

*Assessment of Unconventional Reservoirs Potential : A Multidisciplinary Study of  
Silurian Hot shales and Ypresian limestones Source Rocks in Tunisia*

*Imen Arfaoui, PhD candidate*

The thesis focuses on three major objectives:

- (1)** A **multidisciplinary** study (mineralogy, organic geochemistry, biomarkers) of the **Silurian Hot Shales (Tannezuft Formation)** to assess its potential as an **unconventional shale oil/gas reservoir**.
- (2)** The **depositional environment** variation of the nummulite-rich facies as well as its lateral equivalent globigerinas-rich Fm. Sequence stratigraphy, regional tectonic context, and diagenesis affecting their reservoir potential.
- (3)** Determination of the responsible factors controlling the **unconventional reservoir quality** (Globigerina-rich Fm/Source rock), by studying the **organic matter accumulation**, the **different pores types**, and the **geochemical composition** of the **Bou Dabbous Formation**.

**Paper 1: for Journal of African Earth Sciences****Geochemical and Mineralogical characterizations of Silurian hot shales: implication for unconventional shale gas reservoir potential in Jeffara basin, North Africa.**

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**Geochemical and mineralogical characterizations of Silurian “Hot” shales: Implications for shale gas/oil reservoir potential in Jeffara basin-southeastern Tunisia, North Africa**
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## ABSTRACT

The Silurian organic-rich hot shale deposits represent the origin of 80–90% Paleozoic sourced hydrocarbons on the entire Saharan Platform. As such, it is an area of significant interest for exploring its potential as an unconventional reservoir and gaining new insights into its properties. In this study, the geochemical and mineralogical analysis of eighty-two borehole samples from three studied wells (T, B, and M) located in Jeffara Basin, in southeastern Tunisia, distributed over a depth between 1200 m and 2200 m, show that the hot shale layer has significant potentials of an unconventional shale gas reservoir. According to the rock-*eval* and GCMS results, the total organic carbon (TOC) of the hot shale deposits is good to great, ranging between 0.54 wt% and 23.86 wt%, and the average hydrogen index (HI) is around ~200 mg HC/g of TOC, which indicates that the hot shales were originally rich in type II/III organic matter (OM). The thermal maturity of the preserved OM is determined by the kerogen type with values varying from 0.4% to 1%, and Tmax values reaching 460 °C in T, B, and M wells which indicate that the hot shales preserved early mature to mature OM placed within oil/gas generation window. The calculated geochemical parameters reveal an average hydrocarbon generation potential (HGP) for the three studied wells of 20.57 kg HC/ton rock. In addition, the transformation ratios (TR) in T, B, and M wells are, respectively, 21.12%, 30% and 33.25%. However, only B and M wells show a cross-over layer, with oil saturation index (OSI) exceeding 100%, with significant potential as a hydrocarbon saturated source rock, making it a considerable target for unconventional oil exploration. Relevant results of Rock-Eval, biomarkers and XRD exhibit coherent features that reflect reducing marine conditions during the lower Silurian period. Moreover, the mineralogical composition was investigated to estimate the importance of frackable mineral fractions such as quartz (~15%) and carbonates (calcite-dolomite). Mineral brittleness index (MBI) was calculated and compared to a well-known unconventional reservoir in the Neal shale member of the Floyd shale group in the Black Warrior Basin (US), which displays moderate to low MBI. The hot shales in the study area have a considerable MBI, which could be easily enhanced by hydraulic fracturing to liberate oil/gas from the potentially saturated unconventional shale reservoir.

## 1. Introduction

The scientific community is keenly interested in studying hydrocarbons from source rocks due to their potential applicability in both conventional exploration and unconventional reservoir systems (Uffmann et al., 2012). Therefore, the exploration and production of shale

gas has become of utmost importance for commercial hydrocarbon production worldwide. Petroleum industries in the United States were the first to target source rock formations such as Barnett shales, the Eagle Ford Formation, Floyd-Neal and Woodford shales (Jarvis et al., 2007; Pashin, 2008; Ruble et al., 2012) for non-conventional gas production. Henceforth, more attention has been paid to scientific research

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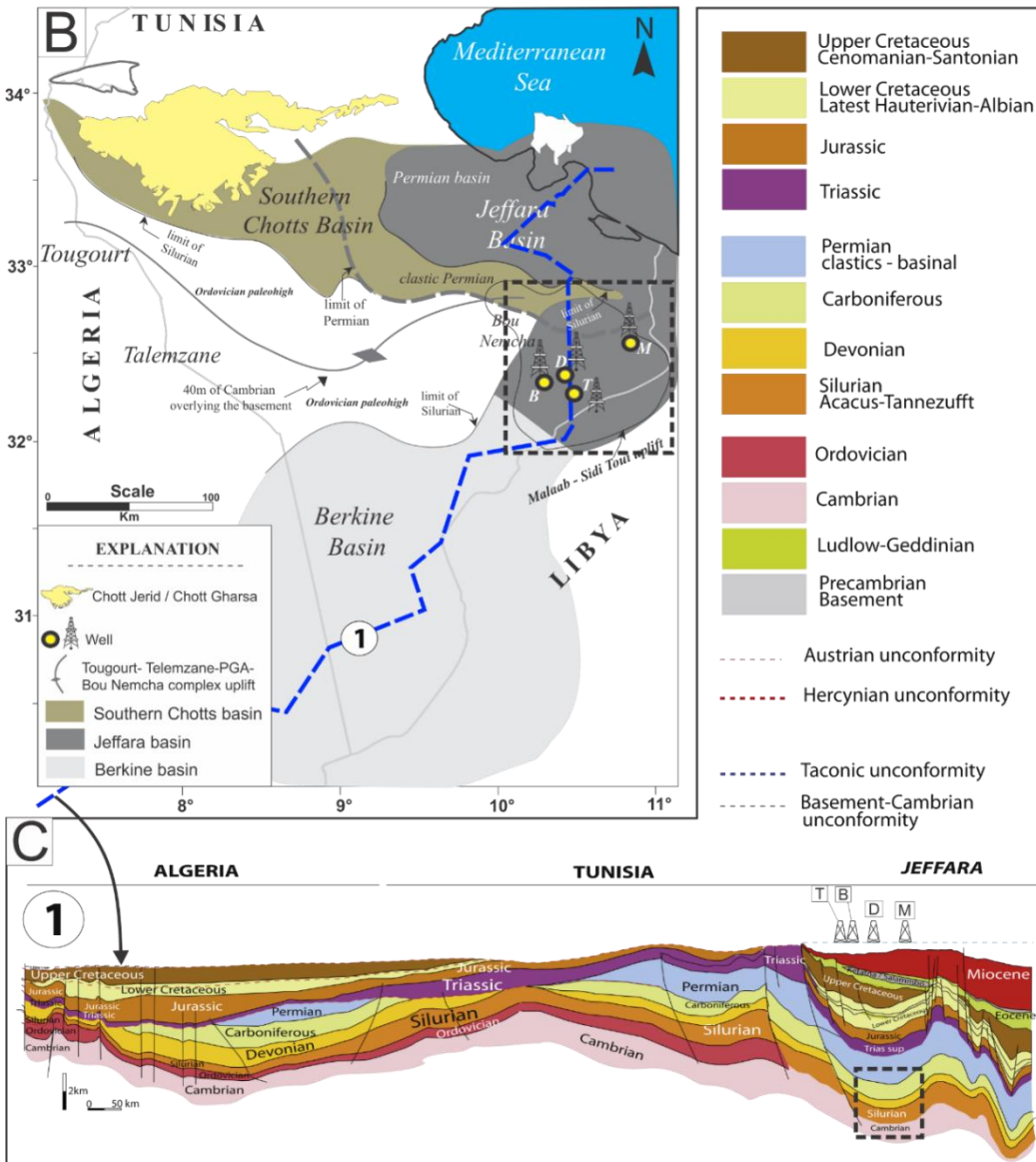
**Published:** 25<sup>th</sup> February 2024

## Geological setting

Located in the south Remada region, Jeffara basin.

The Jeffara basin is related to the whole Gondwanian geodynamic evolution through the Paleozoic tectonic events.

The regular Palaeozoic subsidence, the Hercynian unconformity, which reflects the uplift and erosion associated with the collision event between Gondwana and Laurasia (Achech et al., 2001).



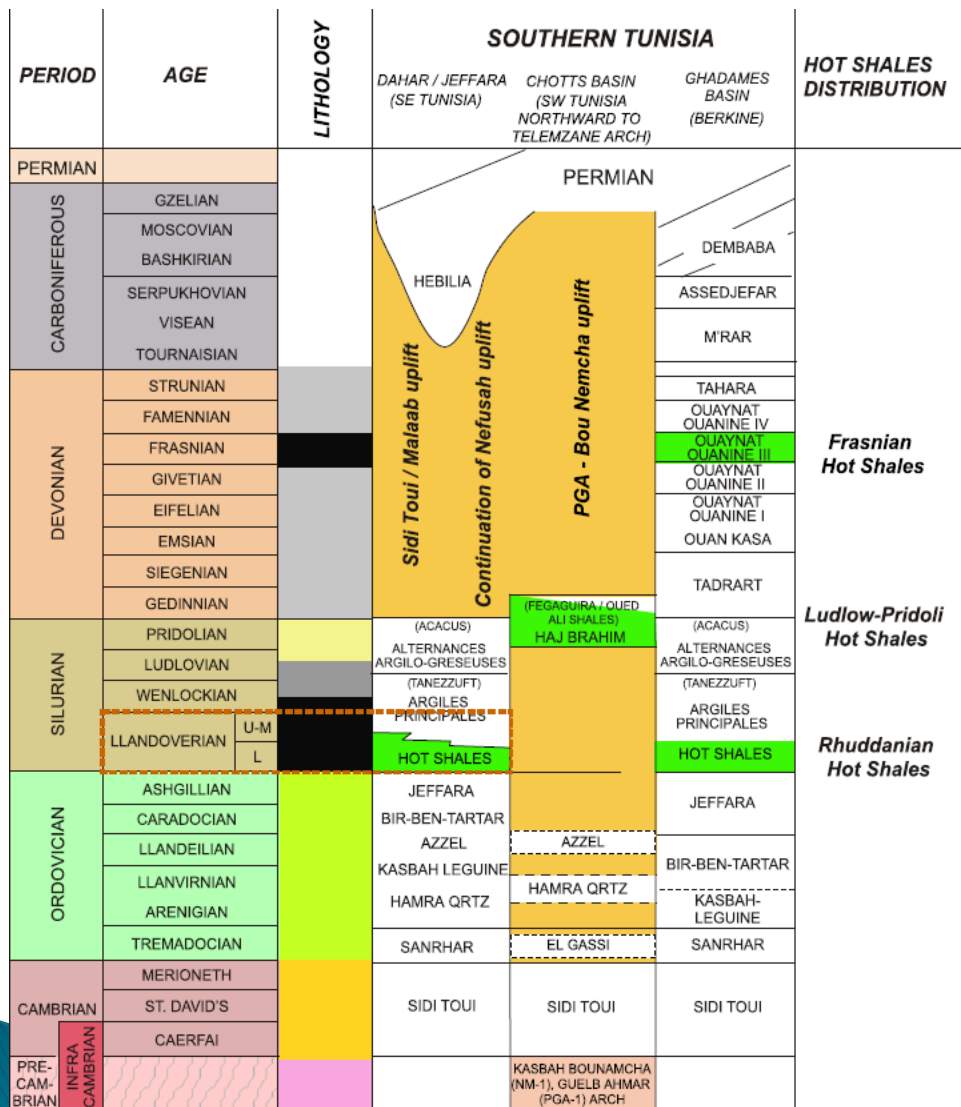
Geological setting and field location (After Soua, 2014)

**Geological setting**

The lower Silurian interval Tannezuft Formation or "Argiles Principales Formation" :  
 'Lean shale' in the top  
 Soft "black shales" in the bottom

This black shale represents a transgressive systems tract (40 m in thickness) deposited under reducing conditions in an anoxic deep-water environment which had occurred during the lower Silurian.

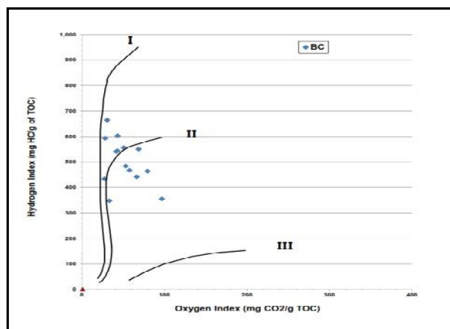
This layer is considered the most important hydrocarbon source rock in the North African basins (Libya, Tunisia, and Algeria) including the southern Jeffara Basin.



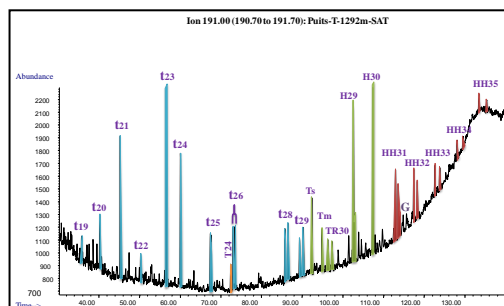
Lithostratigraphic series in Southeast of Tunisia (After Soua, 2014)

Methodology

Rock eval :  
TOC, PI, PP Tmax, S1, S2, OSI, HGP,TR, VR.

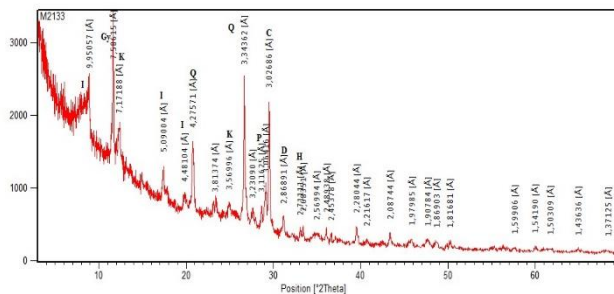


Biomarkers of saturated fraction : GCMS



Mineralogy : X-Ray Diffraction

- Mineralogical composition of the bulk rock,
- Mineralogical composition of the clay fraction,



## Organic geochemistry – Rock-Eval:

Geochemical log (Rock-Eval data) of the borehole cuttings from Silurian formation.

The measured **TOC** show two different intervals:

- Lean shale :

**poor organic matter** content (0,05 wt.% to 1,51 wt.%),

- Hot shale :

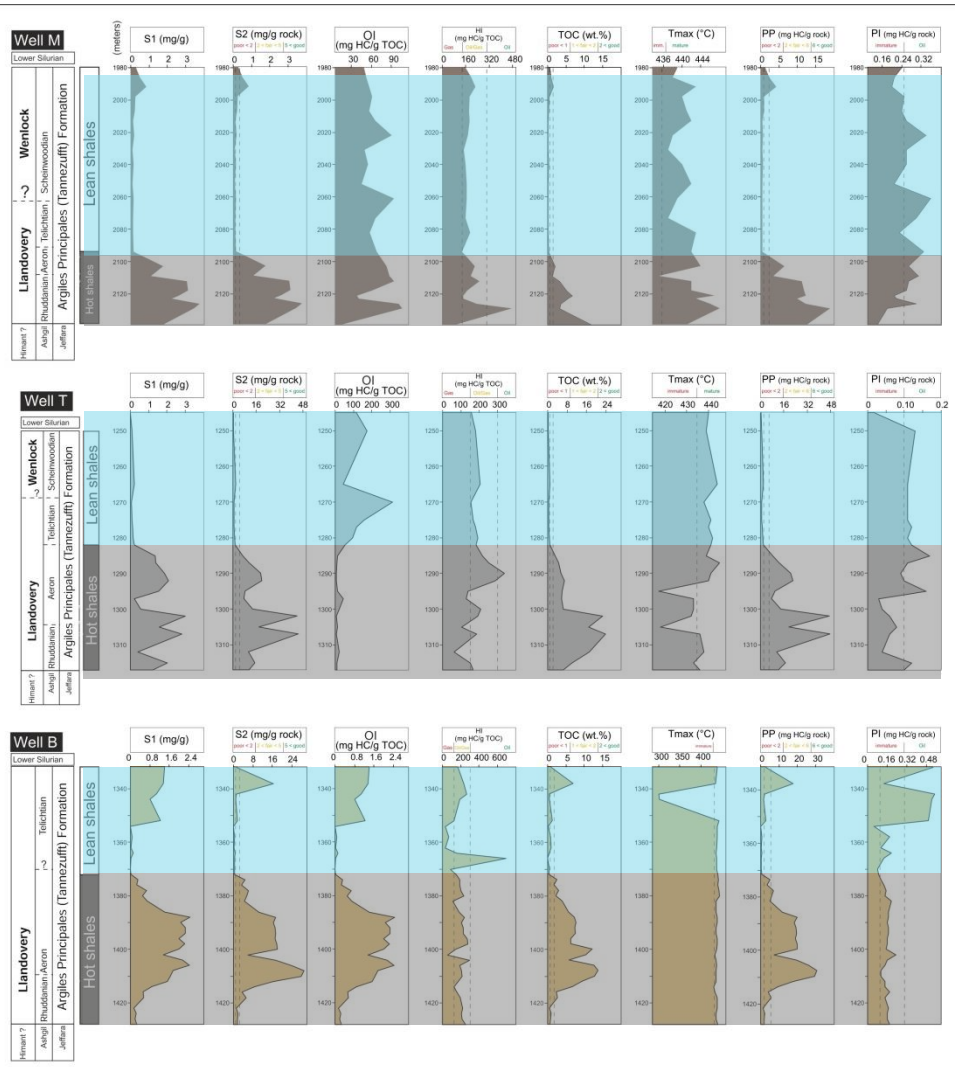
**TOC > 1 wt.%,** max of 23,86 wt.% in T well and significant PP (1.93 – 7.61 HC/ g Rock)

HI max =188, 202, and 214 mg HC/ g rock

→ **A mixed gas and oil kerogen generation,**  
**with main potential of gas generation.**

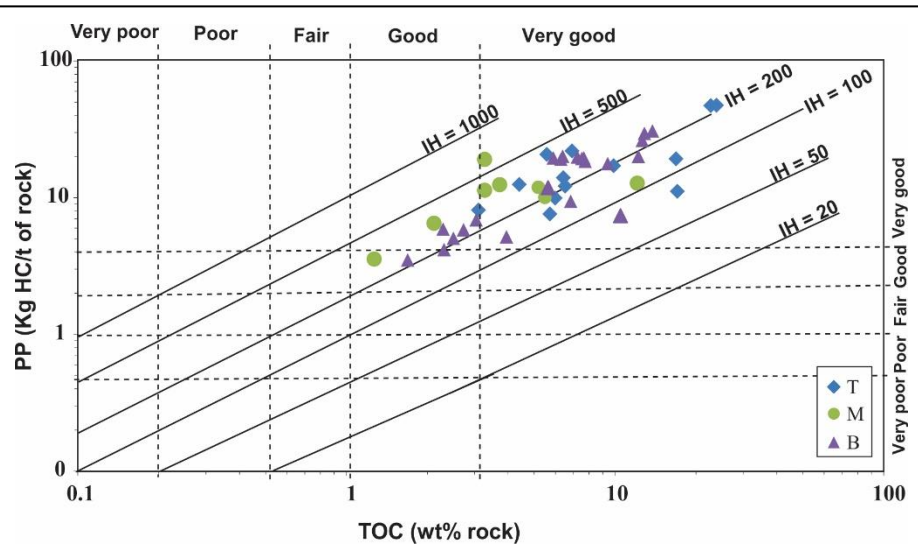
- Tmax > **435°C** (with a maximum of 460°C)

→ **Marginally mature to mature OM**

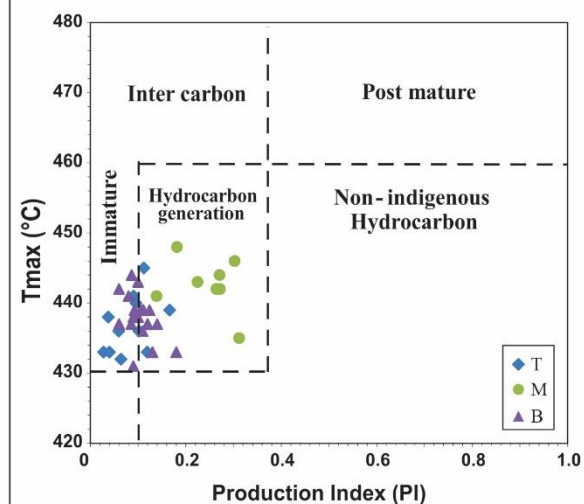
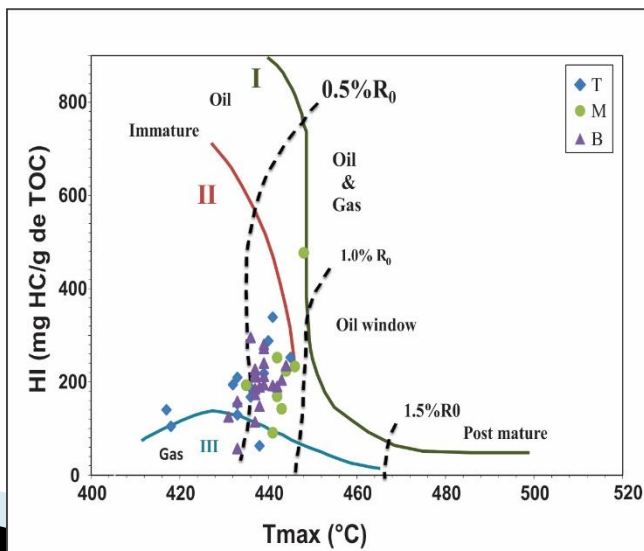


Organic geochemistry – Rock-Eval:

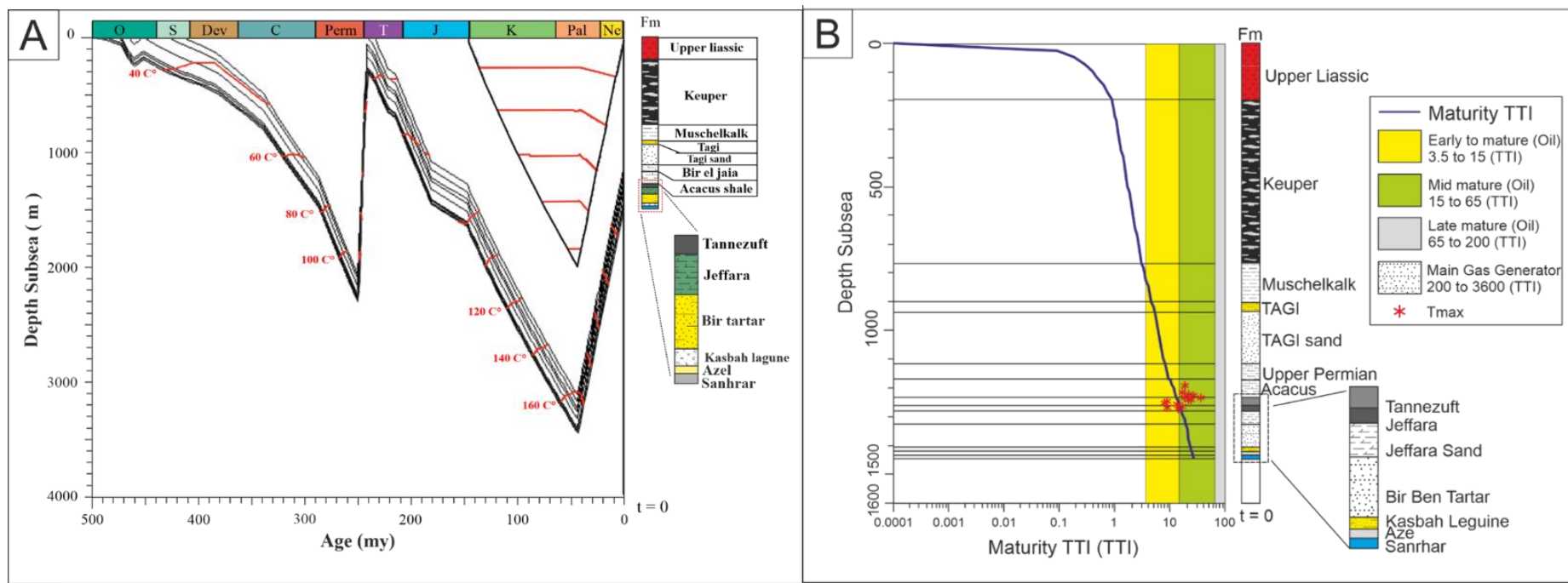
The critical lower limit of TOC content is generally considered out of 0.5 wt. % for shales to be an effective source rock.



OM type II, well preserved at the beginning stage of the oil window



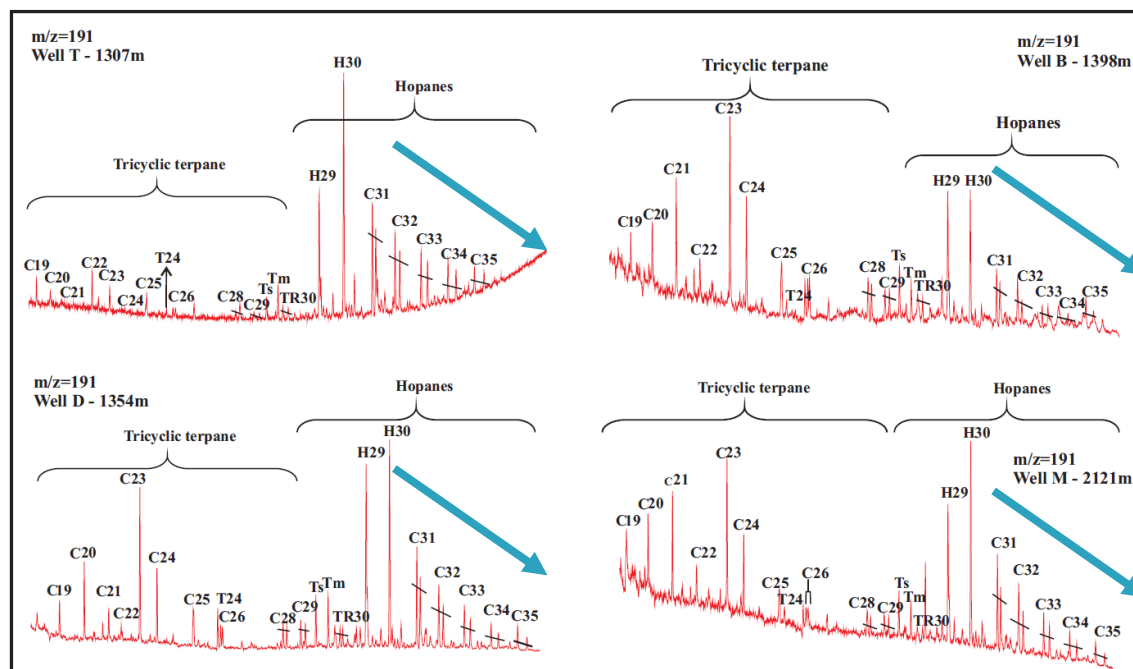
## Organic geochemistry – BasinMod1D:



*Curve of Total subsidence, case study well-T, Basinmod1D. and of curve of hot shale OM maturity*

Two cycles of subsidence and uplift events:

- The first subsidence, between **350 and 250 Ma**, rifting period following the Silurian extension
- The second phase of subsidence, from **Permian to Eocene**, is characterized by an acceleration in subsidence curves, with a significant rate of burial during the Permian and Triassic.

Organic geochemistry – Biomarkers:

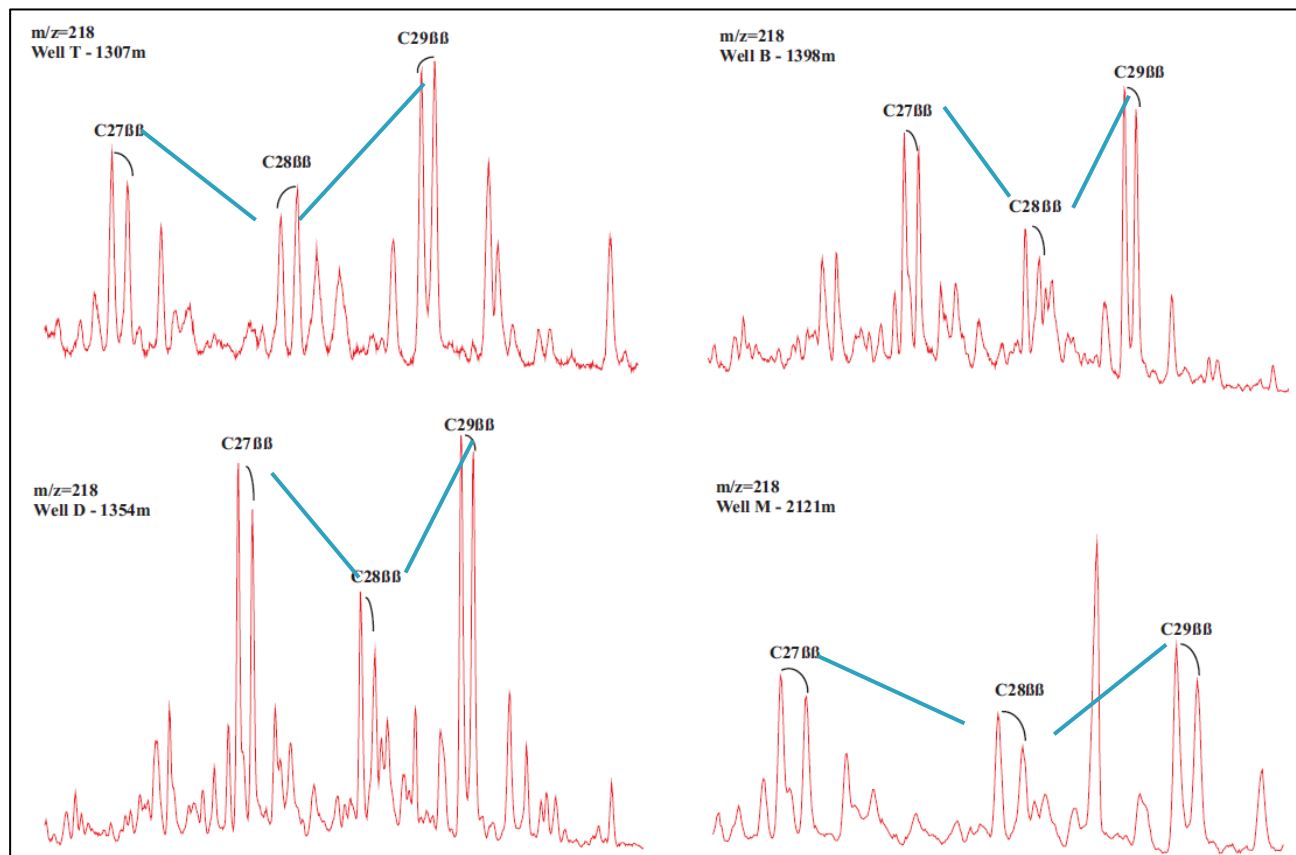
Tricyclic terpanes patterns display:

- the carbon index (from C19 to C26) with an abundance of C21 to C23,
- the tetracyclic terpane C24 TT < the tricyclic terpanes t23
- the C26 tricyclic terpane is more prevalent than the C25.

**Marine origin of OM**

The homohopanes (S and R) trend to decrease from C31 towards C35 HH in all the samples

→ characteristics of syn-depositional **redox conditions**, witnessing that the hot shales OM was deposited within **anoxic marine environment**.

Organic geochemistry – Biomarkers:

- **V shape** of the long chain regular steranes C27 (29% - 41%), C28 (15% - 24%), and C29 (35% - 49%)

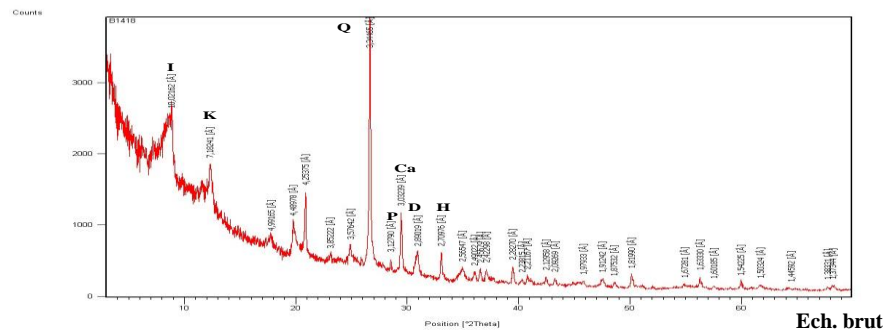
- **High** C30 steranes index (m/z=217)

→ **marine origin** of the OM

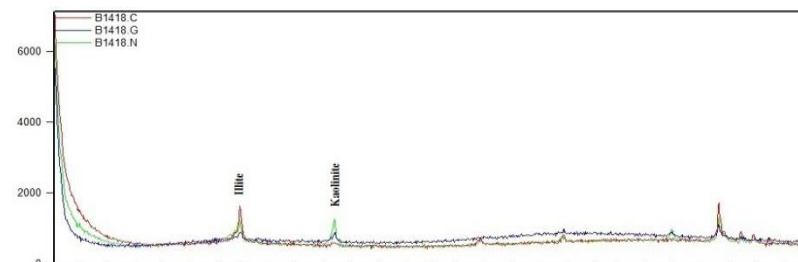
The C29 steranes 20S/ (20S+20R) – between 0.37 and 0.46 which → **marginally mature to mature.**

**Mineralogy:**

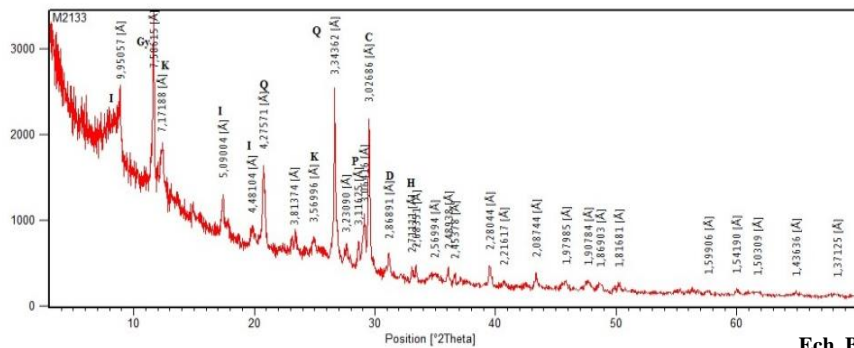
- Clayey couple of **illite-kaolinite**, 36%-59%.
- **Quartz** (5%-20%), **dolomite** (5%-16%), **calcite** (6%-16%), Pyrite (4% to 15%) and traces of siderite.



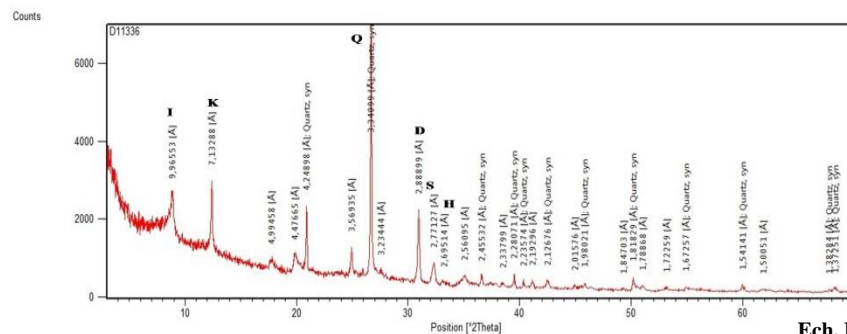
Ech. brut



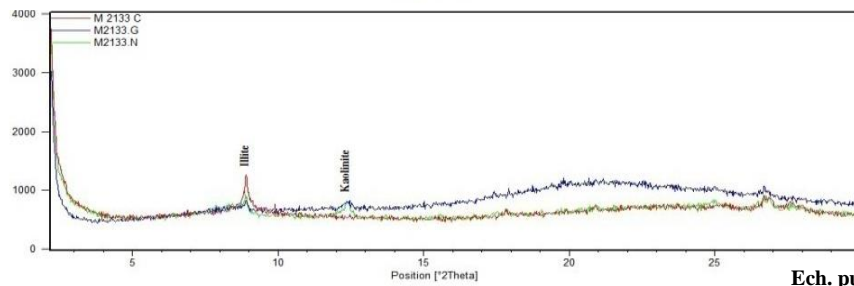
purifié



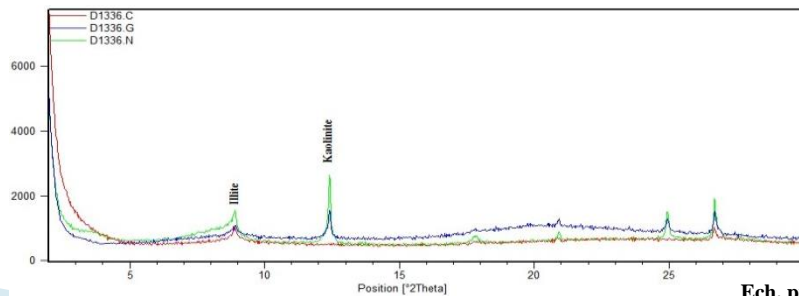
Ech. Brut



Ech. Brut



Ech. purifié



Ech. purifié

## Discussion – Geochemistry:

1- Oil saturation index (OSI) =  $(S1*100)/TOC$  which includes information about the in-situ oil and displaced or migrated HCs.

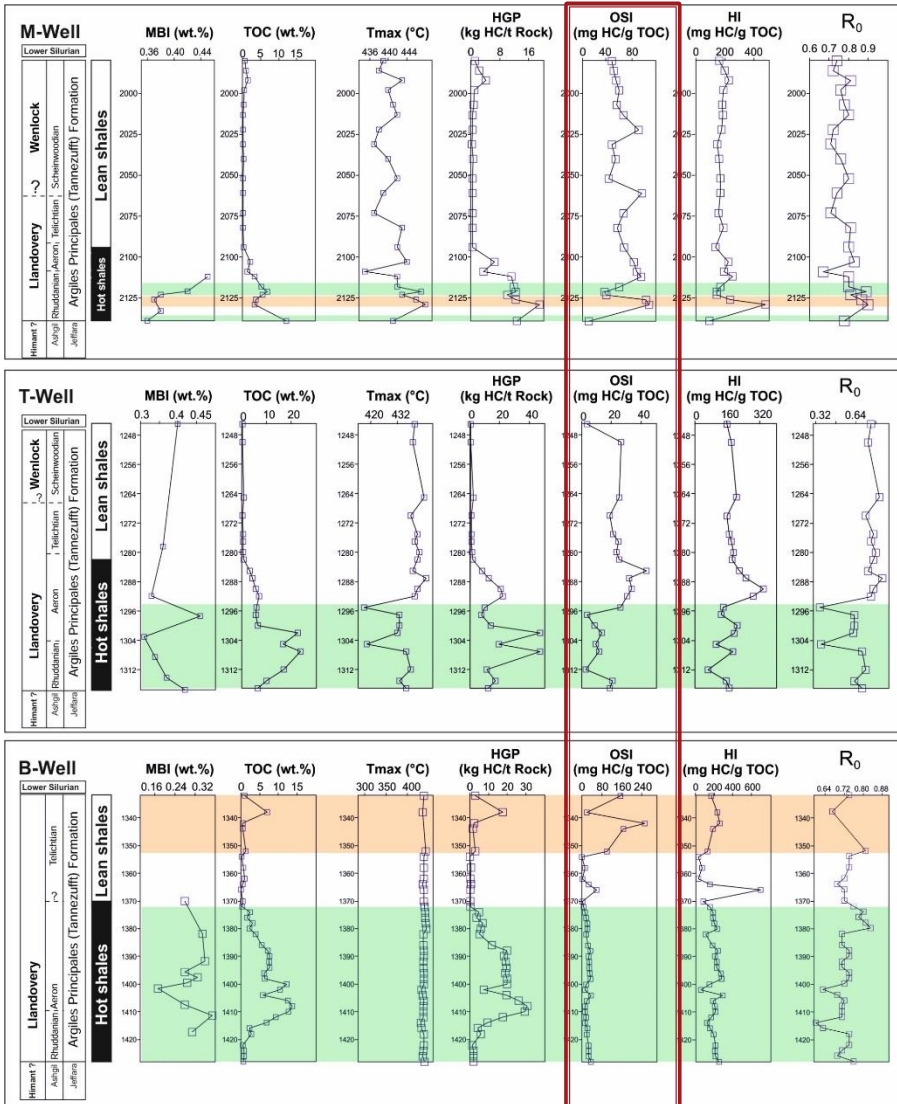
Its ratio estimates the economic potential of oil production and the oil-bearing source rock capacity.

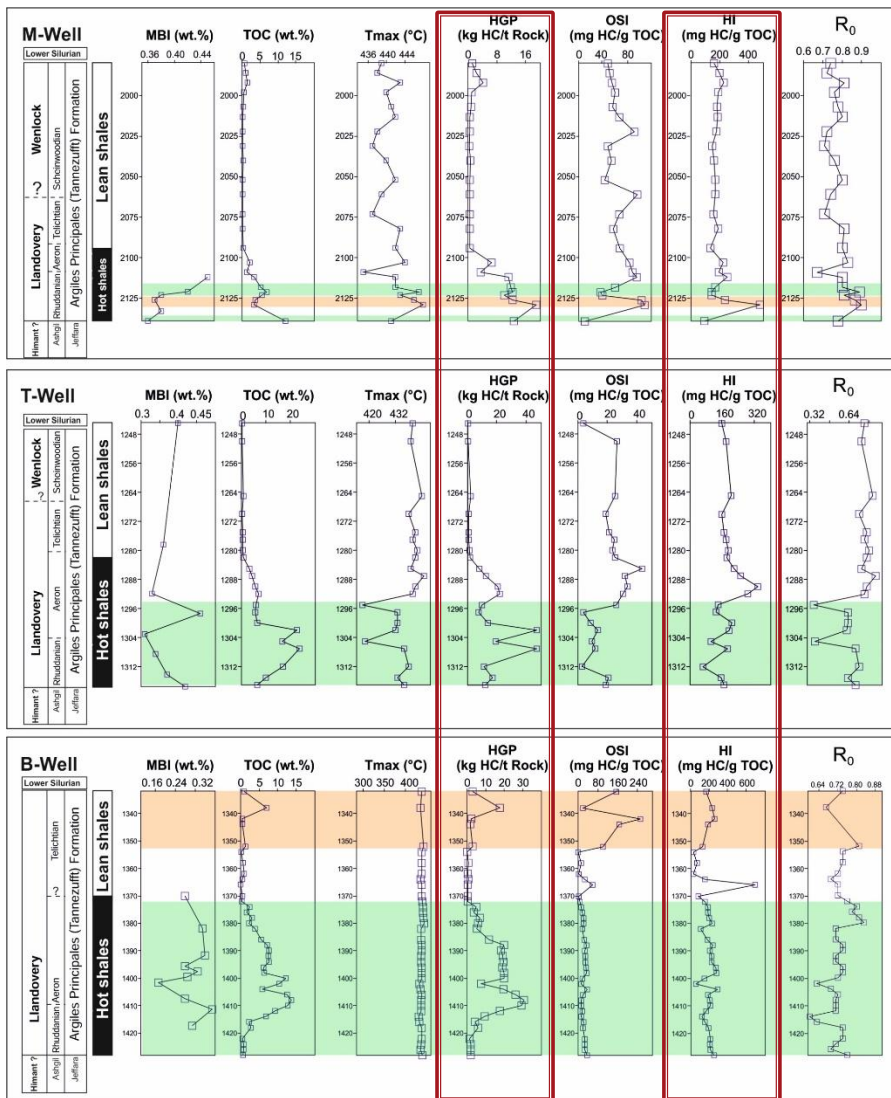
B, and M wells displayed OSI ratios ranging between **100% and 252%**.

B well has a **20m** interval (from 1332m to 1352m),  
M well shows a **3m** interval (from 2126m).

T well presents **2,46% < OSI < 43,55%**; due to the hot shales shallower depths (1250m to 1317m) compared to the neighbouring wells above.

**the high potential of trapped HC (S2), which could be the reason for the absence of cross-over interval.**



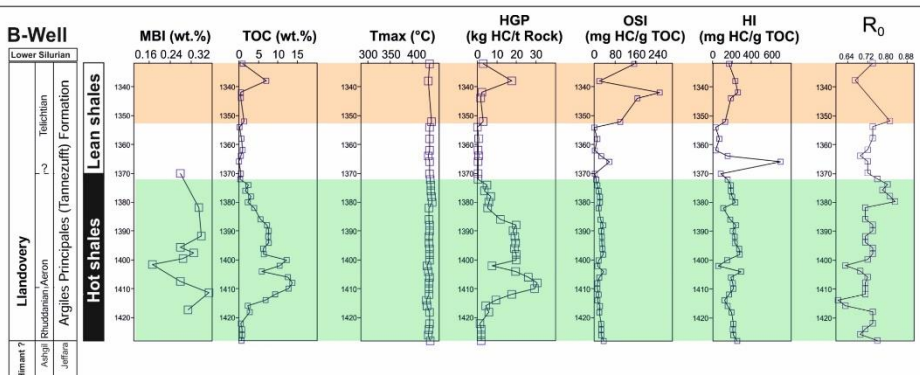
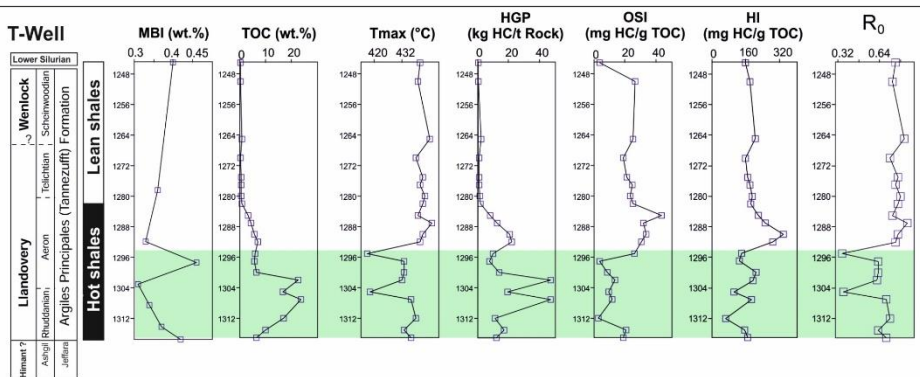
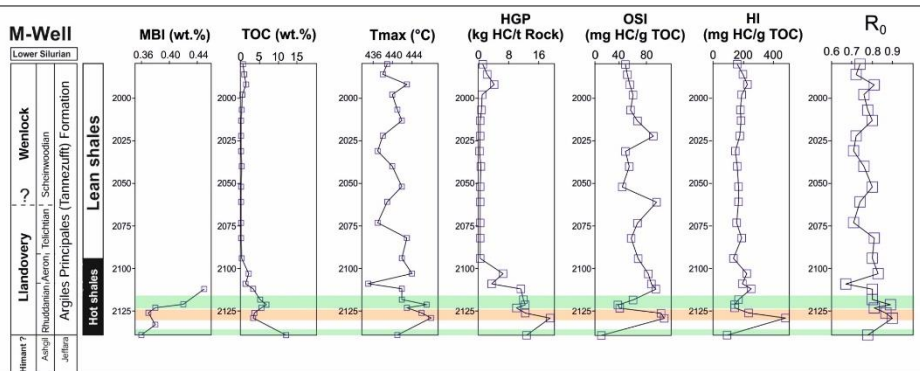


## Discussion – Geochemistry:

2- hydrocarbon generation potential  $HGP = S1+S2$  shows oil-prone generation within the hot shale interval.

- Significant HGP of studied samples is closely associated with **TOC greater than 1%**.
- HGP on well-T reaches 22%, B at 30,84%, and 19,05% in well-M
- HI values  $< 200\text{mg HC/ g TOC}$  indicate an important oil generation and expulsion potential,
- $HI < 150\text{ mg HC/g TOC}$  - OM within dry gas generation.

➔ The hot shale intervals would have a significant potential for shale gas/oil reservoirs.

Discussion – Geochemistry:

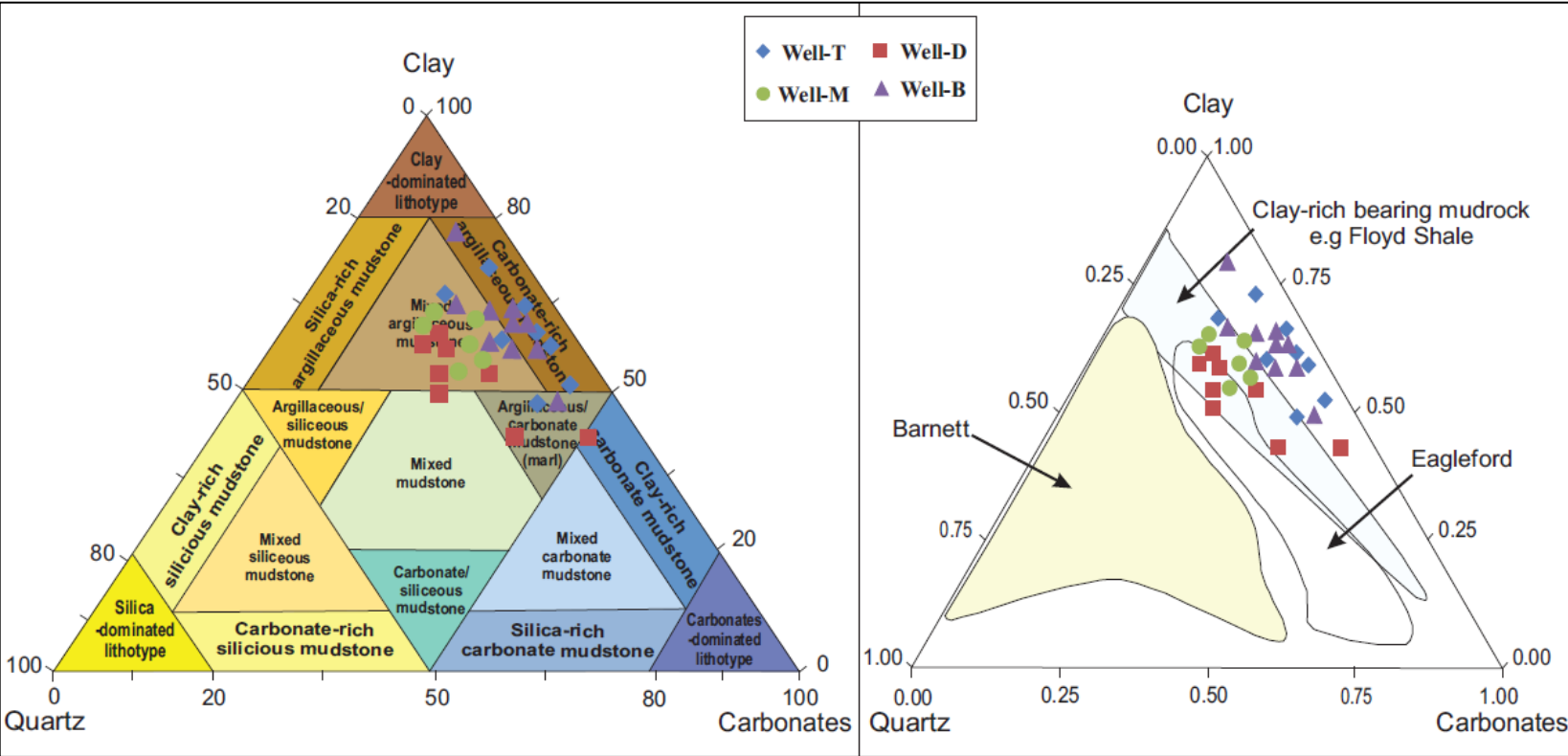
**3-thermal transformation ratio (TR)**, as defined by Jarvie et al. (2007), the amount of OM in a source rock that can produce hydrocarbons at different stages of maturation.

The T, B, and M wells showed high TR amounts of 21.12%, 30%, and 35.25%, respectively.

→ early mature to mature OM within the oil and gas generation window in B and M wells, which is supported by the oil crossover intervals and high total organic carbon (TOC) content.

**4-Mineral Brittleness Index (MBI)** equation, based on the muddy lithology, high carbonates and quartz content, and TOC.  $MBI = \frac{Q+Cal+D}{Q+Cal+D+Clay+TOC}$ .

# Conclusion



*Mineral composition was compared to the most well-known unconventional reservoirs in the world → the Floyd (Neal) shale. It is a source rock for conventional hydrocarbons and has been explored as a gas reservoir with a high quartz content (up to 20%).*

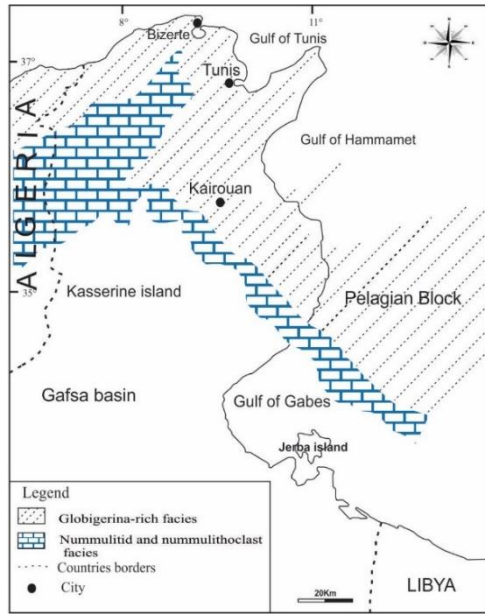
→ These important features highlight the economic potential of the Tannezuft shale and the need to consider them in any future evaluations of its gas production potential.

**Paper 2: for Facies journal**

Sedimentology, sequence stratigraphy and Diagenetic controls of the outcrops equivalent of Ypresian-Lower Lutetian limestones source rock “Bou Dabbous Fm” and reservoir “El Garia Fm”, in northwestern Tunisia.

**Plan:****Introduction****Geological setting** – done**Methods** - done**Results** - done**Stratigraphic and sedimentological description** - done**Lithological description** - done**Source rock analogs: Globigerina-rich OK and TS section** - done**Reservoir analogs: Nummulitidae-rich AG section** - done**Microfacies analysis** - done**Diagenetic features** - done**Discussion** – in progressDepositional model **Writing in progress...**Sequence stratigraphy **Writing in progress...**Diagenetic controls on the limestones pore types **Writing in progress...****Conclusion****In progress 80%**Working time: November 2023 – June 2024Last fieldtrip: February 2024Submission: Late June 2024

**Reminder – Geological setting**



Paleogeographic domains (Jurassic to Miocene p.p.)	Maghrebian Flysch Basin		External Domain		Foreland		
	Tunisian offshore	Northern Tunisia	North African (Maghrebian) Paleomargin				
			Northern Tunisia		Central Tunisia		Southern Tunisia
<i>Adopted terminology (Belayouni et al., 2010, 2012; Guerrero et al., 1993; 2005)</i>	Internal (Mauretanian) sub-Domain	External (Massylian) sub-Domain	Internal and External sub-Domains		Deformed Tunisian Foreland		Undeformed (or slightly deformed) Foreland
<i>Tectonic Zones (Perthuisot, 1981; Moody et al., 2009; Belayouni et al., 2012)</i>	-----	Tellian Numidian (or Tellian Atlas) Zone (TNZ)			Triassic Dome (diapirs) Zone (TDZ)	Intermediate Atlas Zone (IAZ)	Saharian Platform Zone (SPZ)
<i>Tectonic Zones (Perthuisot, 1981; Moody et al., 2009; Belayouni et al., 2012)</i>	La Galite Flysch Unit (Belayouni et al., 2010)	Numidian Nappe (overthrusting)		Djebel Ed Diss	Kasscb	Ain El Bey (para-autochthonous)	----- Saharian Platform
		Col de l'Adissa	Ain Draham				

Paleogeographic and tectonic terminology of the Maghrebian chain and the Tunisian Tell (Belayouni et al., 2010)

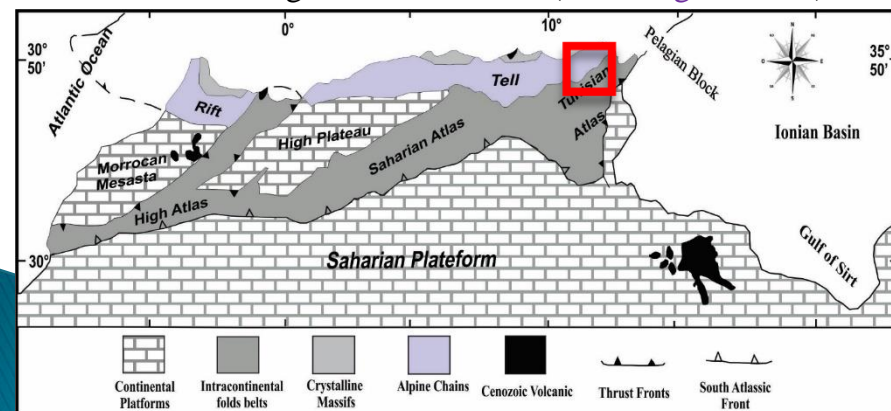
**Bou Dabbous (Source rock)**

- Deposited in the paleodepressions favorable for planctonic foram proliferation
- Carbonates **globigerine-rich**,

**El Garia (reservoir)**

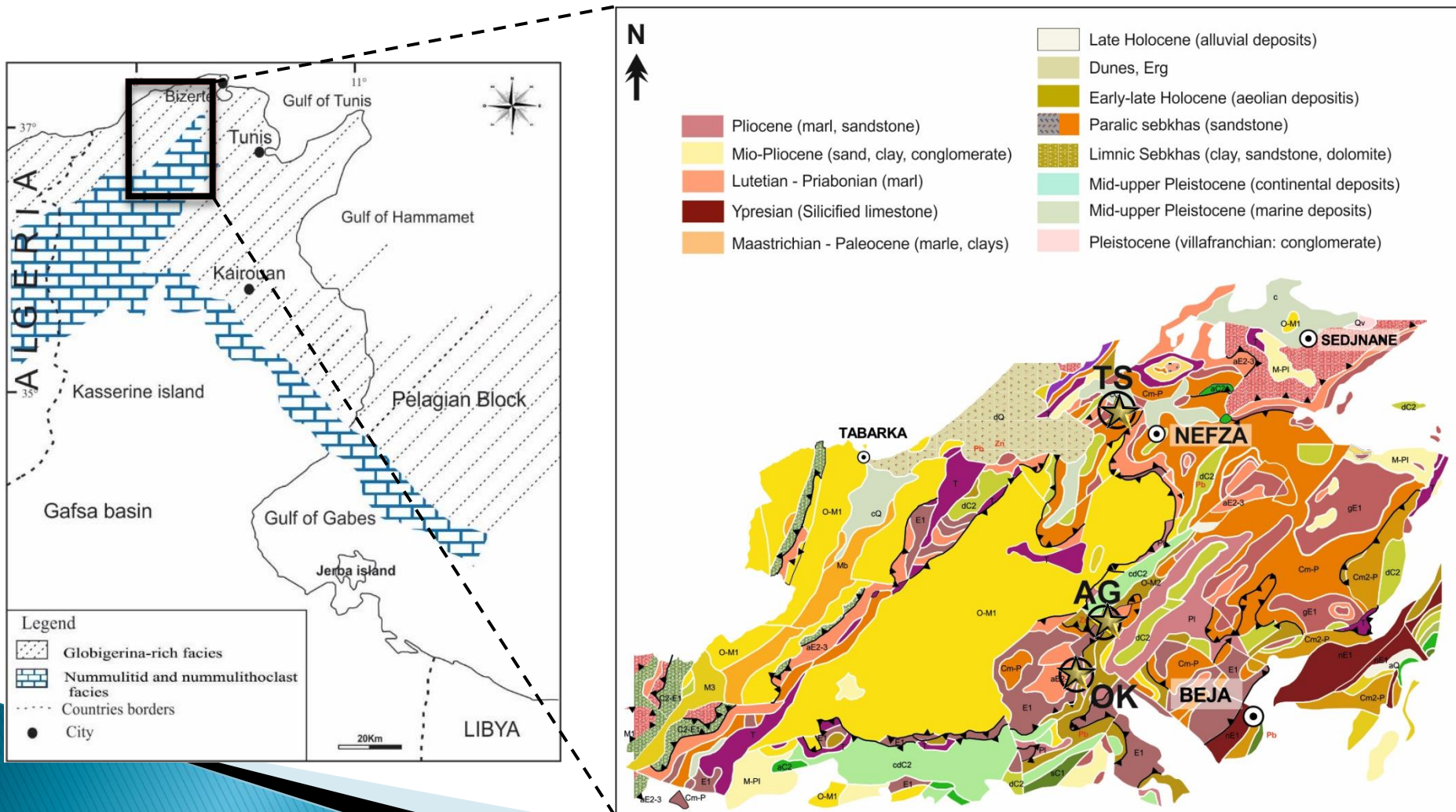
- Deposited in the paleohighs: Benthic foraminifera; **nummulites-rich**, very common in the Mediterranean basins.

Eocene paleogeography in Tunisia: distribution of nummulite-rich and et Globigerinas-rich facies (after Tlig S., 2010).



Structural context of Maghrebin belt [Piqué et al. 1998]

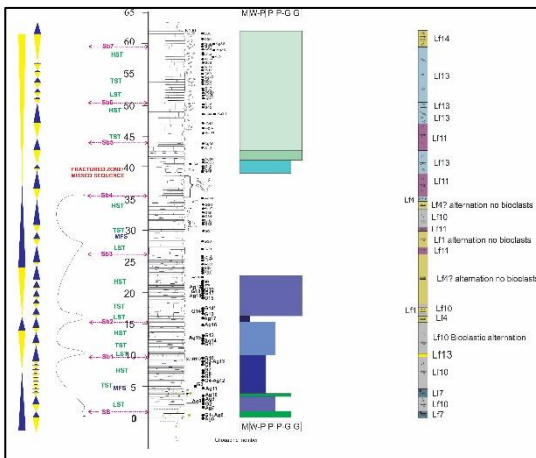
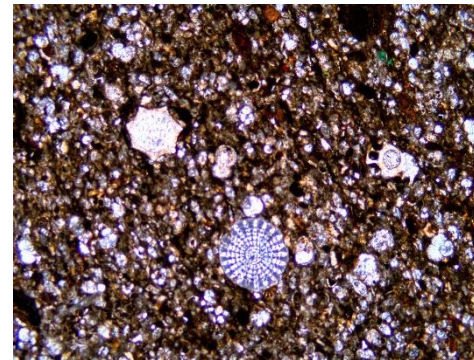
**Reminder – Study area**



Methodology

- Detailed lithological description of the stacked bed couplets (Limestones/marly limestones), and the determination of the significant surfaces based on the field observations.

- Systematic Field sampling for thin sections confection, petrographic and diagenesis studies.



- Detailed litholog, lithofacies, depositional model. A high-resolution sequence stratigraphic

## Part II: Microfacies analysis

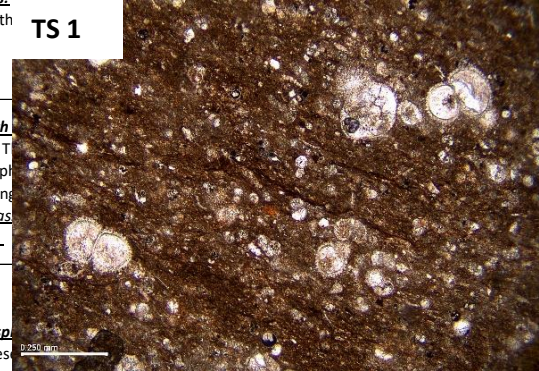
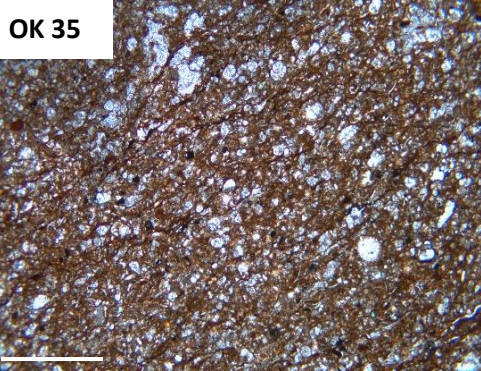
Facies	Facies description - Texture	Fossil content	Depositional Environment	Samples numbers
MF1	<u>Azoic / rare globigerinids Mudstone</u> : micritic matrix, rare foram, mineral content: mega-quartz, automorphic dolomite grains (5-10µm), pyrite.	Planctonic foram: (Rare) Globigerinidae, Globorotalia,	Basin	OK5-OK6-OK10-OK11-OK13-OK14-OK16 AG13-AG17 (Platelet Limestones) Few samples from TS section
MF2	<u>Wack to packstones globigerinids and radiolarian-rich</u> : micritic matrix, benthic and planctonic foram, locally badly preserved planctonic foraminifera, pyrite, OM-filled fractures,	Planctonic foram: (abundant) Globigerinidae, Globorotalia, Globotruncana Protozoan: Radiolarian.	Upper slope	Almost of the samples OK section -OK34 - ok35 - OK61, OK57, OK68 Almost of TS section
MF3	<u>globigerinids and bioclastic packstones</u> : micritic matrix, planctonic foram-rich (70%-85%) , rare benthic foram. Phosphate	Planctonic foram: (abundant) Globorotalia, globigerinids, Benthic foram (rare): Nodosoria (uni, bi, plani-serials), juvenile nummulite. Ostracods debris, echinoids, and pelecypods. Marine algae: Oogonia (rare)	inner-outer platform	ok67-OK74, OK73
MF4	<u>Turbidites, Lithoclasts, globigerinids-rich packstones</u> : micritic matrix, planctonic foram-rich, benthic foram, Thalassinoides, Glauconite, glauconized radiolarian, Phosphate, phosphotized lithoclast, Bioturbated (micritic trace of burrowing organisms). Phosphate. <u>Locally it shows stylolites compaction, associated to Thalassinoides, Planolites.</u>	Planctonic foram: (abundant) Globorotalia, globigerinids, Benthic foram (rare): Nodosoria (uni, bi, plani-serials), juvenile nummulite.	Outer platform	OK24, OK76 to OK178, TS141
MF5	<u>Globigerinids, pelecypods and calcisphere rich wackestone to packstone</u> : micritic matrix, badly-preserved foram, associated to glauconitized phosphate lithoclast, pyrite. Silicification of the cement,	Planctonic foram (abundant): globigerinids, Globorotalia, benthic foram: Nummulithoclasts, nummulites (r), Nodosoria (f), Echinoderm: crinoids. Pelecypods.	middle platform	ok43-OK48-OK58, OK52, OK54(pelecypods)
MF6	<u>Nummulithoclast and Globigerinids rich wackestone and packstone</u> : micritic matrix, Echinoderms and spines associated to Benthic foram and rare phosphate and glauconite grains.	nummulithoclast (a) Protozoan: Radiolarian (frequent), benthic foram: Nodosoria (rare), globigerinids(rare), Planctonic foram (rare): globigerinids, Lamellibranches (rare), Echinoderm: Ostracods	inner/mid platform	AG19, AG21, AG22, AG24, AG25,27
MF7	<u>Nummulithoclasts and red alga packstone to grainstone</u> : Sparitic matrix, elongated A-form nummulites, mixed with rounded form (AG32) associated to red algae (become more frequent going to the top of the uppermost unit). Phosphate and pyrite.	Nummulites, Nummulithoclasts (abundant), Ostracods (frequent), Discocyclus (frequent),	outer part of the inner platform on grabens	AG26, AG28, AG29 AG30 AG31, AG32
MF8	<u>Pelloidal, Operculina and Assilina rich grainstones</u> : Sparitic matrix, rich with Assilina and Operculina, some echinoderms debris,	Peloid, operculina (f)	highs of the inner platform	AG 28
MF9	<u>B-form nummulites, annelids, and bioclasts (Operculina, Assilina, bivalves,...) grainstones</u>	Nummulites(a), annelid (f), operculina (f), Assilina (r ), Echinoderms plates (r )	inner platform	AG 36

# Part II: Microfacies analysis

Facies	Facies description - Texture	Fossil content	Depositional Environment	Samples numbers
MF1	<b>Azoic / rare globigerinids Mudstone</b> : micritic matrix, rare foram, mineral content: mega-quartz, automorphic dolomite grains (5-10µm), pyrite.	Planctonic foram: (Rare) Globigerinidae, Globorotalia,	Basin	OK5-OK6-OK10-OK11-OK13-OK14-OK16 AG13-AG17 (Platelet Limestones) Few samples from TS section
MF2	<b>Wack to packstones globigerinids and radiolarian-rich</b> : micritic matrix, benthic and planctonic foram, locally badly preserved planctonic foraminifera, pyrite, OM-filled fractures,	Planctonic foram: (abundant) Globigerinidae, Globorotalia, Globotruncana Protozoan: Radiolarian.	Upper slope	Almost of the samples OK section -OK34 - ok35 - OK61, OK57, OK68 Almost of TS section
	<b>globigerinids and bioclastic packstones</b> : micritic matrix, planctonic foram (rare): Nodosoria (uni- bi- plani-serials), juvenile nummulites	Planctonic foram: (abundant) Globorotalia, globigerinids, Benthic		

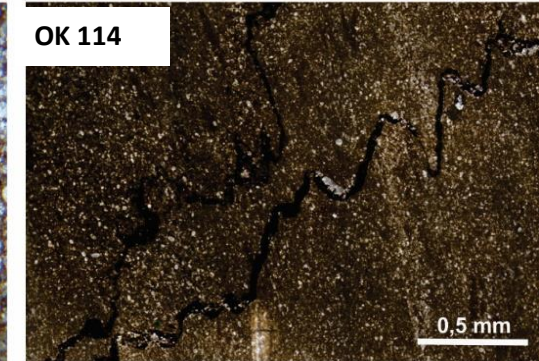
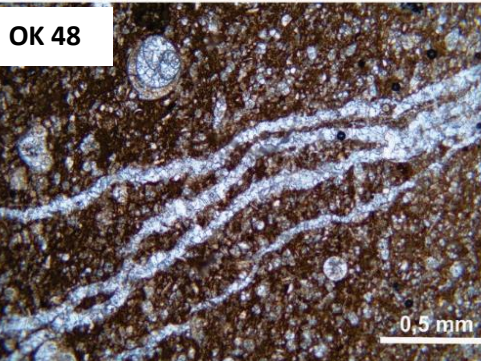
OK 35

TS 1



OK 48

OK 114

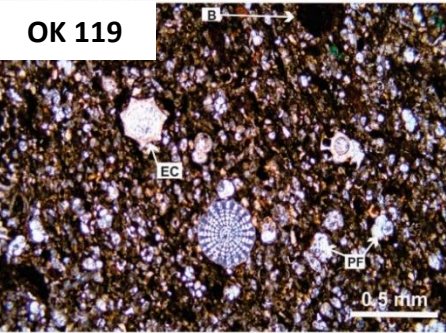
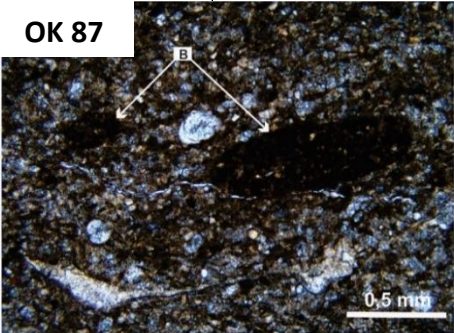
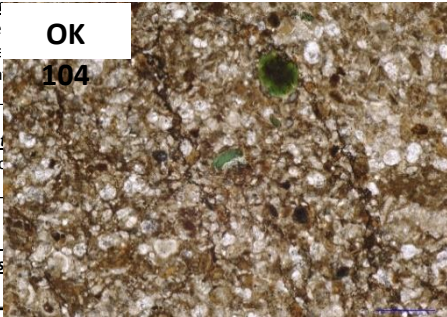
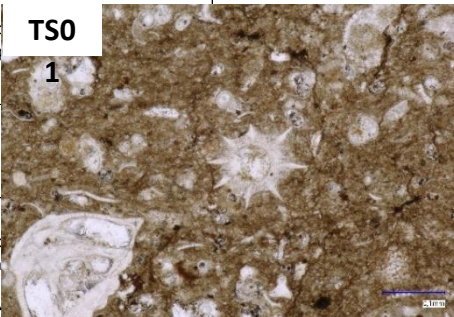


- ✓ Distal slope
- ✓ Diagenesis
- ✓ Secondary porosity:
  - Organic porosity (HC filled stylolites)
  - Inorganic porosity ( mineral filled pores and fissures : Calcite, pyrites,...)
  - Intergranular: dissolution and precipitation of intergranular calcite (in foraminifera).
  - Intraparticle: unconnected (low permeability).

**MF2: Wack to Packstone globigerinids and radiolarian-rich - OK35 / TS 1 / OK 48 / OK 114** – rich in planktonic foraminifera (Globigerina / Globorotalia), radiolarian, rich in fractures and filled stylolites (calcite, organic matter).

MF9	<b>B-form nummulites, annelids, and bioclasts (Operculina, Assilina, bivalves,...) grainstones</b>	Nummulites(a), annelid (f), operculina (f), Assilina (r), Echinoderms plates (r)	inner platform	AG19, AG21, AG22, AG24, AG25,27  AG 36
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# Part II: Microfacies analysis


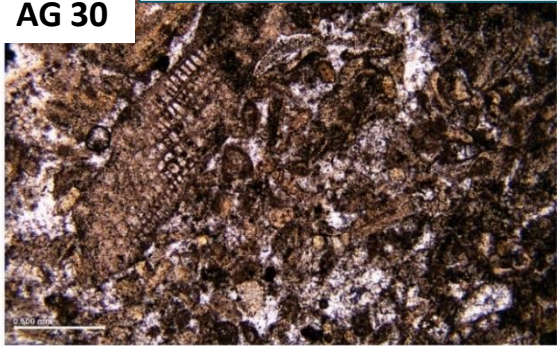
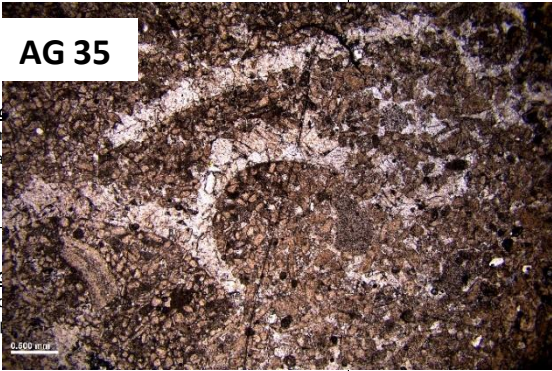
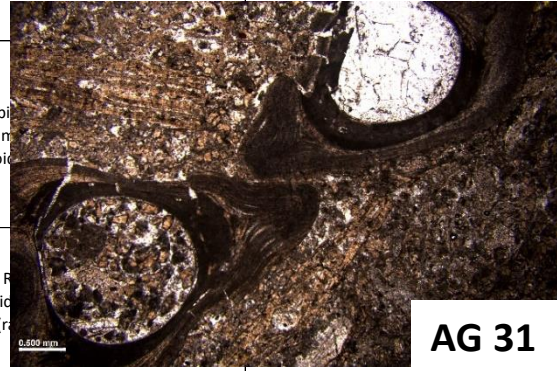
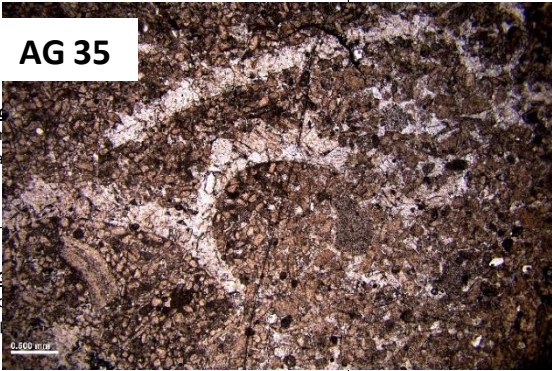
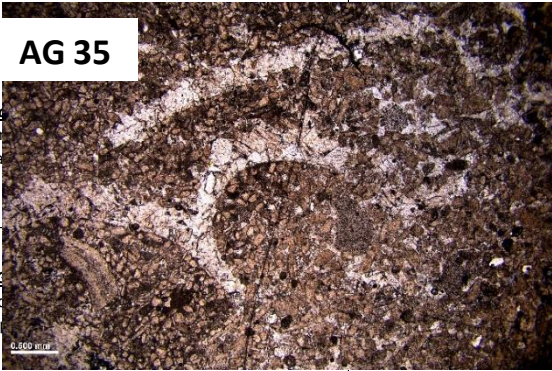
Facies	Facies description - Texture	Fossil content	Depositional Environment	Samples numbers
MF1	<u>Azoic / rare glauconitic</u> mineral content	<ul style="list-style-type: none"> <li>✓ Slope</li> <li>✓ Bioturbated environment</li> <li>✓ Diagenesis</li> <li>✓ Secondary porosity: intergranular: dissolution and precipitation of the calcite intergranular (within foraminifers). Intra-particular: non-connected ( Low permeability).</li> </ul>	Basin	OK5-OK6-OK10-OK11-OK13-OK14-OK16 AG13-AG17 (Platelet Limestones) Few samples from TS section
MF2	<u>Wack to pack</u> matrix, ber... plant		Upper slope	Almost of the samples OK section -OK34 - ok35 - OK61 -OK57 -OK68
MF3	<u>globigerinids</u> foram-r		ic... e... nia	
MF4	<u>Turbidites, Lithoclasts, globigerinids-rich packstones</u> : micritic matrix, planktonic foram-rich, benthic foram, Thalassinoides, Glauconite, glauconized radiolarian, Phosphate, phosphotized lithoclasth, Bioturbated (micritic trace of burrowing organisms). Phosphate. <u>Locally it shows stylolites compaction, associated to Thalassinoides, Planolites.</u>	Planctonic foram: (abundant) Globorotalia, globigerinids, Benthic foram (rare): Nodosoria (uni, bi, plani-serials), juvenile nummulite.	Outer platform	OK24, OK76 to OK178, TS141
MF5	<u>Globigerinids, pelecypods and calcispher packstone</u> : micritic matrix, badly-preserved glauconitized phosphate lithoclast, pyrite. Sil			ok43-OK48-OK58, OK52, OK54(pelecypods)
MF6	<u>Nummulithoclast and Globigerinids rich wack</u> : micritic matrix, Echinoderms and spines associated and rare phosphate and glauconite			AG19, AG21, AG22, AG24, AG25,27
MF7	<u>Nummulithoclasts and red algae packstone</u> : micritic matrix, elongated A-form nummulites, mixed with red algae (AG32) associated to red algae (become more abundant in the top of the uppermost unit). Phosphate	und... rec	on grabens	AG26, AG28, AG29 AG30 AG31,AG32
MF8	<u>Pelloidal, Operculina and Assilina rich grains</u> : micritic matrix rich with Assilina and Operculina, some echinoderms	culi	rm	AG 28
MF9	<u>B-form nummulites, annelids, and bioclasts</u> (bivalves,...) grainstones	ber... pla		AG 36

**MF4: Turbidites, lithoclasts, globigerinids-rich packstone – OK87 / OK 119** – abundant in planktonic foraminifera (Globigerina / Globorotalia), benthic foraminifera (Nodosaria), and radiolarian,

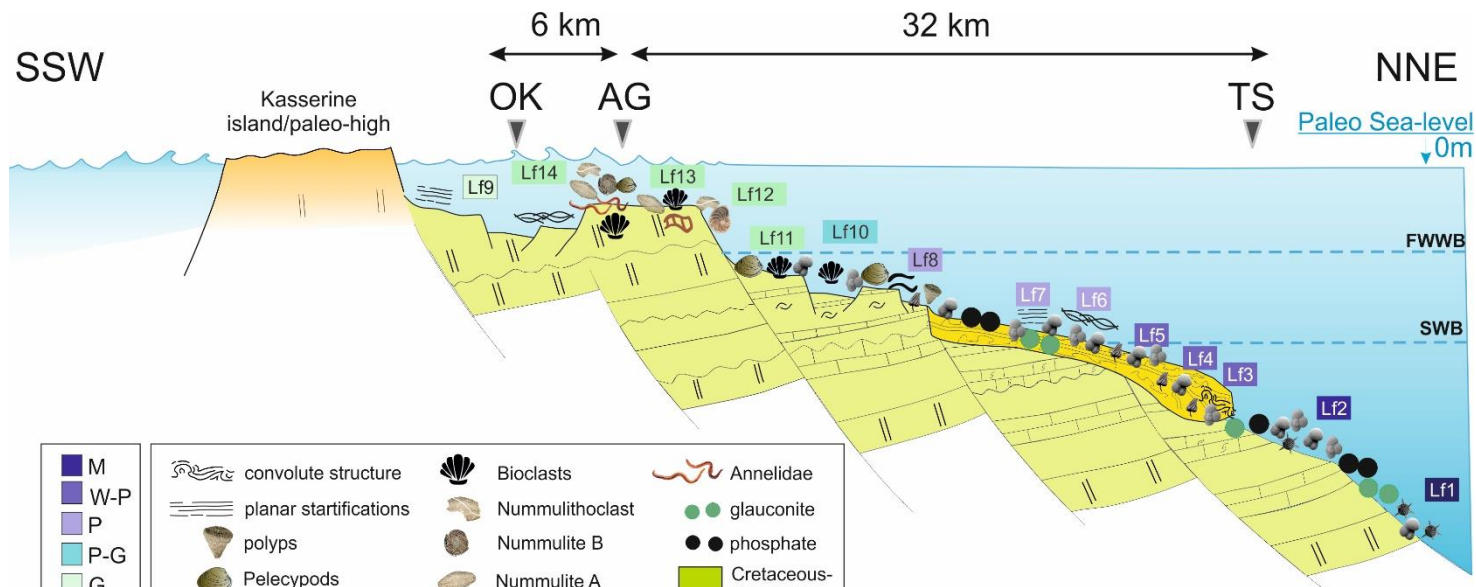
# Part II: Microfacies analysis

- ✓ Inner platform
- ✓ Shallow medium
- ✓ Intergranular porosity (partially filled with calcite/bioclasts).
- ✓ Intergranular porosity.
- ✓ Moldic porosity, precipitation of calcite.

**MF7, MF8 and MF9:** – AG 29 / AG 30 / AG 31 /AG35 – rich in benthic foraminifera (Nummulites), operculina, annelids,

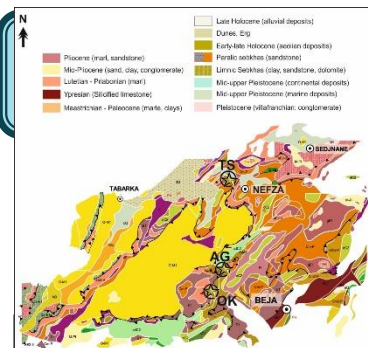
Facies	Facies description - Texture	Fossil content			
MF2	matrix, benthic and planctonic foram, locally badly preserved planctonic for	Globotruncana Protazoan: Rad	<b>AG 29</b>	<b>AG 30</b>	
MF3	<u>globigerinids and bio</u> foram-rich (70%)				ok67-OK74, OK73
MF4	<u>Turbidites, Lithoclasts,</u> planctonic foram-rich glauconitized radiola Bioturbated (micritic) <u>Locally it shows stylolites compaction, associated to Thalassinoides,</u>				OK24, OK76 to OK178, TS141
MF5	<u>Globigerinids, pelecypods</u> <u>packstone</u> : micritic n glauconitized phosph	nt): globi lists, num n: crinoid	<b>AG 35</b>		ok43-OK48-OK58, OK52, OK54(pelycypods)
MF6	<u>Nummulithoclast and C</u> micritic matrix, Echinod and rare	ozoan: R bigerinid nches (r	<b>AG 31</b>		AG19, AG21, AG22, AG24, AG25,27
MF7	<u>Nummulithoclasts and red algae packstone to grainstone</u> : Sparitic matrix, elongated A-form nummulites, mixed with rounded form (AG32) associated to red algae (become more frequent going to the top of the uppermost unit). Phosphate and pyrite.	Nummulites, Nummulithoclasts (abundant), Ostracods (frequent), Discocyclus (frequent),			outer part of the inner platform on grabens AG26, AG28, AG29 AG30 AG31, AG32
MF8	<u>Pelloidal, Operculina and Assilina rich grainstones</u> : Sparitic matrix, rich with Assilina and Operculina, some echinoderms debris,	Pelloid, operculina (f)			highs of the inner platform AG 28
MF9	<u>B-form nummulites, annelids, and bioclasts (Operculina, Assilina, bivalves,...) grainstones</u>	Nummulites(a), annelid (f), operculina (f), Assilina (r), Echinoderms plates (r)			inner platform AG 36

# Part II: Lithofacies and depositional model



Lithofacies LF	Description	Interpretation
<b>LF1</b> Flint nodules rich limestone	Grey brown limestones with flint. Well bedded, grayish cm to dm-thick, with large flint nodules: small radius 10 cm to 20 cm, and long radius around 60 cm in OK section, and m-long :50 to 70 cm large radius flints in TS section.	Abyssal plain deposit
<b>LF2</b>	Wackestone dominant, showing silicified layers, with Globigerina and radiolarian (Mf1/MF2)	Distal slope to the outer platform
<b>LF3</b>	Beige to gray limestones characterized by dark spots indicating silicification, and dark gray to black limestones exhibiting silicified cross laminations, and it exhibits flint's growth lines in the top of Unit 3 in TS section. From MF1 to MF3, rich with globigerina	Distal slope
<b>LF4</b>	Limestone with preferred silicification pathway. Alternances of platelot and convolute structured marly limestone	Distal slope
<b>LF5</b>	Laminated gray to black limestones alternating with beige/gray-brownish platelot/pebbled marly (in AG section) and Dark grey to black limestones with parallel lamination (OK and TS sections). From MF1 to MF3, rich with globigerina.	External platform
<b>LF6</b>	Dolomitic limestone. Greyish to beige dm-thick (70 cm to 1 meter in thickness) dolomitized limestones, alongside dark gray to black massive limestones, occasionally exhibiting crystalline textures. MF1 to MF3.	Proximal outer platform
<b>LF7</b>	Gray to gray purple laminated (parallel and cross laminations) indurated limestones. Gray purple limestones	Turbiditic deposit in outer platform
<b>LF8</b>	Reworked material featuring glauconite and phosphatic debris, in blackish/black marly limestones with parallel laminations, occasionally with lithoclasts.	Distal middle platform
<b>LF9</b>	limestones with irregular width Thalassinoides burrows and dark grey bioclastic limestones rich with Polypes.	Turbiditic deposit in middle platform
<b>LF10</b>	Alternance of gray to beige : bioclastic that exhibits mainly bivalves in the platelot marly limestones with dm-thick indurated limestones. Occurs in the unit 1 and unit 2 of AG section.	Distal to proximal middle platform
<b>LF11</b>	Marly limestones rich with bivalves. Dm-thick beds succession of beige to brownish bioclastic (bivalves and polypes) sandy limestones, sometimes dolomitized. Occurs in the unit 1 and unit 2 of AG section, and alternate with Lf11 and Lf 4 in Unit 2.	Proximal middle platform
<b>LF12</b>	Sandy limestones bivalves-rich. Scattered nummulithoclasts, and Operculina, that are culminated in a grey and beige dolomitic limestones, occurs to the top of unit 2.	Foreland inner platform
<b>LF13</b>	Operculina and nummulithoclasts-rich dolomitic limestones. limestones transition into dm to meter-scale beds abundant in fossil content .Beige fossiliferous sandy limestones, presenting polypes, red algae, Ncl, Operculina, and bivalve debris. It becomes harder to the top, and is interbedded with cm-thick friable marly limestones at its base.	Inner platform
<b>LF14</b>	Bioclastic beige sandy limestones. A-elongated shape nummulites make their appearance at 60 meters, with B-rounded nummulites located 2 meters higher. The upper part of the El Garia Formation is identified in the field by dm to m-thick beds of consolidated, unsorted B-rounded nummulites-rich material, with annelids occurrence, associated with Operculina, pelecypods, and nummulites.	Proximal nummulitic platform

Lithofacies LF	Description	Interpretation
<b>LF10</b>	Alternance of gray to beige : bioclastic that exhibits mainly bivalves in the platelot marly limestones with dm-thick indurated limestones. Occurs in the unit 1 and unit 2 of AG section.	Distal to proximal middle platform
<b>LF11</b>	Marly limestones rich with bivalves. Dm-thick beds succession of beige to brownish bioclastic (bivalves and polypes) sandy limestones, sometimes dolomitized. Occurs in the unit 1 and unit 2 of AG section, and alternate with Lf11 and Lf 4 in Unit 2.	Proximal middle platform
<b>LF12</b>	Sandy limestones bivalves-rich. Scattered nummulithoclasts, and Operculina, that are culminated in a grey and beige dolomitic limestones, occurs to the top of unit 2.	Foreland inner platform
<b>LF13</b>	Operculina and nummulithoclasts-rich dolomitic limestones. limestones transition into dm to meter-scale beds abundant in fossil content .Beige fossiliferous sandy limestones, presenting polypes, red algae, Ncl, Operculina, and bivalve debris. It becomes harder to the top, and is interbedded with cm-thick friable marly limestones at its base.	Inner platform
<b>LF14</b>	Bioclastic beige sandy limestones. A-elongated shape nummulites make their appearance at 60 meters, with B-rounded nummulites located 2 meters higher. The upper part of the El Garia Formation is identified in the field by dm to m-thick beds of consolidated, unsorted B-rounded nummulites-rich material, with annelids occurrence, associated with Operculina, pelecypods, and nummulites.	Proximal nummulitic platform



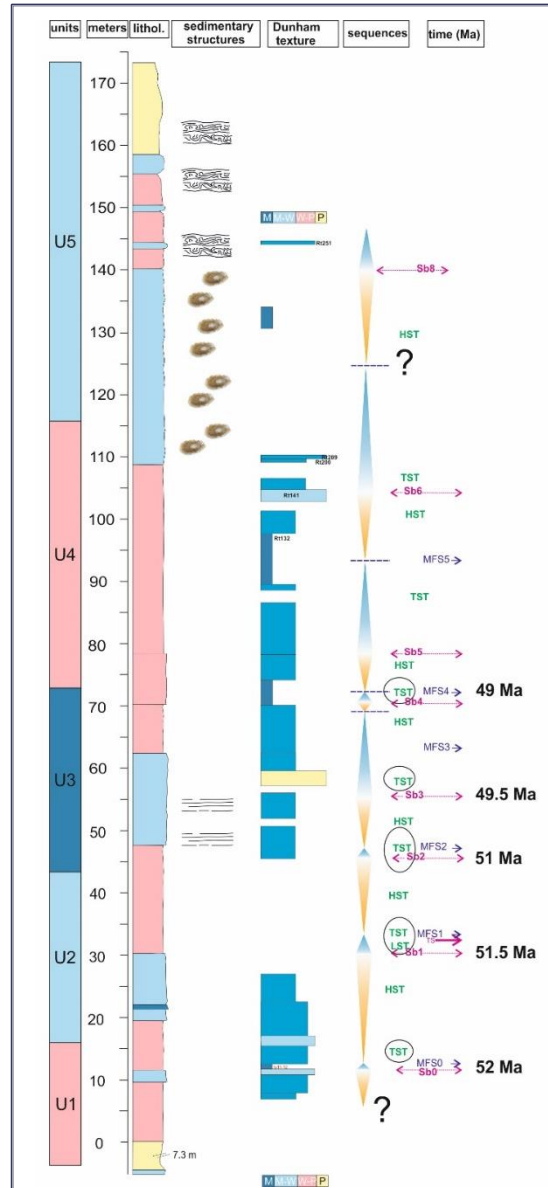
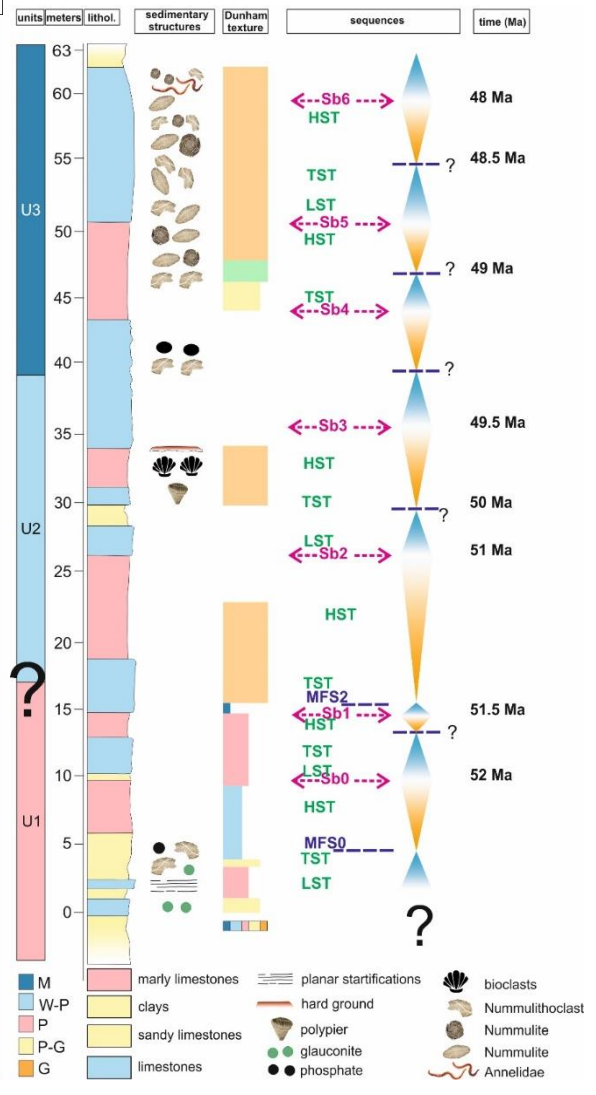
# Paper 1

# Paper 2

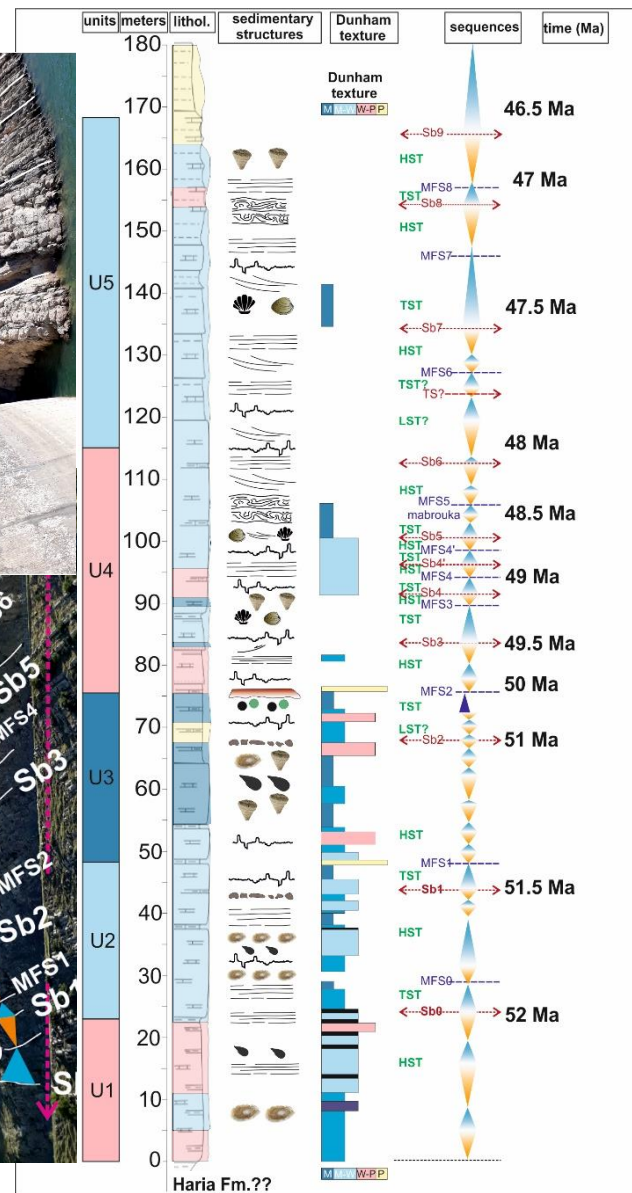
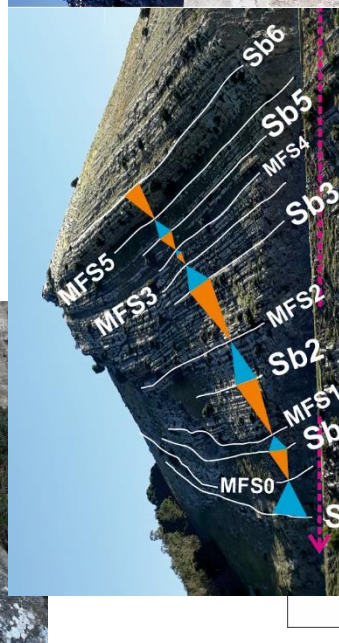
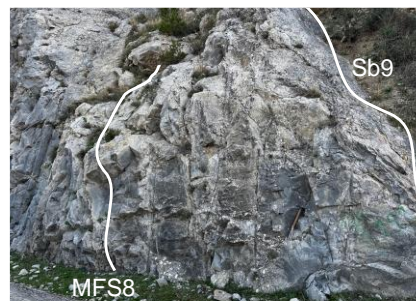
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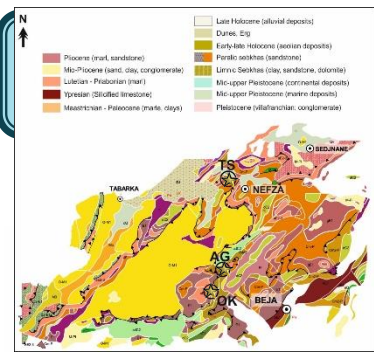
# Perspectives

## Sedimentology and sequence stratigraphy



**Sedimentology and sequence stratigraphy**



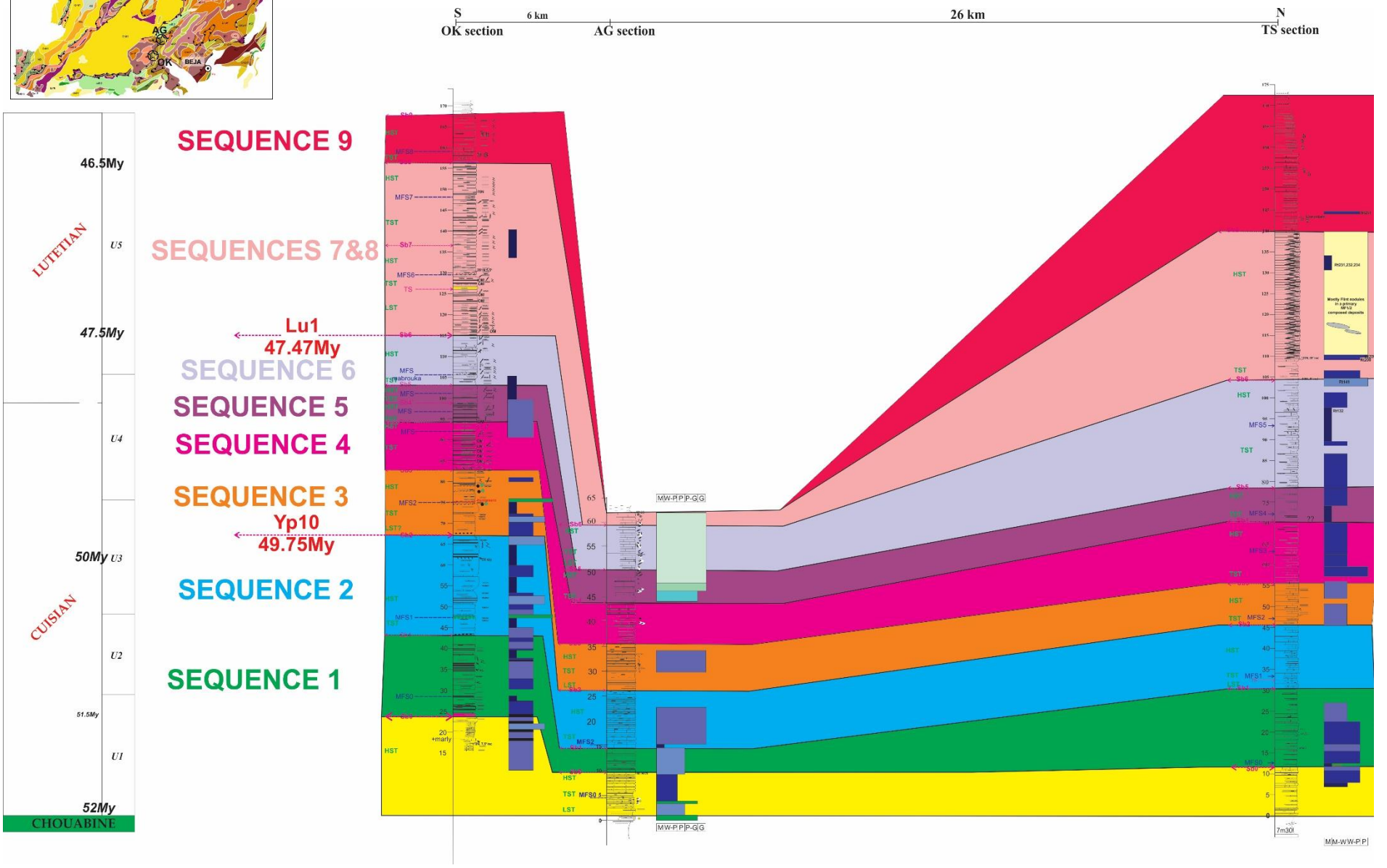


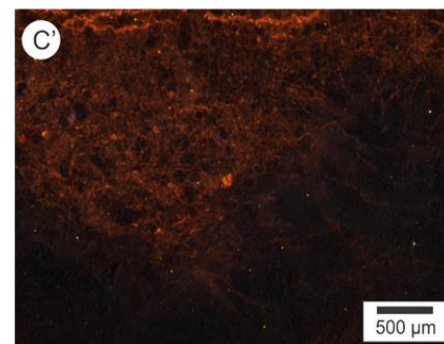
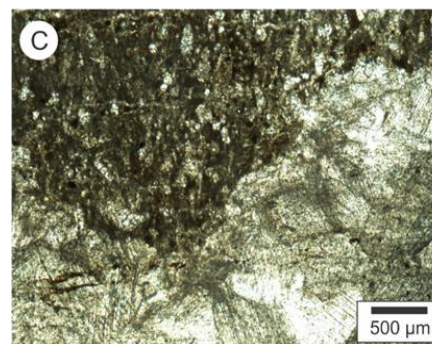
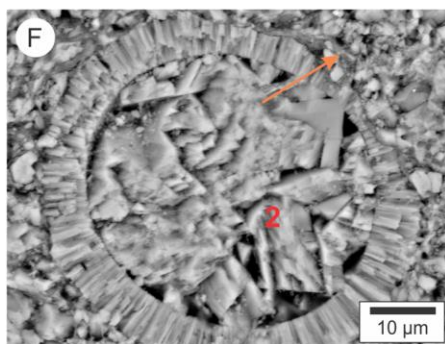
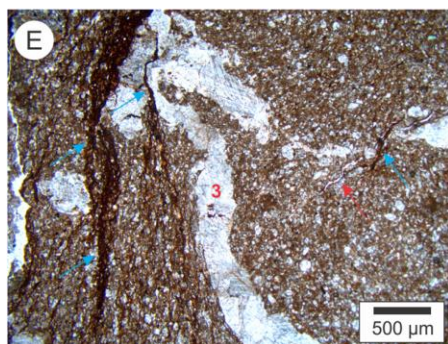
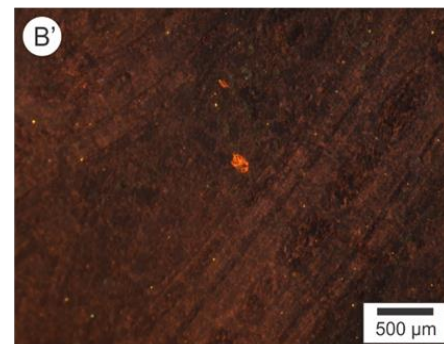
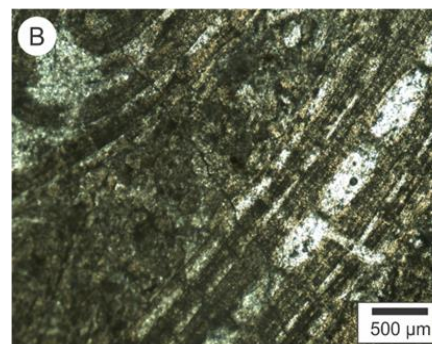
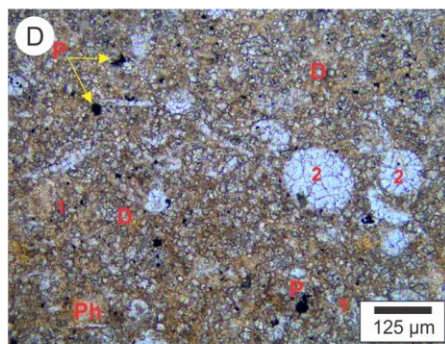
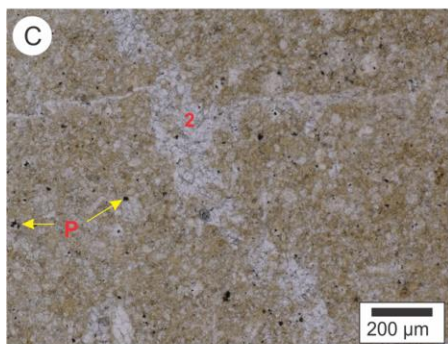
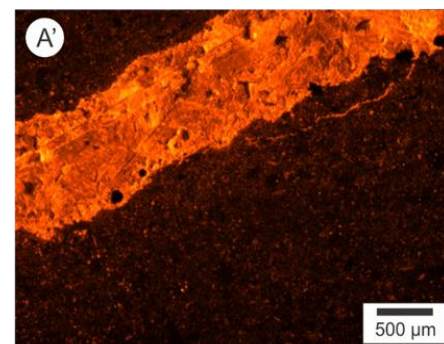
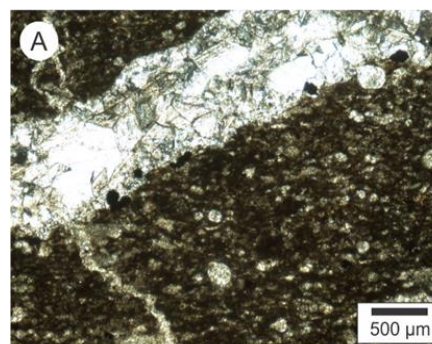
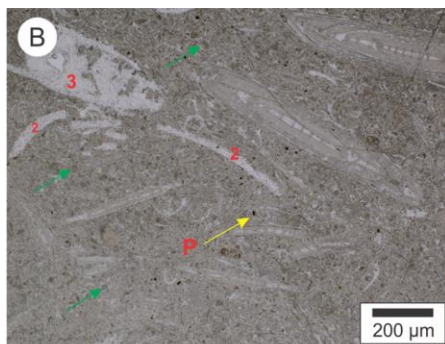
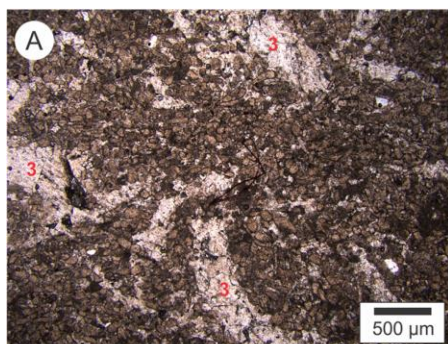
# Paper 1

# Paper 2

# Paper 3

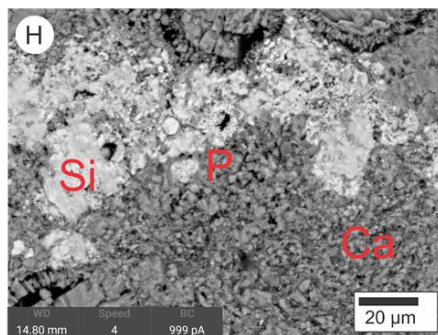
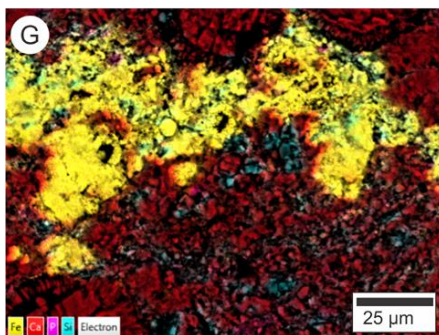
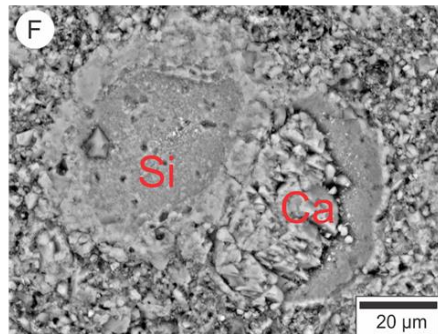
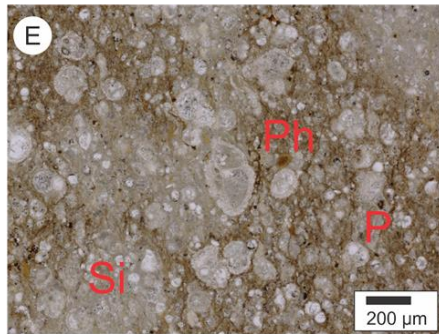
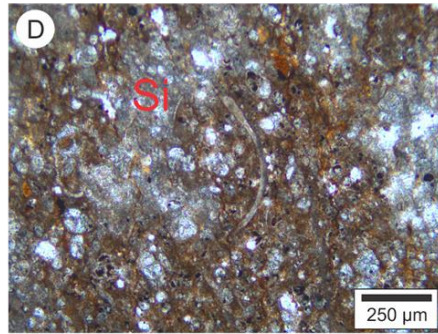
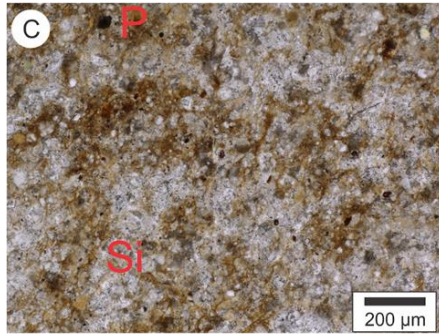
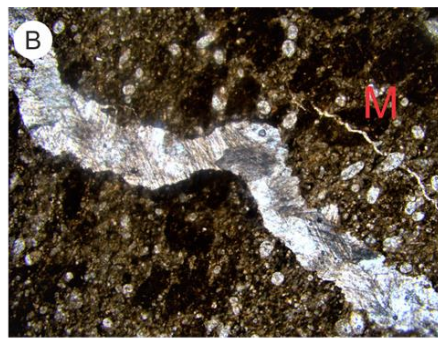
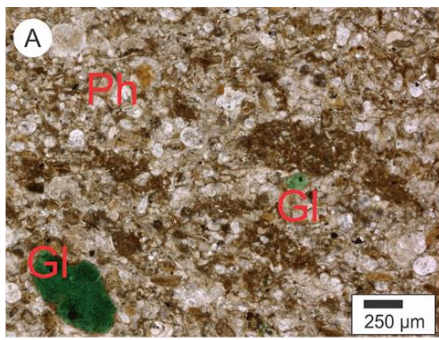
# Perspectives





A/B/C/ - Asphaltene-filled wispy dissolution seams, marked with red arrows. D/E/F - Fractures-filled with calcite cement, red - cemented fractures, blue arrows - flattened foraminiferal test due to compaction. late subsurface

Microphotographs of the same area in transmitted light and under cathodoluminescence. It shows the different diagenesis phases. A/A' - OK57, B/B' - AG31, C/C' - OK161



Photomicrographs of representative diagenetic features, Oued Kasseb and Ragoubet Tasserra fields. A/B - OK104/OK103, respectively) Micritization, Ph. C/D – OK130/ OK58, respectively) silicification, E/F – TS209 Microphotograph of the same thin section in transmitted light and under SEM showing silicification of globigerina loges. G/H - TS209 Back-scattered SEM images of silica precipitation.

## Paper 3 (Chapter 3 : Marine and Petroleum geology)

Implication of diagenesis on pores types on unconventional tight carbonate reservoir potential: case of study outcrop sections of Ypresian source rock, northwest Tunisia .

### Plan:

Introduction

Geological setting - **done**

Methods - **done**

Results **done**

Organic geochemistry-Rock-eval **done**

Mineralogical composition- **done**

Elementary composition- **done**

Discussion **In progress ...**

Reservoir potential

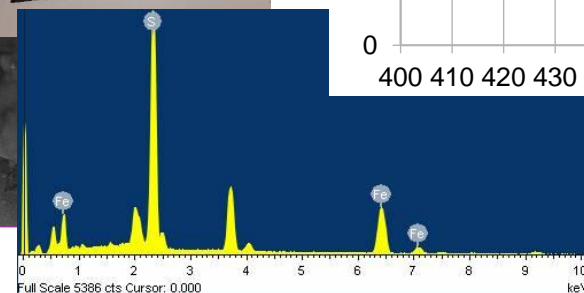
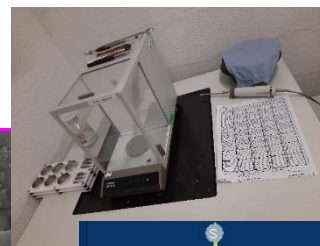
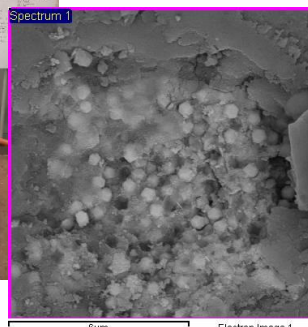
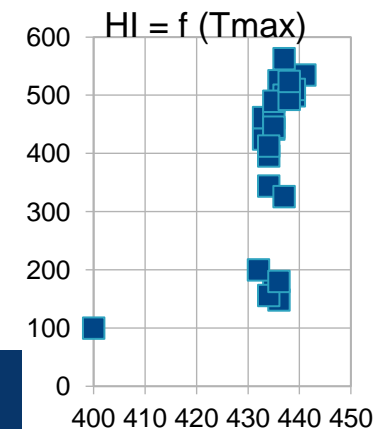
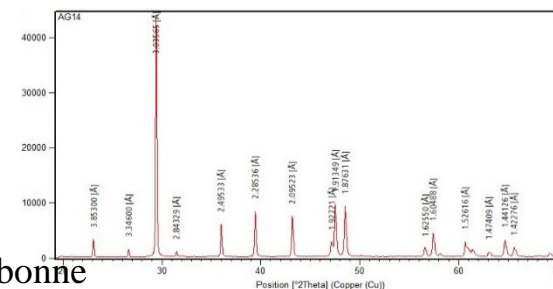
Diagenesis and 3D Pores model

Conclusion

**In progress 60%**

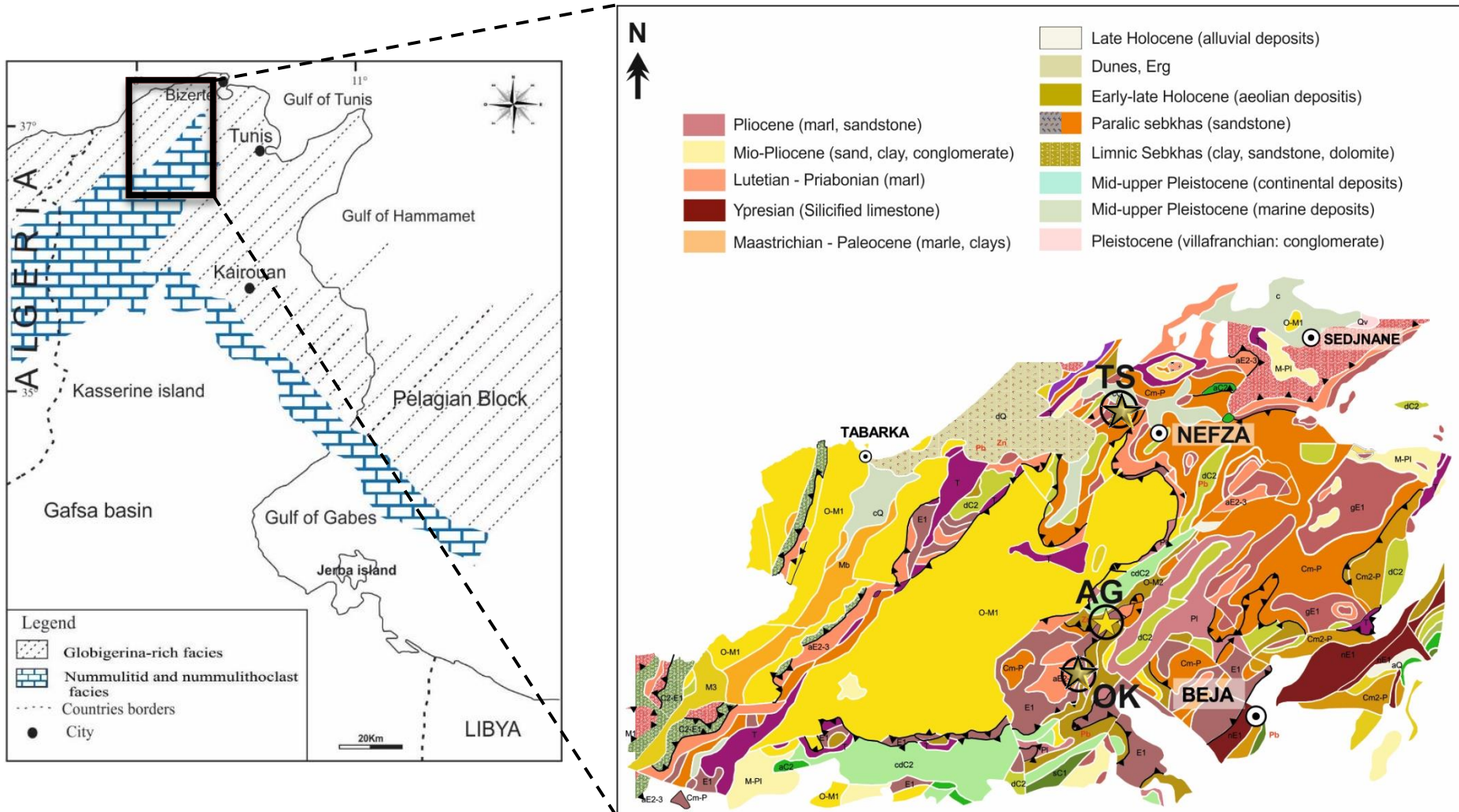
### Methodologies:

- XRD, XRF (ULiège)
- Porosity, permeability (ULiège)
- SEM: 30-31/05 – Université Sorbonne
- Rock-Eval - Université Sorbonne
- Micro CT: 07/2024 - Université de Gand



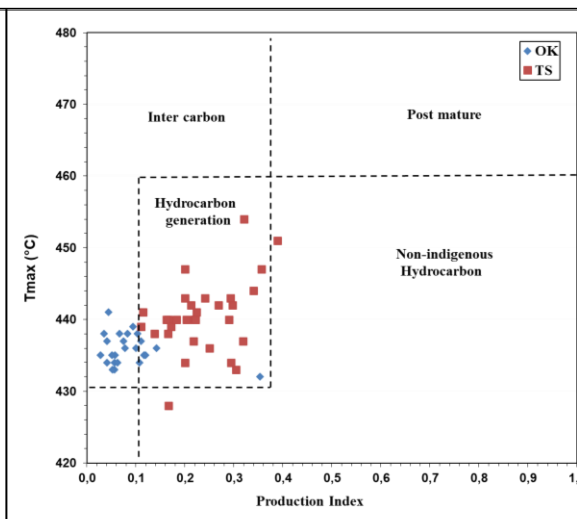
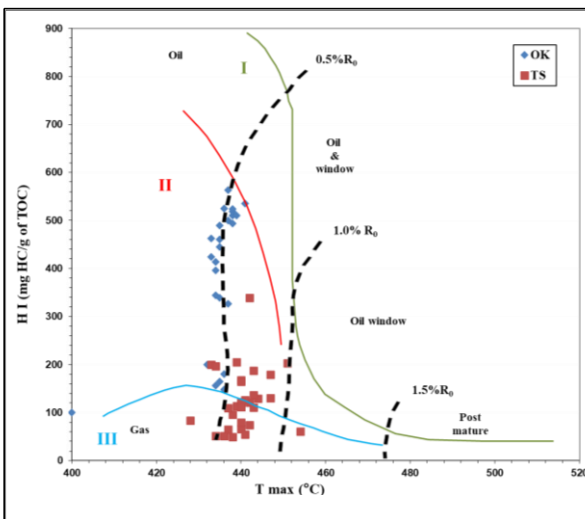
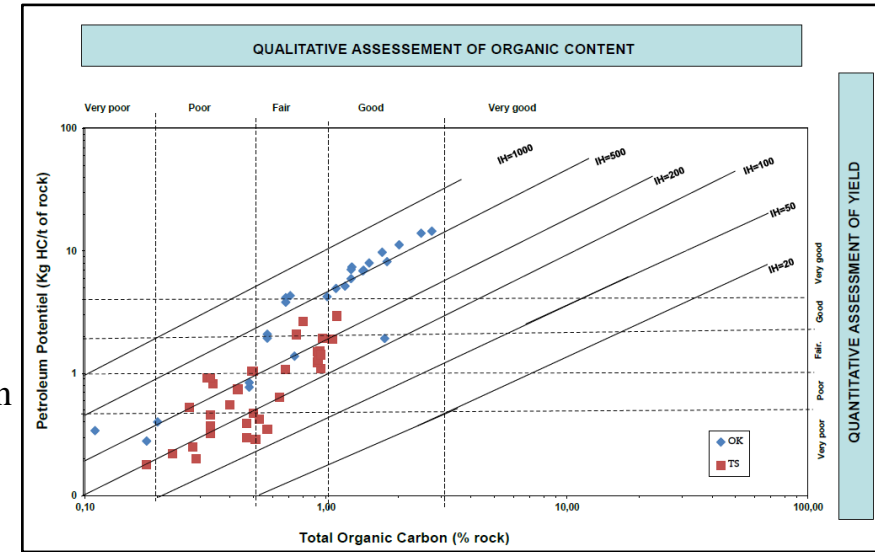
Writing time: July 2024 – August 2024

**Reminder – Study area**



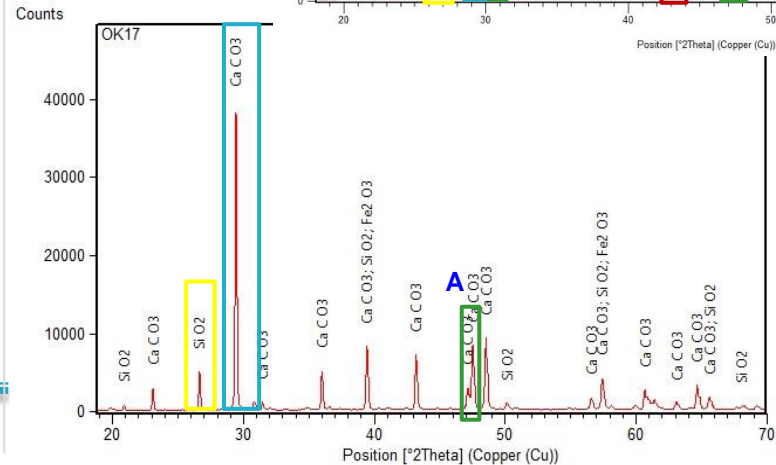
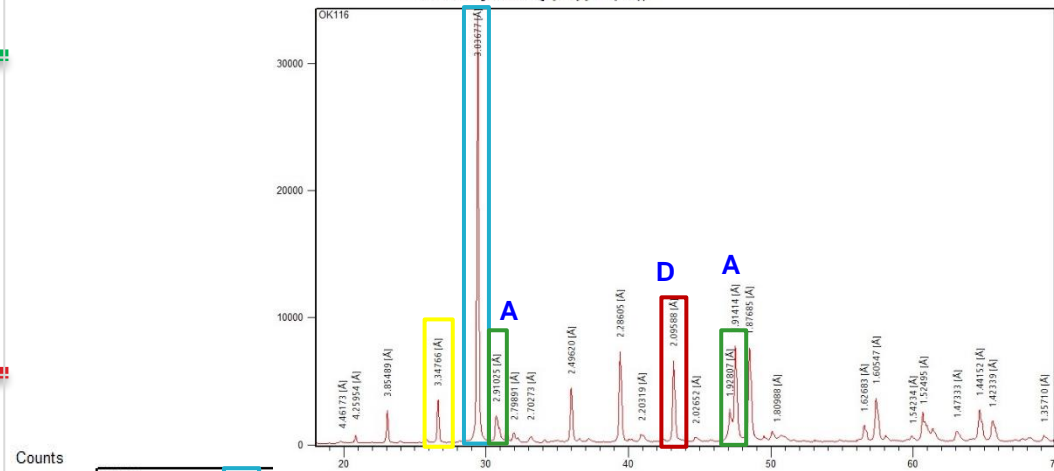
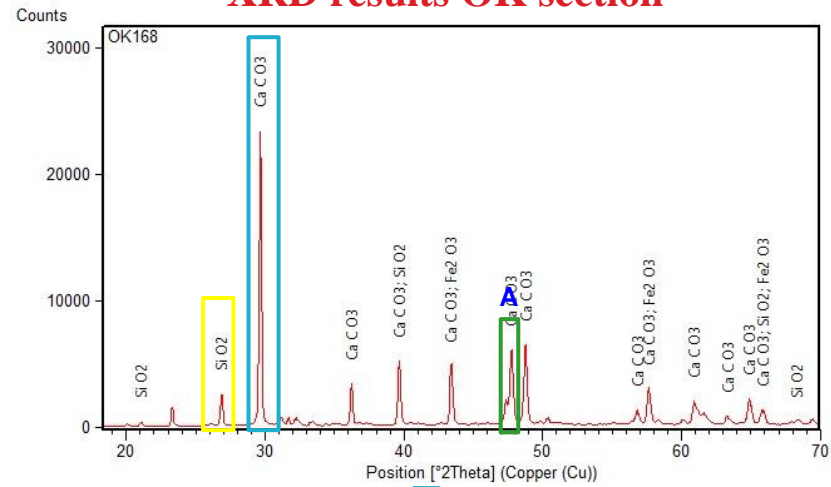
## Discussion – Geochemistry: Rock-eval results

- The TS section is slightly more mature than the OK
- mean  $T_{max}$  values:  $438^{\circ}\text{C}$  and  $435^{\circ}\text{C}$ , respectively,
- higher IP values
- Beginning of the *oil window*.
- The OM higher in OK section (3% TOC at the maximum) than in the TS section (maximum around 1%).



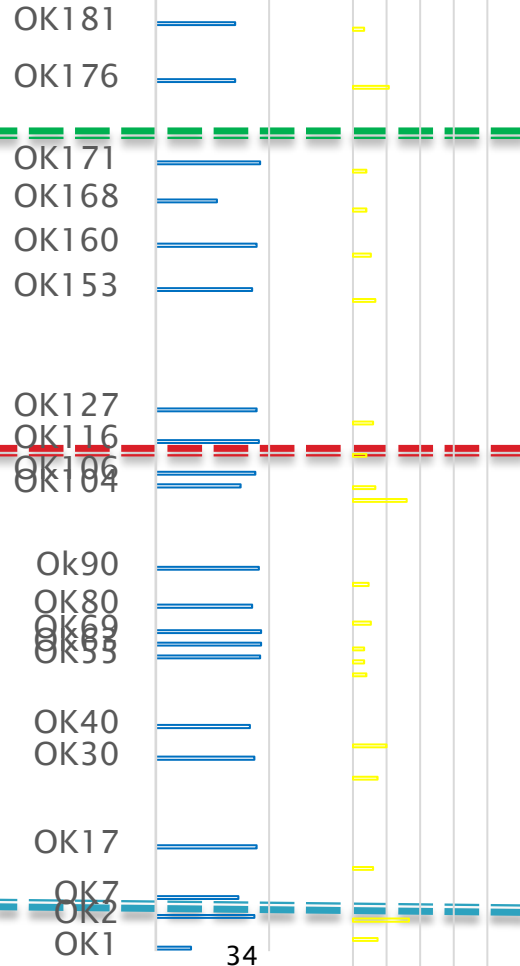
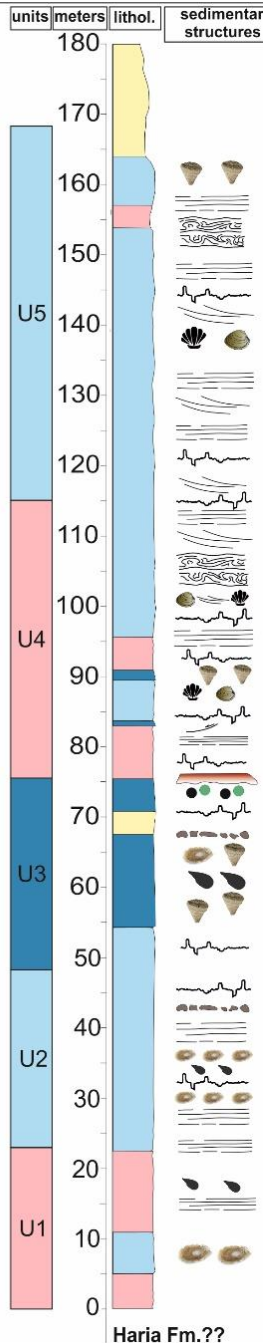
→ The OM *type II* with a clear trend of alteration when TOC and HI decrease.

# XRD results OK section



CaCO3      SiO2

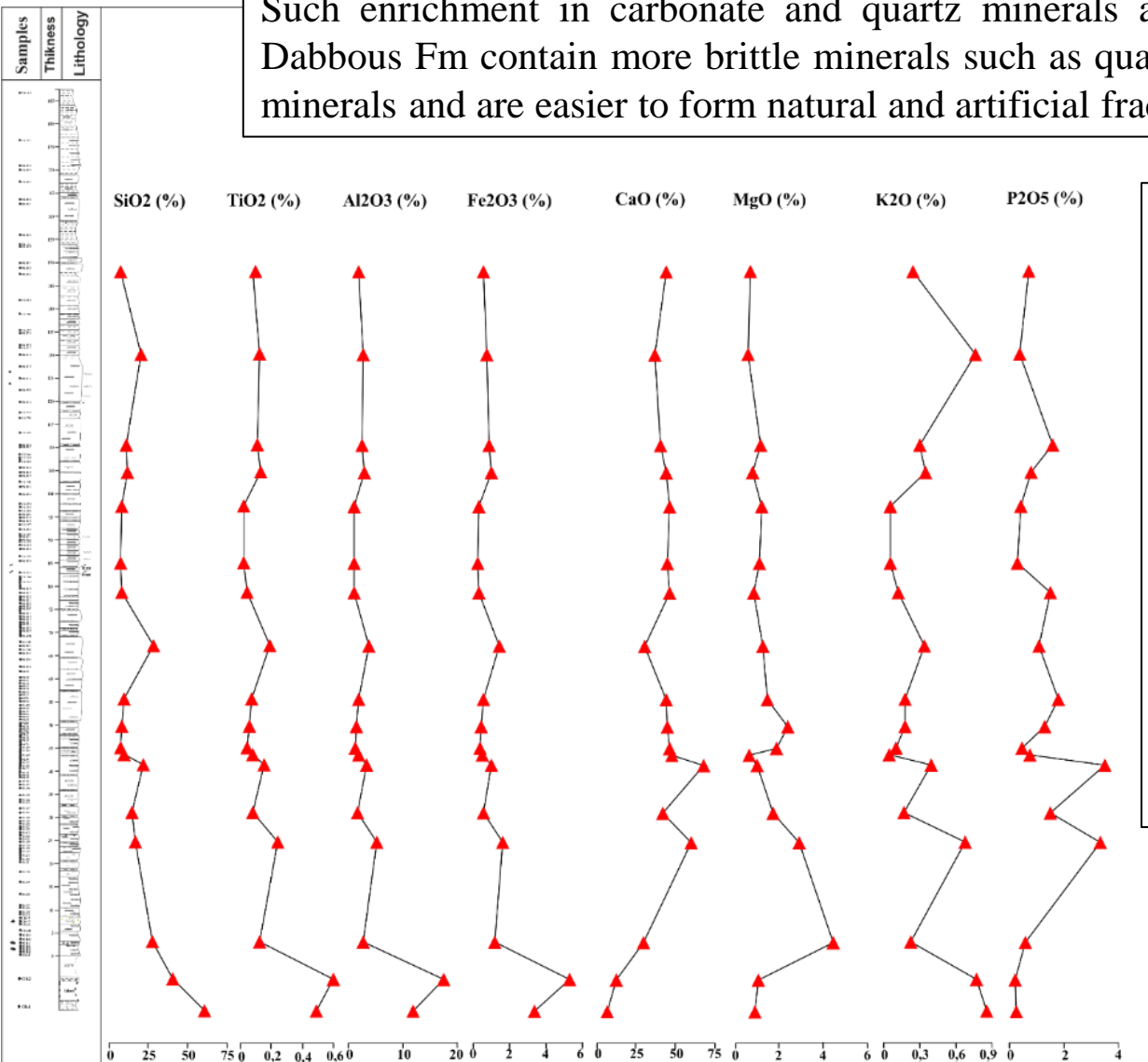
0    100    0 1 5304 56075



Haria Fm.??

## Geochemical composition XRF results – Major elements

Such enrichment in carbonate and quartz minerals are more brittle minerals. The Bou Dabbous Fm contain more brittle minerals such as quartz and carbonate compared to other minerals and are easier to form natural and artificial fractures.

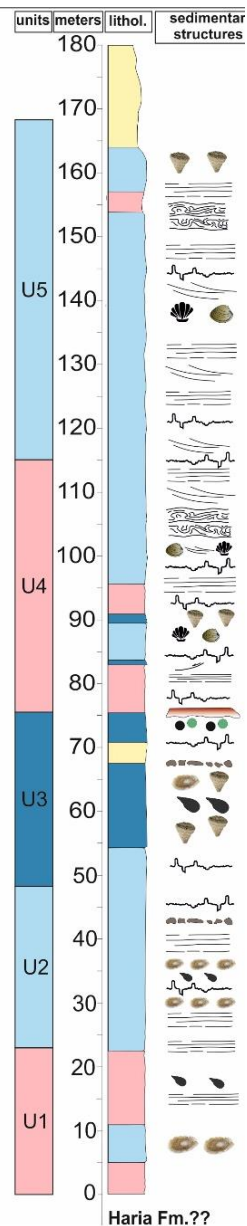


The Bou Dabbous Fm shows an abundance of CaO ranging from 30.43% to 48.10%, and contain other major elements such as :

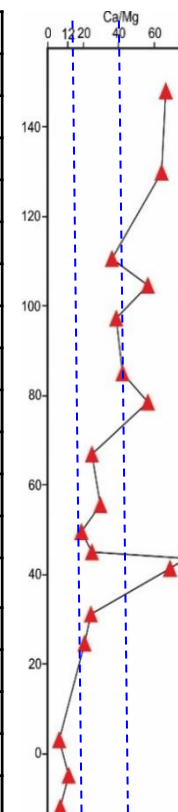
SiO<sub>2</sub> (7.38% to 29.39%),  
 MgO ( 0.60% to 4.56%),  
 P<sub>2</sub>O<sub>5</sub> (0.31% to 1.84%),  
 Al<sub>2</sub>O<sub>3</sub> (0.98% to 3.84%),  
 Fe<sub>2</sub>O<sub>3</sub> (0.27% to 1.46%),  
 TiO<sub>2</sub> (0.02% to 0.20),  
 K<sub>2</sub>O (0.06% to 0.79%).

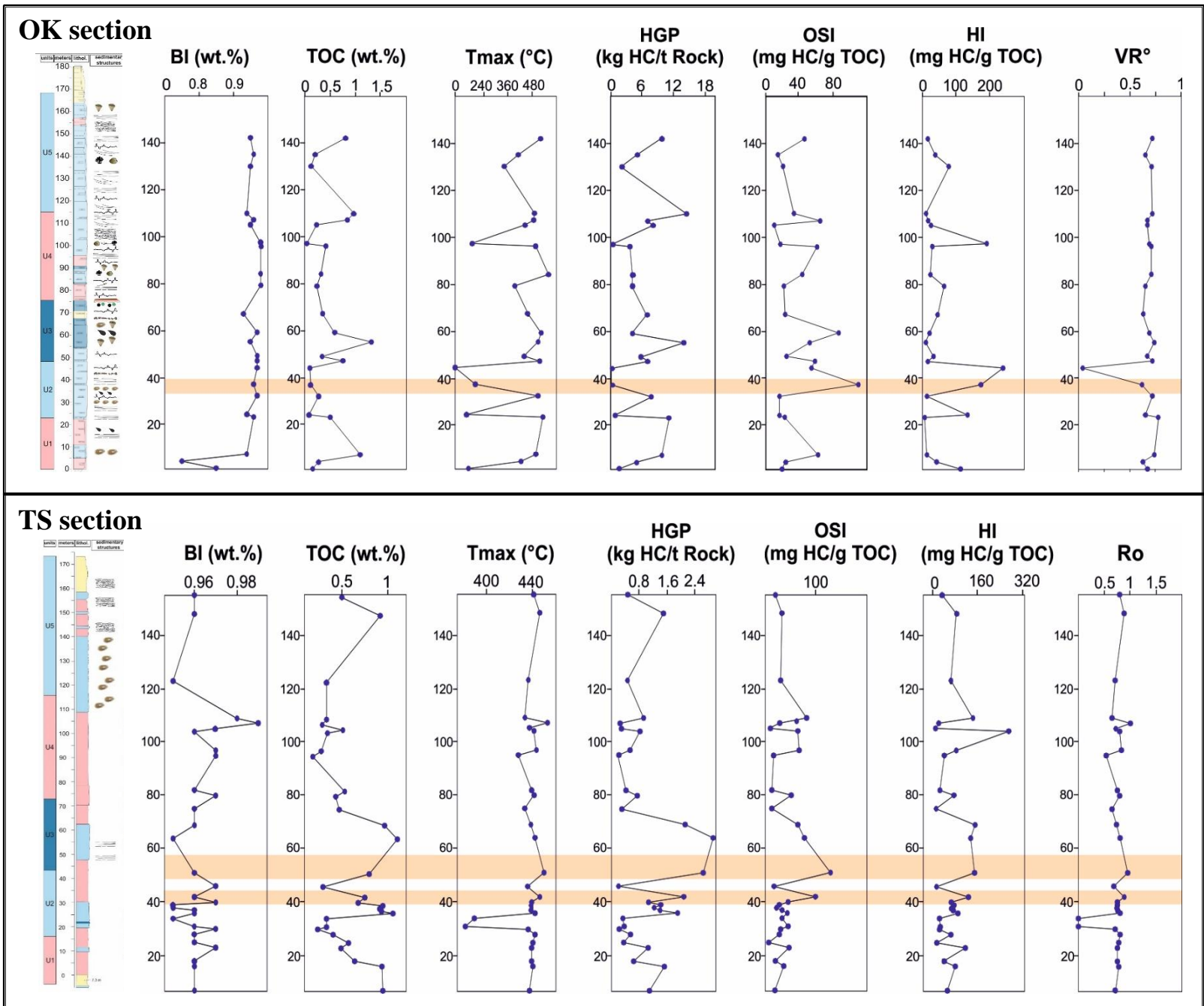
1 Dolomite (1,41-12,30)  
 8 Magnesian calcites (12,30-39)  
 7 Pure limestones (39 à 100)

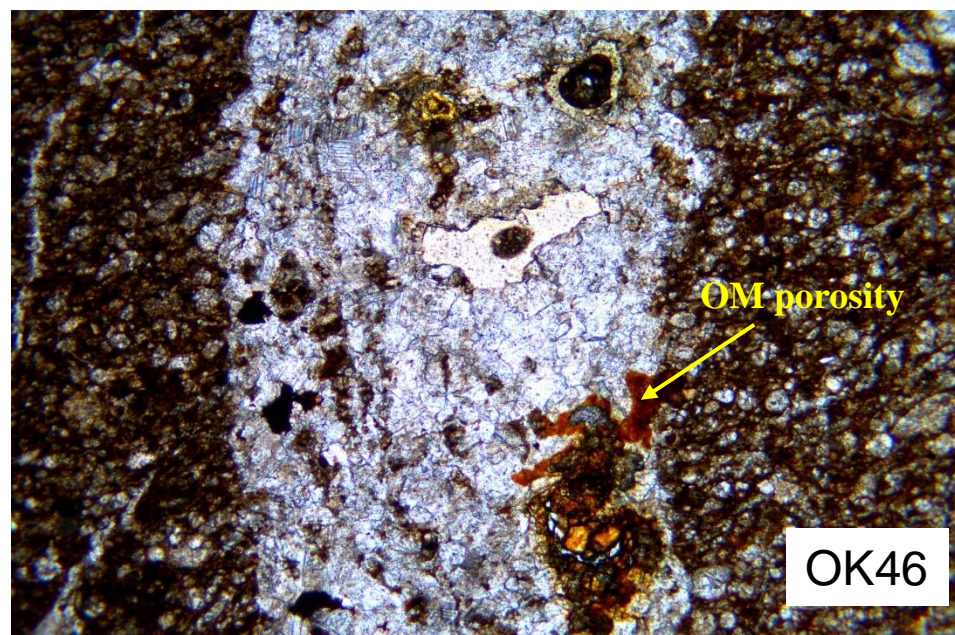
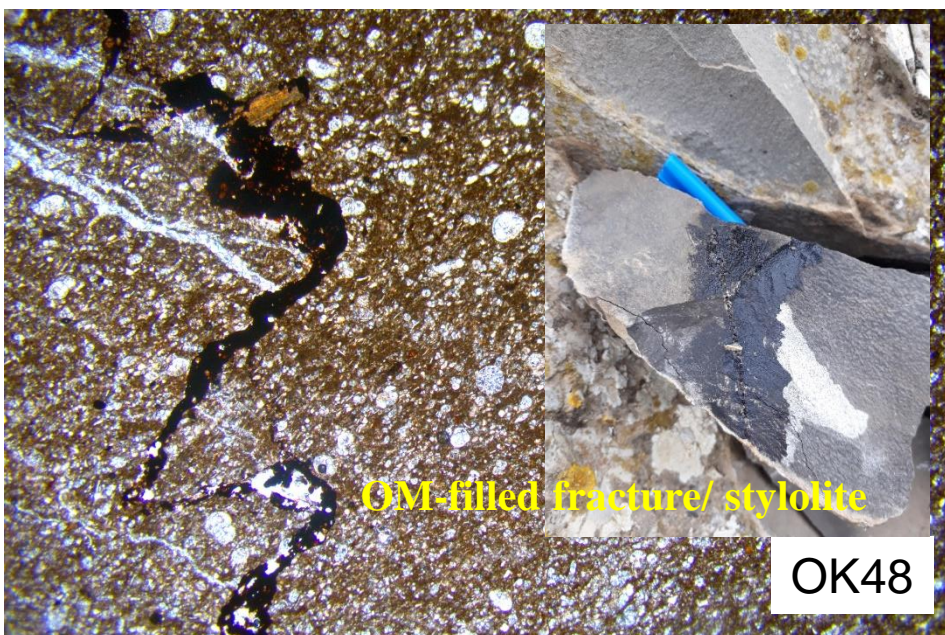
According to the shape of the S5 peaks, some levels may contain magnesian calcite or dolomite, especially those who contain higher TOC.



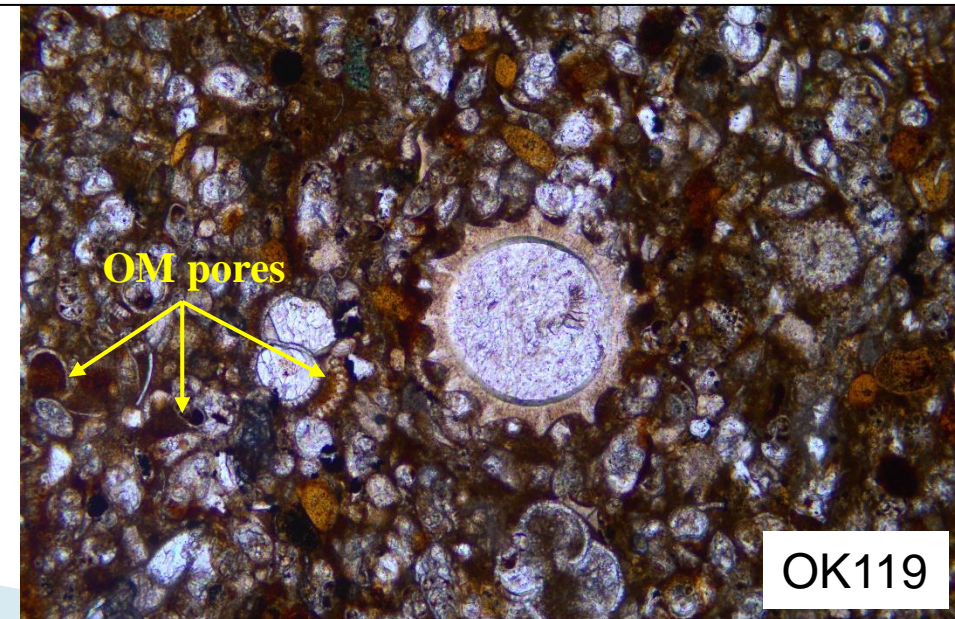
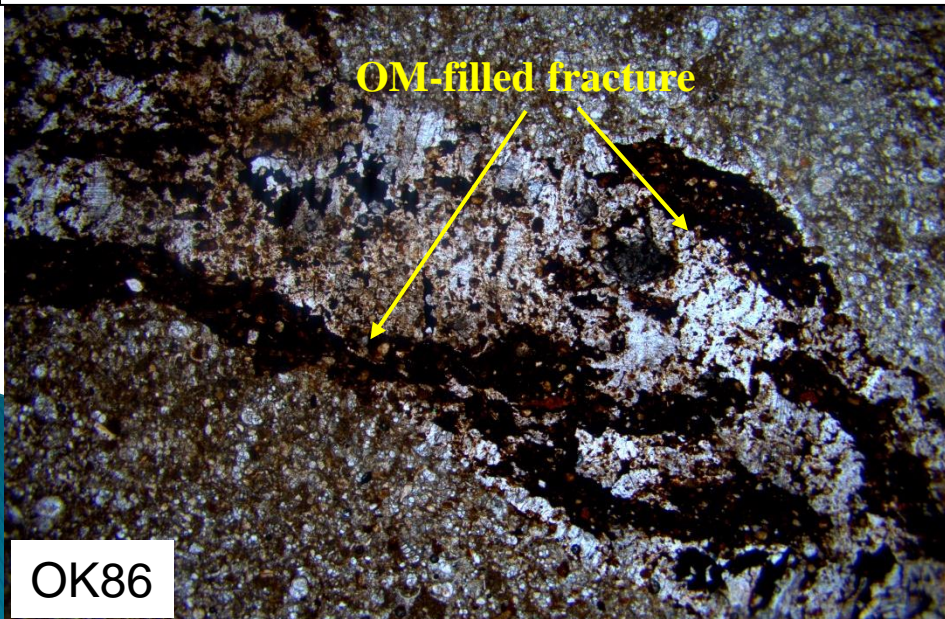
Samples	CaO	MgO	Ca/Mg	Mg/Ca	Name	TOC(%)
OK1	6,74	0,91	7,42375	0,134703	Dolomitic limestone	0,74
OK2	12,76	1,06	12,06722	0,082869	Dolomitic limestone	-
OK7	30,43	4,56	6,674276	0,149829	Dolomitic limestone	2,01
OK30	44,55	2,15	20,76163	0,048166	Magnesian limestone	1,48
OK41	42,82	1,74	24,58175	0,040681	Magnesian limestone	1,51
OK55	48,19	0,70	69,03517	0,014485	Pure limestone	-
OK63	48,17	0,62	77,98904	0,012822	Pure limestone	0,18
OK69	47,47	1,91	24,80407	0,040316	Magnesian limestone	1,28
OK80	45,86	2,44	18,82723	0,053115	Magnesian limestone	1,27
OK90	45,53	1,53	29,8395	0,033513	Magnesian limestone	2,48
OK104	31,91	1,27	25,04576	0,039927	Magnesian limestone	1,43
OK127	48,02	0,85	56,43491	0,01772	Pure limestone	1,01
OK137	47,62	1,13	42,29338	0,023644	Pure limestone	0,71
OK153	48,10	1,23	38,95999	0,025667	Magnesian limestone	0,68
OK160	44,69	0,79	56,79976	0,017606	Pure limestone	1,79
OK168	42,92	1,18	36,38864	0,027481	Magnesian limestone	2,75
OK176	38,80	0,60	64,21606	0,015572	Pure limestone	0,57
OK181	46,79	0,70	67,07155	0,014909	Pure limestone	1,71





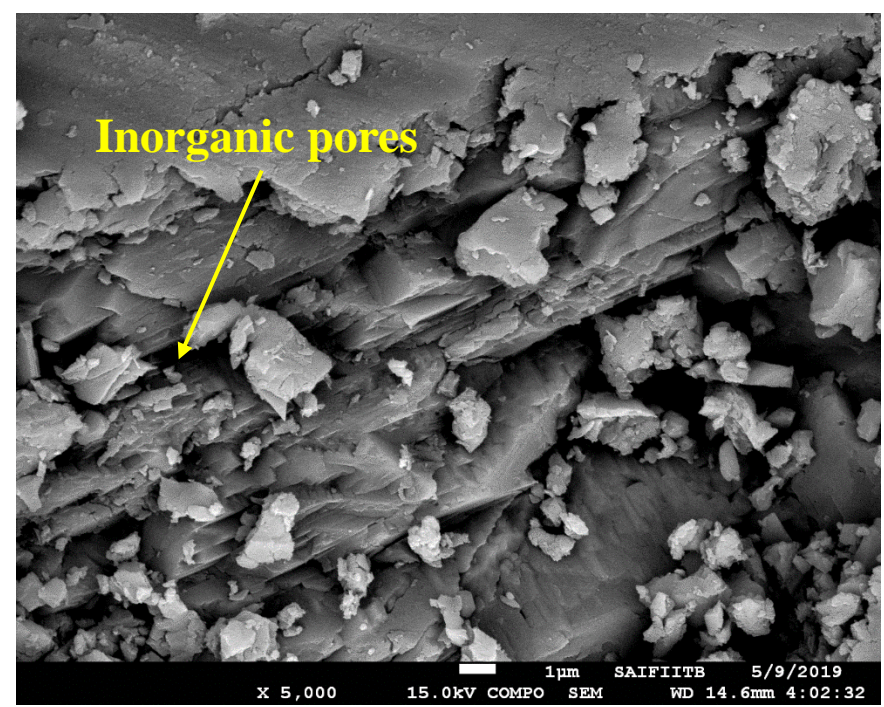
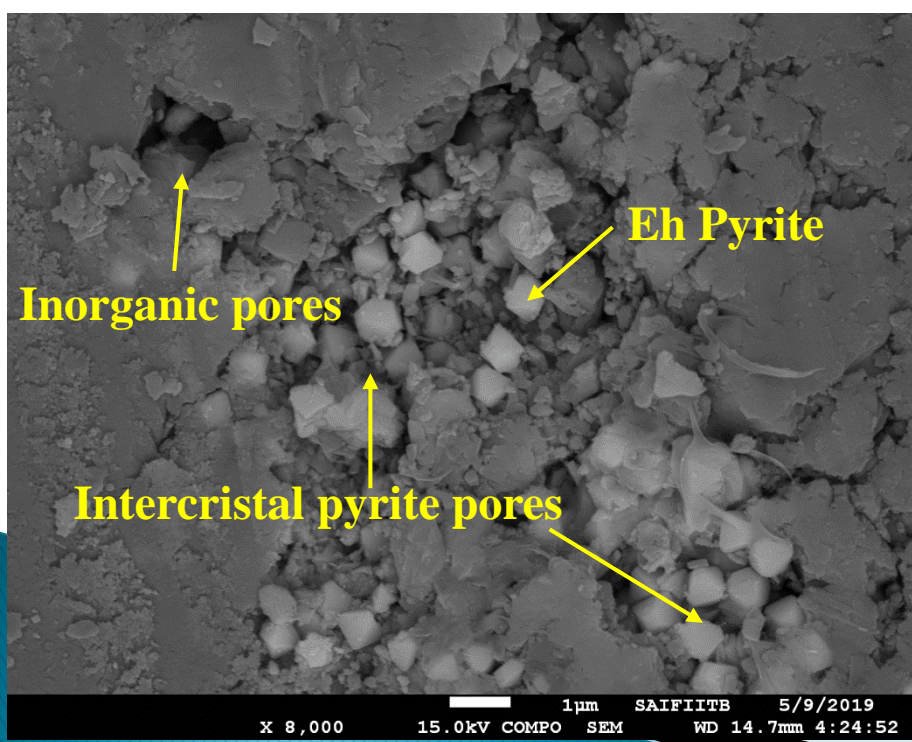
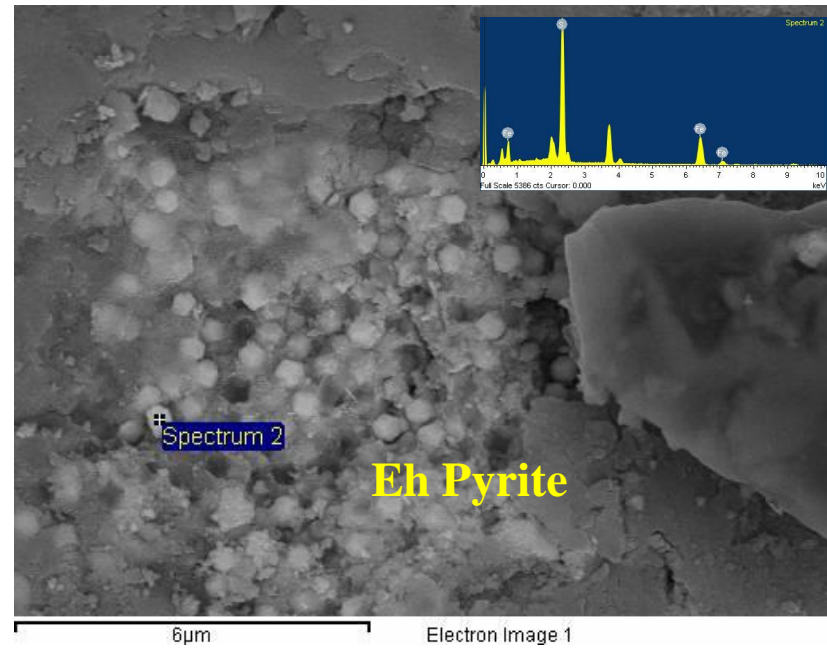


porosity types:  
secondary pores such as OM-filled fracture and dissolution of the shell fragments.  
These pores of the fractures and dissolution of the shell fragments fill with oil brown color under white light.



Correlated with the previous porosity values and the international studied tight reservoirs : the Eocene Radwany carbonate Formation (Porosity between 1.22 and 6wt %) → Bou Dabbous Fm could be considered as a tight reservoir (Porosity 1 to 10 wt %)

Significant amount of space for the storage of oil and gas is provided by intercrystalline pores present in framboidal pyrite and pores formed by intercrystalline pyrite filled with organic matter (Zhao et al., 2016; Han and Li, 2019)



***Paper 3:******Work plan***

- **Writing progression:**

- Mineralogical and chemical assessment to analyze the fracability character of the Eocene source rock (MBI).
- Organic geochemistry : interpretation of Rock-eval results and discussion of the calculated parameters (OSI, TR, VR, HGP).
- Petrophysical and petrography interpretation and correlate the pores type with the calculated parameters to determine its potential as an unconventional tight oil/gas reservoir rocks.
- 3D model of pores network based on Mico CT scans,

<u>Perspectives 2024</u>		2024							
		05	06	07	08	09	10	11	12
	Mind map								
	<u>PhD progression: Papers redaction</u>								
Part I. Geochemical and mineralogical characterizations of Silurian “Hot” shales: Implications for shale gas/oil reservoir potential in Jeffara basin-southeastern Tunisia, North Africa	Published – February 2024								
Part II. Article 2 Sedimentology, sequence stratigraphy and Diagenetic controls of the outcrops equivalent of Ypresian limestones source rock “Bou Dabbous Fm” and reservoir “El Garia Fm”, in western north of Tunisia.	Discussion of the last version								
	Paper finalisation and journal submission								
Part III. Paper 3: implication of pores structures on the unconventional tight reservoir potential: case of study outcrop section of Bou Dabbous source rock.	Figures preparation (XRF, organic geochemistry, SEM)								
	Writing the paper: result and discussion (petrophysics/mineralogy/geochemistry)								
	Paper finalisation (After Thesis defense)								
Thesis submission	Compilation of the thesis (General Introduction and conclusion)- Manuscript submission to the Jury								
<b>Thesis Defense</b>									
Full-time job	Africa Museum –Tervuren (project communication, workshop, International summer school organization, supervising students from RDC and RC, submission for project funds from NGS,.	NGS Submis		Geologica Belgica					

**MERCI POUR VOTRE ATTENTION**

