailed interpretation of the internal stratigraphy of the Alternances was performed by integrating a seismic stratigraphic framework with the stacking pattern analysis from well logs.

Three seismic facies (stratigraphic units A, B and C) were interpreted across the R3 East Area. These seismic facies were differentiated on the seismic amplitude display and with the help of different seismic attributes (instantaneous frequency, sweetness, similarity, and spectral decomposition). This stratigraphic division of the Alternances can be extended beyond the R3 East Area, indicating that there is a succession of correlatable geological events that can be used as regional stratigraphic units.

Including this stratigraphic framework into the hydrocarbon trap analysis will help geological risk assessments of potential new exploration targets in the Alternances.

High-resolution stratigraphic framework

The Sokor Alternances stratigraphic framework proposed here, was first based on the seismic responses observed on the R3 East PSDM seismic volume. It is well documented that seismic facies descriptions have previously been used to identify sedimentological and stratigraphic events in the rock record; some good examples can be found in Posamentier (2011) and Moscardelli *et al.* (2006).

Figure 3 illustrates the interpretation of the three main seismic units/facies in the Alternances, using the amplitude display, frequency and sweetness seismic attributes, where:

(i) The basal Unit A is characterised by continuous reflectors with bright high amplitude reflectors. Frequency and Sweetness attributes exhibit a consistent seismic response.

(ii) Unit B is characterised by discontinuous reflectors and rapid lateral and vertical variations in reflector brightness. Frequency and Sweetness attributes also present patchy responses. The presence of multiple discontinuous seismic reflectors is interpreted as erosive surfaces.

(iii) Unit C at the top of the Alternances is described as a set of fairly continuous reflectors, less bright and with lower amplitudes than the reflectors in Unit A, but with greater continuity than the reflectors in unit B. Seismic attributes of Frequency and Sweetness show moderately continuous events similar to the response observed in amplitude displays.

Using the three stratigraphic seismic units as a foundation, a high-resolution sequence stratigraphic framework (Figure 4) was developed by integrating depositional stacking patterns from well logs with the interpreted seismic facies/units.

The high-resolution sequence stratigraphic framework was built based on the evolution of the relationship A/S; where A = accommodation space and S = sediment supply. The applied sequence stratigraphy methodology for non-marine strata is adapted from similar ones presented by Cross (1991), Allen *et al.* (1996), Kjemperud *et al*. (2008) and Fanti and Catuneanu (2010).

As described by Ramon and Cross (1997), channel sandstones deposited in low A/S conditions are amalgamated and areally continuous. The finer sand and muddy sediments composing the upper parts of channel bars and most floodplain sediment are not preserved. The resulting reservoir sandstone is more homogeneous with high porosity and reduced clay content, enhancing permeability. Higher A/S conditions result in a lower degree of channel amalgamation and increased preservation of floodplain sediment. Channel sandstones tend to be single storey, isolated bodies embedded in floodplain deposits. The geomorphic elements composing the individual channels are better preserved and more mud is deposited.

As seen in Figure 4, when the A/S relationship is higher than 1 the connectivity of channelised sandbodies is reduced and floodplain deposits (silts and clays) are more common. When the relationship A/S is less than 1, channelised sandbodies show greater connectivity generating continuous layers of reservoir facies. An A/S relationship close to 1 can be associated with aggradational stacking patterns of sands and shales.

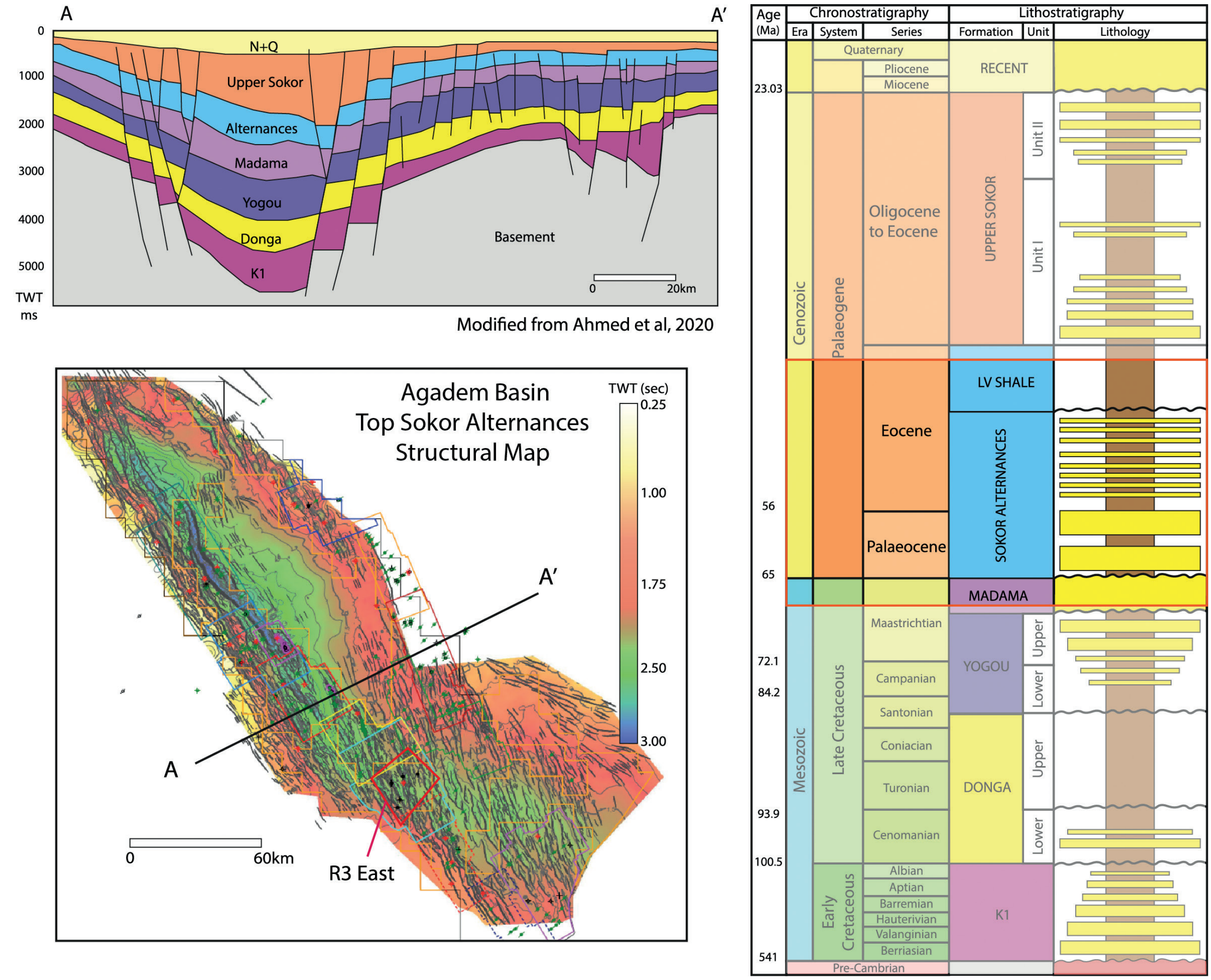

Figure 2 Stratigraphic column and summary of the Agadem Basin structural settings.

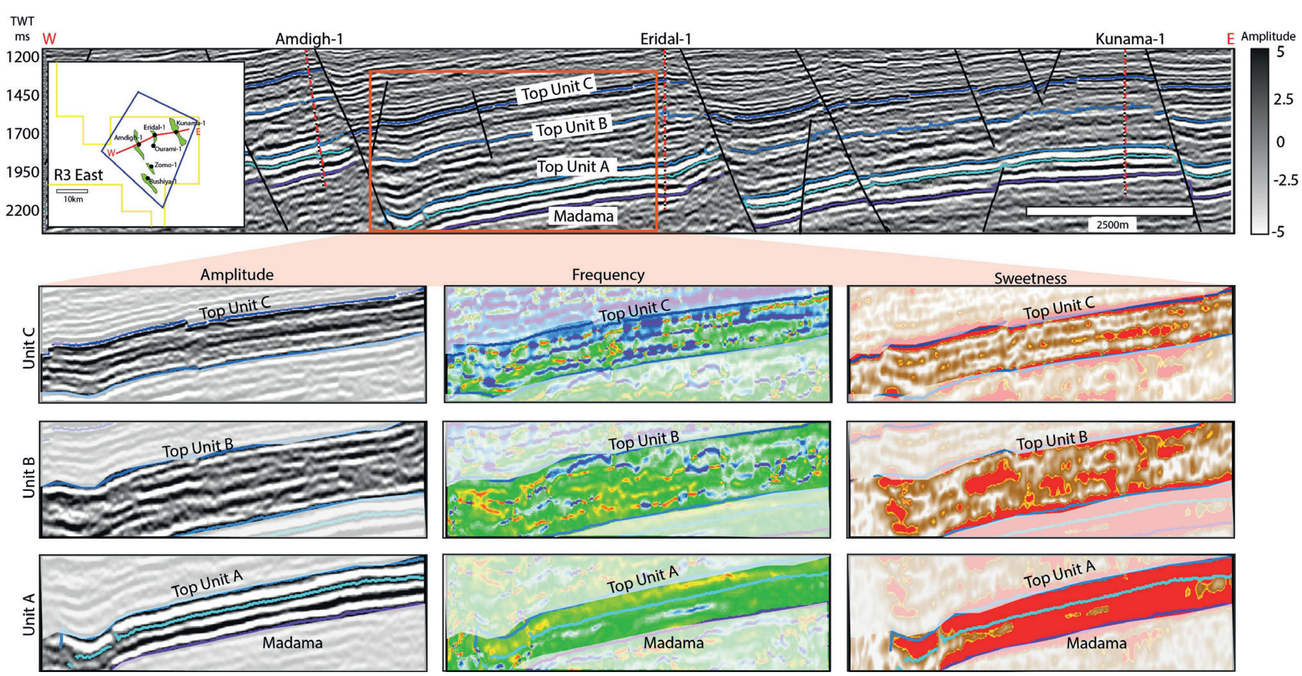

Figure 3 E-W seismic section with Frequency and Sweetness attributes. Identifying the stratigraphic/seismic units: Unit A – continuous bright reflectors; Unit B –discontinuous reflectors and Unit C – moderately continuous reflectors.

Based on the analysis of the evolution of the A/S relationship, it is observed that Unit A could be subdivided into three further sub-units: A1 and A3 sandy units, separated by a shaly unit (A2).

Unit B and Unit C can each be divided into two sub-units. Sub-units B1 and B2 are separated by an inflection point of the A/S relationship where the relationship changes from A/S >1 to A/S<1. Sub-units C1 and C2 can be interpreted as two cycles of variation of the A/S relationship separated by another inflection point. The inflection points on the evolution of the A/S relationships are related to basin wide correlatable flooding events explained in detail the following section.

Sequence stratigraphy description

An erosive surface separates the Alternances from the sandy Madama Formation and is considered a sequence boundary (SB1). Overlying SB1, the deposition of sub-units A1 and A2 occurs during a transgressive event. The top of A2 is interpreted as a maximum flooding surface (MFS1) characterised by an inflection point of the trend of the A/S relationship. The overlying

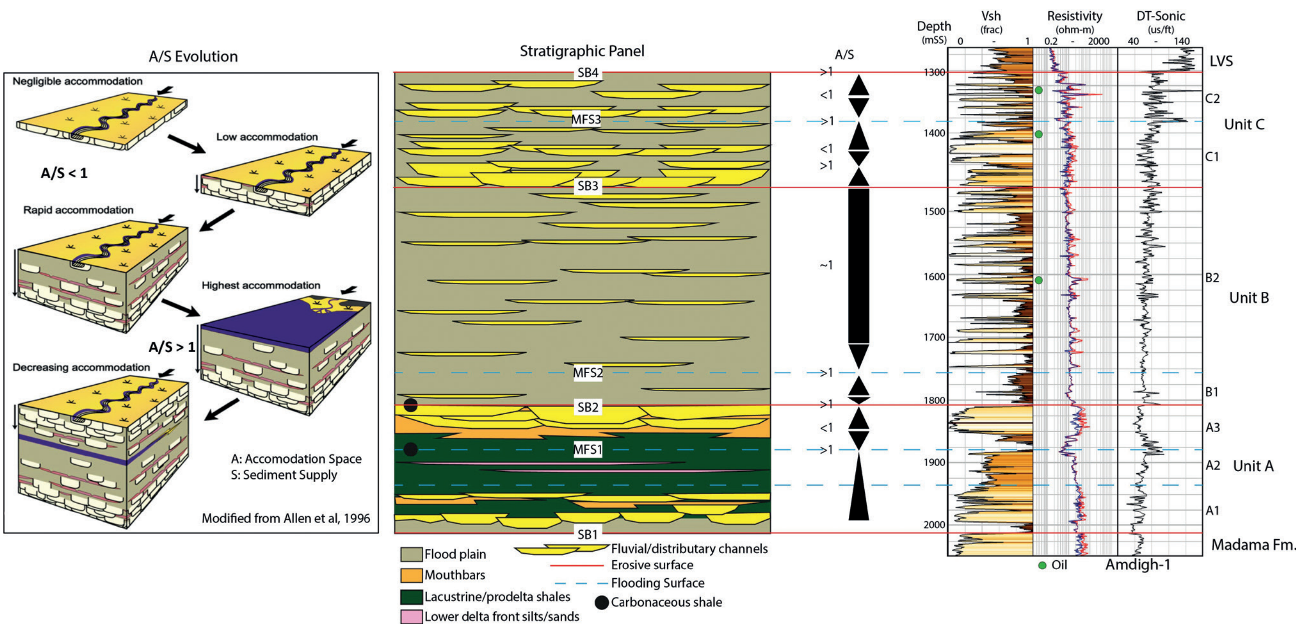

Figure 4 Stratigraphic unit subdivisions. Well log stacking patterns analysis is based on cutting descriptions, gamma ray, resistivity, and sonic log responses.

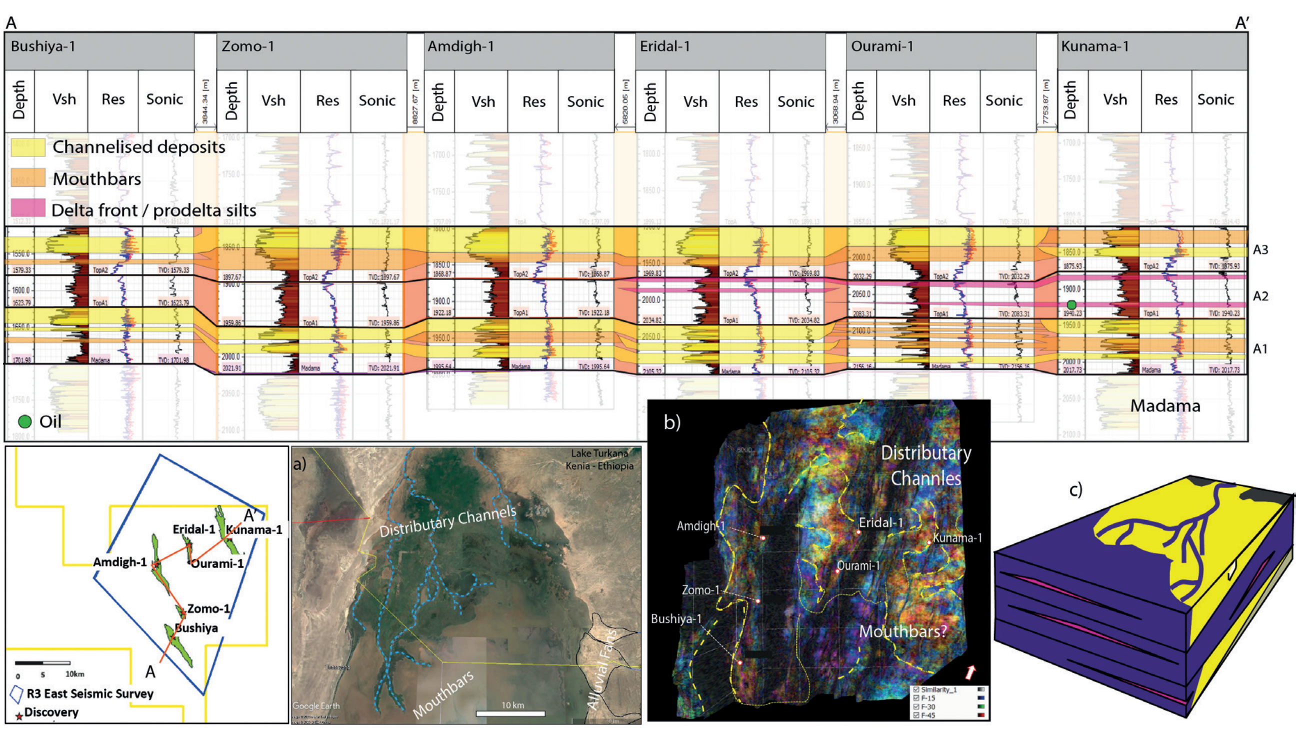

Figure 5 Well log correlation of Unit A including: a) Modern analogue – Lake Turkana. Google Earth Pro v7.3.6.9345 (December 29, 2022). Lake Turkana, Uganda 4° 37′ 01.72′′N 36° 03′ 28.82′′E, eye alt 128.98km. Maxar Technologies 2021. http://www.earth.google.com [2023].; b) Spectral decomposition extraction at the top of Unit A showing features that resemble a deltaic environment and c) a representation of the evolution of Unit A.

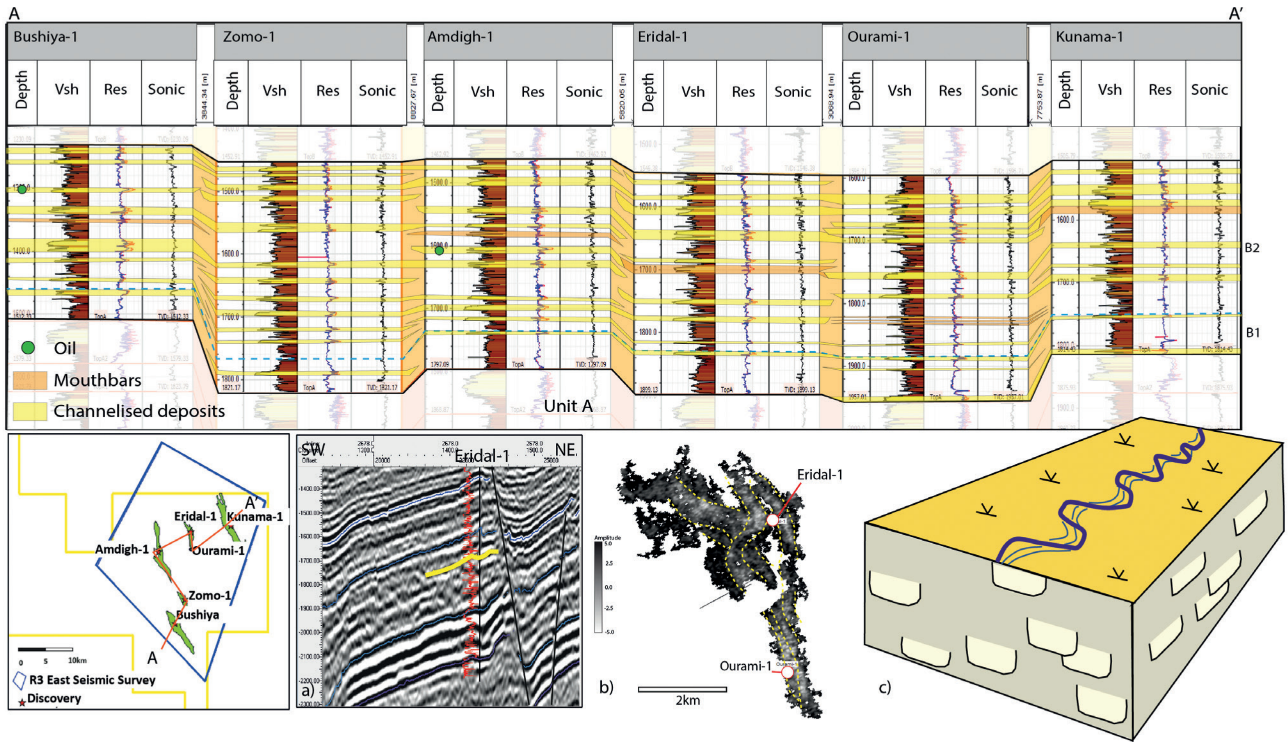

Figure 6 Well log correlation of Unit B including: a) SW-NE seismic line crossing Eridal-1 discovery; b) RMS amplitude extraction at the bright yellow reflector showing features that resemble an eroded channel and c) a representation of the evolution of Unit B (modified from Allen et al., 1996).

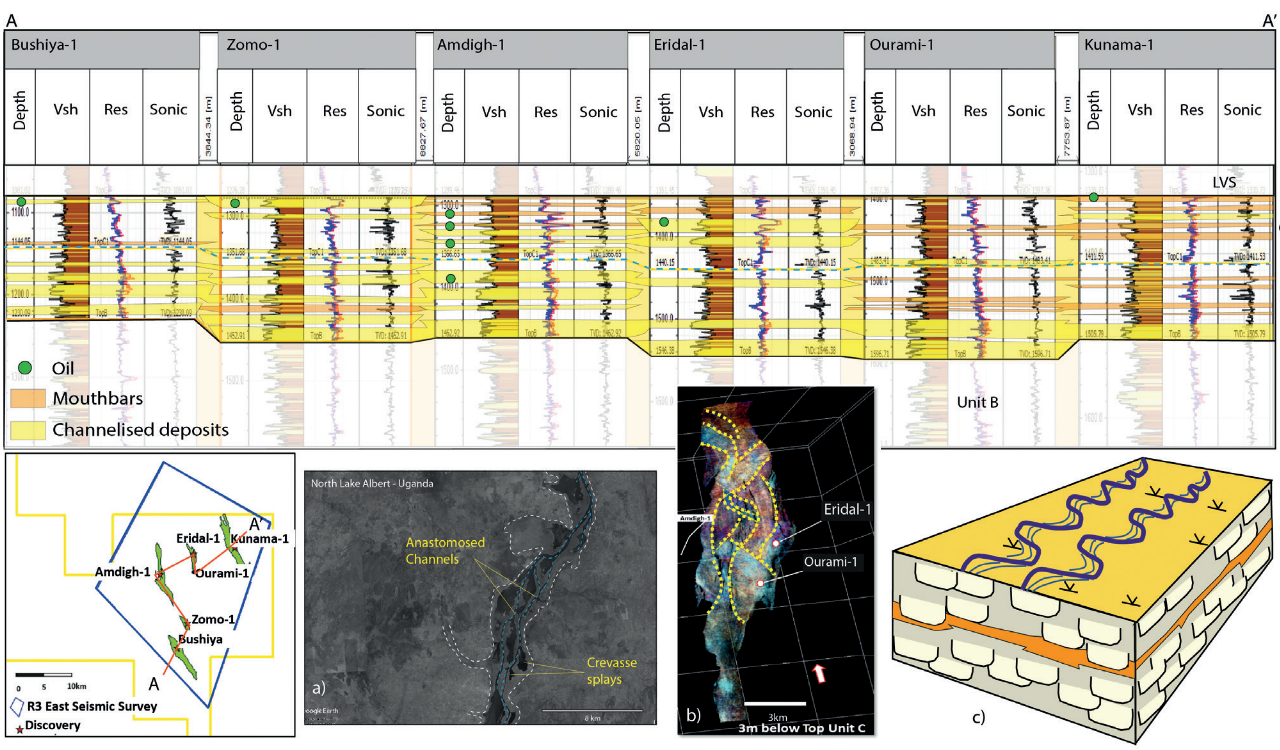

Figure 7 Well log correlation of Unit C including: a) Modern analogue – Lake Albert. Google Earth Pro v7.3.6.9345 (December 29, 2022). Lake Alberta, Uganda 3° 22′ 00.16′′N 31° 39′ 15.76′′E, eye alt 49.47km. Maxar Technologies 2021. http://www.earth.google.com [2023]. b) Spectral decomposition extraction at the top of Unit C showing features that resemble a channel and c) a representation of the evolution of Unit C (modified from Allen et al., 1996).

sub-unit A3 is deposited during a High Stand System Tract. The top of unit A has been interpreted as an erosive surface generating a second sequence boundary (SB2).

A second transgressive event ends at the top of the sub-unit B1 with a second maximum flooding surface (MFS2, another inflection point of the A/S relationship trend). An aggradational stacking pattern of sand and shale intercalations is observed in sub-unit B2. Unit B and Unit C are separated by a third erosive surface (SB3).

Unit C is comprised of two cycles of the A/S relationship variation and can be interpreted as two deltaic cycles (*i.e.* sub-units C1 and C2) separated by a third flooding event (MFS3). The top of unit C is interpreted as the last sequence boundary (SB4) of the Alternances. Finally, a maximum flooding surface related the maximum lacustrine flooding event is interpreted above the SB4 and is considered part of the LVS Formation.

Depositional environment interpretation

In general, the Alternances is interpreted to have been deposited under fluvial, deltaic, and lacustrine depositional systems (Hamidou *et al*., 2023). These depositional systems were filled with fluvial/distributary channels and mouthbar sandy deposits as well as shaly sediments from flood plain, prodelta and lacustrine processes.

Figures 5, 6 and 7 represent the evolution of the depositional environments of the Alternances based on the new stratigraphic framework. The figures show a correlated well log section across the Alternances, along with modern East Africa analogues from Google Earth showing the distribution of depositional environments in a rift lake. A series of seismic attribute extractions also helped to identify events that could be used to create a more detailed depositional environment interpretation.

As observed in Figures 5, 6 and 7, the evolution of the depositional environments of the Alternances within the R3 East Area is described as follows:

(i) Unit A was interpreted to be formed under deltaic condition, specifically the lower delta plain to prodelta and the unit could be subdivided into three sub-units.
(ii) Unit B corresponds to a series of sandy and silty distributary/fluvial channels embedded within a shaly matrix of flood plain and/or clay-filled channels. The channels are eroded and truncated, only preserving lenses of sand with relatively low interconnection within a shaly matrix.
(iii) Unit C can be separated into two cycles of lacustrine upper to lower delta-plain sequences.

Table 1 describes the stratigraphic unit and sub-unit characteristics of the new high-resolution framework.

Beyond the R3 East area

Although the proposed framework has been fully corroborated within the R3 East Area, there is evidence that its applicability could be extended basin wide. Figure 8 is a regional seismic line where the three stratigraphic units described within the R3 East area can be clearly identified within the amplitude display as well as with the instantaneous frequency and sweetness attributes. This shows that the evolution of the depositional conditions of the Alternances were fairly constant throughout the basin. It is only towards the margins of the basin where the three stratigraphic units cannot be differentiated. More detailed work such as seismic interpretation integrated with well data, core descriptions and biostratigraphy is needed to better understand the genetic relationship of the stratigraphic framework at a basin scale, outside the R3 East area.

Controls on the geological risk analysis

As expected, most of the characterisation of the controlling factors of the hydrocarbon accumulations in the Agadem Basin have been focused on the structure, the regional seals and the hydrocarbon migration paths (Zhou *et al*., 2017). By integrating the new stratigraphic framework to the hydrocarbon trapping analysis of the five R3 East discoveries, it can be noted that:

1) Hydrocarbons are very likely to be retained in Unit C, due to the closeness to the Low Velocity Shale (LVS), that works as a regional top and lateral seal.
2) The presence of hydrocarbon accumulations in Unit B is expected to be less frequent than in Unit A because there is not a regional/continuous shale seal. There is also a high risk of sand-sand juxtaposition problems through faults. Reservoir quality is reduced in this unit due to higher content of shale. On the upside, there is the possibility of finding isolated sand lenses which would be ideal stratigraphic traps in this unit.
3) Unit A represents the sands with the best reservoir properties in the Alternances. It can retain hydrocarbons when the trap is a 4-way closure, due to the presence of a continuous top shale that forms the sub-unit A2. In a three-way closure configuration this unit is very likely to have problems with sand-sand juxtaposition through the fault since the sands

Units	Seismic Facies	Sub-units	Description	Depositional Environment
C	Fairly continuous reflectors with sporadic erosive events	C2	Fairly continuous interlayering of sand and shales.	Formed in lower delta plains with channels and mouth bars
		C1	Fairly continuous interlayering of sand and shales	Formed in an upper to lower delta plain with channels and mouth bars
B	Very discontinuous reflectors	B2	Interfingering of sand lenses within a matrix of shales and silts	Fluvial to upper delta plain with sandy channel systems embedded within a shaly matrix
		B1	Interfingering of sand lenses within a matrix of shales and silts	
A	Very continuous reflectors, with bright amplitude (associated with the presence of shales with carbonaceous debris)	A3	Thick and clean sandy unit	Deposited under high energy shoreface conditions
		A2	Shaly unit with some layers of silts or very fine-grained sand	Delta front to pro-delta away from an active deltaic lobe
		A1	Clean sands with some intercalations of shaly layers	Deposited under upper to mid delta plain conditions

Table 1 Description of the Alternances stratigraphic units and sub-units.

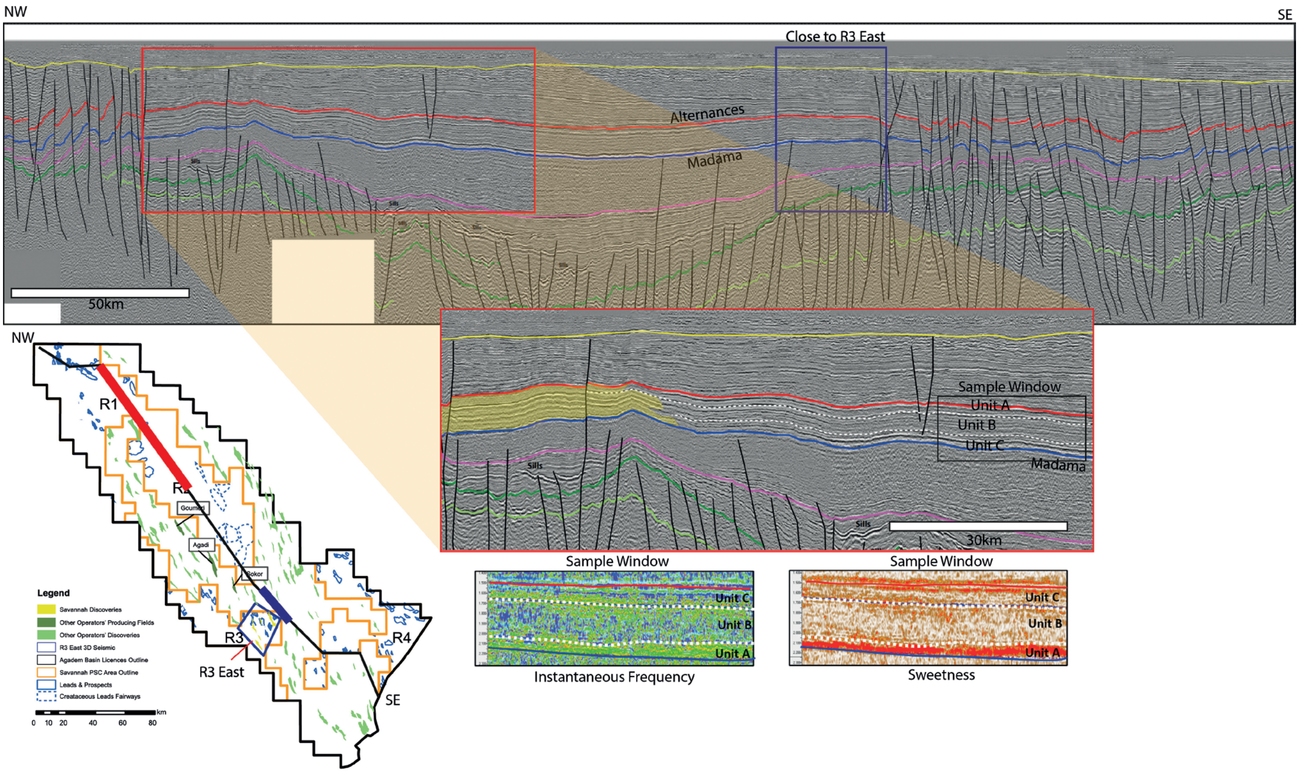

Figure 8 Regional seismic line where the presence of the three stratigraphic units along the Agadem Basin can be observed. It is only towards the northern edge of the basin (yellow zone) where it is not possible to distinguish between them.

will be most likely in lateral contact with shallower Alternances sandy units (footwall drilling) or the deeper sandy Madama Formation (hanging wall drilling).

Results and conclusions

- The proposed consistent stratigraphic framework for the Sokor Alternances is based on an integrated approach using seismic and well log data.
- The stratigraphic framework is comprised of three main units (A, B and C) and can be recognised in the R3 East area in seismic and well log data.
- The surfaces that separate the main stratigraphic units are related to abrupt changes of the accommodation space and sediment supply relationship and were interpreted as sequence boundaries.
- The subdivision of the main stratigraphic units is consistent among the six wells drilled in the R3 East area. The stratigraphic subdivisions have been related to flooding events and can be recognised as inflection points in the evolution of the A/S relationship.
- More well data from outside the R3 East Area need to be included to clearly understand if these subdivisions are regional events or just related to localised geological events like channel avulsions, local source of sediments or minor tectonic.
- It has been observed that the three main stratigraphic units can be extended across the basin. The three seismic facies can be interpreted on seismic data from other areas of the Agadem Basin. The units can be indicative of a sequence of geological events across the basin.
- It is recommended to include the proposed stratigraphic framework in the analysis of the hydrocarbon trapping mechanism within the Sokor Alternances, that will improve the reliability on the estimation of the geological chance of success in future drilling prospects.

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