

Chemostratigraphic Characterization of Euxinic Environments as an Indicator of Good Organic Matter Preservation: The Case of the Ouatt-2X Well, Abidjan Margin, Ivorian Sedimentary Basin

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Abstract

Twenty-seven (27) samples from an offshore petroleum well in the Ivorian sedimentary basin were investigated to characterize euxinic environments using chemostratigraphic proxies and to evaluate their role in organic matter preservation within Cenomanian-Turonian sedimentary deposits. Two complementary methodological approaches were employed: (i) Rock-Eval pyrolysis, used to determine Total Organic Carbon (TOC) content and assess the source rocks' petroleum potential through the S2 parameter, and (ii) X-ray fluorescence (XRF)-based chemical analysis, used to quantify trace elements and evaluate their influence on the evolution of depositional paleoenvironmental conditions. The results reveal significant enrichment in trace elements such as uranium, vanadium, copper, nickel, and molybdenum, indicating anoxic to euxinic conditions throughout the studied interval. The intensity of these reducing conditions is greatest at the base of the section and generally decreases upward, punctuated by a distinct re-oxygenation episode, here identified as a separate megasequence. Among the trace elements identified, vanadium and molybdenum emerge as the most robust redox indicators, whereas nickel and, to a lesser extent, copper, carry a dual signal reflecting both redox conditions and biological productivity. The intervals displaying the highest trace-element enrichments also correspond, according to Rock-Eval data, to good-to-excellent source rocks, with TOC contents ranging from 1.49 to 4.24

wt.% and S₂ values from 2.48 to 27.49 mg HC/g rock. These results indicate that source-rock quality results from the conjunction of at least two factors: sustained primary bioproductivity and redox conditions limiting the activity of bottom-water organic-matter grazers, although basin restriction, sedimentation rate, detrital dilution, and post-depositional metal redistribution cannot be excluded as contributing controls.

Keywords

Chemostratigraphy, Cenomanian-Turonian, Trace Elements, Euxinic Conditions, Source Rocks, Organic Matter Preservation, Offshore Côte d'Ivoire Basin

1. Introduction

The preservation of organic matter (OM) in marine sediments constitutes one of the fundamental conditions of the petroleum system, upstream of hydrocarbon generation and migration [1] [2]. In modern and ancient sedimentary environments, this preservation is closely linked to the redox conditions of the water column and interstitial waters: an environment is termed anoxic when dissolved oxygen content falls below 2 ml/l of seawater [3]. When this anoxia is accompanied by the production of hydrogen sulfide (H₂S) by sulfate-reducing bacteria, the environment is termed euxinic, a term derived from the name of the Black Sea (Pontus Euxinus), the modern archetype of this type of environment [4] [5]. In such an environment, organic matter produced in the photic zone and reaching the seafloor is generally very well preserved [6] [7]. It is therefore in these zones that large quantities of OM accumulate, with contents exceeding 2%, together with a hydrogen-rich Type II kerogen [1] [2], the preferred setting for the formation of good hydrocarbon source rocks. At the geological scale, the major Oceanic Anoxic Events (OAEs), notably OAE2 at the Cenomanian/Turonian boundary (~93.9 Ma), thus generated some of the most important source rocks of the Cretaceous [8]-[10].

The chemostratigraphic characterization of these euxinic environments relies on the analysis of trace and major elements, whose distribution in sediments faithfully records past redox variations. Elements such as molybdenum (Mo), vanadium (V), uranium (U), nickel (Ni), copper (Cu), and zinc (Zn) are particularly sensitive to redox changes and become selectively enriched in sediments deposited under anoxic to euxinic conditions [7] [11]. Elemental ratios such as Mo/Al, V/Cr, Ni/Co, U/Th, together with the enrichment index (EI), constitute robust geochemical proxies, validated on a global scale, that allow redox paleoenvironments to be reconstructed with fine stratigraphic precision [12]-[14].

The Côte d'Ivoire sedimentary basin originated from the breakup of Gondwana, which separated the African and South American continents during the opening of the Equatorial Atlantic approximately 106 million years ago [15]. Since then, numerous studies have progressively enriched the geological knowledge of

this basin. On the geodynamic and structural level, the work of [16] and [17] has clarified the successive phases of emplacement of the Ivorian transform margin. On the stratigraphic level, studies by [18]-[24] have progressively enriched the understanding of the basin's lithostratigraphy, biostratigraphy, palynostratigraphy, and sequence stratigraphy.

However, despite this growing scientific momentum, the chemostratigraphic dimension of the Ivorian basin remains very poorly explored in the published literature. The few studies addressing OM preservation conditions, notably [19] [23], and [25], have highlighted significant OM accumulations at certain stratigraphic levels, correlated with hydrocarbon production currently under exploitation. However, these works did not carry out a systematic analysis of the trace elements indicative of euxinic conditions, leaving unanswered the question of the precise geochemical mechanisms governing these accumulations.

It is within this scientific context that the OUATT-2X well, located at coordinates 5°1'46.88"N 4°40'42.00"W on the so-called Abidjan margin (**Figure 1**), was selected for the present study. Analysis of chemical element composition of its stratigraphic succession aims to characterize the chemostratigraphic signatures of euxinic environments [7] [11] in the Ivorian sedimentary basin, in order to understand the extent to which these redox conditions controlled the accumulation and preservation of hydrocarbon-generating organic matter within the Cenomanian-Turonian interval.

2. Material and Methods

2.1. Study Material

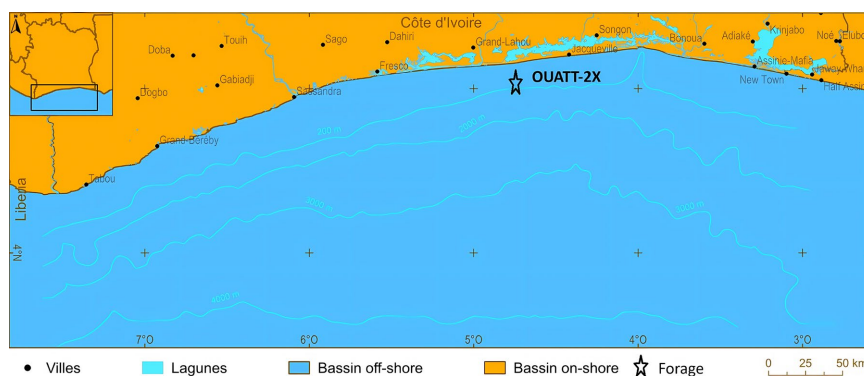


Figure 1. Location map of the OUATT-2X well in the Ivorian sedimentary basin. Base map produced by Dr. Soro Petanki and published by PETROCI (Société Nationale d'Opérations Pétrolières de la Côte d'Ivoire), publicly available at <https://www.petroci.ci/article-detail/22/44/production> (accessed 19 August 2026). The map was georeferenced and edited by the authors using QGIS 3.44.11.

The study material comes from the core repository of the Analysis and Research Center (DCAR) laboratory of PETROCI (the national oil operations company of Côte d'Ivoire). It consists of core and cuttings samples collected from the OUATT-2X well, located on the offshore Abidjan margin. Samples were selected to cover

the Cenomanian-Turonian interval with sufficient vertical resolution to detect chemical variations associated with anoxic episodes [7] [11].

2.2. Sample Preparation and XRF Analysis

Sample preparation followed a standard analytical geochemistry protocol [26]-[28]: 4 g of dry sample was weighed, degreased with dichloromethane (DCM) to remove residual hydrocarbons, oven-dried (50°C, 12 h), sieved, and finely ground (agate mortar and ball-mill vibrator) to a grain size < 63 µm. The resulting powder was mixed with 1 g of organic binder (CEREOX) and pressed under ~15 tons to form 33 mm-diameter pellets.

Major and trace element concentrations were measured using an energy-dispersive X-ray fluorescence (ED-XRF) spectrometer (SPECTRO XEPOS model), a standard non-destructive method for the geochemical analysis of sedimentary rocks [28] [29].

The targeted elements: uranium (U), vanadium (V), copper (Cu), nickel (Ni), molybdenum (Mo), chromium (Cr), cobalt (Co), were selected for their recognized sensitivity to marine redox conditions [6] [7] [30]. Aluminum (Al) was measured as a normalization element.

2.3. Analytical Quality Control

The reliability of XRF measurements was ensured through a quality control protocol applied during each analytical session, in accordance with the recommendations of [28] and [31].

Prior to each analytical session, instrument calibration was verified by analyzing a certified reference standard provided by the manufacturer (SPECTRO/AMETEK, Kleve, Germany). Certified standards were measured, and the resulting concentrations were compared against certified values; a deviation of 0.5% or less between the recorded value and the certified value was required before proceeding with sample analysis. If this criterion was not met, the instrument was recalibrated and the control standard re-analyzed prior to any sample measurements, thereby ensuring the robustness and reliability of the reported trace element concentrations.

2.4. Geochemical Proxies and Interpretation Thresholds

Paleoenvironmental interpretation relies on three complementary approaches: (1) comparison with average shale reference values, (2) classification of bottom-water oxygenation, (3) redox elemental ratios. The thresholds used in this study (Tables 1-3) constitute the single reference framework applied consistently throughout the interpretation of results (Section 3).

Table 1. Reference trace element contents in “average shales” [26], in [7].

Element	Cu	Mo	Ni	U	V	Cr
Average content (ppm)	45	1.3	68	3.7	130	90

Table 2. Classification of bottom-water oxygenation (after [3]).

Environment	Dissolved O ₂ (ml/L)	H ₂ S
Oxic	2.0 - 8.0	Absent
Dysoxic	0.2 - 2.0	Absent
Suboxic	0.0 - 0.2	Absent
Anoxic	0	Absent
Euxinic	0	Present

Table 3. Geochemical ratios and redox interpretation thresholds.

Ratio	Oxic	Dysoxic	Anoxic	Euxinic	Reference
V/Cr	<2	2 - 4.25	4.25 - 8	>8	[12]
Ni/Co	<5	5 - 7	7 - 15	>15	[12]
V/(V + Ni)	<0.46	0.46 - 0.60	0.60 - 0.84	>0.84	[32]
Mo/Al ($\times 10^{-4}$)	<0.1	0.1 - 0.5	0.5 - 2.0	>2.0	[7]

2.5. Aluminum Normalization

Trace element contents were normalized to aluminum (Mo/Al, U/Al, V/Al, Ni/Al, Cu/Al, in $\times 10^{-4}$ g/g) to correct for dilution effects from carbonate phases and the detrital fraction [7] [33]. Aluminum constitutes an excellent proxy for the detrital aluminosilicate fraction, being little affected by diagenesis and redox variations, and allows inter-well comparison with published data [6] [11].

2.6. Chemostratigraphic Processing

Profiles of elemental concentrations and normalized ratios were plotted against depth, enabling a continuous chemostratigraphic visualization of the sedimentary succession [6]. The identification of chemostratigraphic megasequences, sequences, and packages relies on the detection of trend breaks and enrichment anomalies, interpreted as reflecting variations in redox conditions at the water-sediment interface [7] [13]. This principle rests on the fact that changes in seawater chemistry constitute the primary signal of any environmental perturbation, preceding its biological and sedimentary record [5] [10]. A megasequence thus corresponds to a package of sediments whose depositional environment remained under the influence of a coherent regime of enrichment or depletion in redox-sensitive trace elements.

3. Results

3.1. Analysis of Absolute Concentrations

The results for total organic carbon (TOC), petroleum potential (S₂), and biostratigraphic ages were the subject of an earlier publication [23]. The XRF analysis of the medium grey marly sediments of the OUATT-2x well, complemented by the HI, TOC, and S₂ parameters, is presented in **Table 4**.

Table 4. Absolute concentrations (ppm) of trace elements obtained in the OUATT-2x well.

Depth (m)	U	V	Cu	Ni	Mo	Co	Al	Cr
Average reference value (ppm)	3.7	130	45	68	1.3	19	8.89	90
2247	6.1	141.2	54.3	90.8	11.6	22.8	14.71	158.6
2256	5.9	312.4	51.6	86.2	11.3	27.9	14.71	156.4
2262	6.4	511.6	60.6	114.4	28.8	30.5	14.37	93.7
2268	3.6	420	53.2	83.7	3.6	28.9	14.18	125
2273	5.1	115	54.8	82.4	3.5	34.6	13.81	84.2
2278	5	126.1	51.4	100	20.7	13.3	13.03	99.6
2285	9.6	172.6	55.6	123.4	52.7	30	10.61	33.8
2290	8.3	248	57.6	106.7	25.8	25.8	11.65	88
2295	7.8	403.7	51.9	110.6	25.6	32	12.07	108.3
2300	3.2	430	42.7	71.3	3.8	22.5	12.63	109.4
2305	3.7	462.9	50.2	88.1	13.8	29.9	11.56	48.8
2310	2.7	34.7	48.4	76.6	3.7	23.5	12.26	75.9
2315	3.5	50	46	72.4	3.2	24.5	12.37	85.4
2320	3.4	60	45.1	72.9	5.4	25.3	12.22	92.2
2325	7	63	48.5	91.6	18.1	23.5	11.16	69.4
2330	5.5	206	47.1	83.4	17.2	24.3	11.36	83.8
2335	4.2	251	41.1	74.5	16.6	9.5	9.536	17.9
2340	4.9	476.8	51.3	86	24.2	26.9	10	74.5
2345	8.6	296.2	56.2	95.6	31.3	19.1	8.631	61
2350	4.3	256.5	53	85.4	34.7	30.7	5.028	23.9
2355	4.7	737	72.4	102.2	39.4	19	5.831	42
2360	4.9	422.7	63	86.5	38.1	10.6	4.929	41
2365	7.1	598.7	60.1	100.2	42.2	10.3	5.819	40.9
2370	3.6	251.8	63.5	84.1	29.6	18	5.878	50.1
2377	6.5	404.5	56	88	41.6	12.3	4.886	28
2385	6.2	831	50.1	82.2	35.4	13.8	4.72	40.3
2390	5.8	1113	77	124.5	47.4	15.4	7.214	49.6

Uranium (**Figure 2**) fluctuates between 4.2 and 8.6 ppm in the 2390 - 2335 m interval (with the exception of the 2370 m level, at 3.6 ppm), then between 5 and 9.6 ppm between 2295 and 2247 m (with the exception of the 2268 m level, at 3.6 ppm); the remaining levels record concentrations below the reference value (3.7 ppm). Uranium is a good marker of anoxic conditions: soluble under oxic conditions, it becomes less soluble under anoxic and suboxic environments, favoring its adsorption onto organic matter and mineral phases [34]. Since its concentration

does not require the presence of free H_2S , enrichment in U alone only indicates anoxia not necessarily accompanied by sulfidation. The alternation observed thus reflects a long period of anoxia punctuated by episodes of better oxygenation.

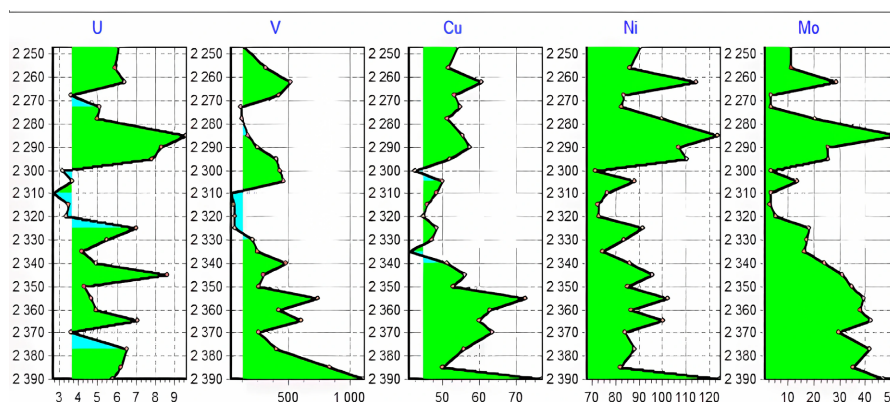


Figure 2. Trace element absolute concentration curves as a function of depth, with average shale reference threshold values [26].

Vanadium (Figure 2) displays, over almost the entire interval (2390 - 2330 m, 2305 - 2285 m, 2268 - 2262 m), contents ranging from 141.2 to 1113 ppm, well above the reference value (130 ppm), signaling an anoxic to euxinic paleoenvironment. These contents are higher at the base than at the top, reflecting a progressive attenuation of redox intensity from the base to the top of the interval. A clear drop below the threshold is observed between 2325 and 2310 m, as well as occasionally between 2278 and 2273 m, marking episodes of better bottom-water oxygenation within the overall reducing regime.

Copper varies between 41.1 and 77 ppm; the majority of values exceed the reference threshold [27], consistent with deposition under reducing bottom waters. Two levels (2335 and 2300 m, at 41.1 and 42.7 ppm) remain below the threshold and suggest occasionally better oxygenation.

Nickel varies from 71.3 to 124.5 ppm over the entire interval, systematically above the reference threshold (68 ppm). This constant elevation, unlike V and Mo, whose enrichment fluctuates markedly suggests that the Ni signal reflects less the redox variations themselves than sustained bioproductivity throughout deposition, as many phytoplankton enzymes are Ni-dependent [35]; this interpretation is consistent with the good preservation of organic matter observed across the entire profile [36].

Molybdenum records values well above the reference threshold (1.3 ppm) throughout the interval, with an average of 23.3 ppm, *i.e.* an average enrichment factor of about 18-fold. Since molybdenum is the element whose authigenic sequestration depends most closely on the presence of free H_2S in the water column [7] [11], this sustained enrichment constitutes the most direct indication of the euxinic rather than simply anoxic character of a large part of the studied interval, consistent with the presence of framboidal pyrite reported by [22] in these same sediments.

In summary, vanadium and uranium become enriched as soon as moderate to strong reducing conditions are established, whereas molybdenum only becomes strongly enriched under fully euxinic conditions; nickel, for its part, carries a signal dominated by bioproductivity. Taken together, these observations indicate a deposit that was initially euxinic, evolving towards anoxic conditions interspersed with a few episodes of better oxygenation.

3.2. Analysis of Geochemical Ratios

In accordance with the thresholds of **Table 3**, the V/Cr ratio exceeds the euxinic value (>8) in the basal interval 2390 - 2330 m as well as at the 2305 m level (**Figure 3**), with values ranging from 9.49 to 22.44 (**Table 5**). The rest of the interval lies mostly in the dysoxic to anoxic domain (2 - 8), with the exception of occasionally oxic values (<2) between 2325 and 2310 m and at the 2247 m level. This distribution confirms that full euxinia, in the strict sense of the V/Cr proxy, is concentrated in the basal part of the series.

Table 5. Variation of geochemical ratios as a function of depth in the OUATT-2x well.

Depth (m)	V/Cr	Ni/Co	V/(V + Ni)	V/Ni
2247	0.89	3.98	0.61	1.56
2256	2	3.09	0.78	3.62
2262	5.46	3.75	0.82	4.47
2268	3.36	2.9	0.83	5.02
2273	1.37	2.38	0.58	1.4
2278	1.27	7.52	0.56	1.26
2285	5.11	4.11	0.58	1.4
2290	2.82	4.14	0.7	2.32
2295	3.73	3.46	0.78	3.65
2300	3.93	3.17	0.86	6.03
2305	9.49	2.95	0.84	5.25
2310	0.46	3.26	0.31	0.45
2315	0.59	2.96	0.41	0.69
2320	0.65	2.88	0.45	0.82
2325	0.91	3.9	0.41	0.69
2330	2.46	3.43	0.71	2.47
2335	14.02	7.84	0.77	3.37
2340	6.4	3.2	0.85	5.54
2345	4.86	5.01	0.76	3.1
2350	10.73	2.78	0.75	3
2355	17.55	5.38	0.88	7.21
2360	10.31	8.16	0.83	4.89

Continued

2365	14.64	9.73	0.86	5.98
2370	5.03	4.67	0.75	2.99
2377	14.45	7.15	0.82	4.6
2385	20.62	5.96	0.91	10.11
2390	22.44	8.08	0.9	8.94

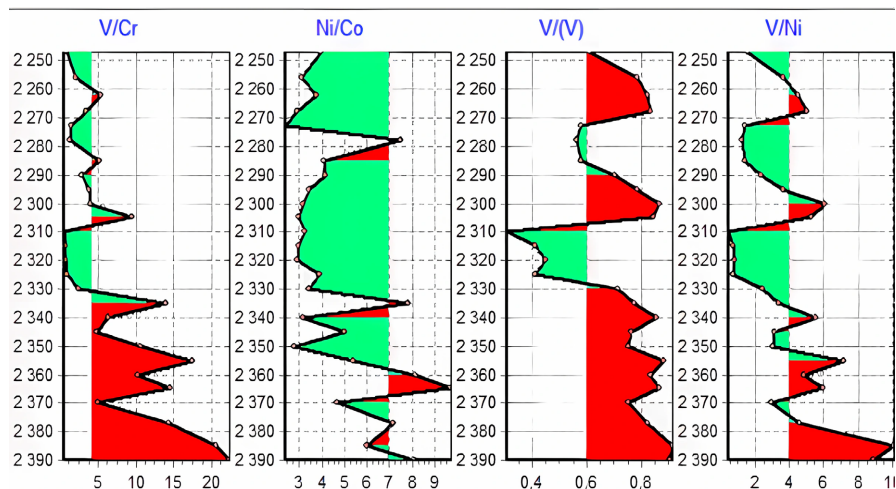


Figure 3. Geochemical ratio evolution curves as a function of depth, with the thresholds of Table 3.

The $V/(V + Ni)$ ratio exceeds the euxinic threshold (>0.84) at several levels of the basal interval (2340, 2355, 2365, 2385, 2390 m) as well as at the 2300 and 2305 m levels (Table 5), and remains within the anoxic domain (0.60 - 0.84) over most of the rest of the profile. A clear and marked drop below the oxic threshold (<0.46) is observed between 2325 and 2310 m (values from 0.31 to 0.45), configuring a well-individualized episode of clear re-oxygenation, which contrasts with the anoxic to euxinic regime dominating the rest of the series.

The Ni/Co ratio, more scattered, exceeds the dysoxic threshold (>5) inconsistently across the profile, with occasional anoxic values (7 - 15) at 2278, 2335, 2360, 2365, and 2377 m. Its greater variability compared to $V/(V + Ni)$ or V/Cr is consistent with the lower sensitivity of this proxy, already noted in the literature [12], and suggests that it should only be used in combination with other indices rather than as a standalone proxy.

3.3. Analysis of Rock-Eval Parameters

Total organic carbon (TOC) ranges from 1.49 to 4.24 wt.%, with an average of 2.80%, indicating good to excellent quantities of organic matter throughout the interval. It is notable that the progressive decrease in redox intensity from base to top is not accompanied by an equivalent drop in TOC: even at the least reducing levels, trace element concentrations remain above the reference shale values, in-

dicating that fully oxic conditions were never durably established. Organic-matter-grazing organisms thus did not have time to durably recolonize the environment, which explains the maintenance of a good level of OM preservation across the entire profile.

The hydrogen index (HI) ranges from 166 to 648 mg HC/g TOC, with an average of 428 mg HC/g TOC, corresponding to a Type II to kerogen. The highest values, characteristic of a Type I kerogen of autochthonous aquatic origin, are concentrated in the basal part of the interval (2390 - 2335 m), consistent with a confined environment with little water renewal and no significant terrigenous input.

Residual petroleum potential (S2) ranges from 2.48 to 27.49 mg HC/g rock (average 12.3 mg HC/g rock), qualified as good to excellent, with the exception of the 2315 and 2310 m levels (low to moderate potential, 2.48 and 4.25 mg HC/g rock respectively, coinciding with the re-oxygenation episode identified in III.2). The best petroleum potentials (11.95 to 27.49 mg HC/g rock) are recorded in the basal interval 2390 - 2340 m, corresponding to the most strongly euxinic zone of the series, followed by the 2300 - 2278 m interval.

In summary, the basal levels (2390 - 2335 m) record the best quantities and qualities of organic matter (Type I to II, predominantly marine in origin), within good to excellent marly source rocks.

Table 6. Aluminum-normalized trace elements and petroleum potential parameters (S2, HI, TOC) in the OUATT-2x well.

Depth (m)	U/Al	V/Al	Cu/Al	Ni/Al	Mo/Al	S2	HI	TOC (%)
2247	0.41	9.6	3.69	6.17	0.79	10.06	339	2.97
2256	0.4	21.24	3.51	5.86	0.77	8.63	294	2.93
2262	0.45	35.6	4.22	7.96	2	8.72	301	2.9
2268	0.25	29.62	3.75	5.9	0.25	12.34	347	3.56
2273	0.37	8.33	3.97	5.97	0.25	4.83	234	2.07
2278	0.38	9.68	3.94	7.67	1.59	20.5	506	4.05
2285	0.9	16.27	5.24	11.63	4.97	21.88	529	4.14
2290	0.71	21.29	4.94	9.16	2.21	11.47	361	3.18
2295	0.65	33.45	4.30	9.16	2.12	15.13	415	3.64
2300	0.25	34.05	3.38	5.65	0.3	11.23	381	2.94
2305	0.32	40.04	4.34	7.62	1.19	6.03	252	2.39
2310	0.22	2.83	3.95	6.25	0.3	4.25	216	1.97
2315	0.28	4.04	3.72	5.85	0.26	2.48	166	1.49
2320	0.28	4.91	3.69	5.97	0.44	5.35	249	2.15
2325	0.63	5.65	4.35	8.21	1.62	12.61	390	3.23
2330	0.48	18.13	4.15	7.34	1.51	8.85	353	2.51

Continued

2335	0.44	26.32	4.31	7.81	1.74	7.02	374	1.87
2340	0.49	47.68	5.13	8.6	2.42	11.95	431	2.77
2345	1	34.32	6.51	11.08	3.63	13.01	426	3.05
2350	0.86	51.01	10.54	16.98	6.9	13.57	524	2.59
2355	0.81	126.39	12.42	17.53	6.76	12.83	510	2.52
2360	0.99	85.76	12.78	17.55	7.73	12.61	536	2.35
2365	1.22	102.89	10.33	17.22	7.25	17.5	599	2.92
2370	0.61	42.84	10.8	14.31	5.04	15	597	2.51
2377	1.33	82.79	11.46	18.01	8.51	15.38	590	2.61
2385	1.31	176.06	10.61	17.42	7.5	12.89	600	2.15
2390	0.8	154.28	10.67	17.26	6.57	27.49	648	4.24

Aluminum normalization confirms the zonation established previously. The U/Al, V/Al, Cu/Al, Ni/Al, and Mo/Al ratios are systematically higher in the basal interval (2390 - 2330 m) than in the rest of the series (**Table 6**), with a Mo/Al maximum of 8.51×10^{-4} (2377 m), far above the euxinic threshold. The Cu/Al ratio drops sharply below the reference threshold during the re-oxygenation episode (2310 - 2325 m), reflecting the transient establishment of an oxic environment, while Ni/Al remains moderately enriched there, confirming that the bioproductivity signal persists independently of the bottom-water redox regime.

3.4. Chemostratigraphic Megasequences

The integration of absolute concentrations, geochemical ratios, and Rock-Eval parameters allows three (03) distinct chemostratigraphic megasequences to be individualized (**Figure 4**), the most notable being the well-circumscribed re-oxygenation episode between 2325 and 2310 m, the amplitude of which (V/(V + Ni) dropping below the oxic threshold of 0.46, Cu/Al (**Table 6**) below its reference threshold, minimum S2 of the entire series) is particularly striking.

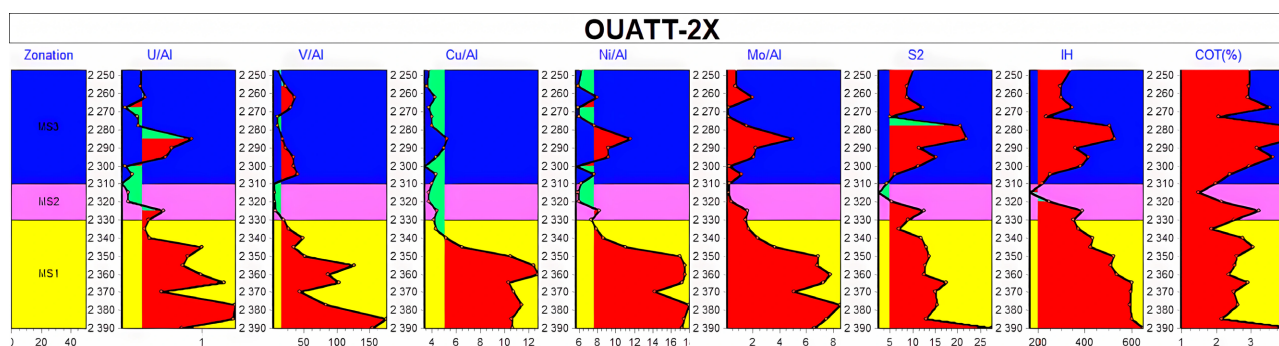


Figure 4. Al-normalized concentration curves accompanied by Rock-Eval parameters in the OUATT-2x well, with megasequence boundaries.

3.4.1. Megasequence 1 (MS1, Base: 2390 - 2330 m): Sustained Euxinic Regime

This interval records the highest absolute concentrations of U, V, Cu, Ni, and Mo of the entire series, as well as the strongest values of the V/Cr, V/(V + Ni) ratios and of the aluminum-normalized ratios, regularly exceeding the euxinic thresholds of **Table 3**. The environment is interpreted as confined, devoid of benthic grazing organisms and without significant terrigenous input, having allowed the accumulation of marine-type organic matter (Type I to II kerogen) within good to excellent source rocks (TOC up to 4.24%, S₂ up to 27.49 mg HC/g rock).

3.4.2. Megasequence 2 (MS2, Intermediate: 2325 - 2310 m): Re-Oxygenation Episode

This megasequence marks a clear break in the trend: V/(V + Ni) drops below the oxic threshold (0.31 to 0.45), V/Cr falls back below 1, and Cu/Al drops below the reference shale value, signaling the transient establishment of an oxic to dysoxic environment. This break coincides with the lowest TOC (1.49% - 2.39%), HI (166 - 252 mg HC/g TOC), and S₂ (2.48 - 5.35 mg HC/g rock) values of the entire series, confirming that even a brief interruption of bottom-water anoxia is sufficient to significantly degrade the organic matter deposited, independently of the level of primary productivity. However, an exception to this interpretation is noted within this megasequence. Indeed, the sample located at a depth of 2325 m displays anomalously high values (a TOC of 3.23%, an HI of 392 mg HC/g TOC, and an S₂ of 12.61 mg HC/g rock) more consistent with an anoxic depositional environment than with the oxic conditions attributed to this interval. This discrepancy could be explained by a time lag between the shift in redox conditions, as recorded by the geochemical proxies (V/(V + Ni), V/Cr), and its impact on organic matter and petroleum potential, which would only become apparent at a later stage. Although no major lithological change accompanies this break, the sediments remaining marls [22], the chemostratigraphic signal is sufficiently clear to represent a genuine discontinuity surface, potentially correlatable to a sequence boundary at the basin scale.

3.4.3. Megasequence 3 (MS3, Top: 2305 - 2247 m): Intermittent Anoxic-Euxinic Regime

Following the return to reducing conditions from 2305 m onward (V/(V + Ni) = 0.84; V/Cr = 9.49), this interval records a fluctuating anoxic to euxinic regime, with well-marked peaks at 2300, 2268, and 2262 m, separated by phases of lesser intensity (2285 - 2273 m). The overall intensity of anoxia remains nonetheless lower than that of MS1, consistent with the progressive attenuation of the reducing character toward the top of the Cenomanian-Turonian interval already noted in the regional literature [22] [23]. Petroleum potential remains good here (average S₂ ~11 mg HC/g rock), with a predominantly Type II kerogen, sometimes Type II/III.

3.4.4. Integrated Paleoenvironmental Interpretation

Within MS1, the concomitant enrichment in Mo and V and, to a lesser extent, in

U, indicates euxinic conditions associated with intense bacterial sulfate-reduction activity, generating free H_2S [37]-[39], in [40], which favors the preferential fixation of Mo and V in the sediments. The clear break observed in MS2 reflects a punctual but effective ventilation of the water column, before the return to a fluctuating reducing regime in MS3, where the intensity of anoxia nonetheless remains durably lower than at the base.

Across the entire profile, TOC varies between 1.49% and 4.24% (average 2.80%), consistent with conditions globally favorable to the preservation of organic matter, with bioproductivity (Ni signal) constituting an additional factor in this accumulation. The associated petroleum potential, moderate to excellent (2.48 to 27.49 mg HC/g rock, average 11.98 mg HC/g rock), confirms the interest of all of these levels as potential source rocks, with MS1 constituting the priority target.

3.5. Partial Conclusion

The enrichments observed in U and V, associated with the strong presence of Mo, indicate anoxic to strictly euxinic environmental conditions, while Ni and, to a lesser extent, Cu, reflect strong bioproductivity sustained throughout the profile. These enrichments, more pronounced at the base of the interval (MS1) than at its top (MS3), and interrupted by a clear re-oxygenation episode (MS2), sketch out a paleoenvironmental evolution in three stages rather than a simple continuous decreasing trend. The combination of these oxygen-minimum environments and good bioproductivity allowed the preservation of a good to excellent quantity of organic matter, within formations whose petroleum potential justifies the designation of source rocks.

4. Discussion

4.1. Euxinic Signature (Mo, V, U): Agreement with the Regional Literature

In the sediments of the studied interval, and more specifically within MS1, strong enrichment in Mo and V was observed, interpreted as evidence of a euxinic environment. These trace elements were used in a similar perspective by [41] on sediments of the northwest African continental shelf, to characterize black shales deposited during OAE2 of the Cenomanian-Turonian, these authors likewise concluding to a euxinic environment on the basis of strong joint enrichment in Mo and V associated with sulfidic conditions. Similarly, [42]-[44] show that simultaneous enrichment in V, Mo, and U in Italian black shales systematically characterizes a euxinic environment.

In Upper Jurassic shales of northwest Europe, [40] show that Mo and V are only significantly enriched in sediments where considerable amounts of OM (TOC > 7%) accumulated, the result of strongly reducing conditions that favored its burial. The present study, although the observed TOC values (up to 4.24%) remain below this threshold, confirms the same general trend: the levels most enriched in Mo-V correspond to the best preserved organic matter qualities.

For [12] and [45], certain chalcophile elements (Mo, Zn) precipitate as sulfides under euxinic conditions, consistent with the framboidal pyrite identified in the MS1 sediments [22]. According to [46], vanadium and uranium become enriched as soon as moderate to strong reducing conditions are established, whereas molybdenum only becomes significantly enriched under fully euxinic conditions (free H₂S in the water column), a pattern fully in agreement with the results obtained here.

Vanadium in particular constitutes, at the scale of the international literature, a reliable and widely used indicator of anoxia [6] [7], anoxic marine deposits typically displaying strong V enrichment correlated with Mo and U as observed in present-day oxygen minimum zones of the Pacific, the Black Sea, and the Gulf of California [34]. In euxinic environments, V shows a particular affinity for sulfurized organic compounds, which reinforces its fixation in sediments and indirectly makes it a good indicator of OM preservation [47].

4.2. Biological Productivity and Organic Matter Accumulation

[46] Interpret the correlations between certain elements (Ni, Cu, Zn) and total organic carbon as reflecting increased biological productivity, these elements often being associated with organic matter and enriched in high-productivity environments. Nickel additionally shows a strong affinity for organic matter [36] and can be associated with terrigenous or volcanic inputs; in reducing environments, it is frequently enriched in sediments rich in metal sulfides (NiS, Ni-Fe sulfides), and linked to biological productivity through the numerous Ni-dependent enzymes of phytoplankton [35]. During OAE2, several basins recorded combined enrichment in Ni, V, Mo, and U [43], reflecting the coexistence of reducing conditions and good bioproductivity a configuration also encountered in the present study.

4.3. Verticality and Variability of Anoxia

The transition between MS1 and MS3, marked by a progressive decrease in U, V, Cu, Ni, and Mo enrichments, together with the clear re-oxygenation episode identified as MS2, are comparable to the vertical pattern described by [41] in Cenomanian-Turonian sections of northwest Africa, where an intense euxinic environment alternates with periods of progressive re-oxygenation. This convergence confirms that the intensity of anoxia can vary locally through time, including at the scale of just a few meters of sedimentary series, as shown here by the individualization of MS2.

4.4. Implications for Petroleum Potential

The TOC values (1.49 - 4.24 wt.%) and petroleum potential (2.48 - 27.49 mg HC/g rock) obtained in this study fit well within the range reported for OAE2 black shales of the northwest African margin [41], which explains the strong hydrocarbon-generation potential of these sequences through euxinic conditions favorable

both to the preservation of OM and to its subsequent maturation. The analogy with the Tarfaya basin formations in Morocco [42] is particularly robust, reinforcing the exploration interest of the basal interval (MS1) of the OUATT-2x well for the regional characterization of Cenomanian-Turonian source rocks.

5. Conclusion

In light of the work carried out, the redox trace elements (U, V, Cu, Ni, Mo) demonstrate the existence of a euxinic to anoxic environment in the Ivorian basin within the OUATT-2x well, and correlate this period of oxidation-reduction with the preservation of a good to excellent quantity of organic matter, giving rise to good source rocks. The integrated analysis of absolute concentrations, geochemical ratios, and Rock-Eval parameters allows a division into three chemostratigraphic megasequences to be proposed, a sustained euxinic regime at the base (MS1), a clear intermediate re-oxygenation episode (MS2), and an intermittent anoxic-euxinic regime at the top (MS3). This approach confirms the value of chemostratigraphy as a tool for correlation and source-rock characterization in the Ivorian sedimentary basin, and opens the way to its extension to other wells of the Abidjan margin in order to test the lateral persistence of the megasequences defined here.

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Author Contributions

Conceptualization, Ouattara Ismaël Ben and Digbehi Zeli Bruno; methodology, Ouattara Ismaël Ben and Ahientio Hugues; software, Ahientio Hugues; validation, Ahientio Hugues, Kouao Assiè François Aristide and Digbehi Zeli Bruno; formal analysis, Ouattara Ismaël Ben; investigation, Ouattara Ismaël Ben; data curation, Ouattara Ismaël Ben and Chia Marie Reine Kokoa; writing original draft preparation, Ouattara Ismaël Ben; writing review and editing, Kouao Assiè François Aristide, Chia Marie Reine Kokoa, Ahientio Hugues and Digbehi Zeli Bruno; visualization, Ouattara Ismaël Ben; supervision, Digbehi Zeli Bruno; project administration, Digbehi Zeli Bruno. All authors have read and agreed to the published version of the manuscript.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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