Iraqi National Journal of Earth Science
www.earth.mosuljournals.com

Uranium and Organic Geochemistry of Oil Shale in Attarat Um Ghudran, Jordan

Khalil M Ibrahim [1*], Hanan B. Abdel Rahman [2]

[1,2] *Department of Earth and Environmental Sciences, Prince El-Hassan bin Talal Faculty of Natural Resources and Environment, The Hashemite University, Zarqa, Jordan.*

Article information

Received: 17- Aug -2023

Revised: 30- Sep -2023

Accepted: 11- Oct -2023

Available online: 01- Jan – 2024

Keywords:
Oil shale
Jordan
Uranium
Fischer assay
Organic carbon

Correspondence:
Name: Khalil M Ibrahim

Email: ibrahim@hu.edu.jo

ABSTRACT

Oil Shale is well-known worldwide. The Jordanian "oil shale" actually is not shale but rather bituminous carbonates, which are locally referred to as oil shale. Thirty representative oil shale core samples are collected from seven boreholes drilled in Attarat Um Ghudran (AUG) in central Jordan. They are prepared, analyzed, and characterized using X-ray fluorescence spectrometry (XRF). The organic matter content is analyzed for organic carbon, elemental analysis, and Fischer assay. Uranium (U) is determined by XRF attaining an average concentration of 21.15 ppm. It varies from a minimum value of 12 ppm to a maximum value of 34.2 ppm. The oil content values are in the range varying from a minimum of 4.47% to a maximum of 12.20%, and the average content of the whole deposit is 8.5%. The deposits have a hydrogen content of 4.09% and a nitrogen content of 1.84%. However, the sulfur content is generally high with an average of 6.85%. In Jordan, the oil shale deposits have a significant sulfur content ranging from 1.18% to 8.94% by weight, which is higher than in many other oil shale deposits worldwide. Moreover, the study discovers a positive correlation between the total organic carbon content and U in Attarat Um Ghudran deposits indicating that the organic matter is responsible for the Uranium presence not related to the rock-forming minerals.

DOI: 10.33899/earth.2023.142670.1133,

جيوكيميائية اليورانيوم والمواد العضوية المصاحبة لبعض خامات الصخر الزيتي في عطارت ام غدران، الأردن

خليل ابراهيم [1*]، حنان عبدالرحمن [2]

[2،1] قسم علوم الأرض والبيئة، كلية الأمير الحسن بن طلال للموارد الطبيعية والبيئة، الجامعة الهاشمية، الزرقاء، الأردن.

معلومات الارشفة

تاريخ الاستلام: 17- اغسطس 2023

تاريخ المراجعة: 30- سبتمبر -2023

تاريخ القبـول: 11- اكتوبر -2023

تاريخ النشر الالكتروني: 01- يناير -2024

الكلمات المفتاحية:
الصخر الزيتي
الأردن
اليورانيوم
جهاز تقطير الزيت
الكربون العضوي

المراسلة:
الاسم: خليل ابراهيم
Email:ibrahim@hu.edu.jo

الملخص

يعرّف الصخر الزيتي عالميا على أنه غضار يحوي كميات كبيرة من المادة العضوية البتومينية. بخلاف ما هو متعارف عليه محليا باسم الصخر الزيتي، فإن الوحدات الصخرية المستهدفة اقتصاديا والحاوية للمادة العضوية في الأردن فهي في الواقع صخور رسوبية كربوناتية بتيومينية. تمت دراسة 30 عينة بئرية من الصخر الزيتي من سبعة ابار حفرت في منطقة عطارات أم غدران في وسط الأردن. وتم تحضيرها وتحليلها وتوصيفها باستخدام تقنيات حيود الأشعة السينية والكربون العضوي وتحليل العناصر وجهاز تقطير الزيت. كما وتم تحديد اليورانيوم باستخدام جهاز حيود الأشعة السينية. وتوصلت الدراسة الى أن محتوى اليورانيوم يصل في متوسطه الى 21.15 جزء في المليون، حيث تتراوح قيمه في حدها الأدنى حوالي 12 جزء من المليون وفي حدها الاعلى 34.2 جزء من المليون. بينما أظهرت قياسات الكتلة النسبية لمحتوى الزيت قيما جيدة اقتصاديا تراوحت بين حدها الأدنى بنسبة 4.47٪ وحدها الأقصى بنسبة 12.20٪ بمعدل اجمالي 8.5٪. كان المحتوى الهيدروجيني أيضا حاضرا بقيم ملفتة حيث بلغ في متوسطه 4.09٪ بالاضافة الى المحتوى النيتروجيني الذي بلغ في متوسطه 1.84٪. واحتوت عينات الصخر الزيتي المقاسة على نسبة عالية جدا من الكبريت تراوحت من 1.18٪ إلى 8.94٪ وبمتوسط يصل الى 6.85٪. والتي يمكن اعتبارها واحدة من أعلى المعدلات بالمقارنة مع ترسبات الصخر الزيتي الأخرى حول العالم. وأظهرت الدراسة ارتباطًا إيجابيًا بين محتوى الكربون العضوي الكلي واليورانيوم في ترسبات عطارات أم غدران، مشيرة إلى أن المادة العضوية مسؤولة عن وجود اليورانيوم وليس التركيب المعدني او الصخري.

DOI: 10.33899/earth.2023.142670.1133, ©Authors, 2024, College of Science, University of Mosul.

Introduction

The oil shale is a sedimentary rock containing varying amounts of solid organic substances, mainly kerogen that produces significant quantities of oil when heated to high temperatures (Allaby, 2008). Oil shale deposits are found in many parts of the world including the United States, China, Estonia, Brazil, and Jordan. (Cohen and Cohrssen, 2010).

Jordan has one of the largest oil shale reserves in the world estimated at over 70 billion tons according to the Natural Resources Authority (NRA) of Jordan (Alali *et al.*, 2019). As stated by Ali Hussein (2014), the oil shale in Jordan is mainly bituminous limestones and marls, although referred to as oil shale. Most of the oil shale reserves are located in central Jordan (Fig. 1). The first oil shale working mine in Jordan is in the Attarat Um Ghudran area. The Jordanian oil shale is mainly made of calcite, while the minor part is dolomite. Besides, there are quartz, carbonate fluorapatite, pyrite, clay minerals (illite, kaolinite), and sulfur minerals, besides trace metals, which are associated with organic matters (e.g. Cr, V, Pb, U, Ni, Mo, Co, Cd, Zn, and Ba) (Ibrahim and Jaber, 2007; Ibrahim *et al.*, 2018). These trace metals are present at higher concentrations than normal (Hamarneh, 1998; Abed *et al.*, 2009, Ibrahim and Abdel Rahman, 2023). Exploiting Jordan's oil shale resources has the potential to create a reliable energy source and decrease the country's dependence on imported energy. The International Energy Agency (IEA) predicts that by 2030, Jordan's oil shale production could produce 50,000 barrels per day, meeting about 20% of the country's energy requirements (IEA, 2015). However, oil shale exploitation in Jordan faces significant challenges such as environmental, social, technical, and economic concerns. The production of shale oil necessitates considerable water and energy usage, and processing oil shale can lead to significant greenhouse gas emissions that contribute to climate change. In addition, mining and processing oil shale could adversely impact local communities leading to displacement of residents and environmental damage (Alali *et al.*, 2018).

Uranium as a chemical element with atomic number 92 is a silvery-white metal. Uranium is a radioactive element, and it has several naturally occurring isotopes (or radionuclides). The most encountered uranium isotopes are uranium-238 (U-238) constituting approximately 99.3%; and uranium-235 (U-235) comprising about 0.7%, along with a much smaller amount of uranium-234 (U-234). Uranium occurs naturally in low concentrations of a few parts per million in soil, rock, and water, and is commercially extracted from uranium-bearing minerals such as uraninite (Encyclopedia Britannica, 2023). Uranium is also the highest-numbered element to be found naturally in significant quantities on Earth and is almost always found combined with other elements (Hammond, 2000).

The geological setting of the Attarat Um Ghudran area is dominated by the widespread deposition of carbonates in the late Cretaceous succession represented by the Balqa Group. This group (Cretaceous-Tertiary rocks) consists of a well-exposed sequence of carbonate, chert, and phosphate rocks. They cover a large area inside and close to the Attarat Um Ghudran area (Madanat *et al.*, 2009, Jaber *et al.*, 2011).

Attarat Um Ghudran oil shale is geologically classified as marlstone because of the large percentage of carbonate (Ghannam and Roussan, 2007). The rocks are mainly limestone and marlstone in which the organic matter is heterogeneous and finely dispersed in the rock (Jaber *et al.*, 2011).

The Attarat Um Ghudran oil shale deposit is located 50 km east of the village of Al Qatrana, which is itself located 70 km south of Amman at the main desert highway between Amman and Aqaba. The study area and the distribution of the boreholes are illustrated in Figure (2).

This study focuses on the organic geochemistry of oil shale in Attarat Um Ghudran. There are few investigations on the distribution characteristics of U in the Jordanian oil shale. This work aims to investigate the organic geochemistry of the Jordanian oil shale in central Jordan and to explore the vertical and spatial distribution of U in the area.

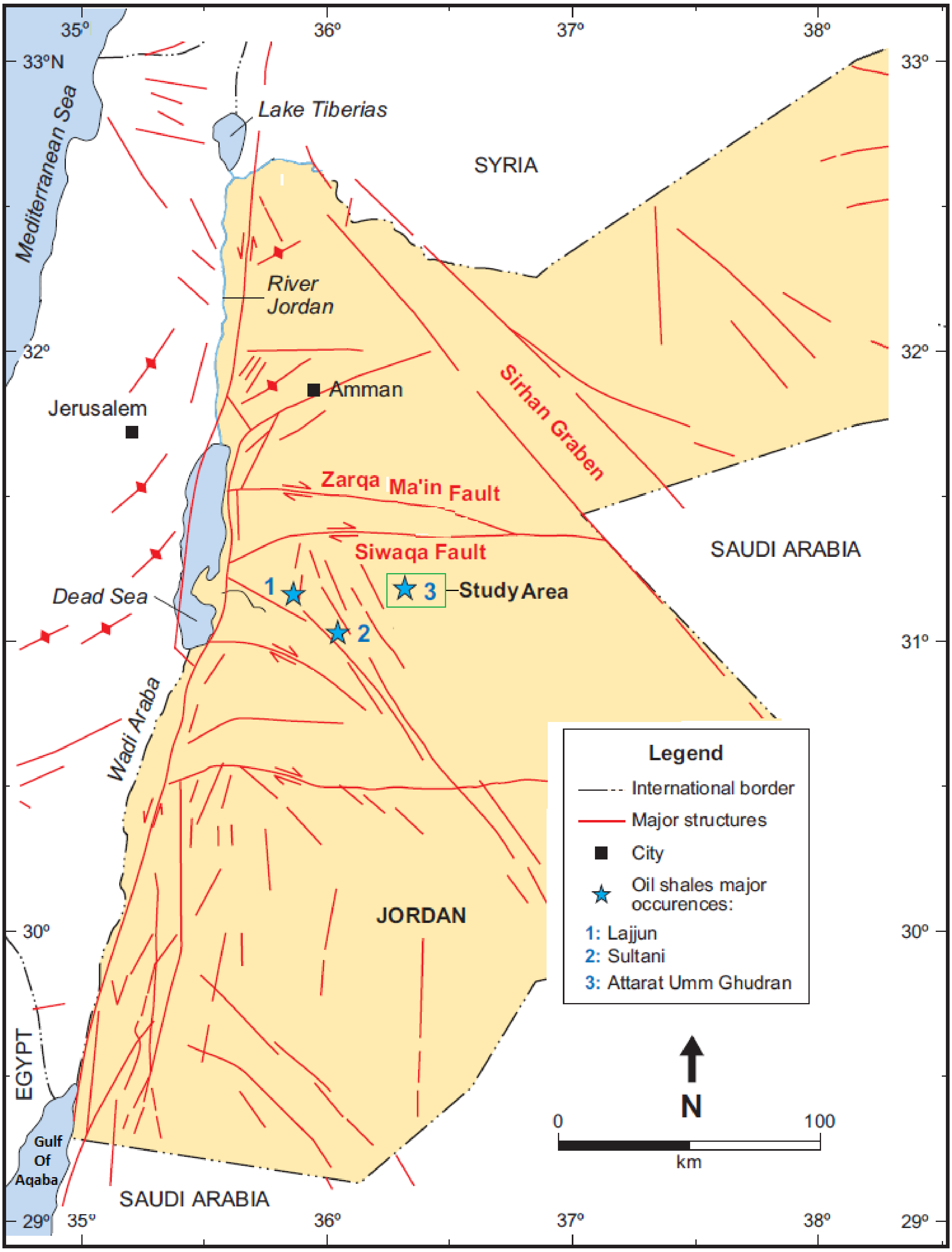
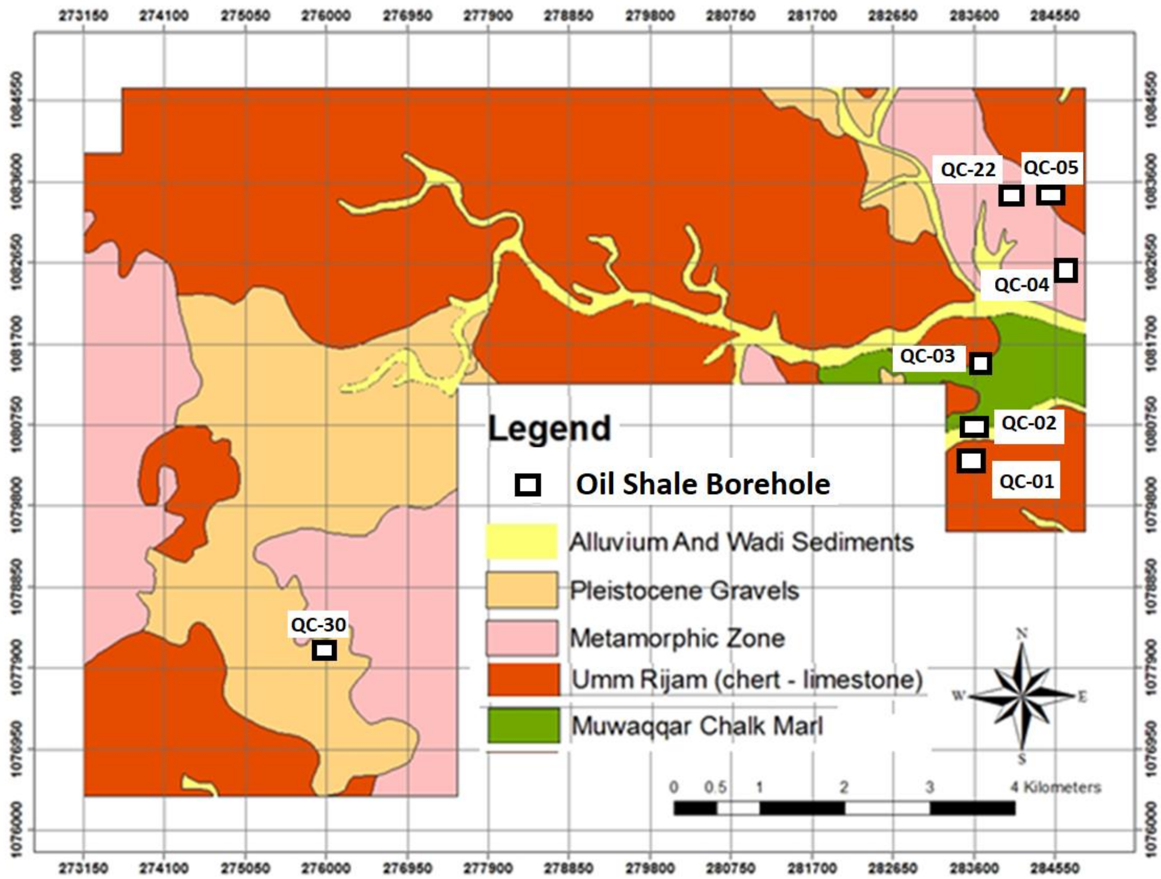


Fig. 1. Location map of selected oil shale deposits in central Jordan (Ali Hussien, 2014).



Borehole No.	Thickness (m)			Total depth (m) OB
	OB	Oil shale	AHP	
QC-01	61	35	QC-01	61
QC-02	70	30	QC-02	70
QC-03	88	23	QC-03	88
QC-04	64	36	QC-04	64
QC-05	67	33	QC-05	67
QC-22	61	37	QC-22	61
QC-30	88.5	46.5	QC-30	88.5

Fig. 2. Distribution of boreholes and exploration data (Abdel-Rahman, 2018, Ibrahim and Abdel Rahman, 2023) (AHP: Al Hasa Phosphorite Formation, OB: overburden).

Materials and Methods

30 samples from seven boreholes are provided by the Qamar for Energy and Infrastructure Ltd. Co. (QEI). The samples represent core samples from different depths. The oil shale samples are crushed and pulverized to the desired size in the laboratories of Hashemite University. The following analysis and studies (XRF, CHNS- Analyser, Fischer assay, and total organic carbon, TOC) are conducted following the standard methods described by Gülamber *et al.* (2019).

For the (XRF) analysis of U concentrations (ppm) in samples, a pressed powder pellet technology is employed for the full range of elements; they are prepared and analyzed in the labs of the Jordan Atomic Energy Commission using the S4 Pioneer Spectrometer by Bruker AXS GmbH. It is equipped with an X-ray tube featuring a rhodium anode operating at 3 kW.

Geochemical data for U are presented as colored maps within the ArcGIS software by converting digitizing and geo-referencing the study area map to raster data.

The Fischer assay is a standardized laboratory test for determining the oil yield from oil shale to be expected from a conventional shale oil extraction (Dyni, 2006). Oil shale samples have been tested for their oil shale retorting properties using the Fischer assay as described by Gülamber *et al.* (2019).

CHNS-Elemental Analyser dedicated to the simultaneous determination of the percentage amount of carbon, hydrogen, nitrogen, and sulfur. The sample is weighed in milligrams housed in a tin capsule and dropped into a quartz tube at 1020°C with constant helium flow (carrier gas). The main apparatus is the EuroEA3000 series. The elemental analyzer is available at the Ministry of Energy and Mineral Resources.

The total organic carbon content is determined by the Ministry of Energy and Mineral Resources. The sample is weighed in milligrams and used for this analysis. Carbonate is removed by treatment with 10% dilute hydrochloric acid. TOC content is determined in the samples using the elemental analyzer. Organic carbon is obtained by the difference between total carbon determined and inorganic carbon determined by the reaction with hydrochloric acid (Patterson *et al.*, 1987).

The calorific value is identified as the heating value, using the equation as in Pahari and Chauhan, (2006). Water content (moisture) is determined and calculated following the ASTM (2023).

Results

1-Uranium

In the studied oil shale, uranium varies from a minimum value of 12 ppm to a maximum value of 34.2 ppm. The highest average is noticed in borehole QC-02, whereas the lowest average is reported in boreholes QC-04, QC-22, and QC-30 (Table 1). The average U in all samples is 21.15 ppm, which is lower than the average U in the Sultani and Allujun oil shale in Jordan (Table 2). Oil shale deposits with significant U content have also been identified in other regions of the world, for example, in Estonia, where the uranium concentration in oil shale has been reported to be around 30 ppm (Kruusement *et al.*, 2008). In Jordan, some oil shale deposits have been found to contain up to 100 ppm of uranium (Alali *et al.*, 2013). In Australia, the uranium concentration in oil shale from the Julia Creek deposit has been reported to range from 6 to 10 ppm (Radke *et al.*, 2005). U can be found in oil shale; it is typically present in low concentrations and there are numerous technical and environmental challenges associated with extracting and utilizing the uranium resources (Al-Aasm *et al.*, 2004).

Table 1: Concentration of U element in the boreholes.

ID	Depth (m)	U (ppm)	ID	Depth (m)	U (ppm)
QC-01	84-87	12.1	QC-04	91-94	12
QC-01	87-90	17.6	QC-04	94-97	18.6
QC-01	90-93	26.4	QC-04	97-100	12
QC-01	93-96	12	QC-04	100-102	22.5
QC-01	96-99	12.2	Average		16.3
QC-01	99-102	12			
Average		15.4	QC-05	91-94	12.1
			QC-05	94-97	12
QC-02	85-88	12	QC-05	97-100	12
QC-02	88-91	12.1	QC-05	100- 102	12.2
QC-02	91-94	34.2	Average		12.1
QC-02	94-97	17.6			
QC-02	97-100	16.6	QC-22	88-91	12
QC-02	100- 102	12.2	QC-22	91-94	12.1
Average		17.5	QC-22	94-97	12.1
			QC-22	97-100	12
QC-03	91-93	12	Average		12.1
QC-03	96-99	15.7			
QC-03	93-96	12.3	QC-30	90-93	12
QC-03	99-102	13	QC-30	93-96	12.1
Average		13.3	Average		12.1
min		12	max		34.2

Table 2: Uranium in oil shale deposits in Jordan.

	Attarat Um Ghudran			Sultani[4]	Allujun[5]
	1	2	3		
U (ppm)	21.15	34	21	25	29

[1] This study, [2] Jaber and Ibrahim (2011); [3] Voolma et al (2016);[4] Hamarneh (1998); [5] El-Hasan (2008)

1.1 Vertical variation of U

The vertical variation of U in Attarat Um Ghudran boreholes is presented in Figure (3). In borehole QC-01, U concentrations increase with depth from 12 ppm at a depth of 84 m to 26.4 ppm at a depth of 93 m. With a depth deeper than 93 m, the concentration of U is 12 ppm. The average concentration of U in borehole QC-01 is 22 ppm. At depth 91- 94 m, U is of significant concentration of 34.2 ppm in borehole QC-02 with the highest concentration in the study area, the highest average of U is noticed in borehole QC-02 is 23 ppm. The maximum value of 15.7 ppm in borehole QC-03 is noticed at depths between 96- 99 m, the average concentration in borehole QC-03 is 16 ppm. The average concentration of U in borehole QC-04 is 21 ppm, it varies from a minimum value of 12 ppm to a maximum value of 22.5 ppm at depths of 100 to 102 m. The average concentration of U in borehole QC-05, borehole QC-22, and borehole QC-30 is around 12 ppm.

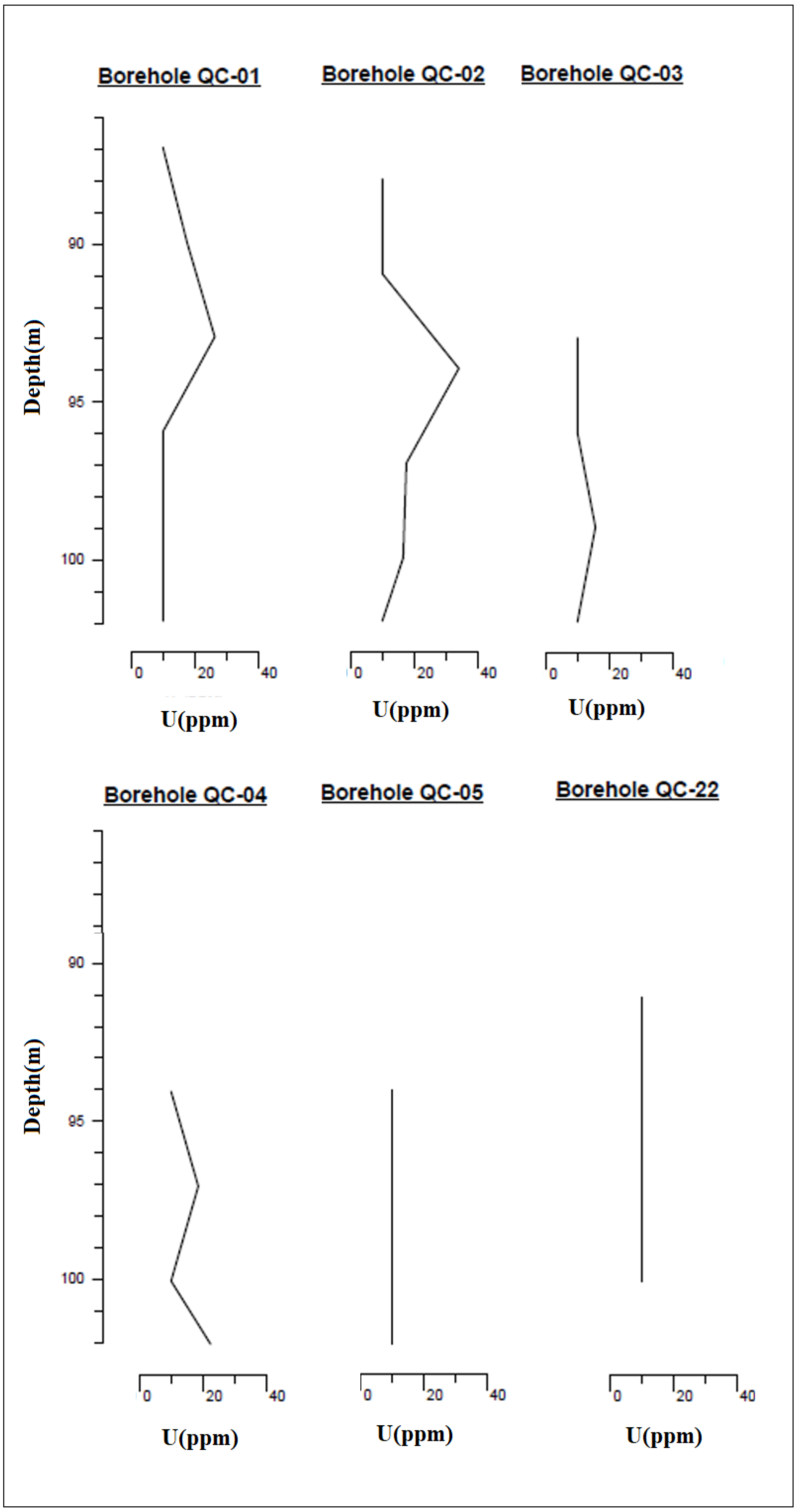


Fig. 3. Vertical variation of U in AUG boreholes.

1.2 Spatial variation of U

The geochemical distribution map for the average U in the study area is presented in Figure (4). The geochemical map derived for U concentration indicates that uranium is relatively dominant in the southern region and the eastern region. Whereas in northern regions, U concentration is characterized by lower values of uranium. However, the central portion is marked by a relatively moderate concentration of uranium.

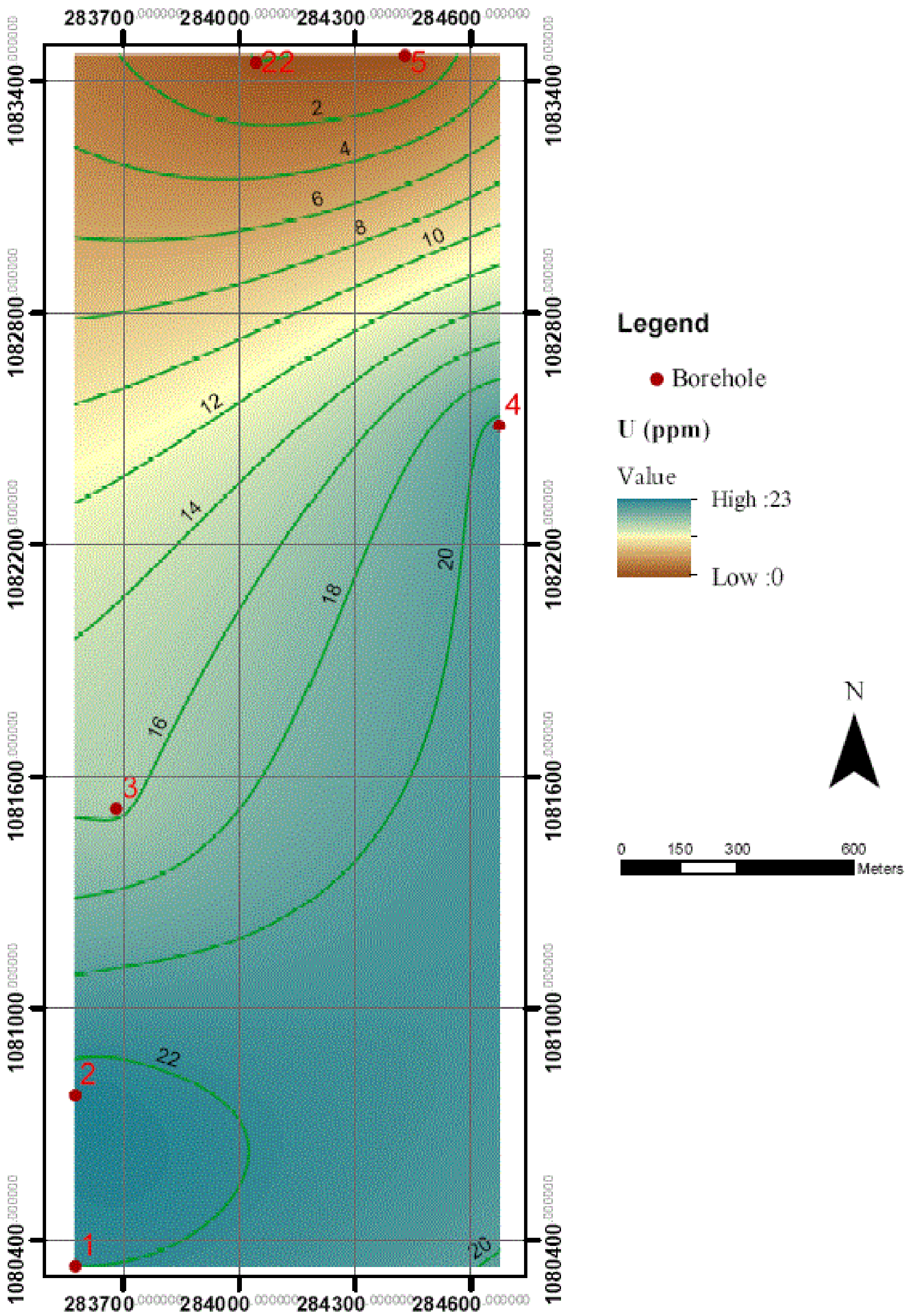


Fig. 4. Geochemical maps of the study area of the average uranium concentration.

2 -Organic Geochemistry

2.1 Oil content analysis

Selected core samples of oil shale within the study area are identified for organic geochemical analyses. Table (3) summarizes the results of the weighted average composition of the oil yield, gas loss, and spent shale (as wt. %). It is found that the oil content in the deposit varies from a minimum value of 4.47 % to a maximum value of 12.20 %, and the average content of the whole deposit of the study area is 8.5 %. The highest oil content is found in borehole QC-02, which is 12.2 %. A standard technique for determining the amount of oil that can be extracted from organic material in oil shale is to analyze its oil content. This involves measuring the quantity of kerogen present in the shale, which serves as a precursor to oil (Speight, 2016). Except for oil shale samples obtained from (QC – 22 and QC-30), the average oil weighted average amount of gas yield is 3.34 %. The highest gas loss in borehole QC-02 is 4.48 % and the lowest gas loss in borehole QC-22 is 1.65 %. The weighted average amount of water yield is 1.85%, the highest average water yield is noticed in borehole QC-04, whereas the lowest average is reported in borehole QC-22 and is 1.3 %. Spent shale is the term used to describe the remaining material after shale oil has been extracted from oil shale. It can also be referred to as spent oil shale or oil shale ash. This material is generally composed of fine particles with a high mineral content and low organic matter (ASTM D3908-19, 2019). The average amount of spent shale yield in the study area is 86.43 %, and the highest average of spent shale is noticed in borehole QC -22, and the lowest average of spent shale is noticed in borehole QC -02. The percentage of spent oil depends on the extraction process used, there are some general benefits of spent oil shale such as the utilization of spent oil shale can aid in the remediation of polluted sites by serving as a means to absorb heavy metals from contaminated soil or water (Ucar *et al.*, 2016). The utilization of spent oil shale has been shown to have benefits in the reclamation of land that has been previously used for mining activities. It can act as a valuable soil amendment, enhancing both soil fertility and structure (Zhang *et al.*, 2019), also spent oil shale's high mineral content makes it a viable material for use in construction applications, such as bricks and cement (Liu *et al.*, 2019).

Table 3: Fischer assay data of Attarat Um Ghudran oil shale.

Boreholes	**Water wt.%**	**Oil wt.%**	**Spent shale wt.%**	**Gas loss wt.%**
QC-01	1.5	9.1	85.9	3.5
QC-02	2.2	12.2	81.1	4.5
QC-03	1.9	9.3	85.8	3.0
QC-04	2.3	7.7	87.6	2.4
QC-05	1.9	9.8	82.7	5.7
QC – 22	1.3	4.4	92.7	1.7
QC-30	1.9	6.7	88.8	2.7
Average	1.9	8.5	86.4	3.4

Table (4) represents the average component of Fischer assay results for oil shale in the world compared to the oil shale in the study area. The result of the Fischer assay in Attarat Um Ghudran is within the range of the result of the Fischer assay in the world, although oil content in the study area is higher than in China and Brazil.

Table 4: Comparison of properties of world oil shale deposits to Jordanian oil shale (Besieso, 2007).

Locality	Water wt.%	Oil wt.%	Spent shale wt.%	Gas loss wt.%
USA	1.4	10.4	86.7	2.5
Brazil	1.2	6.9	83.6	3.7
Estonia	1.9	22.0	70.5	5.6
China	3.2	7.3	80.6	3.9
Jordan (Allujun)	1.4	10.1	80.8	3.7
AUG** Study area	1.9	8.5	86.4	3.4

2.2 Association between oil yields with U

The extraction of oil from oil shale is commonly referred to as oil yield. Recent research has shown that the uranium content of oil shale is directly linked to its oil yield. For example, a study by Hu *et al.* (2021) conducted on oil shale deposits in the Qingshankou Formation of the Songliao Basin in China found a positive correlation between the uranium content of the oil shale and its oil yield. The correlation was more pronounced in regions with higher thermal maturity. Similarly, Huang *et al.* (2015) reported a positive relationship between uranium content and oil yield in their study of oil shale samples from northeastern China. They suggested that clay minerals, which are known to adsorb organic matter and uranium, could be responsible for this relationship. Considering the relationship between uranium and oil yield in oil shale is therefore crucial (Fig 5).

The concentration of uranium (U) in oil shale does not necessarily eliminate the extraction of organic matter; however, it significantly impacts the efficiency and economic aspects of the extraction process. The interplay between uranium concentration and oil yield in oil shale is intricate and subject to variation due to numerous factors. Uranium can form associations with organic matter within oil shale, potentially affecting the efficiency of organic matter extraction during retorting or pyrolysis processes. Elevated uranium concentrations could lead to increased energy consumption and operational challenges during the extraction process (Dyni, 2010). Additionally, higher uranium content in oil shale can pose environmental issues due to the radioactivity of uranium. Managing and disposing of oil shale with high uranium content may require extra care and compliance with specific geological regulations (Dyni, 2010). To address these challenges, scientists and engineers have explored various technological solutions including shale pre-treatment, optimization of processing conditions, and the development of uranium recovery methods (Hutton, 1978).

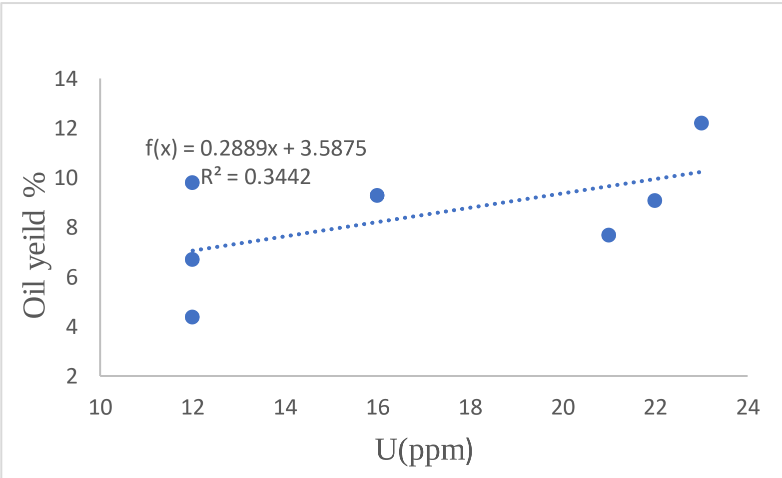


Fig. 5. Binary variation diagram between U and oil yield.

3- Oil Shale Elemental Analysis

The elemental analysis data of the studied oil shale borehole samples are given in Table (5). The average value of total carbon in all samples is 46.83 %, it varies from a minimum of 15.13 % to a maximum of 59.97 %. The average of organic carbon in all samples is 12.75 %, it varies from a minimum of 3.02 % to a maximum of 18.89 %. The average of inorganic carbon in all samples is 34.07 % and it varies from a minimum of 12.15% to a maximum of 41.08 %. The highest average of the total carbon is noticed in borehole QC-02, whereas the lowest average is noticed in borehole QC-30 in the study area, also the highest organic carbon is noticed in borehole QC-02, whereas the lowest value is noticed in borehole QC-30. The highest average of inorganic carbon is noticed in borehole QC-02, whereas the lowest average is noticed in borehole QC-30 in the study area.

Table 5: Elemental analysis, calorific value, and moisture result.

Borehole ID	QC-01	QC-02	QC-03	QC-04	QC-05	QC-22	QC-30	Average
Organic carbon (wt.%)	10.49	18.89	18.87	12.84	11.37	13.8	3.02	12.75
Inorganic carbon (wt.%)	36.29	41.08	39.12	34.12	42.27	33.49	12.15	34.07
Total carbon (wt.%)	46.78	59.97	57.99	46.96	53.64	47.29	15.17	46.83
Hydrogen (wt.%)	4.42	4.85	4.84	4.16	5.18	4.24	0.97	4.09
Nitrogen (wt.%)	1.87	1.81	1.94	1.75	2.1	1.72	1.66	1.84
Sulfur (wt.%)	7.21	8.94	7.84	6.63	8.67	7.29	1.18	6.82
Calorific value (Kcal/Kg)	1335.6	2388.4	2414.6	1633.9	1451.1	1785.2	333.5	1620.35
Moisture %	0.83	0.57	1.61	0.75	0.73	1.15	0.81	0.92

The relationship between organic carbon content and uranium in oil shale is generally positive, with higher organic carbon content leading to higher uranium concentrations as exhibited in Figure (6).

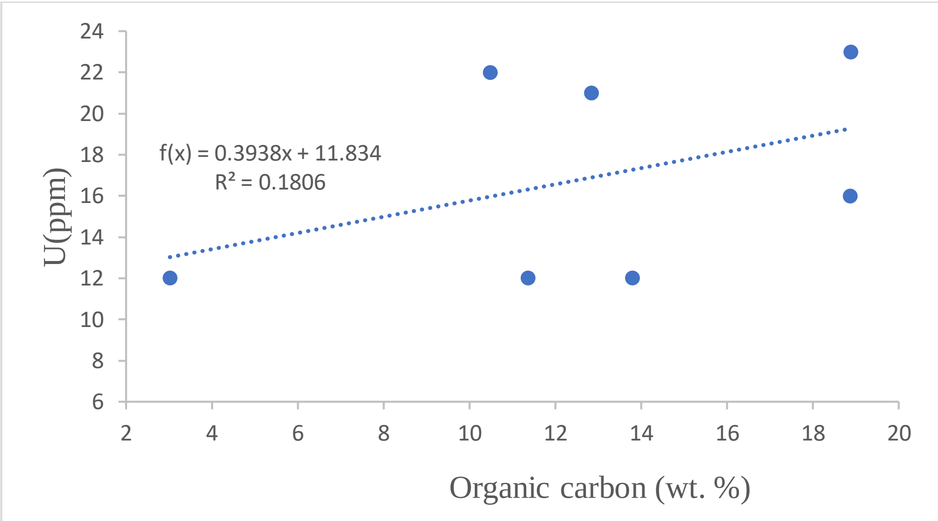


Fig. 6. Binary variation diagram between the organic carbon content and uranium.

The association between organic carbon content and uranium is attributed to the extensive high surface area of the organic matter, which provides numerous sites for uranium adsorption (Islam *et al.*, 2015), where the organic matter adsorbed the uranium through a mechanism of surface complexation (Dang *et al.*, 2016). Numerous studies have established a positive correlation between uranium and organic carbon content in sedimentary rocks. For instance, Michalik *et al.* (2011) discovered a strong correlation between uranium content and total organic carbon content in sedimentary rocks from the Kupferschiefer black shale of Poland. Similarly, Hu *et al.* (2015) found a positive correlation between uranium and total organic carbon content in sedimentary rocks from the Athabasca Basin, a significant uranium-producing region in Canada. However, the presence of sulfides is an additional factor that should be taken into consideration as it can act as a reducing agent, impacting the mobility of uranium in the sedimentary environment and subsequently affecting the relationship between uranium and organic carbon content.

The total sulfur varies between a minimum value of 1.18 % to a maximum value of 8.94 % and is noticed in borehole QC-02 with an average of 6.82 wt. %. According to a study by Alali *et al.* (2018), the sulfur content in Jordanian oil shale ranges from 0.54% to 4.1 % by weight with an average of 1.6 %. Similarly, a study by Al-Harahsheh *et al.* (2015) reported sulfur content in Jordanian oil shale in the range of 0.9 % to 3.3 % by weight, with an average of 1.7 %. In another study, Wang *et al.* (2019) reported sulfur content in Chinese oil shale in the range of 0.36 % to 7.2 % by weight with an average of 2.9 %. A study by Tiikma *et al.* (2018) reported sulfur content in Estonian oil shale in the range of 2.2 % to 3.6 % by weight, so sulfur in the AUG study area is very high. The relationship between sulfur content and uranium in oil shale is generally positive (Fig. 7).

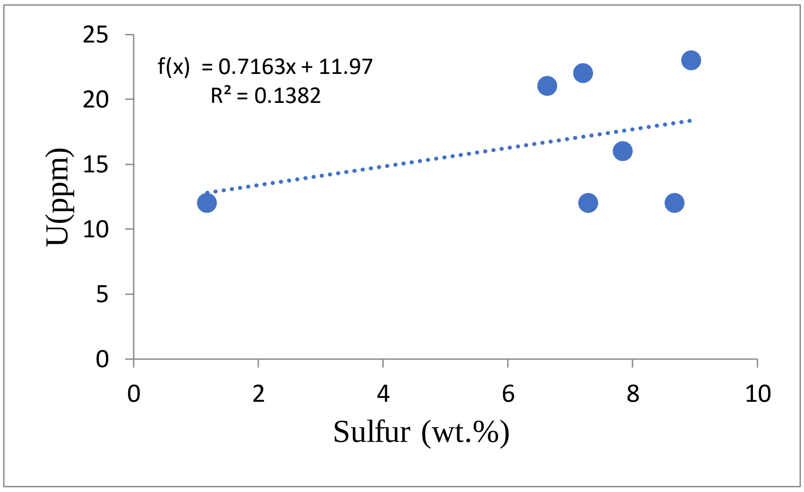


Fig. 7. Binary variation diagram between Sulfur and Uranium.

The average nitrogen in all samples is 1.84 %; its value varies from a minimum of 1.66% to a maximum of 2.1 %. U shows a negative insignificant correlation with Nitrogen as in Figure (8). The average of hydrogen in all samples is 4.09%; its value ranges from a minimum of 0.97 to a maximum of 5.18 %. There is an insignificant relationship between Uranium with hydrogen, with a positive trend in a scatter plot of U with Hydrogen (Fig. 9).

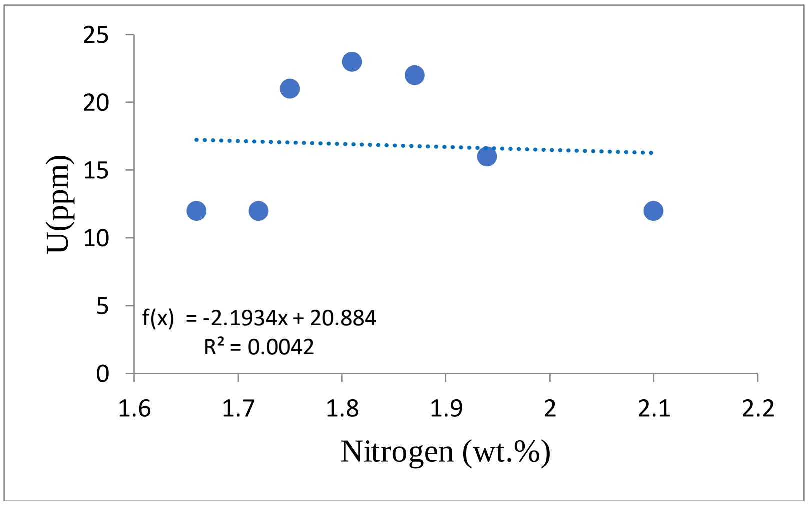


Fig. 8. Binary variation diagram between Nitrogen and Uranium.

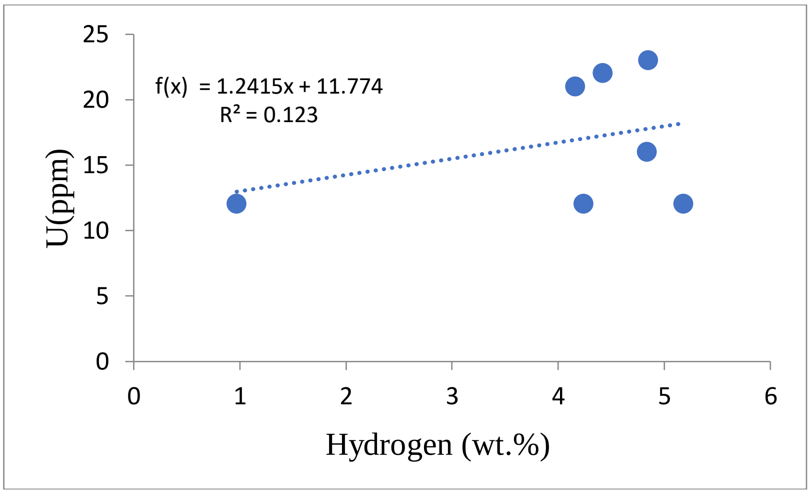


Fig. 9. Binary variation diagram between Hydrogen and Uranium.

4- Calorific Value

Calorific value is referred to as the heating value during the combustion of a unit weight of oil shale. It is an important parameter of oil shale quality (Li *et al.*, 1998; Dawei *et al.*, 2015). The calorific value results have indicated an average heating value of 1620.35 Kcal / Kg. As can be seen from Table (6), the calorific value of oil shale samples varies from a minimum of 333.48 to a maximum of 2388.44 Kcal/ Kg. Accordingly; we have calculated oil content based on the calorific value results with average oil content of 8.5%. The Attarat Um Ghudran oil shale deposit is considered a high grade in terms of oil yield and calorific value (Jaber *et al.*, 2011). The calorific value of oil shale is a crucial parameter that determines its efficiency as a fuel and can be used to assess the potential of oil shale deposits for energy production. However, this value can vary greatly due to factors such as the shale's organic and mineral composition, as well as its geological source (Tefanova *et al.*, 2015). Except for oil shale samples obtained from (QC-22 and QC-30), the average oil yield is 9.62 %, these results indicate that oil content and heating value is very high. The relationship between gross calorific value, which is the most important factor when burning oil shale (Jaber *et al.*, 2011), and each of carbon, hydrogen, oxygen, and sulfur, is due to the following formula to calculate calorific value:

$\text{Cross Calorific value} = \frac{1}{100}\left[8080 * C + 34500\left[H - \frac{O}{8}\right] + 22408 * S\right], \frac{\text{Kcal}}{\text{Kg}}$ (Pahari and Chauhan, 2006).

Calorific value, oil yield, organic carbon, and uranium of oil shale.

Seven boreholes were drilled in the Attarat Um Ghudran oil shale deposit. According to (Jaber *et al.*, 2011), the most significant values are:

-Calorific Value

-The oil yield, which determines the economics of the oil shale deposit: Fig. 10 and Fig. 11 show a relationship between calorific value and oil yield, organic carbon, and oil yield.

The linear relationship between calorific value and oil yield is exhibited in Figure (10), and the study also indicates that the calorific value of oil shale generally increases with increasing organic content and decreasing ash content (Saidi *et al.*, 2013).

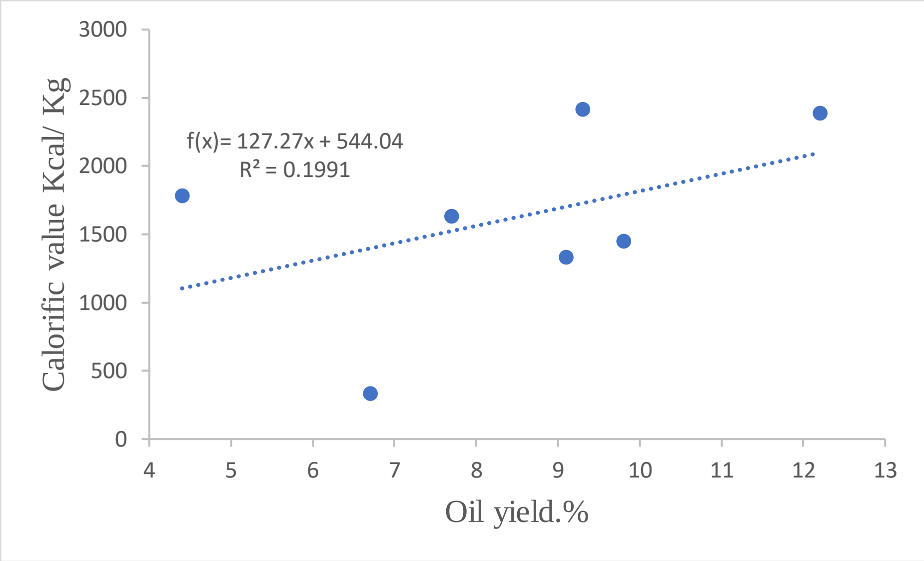


Fig. 10. Binary variation diagram between Calorific value and oil yield.

A linear relationship between organic carbon and oil yield is exhibited in Figure (11). The relationship between organic carbon content and oil yield in oil shale from a study by Bao *et al.* (2019) is positive, that the oil yield increased as the organic carbon content increased up to a certain threshold, beyond which the yield leveled off. The researchers suggested that the saturation of available hydrocarbon-generating sites in the organic matter is responsible for this plateauing effect.

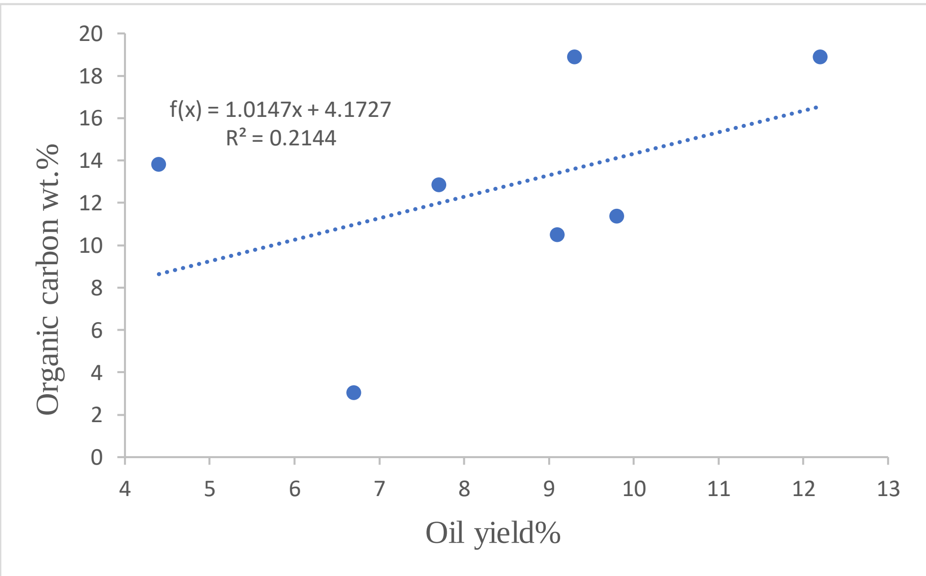


Fig. 11. Binary variation diagram between organic carbon and oil yield.

Conclusion

The Attarat Um Ghudran area in central Jordan is dominated by widespread deposition of marine carbonates, in parts enriched with organic matter forming oil shale deposits. The oil shale contains insignificant amounts of uranium. It is indicated that uranium content is irregularly distributed in space and time. The obtained results indicate that the Jordanian oil shale has a high oil content.

Results indicate that uranium is associated with organic carbon, this is most probably due to the extensive large surface area of organic matter, which created numerous sites for uranium adsorption. The study found a positive correlation between uranium and total organic carbon content in the deposits.

Sulfur content in the oil shale is generally high ranging from 1.18% to 8.94% by weight. This is higher than the sulfur content in many other oil shale deposits around the world.

The study relied on the average content of uranium and organic matter in the raw material for mining purposes without analyzing the lateral changes at the formation level. More detailed studies could contribute to understanding the relationships between the components, and the current study recommends further research in this regard**.**

Acknowledgments

We are grateful to Al-Qamer for Energy and Infrastructure Ltd Company for providing samples from the drilled boreholes in the study area and providing other related information about the study area. This research was funded by the Deanship of Scientific Research - the Hashemite University through the project entitled “Geological and geochemical characterization of oil shale resources in Jordan”. Special thanks also to the Jordan Atomic Energy Commission for the support in XRF analysis, Hashemite University, and the University of Jordan for providing lab facilities and instrumentations

References

Abed, A.M., Arouri, K., Amireh, B.S. and Al-Hawari, Z., 2009. Characterization and genesis of some Jordanian oil shales Dirasat, 36 (1), pp. 7-17.

Abdel-Rahman, H., 2018. Uranium and heavy metals geochemistry associated with selected Jordanian oil shale, MSc. Thesis, Hashemite University.

Al-Aasm, I.S., Lavoie, G.L., Marcano, J.A. and Verreault, J.M., 2004. Petrographic and geochemical characteristics of the Devonian-Mississippian Woodford shale, Oklahoma, USA. International Journal of Coal Geology 58 (1-2), pp. 107-131.

Alali, J., Abu Salah, A., Yasin, S. and Al Omari,W., 2015. Mineral status and future opportunity of oil shale Ministry of Energy and Mineral Resources. Technical report.

Alali, J., Abu El-Rub, Z. and Al-Harahsheh, M., 2018. Characterization of sulfur and mineral matter in Jordanian oil shale. Energy Sources, Part A: Recovery, Utilization, and Environmental Effects, 40 (6), pp. 671-679.

Alali, J., Al-Mashaqbeh, O. and Al-Qawasmi, A., 2019. Oil shale resources and potential development in Jordan: A review. Journal of Petroleum Science and Engineering, 181 P.

Alali, J., Al-Mashaqbeh, O. and Al-Qawasmi, A., 2012. Oil shale in Jordan: Technical, economic, and environmental challenges. Renewable and Sustainable Energy Reviews, 16 (4), pp. 2111-2118.

Alali, J., Al-Mashaqbeh, O., Al-Kofahi, M., Abu Salah, A., Al-Harahsheh, M. and Al-Tarawneh, K., 2013. Uranium content of Jordanian oil shale. Journal of Radioanalytical and Nuclear Chemistry, 296 (1), pp. 353-359.

Al-Harahsheh, M., Al-Qurnawi, M., Al-Shyoukh, A., Al-Tarawneh, K. and Ahmad, M. N., 2015. Jordanian oil shale: Characterization, retorting and combustion. Journal of Analytical and Applied Pyrolysis, pp. 113, -11.

Ali Hussein, M., Alqudah, M., van den Boorn, S., Kolonic, S., Podlaha,O. G., Mutterlose, J., 2014. Eocene oil shales from Jordan -their petrography, carbon and oxygen stable isotopes. GeoArabia, 19, pp. 139-162.

Allaby, M., 2008. Earth Sciences. Third edition. Oxford University Press Inc, New York.

Altun, N. E., Hicyilmaz, C., Hwang, J., Suatbagci, A. and Kok, M. V., 2006. Oil shale in the world and Turkey; reseves, current situation and future prospect: a review. Oil Shale Journal.Vol.23, No.3, pp. 211-227.

ASTM D3908-19, 2019. Standard Test Method for Determination of Total Sediment in Industrial Aromatic Hydrocarbons and Related Materials, ASTM International, West Conshohocken, PA.

ASTM International (n.d.), 2023. Standard Test Methods for Laboratory Determination of Water (Moisture) Content of Soil and Rock by Mass. ASTM International, from https://www.astm.org/Standards/D2216.htm.

Bao, S., Zhang, S., Zhang, T., Zhang, X., Wang, Y., Li, Y. and Wang, H., 2019. Characteristics of shale oil in the Upper Permian Qungming Formation in western Guizhou. Petroleum Exploration and Development, 46 (3), pp. 506-514.

Besieso, M., 2007. Jordan's Commercial Oil Shale Strategy. 27th Oil Shale Symposium. Colorado School of Mines, Colorado, USA.

Cohen, J.T. and Cohrssen, J.J., 2010. Health and environmental impacts of oil shale and implications for energy policy. Journal of Occupational and Environmental Medicine, 52 (4), pp. 391-398.

Dang, Y., Zhu, R., Zhang, L., Li, X., Wang, W., Chen, Y. and Wu, Z., 2016. Uranium distribution and accumulation in oil shale from the Upper Cretaceous Songliao Basin, China. Fuel, 171, pp. 1-8.

Dawei, L., Li, Z., Liu, H., Li, Y., Feng, T., Wang, D., Wang. P. and Li, S., 2015. The characterization of coal and oil shale in the coastal sea area of Huangxian Coalfield, eastern China. 32 (3), pp. 204–217.

Dyni, J. R., 2003. Oil Shale, 20(3), pp. 193–252.

Dyni, J. R., 2006. Geology and resources of some world oil-shale deposits U.S. geological survey scientific investigations report 2005–5294, 42 P.

El-Hasan, 2008. Geochemistry of redox-sensitive trace elements and its implication on the mode of formation of the Upper Cretaceous oil shales, Central Jordan", Neues Jahrbuch für Geologie und Paläontologie Abhandlungen, 249, pp. 333-344.

Encyclopedia Britannica (n.d.), 2023. Uranium. https://www.britannica.com/science/uranium.

Ghannam, A. and Roussan, A., 2007. Wadi Attarat Um Ghudran oil shale deposit. internal report, Exploration Studies Division, Geology Directorate, Natural Recourses Authority, Amman, Jordan.

Graham, R., 1996. Dictionary of Mining, Mineral, and Related Terms. Second Edition. L American Geological Institute

Gülamber, C., Ibrahim, K. M., Aljurf, S. and Rahman, H. A., 2019. Introduction of analytical methods for oil shale resource evaluation. IMCET 2019, Antalya, Turkey, 16 – 19 April 2019, 1154-1168.

Hamarneh, Y., 1998. Oil shale resources development in Jordan. Ministry of Energy and Mineral Resources. Natural Resources Authority, Amman.

Hamarneh, Y., Alali, J. and Sawaged, S., 2006. Oil Shale Resources Development in Jordan. Amman: Natural Resources Authority of Jordan.

Hammond, C. R., 2000. The Elements, in Handbook of Chemistry and Physics. CRC press.

Hang, C., Chen, Y., Li, Q, Li, Y., Li, W., Li, B. and Wu, M., 2019. Preparation of lightweight aggregate using spent oil shale and municipal solid waste incineration fly ash. Journal of Cleaner Production, 210, pp. 1204-1215.

Hu, B., Linnen, R.L., Fayek, M. and Hanley, J., 2015. Geochemistry of uranium in Athabasca Basin sedimentary rocks, Saskatchewan, Canada: Implications for uranium transport and ore deposition. Chemical Geology, 397, pp. 87-101.

Hu, P., Liu, Y. and Dong, X., 2021. The relationship between uranium content and oil yield in the Qingshankou Formation shale oil reservoir, Songliao Basin. Journal of Petroleum Science and Engineering, 203, 108813. https://doi.org/10.1016/j.petrol.2021.108813.

Huang, S., Wang, Y., Zhang, J. and Yan, D., 2015. Geochemical characteristics of uranium and its relationship with oil yield of the Upper Jurassic-Lower Cretaceous strata in the Songliao Basin. Energy Sources, Part A: Recovery, Utilization, and Environmental Effects, 37(1), pp. 28-35.

Ibrahim, K.M. and Abdel Rahman, H., 2023. Geochemistry and mineralogy of oil shale from Attarat Umm Ghudran area, Jordan. Advance Journal of Energy and Earth Sciences, 55 (1), pp. 1-11. ISSN: 2096-3246.

Ibrahim, K. M., Aljurf, S. and Abu Hawas, J., 2018 Metal sulphides associated with Attarat oil shale, Jordan, 2nd International Oil Shale Conference (BAU-SIOSC), 9-11 October 2018, As Salt- Jordan.

Ibrahim, K.M. and Jaber, J.O., 2007 Geochemistry and environmental impacts of retorted oil shale from Jordan", Environmental Geology, 52, pp. 979–984.

International Energy Agency, 2015. Oil Shale in Jordan. Retrieved from https://www.iea.org/reports/oil-shale-in-jordan.

Islam, A., Hower, J. C., Helble, J. J. and Dai, S., 2015. Uranium distribution in oil shale of the Green River Formation, USA: Relations to depositional environment and organic matter. Journal of Radioanalytical and Nuclear Chemistry, 306 (2), pp. 613-624.

Jaber, J.O., Amri, A. and Ibrahim, K., 2011. Experimental investigation of effects of oil shale composition on its calorific value and oil yield. Int. J. Oil, Gas and Coal Technology, 4 (4), pp. 307–321.

Kruusement, K., Isakar, K. and Vallner, L., 2008. Estonian oil shale resources and usage. Oil Shale, 25 (4), pp. 403-414.

Kurniawan, A., Jasmine A.P. and Kenzie, J.M., 2009. General Dictionary of Geology. Environmental Geographic Student Association. United States of America.

Li, Z. X., Wei, J. C., Li, S. C., Han, M. L., Lan, H. X., 1998. The basin-filling Features and sequence division in the Paleogene Huangxian fault basin, Shandong. Lithofacies Palaeogeography, 18 (4), pp. 1–8.

Liu, J., Zhang, X., Chen, C., Liu, H., Huang, L. and Wang, M., 2019. Preparation of cementitious materials using spent oil shale and fly ash. Journal of Cleaner Production, 238, 117958.

Madanat, M., Ghannam, A. and Moumani, K., 2009. Oil shale in Jordan: occurrences and investment opportunities. Tallinn University of Technology, 8– 11 June, Tallinn, Estonia.

Michalik, M., Kierczak, J. and Matysik, M., 2011. Organic carbon and uranium concentration and distribution in the Lower Permian black shale of the Fore-Sudetic Monocline, SW Poland. Geological Quarterly, 55 (4), pp. 419-430.

Pahari, A. and Chauhan, B., 2006. Engineering Chemistry. New Delhi: Laxmi Publication Ltd.

Patterson, J.H., Dale, L.S., Fardy, J. and Ramsdent, A. R., 1987. Characterization of trace elements in oil shales. Third Australian Workshop on Oil Shale', Australia, Vol. 66.

Qian, J.L. and Li, S.Y., 2010. Oil shale –petroleum alternative. China petrochemical press

Radke, B.M., Cheng, Y.P. and Walters, C.C., 2005. Potential of oil shale as a uranium resource in Australia. Australian Journal of Earth Sciences, 52 (6), pp. 811-823.

Smith, J., 2006. The Facts on File Dictionary of Earth Science. Revised Edition. Market House Books Ltd, Aylesbury, UK

Saidi, A., Sarout, J. and Crawford, R. W., 2013. Characterization of Oil Shale for Combustion: A Review. Journal of Energy Resources Technology, 135 (3), 031201.

Speight, J. G., 2016. Handbook of shale gas law and policy. Academic Press.

Tefanova, M., Spasova, I. and Kostova, I., 2015. Thermal behavior of Bulgarian oil shale. Journal of Thermal Analysis and Calorimetry, 119 (2), pp. 983-989.

Tiikma, T., Kuusik, R., Vali, E., Kirsimae, K. and Lill, J., 2018. Leaching of sulfur and trace elements from Estonian oil shale ashes. Fuel Processing Technology, 178, pp. 29-35.

U.S. Energy Information Administration. (n.d.). Oil shale. Retrieved March 24, 2023, https://www.eia.gov/energyexplained/oil-and-petroleum-products/oil-shale.php.

Ucar, S., Karaca, Z. and Koyunoglu, C., 2016. A review of oil shale ash: Generation, composition, and environmental applications. Journal of Cleaner Production, 112, pp. 2852-2863.

United States Geological Survey (USGS), 2022. Oil Shale. Retrieved from https://www.usgs.gov/centers/energy-and-minerals-science-center/science/oil-shale?qt-science_center_objects=0#qt- science _center_ objects.

Voolma, M., Soesoo, A., Puura, V., Hade, S., Aosaar, H., 2016. Assessing the geochemical variability of oil shale in the Attarat Um Ghudran deposit, Jordan, Estonian Journal of Earth Sciences, 65, pp. 61–74.

Wang, J., Li, X., Li, Y., Ma, X., Liu, G. and Li, J., 2019. Characterization of sulfur in Chinese oil shale by X-ray absorption near-edge structure spectroscopy. Fuel, 246, pp. 11-18.