

# **PS Discovery of an Eolianite in the Upper Dalan Member, Khuff Formation, South Pars Field, Iran\***

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## **Abstract**

A laterally continuous, three metres thick bed of oolitic grainstone has been studied in cores of two offshore Fars wells (Iran), the largest exploited gas field. This hectokilometric, locally late burial compacted, high porosity but low permeability layer forms the top of the gas stocking interval located in the Upper Dalan Member (Permian), at the top of the informal K4 reservoir subdivision.

This layer, easily traceable between the wells, lies over high-energy marine deposits of coarse, fauna rich, bioclastic shoals, and mainly consists of oomoldic, fine grained, azoic grainstone with coarser centimetric levels. Horizontal to oblique lamination or steep foresets were found, but no clear evidence of marine sedimentary processes were observed. The petrography reveals a pure oomoldic grainstone affected by emersion related features: pedogenetic imprints (chitonic rims and rhizolitic network), superimposed by early meteoric diagenesis (pendant, meniscus and pseudophreatic cements), prior to early total porosity inversion. The combination of the observed sedimentary, pedogenetic and diagenetic features indicates a supratidal, eolian deposition. This hypothesis is confirmed by the observation of clear pinstripe lamination, the only reliable criterion for eolian recognition.

This layer is the first eolianite discovered within the Upper Dalan Formation, and the first hydrocarbon bearing eolianite ever described in a producing interval. These sedimentary bodies, difficult to identify in subsurface, are often misinterpreted as emergent shoal deposits, misleading sequence stratigraphic interpretations. Moreover, their recognition is crucial for the correct positioning of associated sequence boundaries and for eustatic variations analysis, especially in peritidal aggrading granular intervals.



# DISCOVERY OF AN EOLIANITE IN THE UPPER DALAN MEMBER, KHUFF FORMATION, SOUTH PARS FIELD, IRAN

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## INTRODUCTION

### ABSTRACT

A laterally continuous, three metres thick bed of oolitic grainstone has been studied on cores of two offshore Fars wells (Iran), actually the largest exploited gas field. This hectokilometric, locally late burial compacted, high porosity but low permeability layer forms the top of the gas stocking interval located in the Upper Dalan Member (Permian), at the top of the informal K4 reservoir subdivision.

This layer, easily traceable between the wells, lies over high-energy marine deposits made of coarse, fauna rich, bioclastic shoals. It mainly consists of oomoldic, fine grained, azoic grainstone with coarser centimetric levels. Horizontal to oblique lamination or steep foresets were found, but no clear evidence of marine sedimentary process was observed.

The petrography reveals a pure oomoldic grainstone affected by emersion related features: pedogenetic imprints (chitonic rims and rhizolitic network),

superimposed by early meteoric diagenesis (pendant, meniscus and pseudophreatic cements), prior to early total porosity inversion.

The combination of the observed sedimentary, pedogenetic and diagenetic features states for a supratidal, eolian deposition. This hypothesis is confirmed by the observation of clear pinstripe lamination, the only reliable criterion for eolian recognition.

This layer is the first eolianite discovered within the Upper Dalan Formation, and the first hydrocarbon bearing eolianite ever described in a producing interval. These sedimentary bodies, difficult to identify in subsurface, are often misinterpreted as emergent shoal deposits, misleading sequence stratigraphic interpretations. Moreover, their recognition is crucial for the correct positioning of associated sequence boundaries and for eustatic variations analysis, especially in peritidal aggrading granular intervals.

### A PROBLEMATIC UNIT

The South Pars field is located offshore Iran in the North Dome superstructure along the Qatar Arch, in the Khuff formation. It covers 3700 out of 6000 km<sup>2</sup>, and bears 360 out of 1'250 TCF (Ehrenberg et al. 2007), which is approximately 6% of the world's reserves. The Khuff Formation is unofficially subdivided into four reservoir intervals, ranging downwards from K1 to K4. The studied hydrocarbon bearing layers are part of the Permian Upper Dalan Member, represented by the Wuchapingian-Changhsingian K4 and K3 intervals (Insalaco et al. 2006). 55% of the Qatari North Field reserves (495 out of 900 TCF) are stocked in the K4 cretaceous oomoldic interval (Bashari 2005).

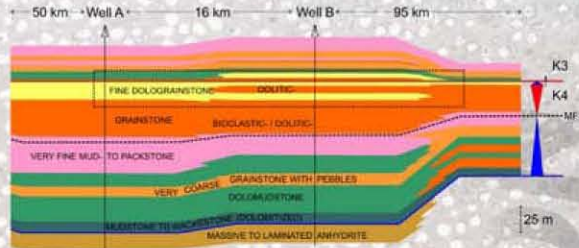
The problematic interval consists in pure, azoic oomoldic (dolo-)grainstone. It is interpreted as a transgressive pulse related shoal that developed on the final regressive facies of the K4 cycle. It can reach a hectokilometric lateral extent. Due to the lack of microfauna and its anomalous sequence-stratigraphic character, the Wuchapingian-Changhsingian boundary could not be placed with certitude, and lateral correlation and exploitation problems occurred. In order to better constrain the sequence-stratigraphy and the depositional model, two cores drilled in the K4 and K3 reservoirs were studied.



Location of the North Dome superstructure across the Qatar/Iranian national water boundary and the associated hydrocarbon fields.

Reservoir layer	Iranian nomenclature	Chronostratigraphy
K1	Kangas Fm.	Induan
K2		
K3		Changhsingian
Oomoldic reservoir layer		
K4	Upper Dalan Fm.	Wuchapingian
	Nar Anhydrite	
	Lower Dalan Fm.	Capitanian

Informal subdivision, main formations, local nomenclature and stratigraphy of the Khuff Formation within the South Pars field. Modified from Insalaco et al. 2006.



Facies cross-section of cycles K4 and K3 with simplified stratigraphic sequencing. The black box shows the studied interval. Modified after Insalaco et al. 2006.

### THE HYPOTHESIS: THE PRESENCE OF EOLIANITES

The hypothesis was triggered by the surprising facies similarity between Pleistocene Qatari carbonate coastal dunes (A) and the oomoldic layer (B) and the fact that the rather complicated and unusual stratigraphic-sequencing would be simplified by the eventual reinterpretation of this interval into supratidal deposits.

The recognition of carbonate eolian deposits is difficult in ancient series because of their great similarity with the nearshore environments (Fairbridge & Johnson 1978; McKee & Ward 1983; White & Curran 1988; Rice & Loope 1991; Kindler & Davaud 2001; Le Guern & Davaud 2005; Frébourg et al. 2008). Hence, a very critical approach using converging sedimentological, diagenetic and

sequence-stratigraphic clues was used. Several investigation techniques such as core logging, wireline logging, intra-well imaging, standard petrography, and image analysis helped to gather discriminative criteria. 3D tomography proved to be of invaluable help to discernate meaningful density variations and sedimentary features. The scanner used was a General Electric "Lightspeed 16" with a voxel resolution of 0.25 mm (X,Y,Z).

Furthermore, a more than 1100 thin-section database of carbonate eolian facies from across the world was used for useful comparisons and understanding of eolian depositional and diagenetic phenomena (C).



Grainfall deposited eolian oolitic grainstone showing quasi-total porosity inversion due to early vadose diagenetic phenomena. Normal light, vertically oriented. 1x1.5 cm. Top of K4 cycle, Wuchapingian, South Pars Offshore Field, Iran.



Oomoldic grainstone with total early vadose porosity inversion interpreted as grainfall deposited eolian facies. Normal light, vertically oriented. 1x1.5 cm. Top of K4 cycle, Wuchapingian, South Pars Offshore Field, Iran.



Locations sampled in the carbonate eolian facies thin-sections database: (1) Punta Civato, Baja California, Mexico; (2) Bahía Magdalena (carbonate poor), Baja California, Mexico; (3) Bahamas (several locations); (4) Sale Coast, Morocco; (5) Sardinia (several locations); (6) Southeastern Tunisia (several locations); (7) Chios Island, Crete; (8) Akamas Peninsula, Cyprus Island; (9) Qatar (several locations); (10) Sultanate of Oman (several locations); (11) Ningaloo area, Western Australia; (12) Dirk Hartog area, Western Australia; (13) Robe area, Southern Australia; (14) Coorong area, Southern Australia. Black dots are Pleistocene-Holocene carbonate coastal dunes (Brooke 2001).



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## EOLIANITE CRITERIA

### EOLIANITE SEDIMENTOLOGY

Eolianites are most of the times easy to recognize at the outcrop. Preferential diagenesis often emphasize the diagnostic depositional features, and wide-outcropping conditions associated to 3 dimensional surfaces facilitate the

diagnosis. However, their large scale structures are not easily shown at core scale, and the smaller scale features can be misleading.

#### TYPICAL FEATURES

Large landward dipping foresets



Large landward dipping foresets. Red arrow points at slumped interval. Eemian, Northern coast of Salé, Morocco

Grainflow structures



Grainflow lenses in a quarry horizontal cut. Réjiche Fint., Pleistocene, Slob ech Chergui quarry, Southeastern Tunisia

Pinstripe lamination



Pinstripe lamination (Wood-grain fabric), Sidi Salem Fint., Upper Holocene, Jerba Island

Pedoturbation



Dense root network. Early Holocene, Akamas Peninsula, Cyprus Island

#### UNUSUAL FEATURES

Uniform thickness



Eolian deposits 60 kilometers inland showing uniform thickness on several kilometers. Red arrow points at paleosol. MIS 6, Al Jabin Plateau, Sultanate of Oman

Transgression evidences



Transgressed eolianite top showing biopores and coral blossoms (Cladocora caespitosa) growing over the surface. Pleistocene, Akamas Peninsula, Cyprus Island

Early polygonal fracturation



Post-depositional polygonal early fracturation of an eolianite under its own weight. MIS 5e, Al Fuwailat, Qatar

Keystone-vugs



Pinstripe lamination with storm associated keystone vugs layer (Bain & Kindler 1994; red arrow). Pleistocene, Jabal Marm, Qatar

#### MISLEADING FEATURES

Unidirectional [dm] foresets



Unidirectional decimeters thick foresets beds similar to subtidal hydraulic dunes patterns. MIS 6, Al Jabin Plateau, Sultanate of Oman

Small scale trough X-stratification



Small scale trough cross-stratification. MIS 6, Al Jabin Plateau, Sultanate of Oman

Syn-depositional reworking



Reactivation surface reworking early lithified underlying deposits from the same eolian unit. MIS 6, Al Jabin Plateau, Sultanate of Oman

Planar-bedding



Interdune facies showing sub-horizontal planar-bedding. Red arrows point at vegetation patches. Soltanian, Northern coast of Salé, Morocco

### EOLIANITE RECOGNITION CRITERIA

The only reliable eolian recognition criterion is the "pinstripe lamination" (Fryberger & Schenck 1988). These subcentimetric inverse-graded laminae are resulting of the accretion of the Climbing Translateral Ripples (Hunter 1977). This criterion is issued from the observation of the siliciclastic eolian systems and is even used with confidence on Mars to detect eolian processes (Grotzinger et al. 2005).

Sedimentary structures in heterogeneous carbonate sands are blurred by the lack of sorting of the particles, due to their broad range of hydro- and aerodynamic behaviour (Abegg et al., 2001; Jorj et al. 2006; Yordanova & Hohenegger, 2007). If the process physically takes place, the inverse grading is

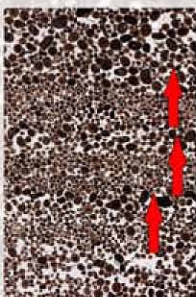
not recorded (Frébourg et al. 2008), unless the sand is more or less homogeneous, such as oolitic sand.

Moreover, this feature often forms in the interdune area where it can be misinterpreted as plane-bed if the inverse grading is not well developed. Pinstripe lamination have been observed to form on steep angle slopes, and even reaching the repose angle.

In absence of pinstripe lamination, the recognition of eolian deposits must be based on multiple and converging sedimentary, petrographic and diagenetic clues (Frébourg et al. 2008).



Left: Coarse eolian deposit in heterogeneous carbonate sand. Particles of variable size but similar aerodynamic behaviour are deposited together. 1x1.5 cm, vertically oriented. Present day, Chirisi Island, Crete



Right: Pinstripe lamination in trimodal oolitic sand. The red arrows indicate grain size increasing. 1x1.5 cm, vertically oriented. Holocene- 950 BP, Joulter Cays, Bahamas



Climbing Translateral Ripples forming in a sediment starved system, showing coarser grains at the crest (darker colors), and finer particles in the lows (lighter colors). Top of a large active barchan dune, Southern Qatar.



Climbing-Translateral-Ripples forming near the critical repose angle of the slope, as the spontaneous grainflow (red arrow) testifies to. Active siliciclastic dune field, Bahia Magdalena, Baja California, Mexico.



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## RESULTS

### SEDIMENTOLOGY: two distinct units (A, B) on top of K4

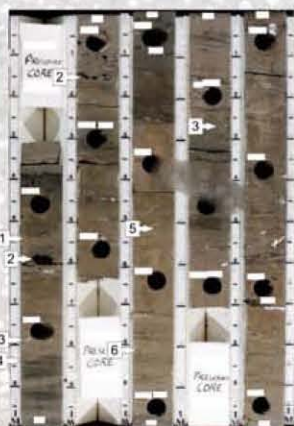
#### UNIT A: Marine features and marine early diagenesis

This unit shows distinctive marine discriminative features such as: (1) Pack-stone or mud rich layers, (2) Burrows (infilled with coarser sediment or with anhydrite) (3) Shell molds (with voids remaining open or filled by anhydrite) (4) Scour and Fill structures (5) Trough cross stratification (6) Plane bed.

The tomographic study revealed the presence of sporadic lumachellic gastropod beds, and confirmed the abovementioned features.

Petrographically, this unit shows marine phreatic cementation as first diagenetic phase, and vadose meteoric features such as pendant and meniscus cements as second imprint. The content displays sometimes abundant and

diverse foraminifera (*Charliella*, *Cribrogenerina*, *Cryptoseptida* (?) sp., *Dagmarita*, *Earlandia*, *Eostaffella* (?), small *Globivalvulinids*, *Graecodiscus*, *Hemigordiolina*, *Hemigordiopsis*, *Insolentitheca*, small *Hemigordiids*, small *Lagenids*, *Multidiscus*, *Nankinella*, *Pachyphloia*, *Paleonubecularia*, *Paradagmarita* spp., *Paradagmarita monodi*, *Paraglobivalvulina*, *Paraglobivalvulinoides*, *Polarisella elabugae*, *Pseudodunbarula*, *Pseudovermiporella*, *Rectomillerella*, *Rectostipulina*, *Reichelina*, *Robuloides*, *Septoglobivalvulina*, *Sphaerulina*, *Tetraxis*, and *Urushtenella* (Insalaco et al., 2006).), lithoclasts, echinoderm fragments and plates and ostracods.



Photomicrograph of Unit A's facies, 5 mm across



Tomographic slice perpendicular to the core. Red arrow points at shell mold. Picture is 10 cm wide

#### UNIT B: No unequivocal marine features and early vadose diagenesis

This unit overlies Unit A, separated from the latter by a stylolitized calcrete. It does not show any clear, univocal marine feature. It displays: (1) calcrete at the top and within the unit, (2) rootlet casts, (3) steep foresets that can reach between 30° and 40°, (4) early subvertical fracturation (5) Gypsum freckles, and a stylolitized calcrete at the base (6).

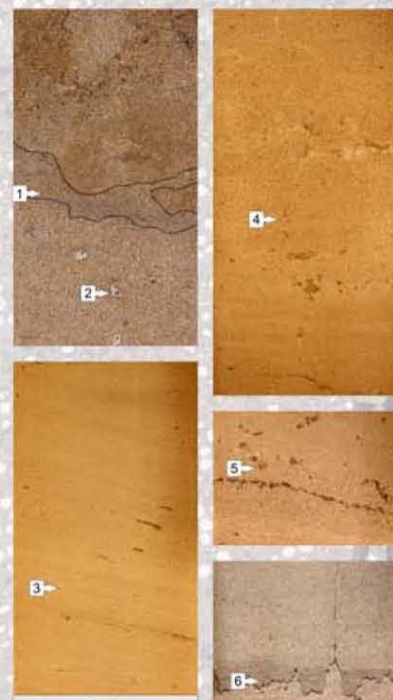
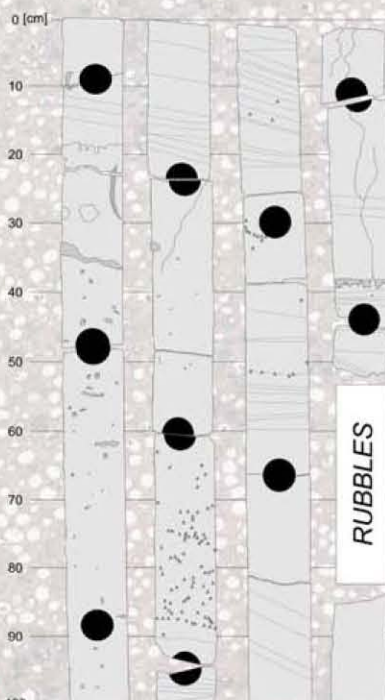
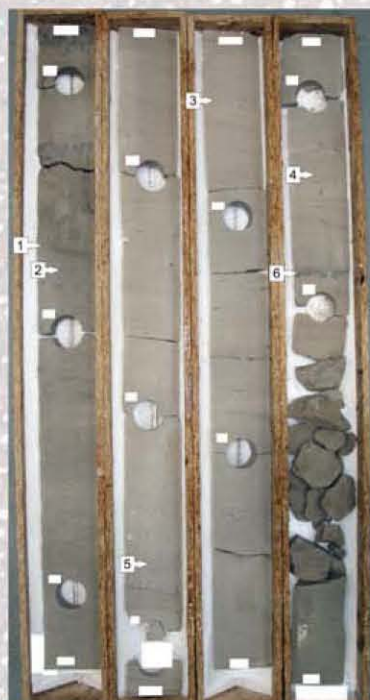
It bears no macrofauna nor microfauna exception made for extremely rare, reworked and strongly abraded *Paradagmarita* sp.

The tomographic study confirms the steep angles of the foresets and the absence of the macrofauna, and reveals the presence of large rhizolites with micritic sheathed

rootlets radiating from the principal, vertical roots. The early fractures are open and follow a polygonal pattern.

The petrography reveals a purely oomoldic, azoic, grainstone with total or partial porosity inversion. The larger pore network display early vadose cementation such as meniscus and pendant cements. Pseudophreatic processes took place in the tighter pores, as undissolved ooids within finer laminae testify to.

Clear pinstripe lamination was also observed (see next poster)





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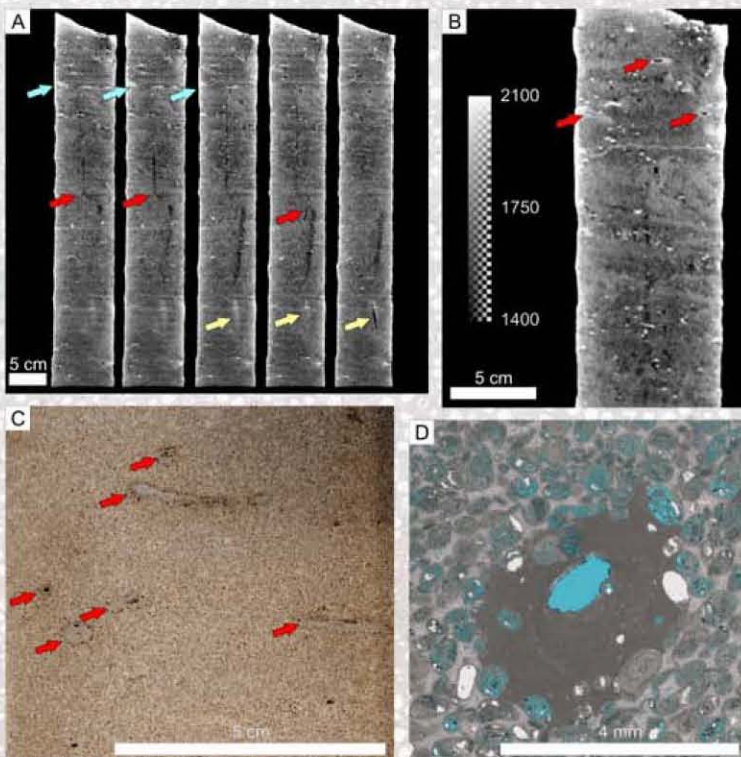
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## RESULTS

### UNIT B: RHIZOLITES



The tomographic study of the oomoldic interval showed subvertical, thinning-downwards, bifurcating structures that are less dense than the matrix, interpreted as rhizolites (A, red arrows). Their occurrence increases towards the top of the layer. They tend to develop a denser, micritic sheath around themselves when reaching under a certain diameter of a few millimeters (A, yellow arrows). Some millimetric rootlet casts with micritic coatings associated to the action of symbiotic fungi (Abegg & Robertson Hanford 2001) are seen to radiate from the main roots (B, C, D). Moreover, these structures are stopped by even minute calcretes, and grow along its surface (A, turquoise arrows; E, Holocene example).

Though rhizolites are not an eolian depositional criterion, they indicate an emersion surface.



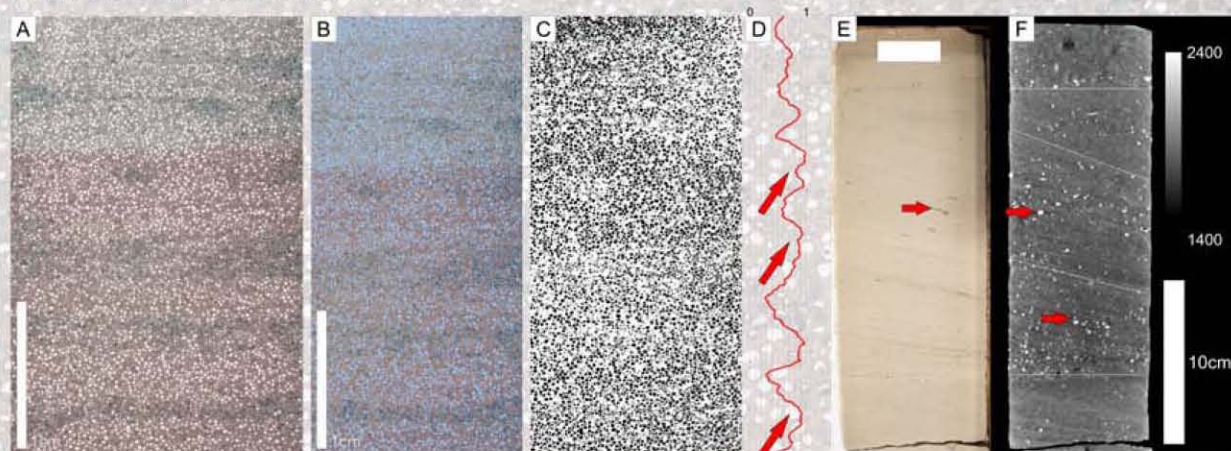
(A) Five vertical tomographic slices with 2 or 3 mm shift between slices. (B) Close-up of a vertical tomographic slice. The red arrows point at small rhizolites. The white (denser) coating sheaths the void left open by the wood fibers' decay. (C) Stabbed core's surface displaying small rhizolites with micritic coatings with open voids due to organic matter's decay (red arrows). (D) Microphotograph of a section through a micritic-coated rhizolite (vertically oriented). (E) Centric diameter rhizolites following a very early carbonate developed along a gentle-sloped foreset plane, Upper Holocene, Lella Meriame, Southeastern Tunisia

### UNIT B: PINSTRIPE LAMINATION

Image analysis was performed on some thin-sections issued from the routine plugs showing lamination (A) using JMicroVision 1.3.7 software (Roduit 2007; downloadable for free at [www.jmicrovision.com](http://www.jmicrovision.com)).

Since some of the oomolds were injected with blue resin, others remained devoid of it and some ooids were not dissolved, a synthetic "injected" image (B) and a binary image was built adding the binary images of the three different categories (C).

A grainsize extraction made on around 50'000 objects yielded a curve showing clear, subcentimetric, inverse graded laminae, corresponding to Pinstripe Lamination (D). The interval corresponding to the thin-sections represents more than one meter in thickness. Laminae sets with angles superior to 20° (E), confirmed by tomographic analysis (F), indicate that these structures correspond to wind ripples draping the lee side of a dune.



(A) Normal light digitalized image of a lamination-bearing thin-section. (B) Composite image with simulated injected porosity. (C) Synthetic binary image made by the addition of the three extracted groups of ooids. (D) Smoothed granulometric curve. The red arrows shows inverse grading. (E) Stabbed surface of a core showing oblique laminae. (F) Tomographic section of average maximum dip of the latter interval with oblique laminae sets reaching 20° (red arrows point at gypsum freckles).

➔ **EOLIANITE CONFIRMED!**



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DISCUSSION

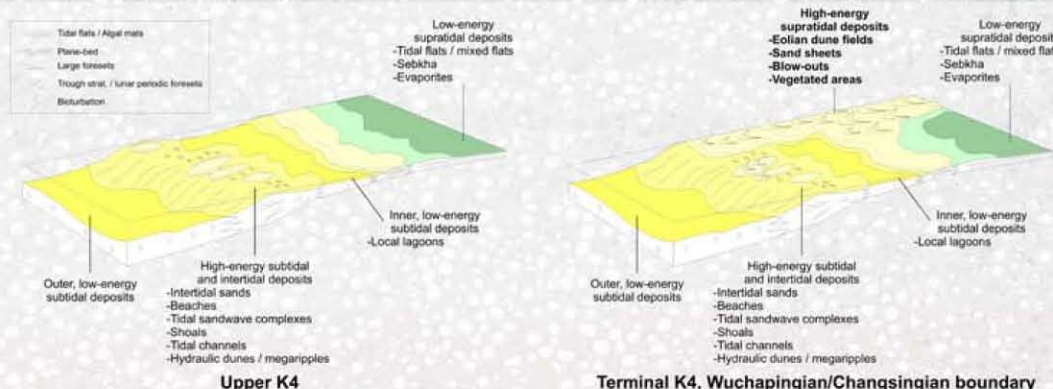
## SEQUENCE STRATIGRAPHICAL IMPLICATIONS

The reinterpretation of the oomoldic layer into an eolianite simplifies the stratigraphic sequencing. Instead of placing a transgressive pulse located at the top of a transgressive-regressive sequence, the K4 cycle will end logically with a complete regression from subtidal to supratidal.

If the occurrence of eolianite within a sequence can simplify the stratigraphy, attention should be drawn on the lateral implications. Being deposited landward

in a subaerial environment, eolianites do not obey to classical sequence-stratigraphic rules that apply to subaqueous deposition. Eolianites may not record precisely the eustatic variations of the source's basin, for a long period may elapse before the sea transgresses back over the eolian deposits' positive topography.

## DEPOSITIONAL MODEL FOR THE UPPER K4 CYCLE



## EOLIANITES IN RESERVOIRS: IMPLICATIONS

Carbonate eolian deposits are easily misinterpreted as high-energy marine subtidal deposits, such as shoals (Frébourg et al. 2008). If their correct interpretation may not change their petrophysical properties, their deposition dynamics are radically different. The submarine deposition occurs basinwards, towards the depocenter, whereas supratidal deposition is directed landwards. The misinterpretation of eolianites may result in a deviation of the reservoir response or behaviour compared to the predictive model, and their correct

interpretation may help to correctly plan the exploitation.

Since these bodies may be subject to total porosity inversion or cementation due to early vadose diagenetic phenomena, eolianites can also make barrier layers for oil extraction (e.g. St Louis and Ste Genevieve Fmts, Southwestern Kansas, Loope & Abegg 2001), whereas gas production will less be affected by low permeabilities.

## CONCLUSIONS

The gas-bearing oomoldic layers do not show unequivocal marine depositional criteria. Moreover, they display sedimentary and diagenetic features clearly related to eolian deposition. This assumption is supported by the presence of pinstrake lamination, only reliable and univocal eolian criterion, with stratification angles higher than 20°.

This would make the "transgressive shoals" located at the top of the K4 reservoir layer and end of KIV cycle misinterpreted eolianites.

The presence of eolianites at the end of cycle KIV simplifies the stratigraphical sequencing by turning the terminal transgression into the continuity of the underlying

regression. The KIV cycle would be composed of a transgression followed by a complete regression, rather than an uncommon transgressive-regressive-transgressive sequence.

These eolianites would be the first described in a hydrocarbon producing interval, giving them the status of potential reservoir rock.

The recognition of eolian deposits within hydrocarbon reservoirs can have crucial implications for stratigraphic-sequencing, modelling and exploitation, regarding the extent and depocenter of these bodies and the degree of diagenetic alteration potentially favouring or reducing their reservoir potential.

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