

Article

Genetic Mechanism of Uranium Concentration in Ferruginous Sandstone of the Wajid Group in Southern Saudi Arabia

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Abstract: Uranium anomalies were discovered in ferruginous sandstone in the Khusayyayn Formation of the Wajid Group in southern Saudi Arabia. Based on field surveys, ground radiometric surveys, and chemical analysis, this paper summarizes the characteristics of the lithology and lithofacies of the ferruginous sandstone and analyzes the genetic mechanism of uranium concentration in ferruginous sandstone. Ferric iron basically exists in the form of Fe_2O_3 in ferruginous sandstone, with an average content of 28.95 wt.%. The formation period of the ferruginous sandstone occurred during the early synsedimentary and later diagenesis stages from the Carboniferous to the Devonian. The uranium anomaly is hosted in thin-bedded and lenticular ferruginous sandstone, with a uranium content ranging from 50 to 766 ppm. The average U-Ra equilibrium coefficient of ferruginous sandstone was 1.00, indicating that the uranium was weakly reformed after the uranium concentration. Ferric ions are closely related to uranium mineralization. The initial concentration of the uranium occurred during the deposition of the ferruginous sandstone. Most of the uranium was adsorbed by a ferric colloidal solution, and part of it was reduced by Fe^{2+} , organic carbon, and sulfur in the uranium preconcentrated stage during the deposition of ferruginous sandstone. The uranium ore was superimposed, transformed, and concentrated due to the change in the pH environment in the early Neogene.

Keywords: uranium concentration mechanism; ferruginous sandstone; Wajid group; southern Saudi Arabia



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1. Introduction

Sedimentary iron ore is an important type of iron ore deposit. Its regional geology, lithology, lithofacies characteristics, and genesis have been studied [1–3]. They are mainly distributed in shallow marine, sea land alternating, or lacustrine sedimentary facies, mainly composed of iron quartz sandstone, rich in hematite, limonite, iron carbonate, and iron sulfide [4,5]. Under the humid and hot paleoclimate conditions, the iron-bearing rocks of the ancient continent were lateritized and provided a sufficient source of iron, and the colloidal state of iron was transported to the sedimentary area. Seasonal periodic changes in oxidation potential lead to the interactive deposition of iron hydroxide and sandstone. Generally, the acidic rainy climatic conditions are conducive to the formation of ferruginous sandstone [6,7]. It is also noted that a small part of ferruginous sandstone is rich in radioactive elements such as uranium and yttrium [8–13]. Uranium anomalies were found in the ferruginous sandstone of the Wajid Group in southern Saudi Arabia [14,15]. This study is based on field surveys and radiometric ground surveys in the Wajid Group sandstone outcrop and sample testing research to analyze the metallogenic conditions of the uranium, evaluate the uranium potential, and delineate the uranium prospects. The purpose of this paper is to generally summarize the characteristics of the lithology and lithofacies of the ferruginous sandstone and to comprehensively analyze the genetic mechanism of uranium concentration in ferruginous sandstone.

2. Regional Geology

2.1. Regional Geological Settings

The Wajid Group is a Cambrian through Permian siliciclastic succession that is widely exposed in southern Saudi Arabia, over 196,000 km² between Najran in the south and Wadi Ad Dawasir in the north (Figure 1) [16–18]. The total thickness of the Wajid Group is approximately 900 m to 4500 m [19]. Wajid Sandstone is one of the most important groundwater reservoirs and has recently also been an exploration target for hydrocarbons [20–22]. The lithofacies, depositional environments, and stratigraphic architecture of Wajid Sandstone have recently been described and interpreted in detail [23–26].

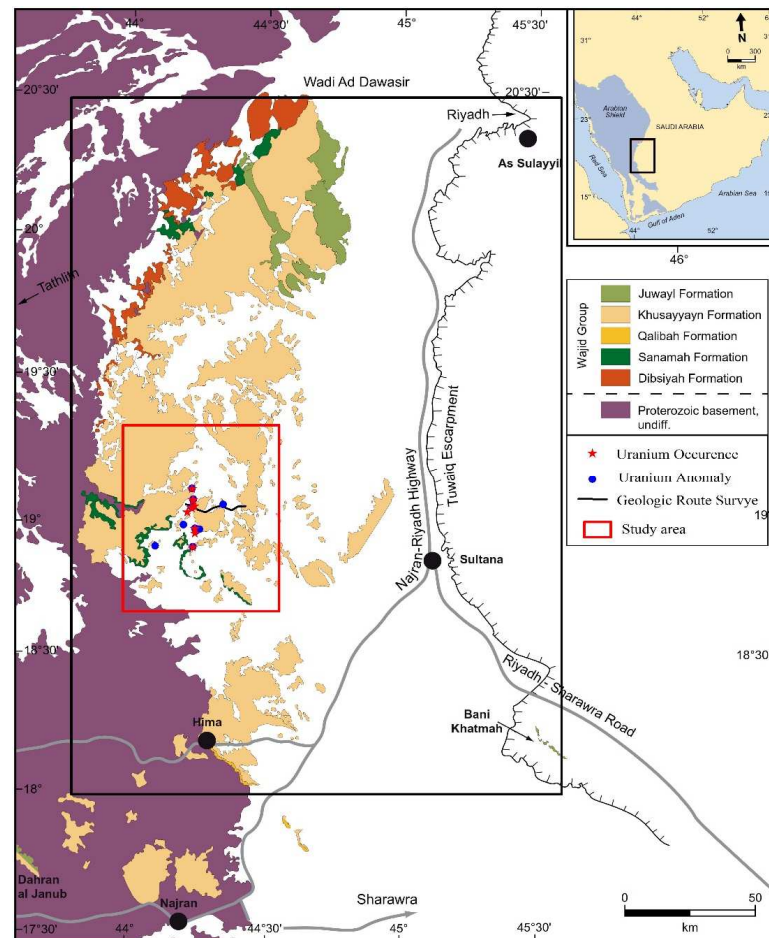


Figure 1. Geological map showing the Location of Wajid Group (after Al Ajmi, 2015 [26]).

The study area is located in the eastern Wajid Basin adjacent to the south margin of the Arabian Shield in southern Saudi Arabia. The Proterozoic basements of Arabian Shield to the west are the possible uranium sources in the study area. The sedimentary cover of the Arabian plate is quite thick, with ages ranging from the infra-Cambrian to the Neogene [27,28]. The rifting of the Arabian Shield resulted in the easterly tilt of the Arabian Shield and the Arabian Platform [16,29,30]. The strata in the Wajid Basin dip eastward from the western basement, and the dip angle is only 1 to 5 degrees [15,31]. The dip angle was beneficial to the posterior transformation of the Wajid Group and provided favorable structural and hydrogeological conditions for the metallogenesis of uranium deposits.

2.2. Wajid Group

The Wajid Group of southern Saudi Arabia was named by Gierhart and Owen in 1948 [32–34]. It unconformably overlaid the Precambrian basement rocks and was overlain by the late Permian Khuff Formation [35,36]. The lithology of the Wajid Sandstone, ranging

in age from the Cambro–Ordovician to the Lower Permian, consists primarily of medium and coarse-grained sandstone. The former research results indicated that the Wajid Group could be divided into five formations: the Dibsiyah Formation, the Sanamah Formation, the Qalibah Formation, the Khusayyayn Formation, and the Juwayl Formation [23,37,38]. Most of these formations are separated by major unconformities (Figure 2).

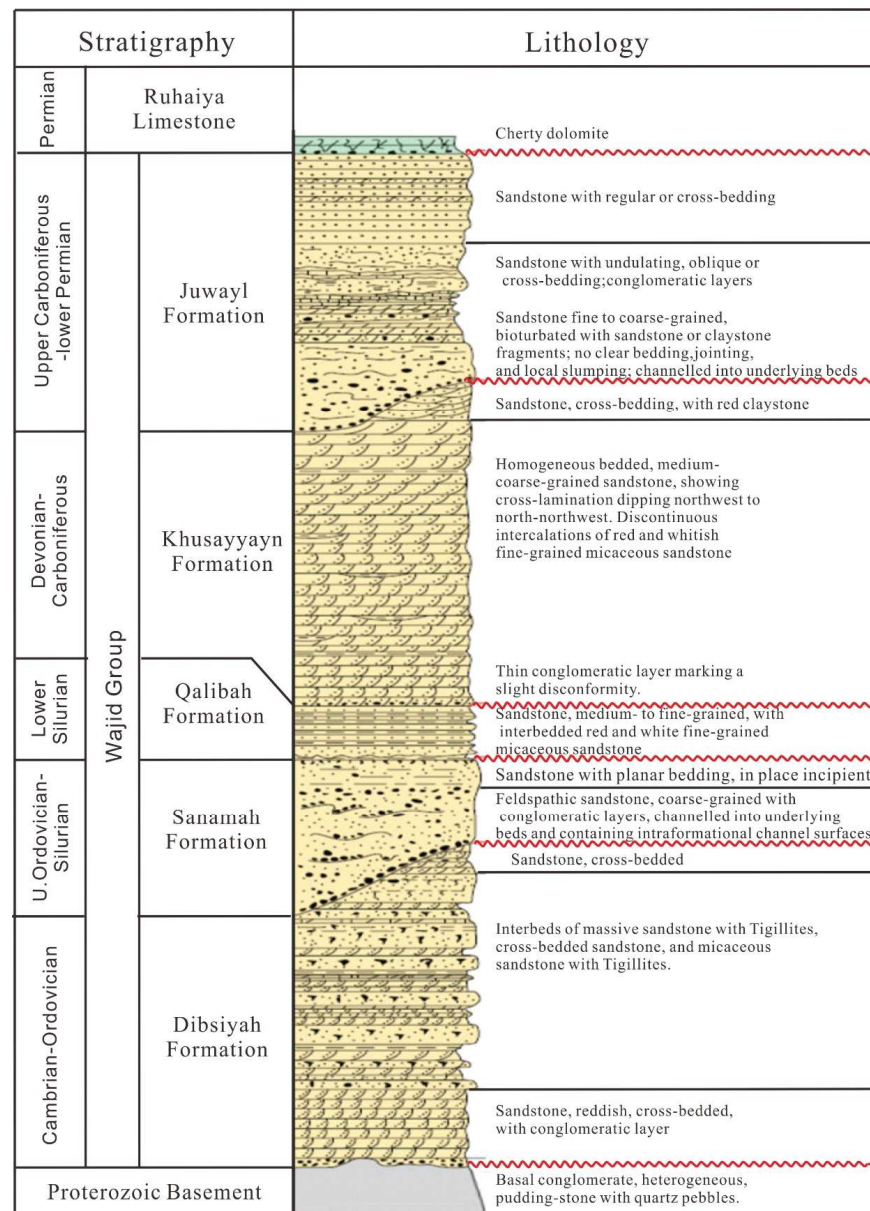


Figure 2. Lithology and sequence stratigraphy of the Wajid Group (Abdulkadir, 2013 [23]).

The lower member of the Dibsiyah Formation is predominantly composed of medium to coarse-grained sandstone, trough cross-bedded sandstone deposited in high-energy braided stream channel environments [36–39]. The Upper Dibsiyah Formation represents a vast sand-sheet complex with the core and margin facies formed under fluvial to shallow-marine conditions. The Sanamah Formation records the Late Ordovician Hirnantian glaciation with coarse sandstones and conglomerates [23,40]. A variety of glacier-induced sedimentary structures are present. The latest of these cycles is overlain by a few meters of marginal-marine sediments of the Qalibah Formation. The Khusayyayn Formation, probably deposited during the Early Devonian, represents a shore environment characterized by the dominance of mega-scale and giant cross-beds and bed sets [41–43]. The Juwayl

Formation of the late Carboniferous was deposited at the interface of the Late Palaeozoic Gondwana ice shield, with a large lake that may have covered most of southern Arabia and the adjacent areas [23,44].

2.3. Ferruginous Sandstone

In the geological field survey, ferruginous sandstone was mainly found in the Khusayyayn Formation and occasionally in the Dibsiyah and Sanamah Formation of the Wajid Group [45,46]. The Khusayyayn Formation is a marine shore deposit, and the lithology is mainly brownish-yellow coarse sandstone, and mudstone is rarely seen in the study area (Figure 3). The thickness of the body of the ferruginous sand is between 1 and 3 m, and it has a massive structure, medium sorted and rounded, with large cross-bedding and parallel bedding [47,48]. The ferruginous sandstone is mainly distributed along the bottom or bedding of the sandstone. It was thin-bedded and lenticular, with a thickness from 0.1 to 1.5 m and a distribution range from 10 to 100 m. The ferruginous sandstone was dense, hard, and water permeable. Uranium anomalies were discovered in the Wajid Group, primarily hosted in the ferruginous sandstone in the Khusayyayn Formation [12,15].

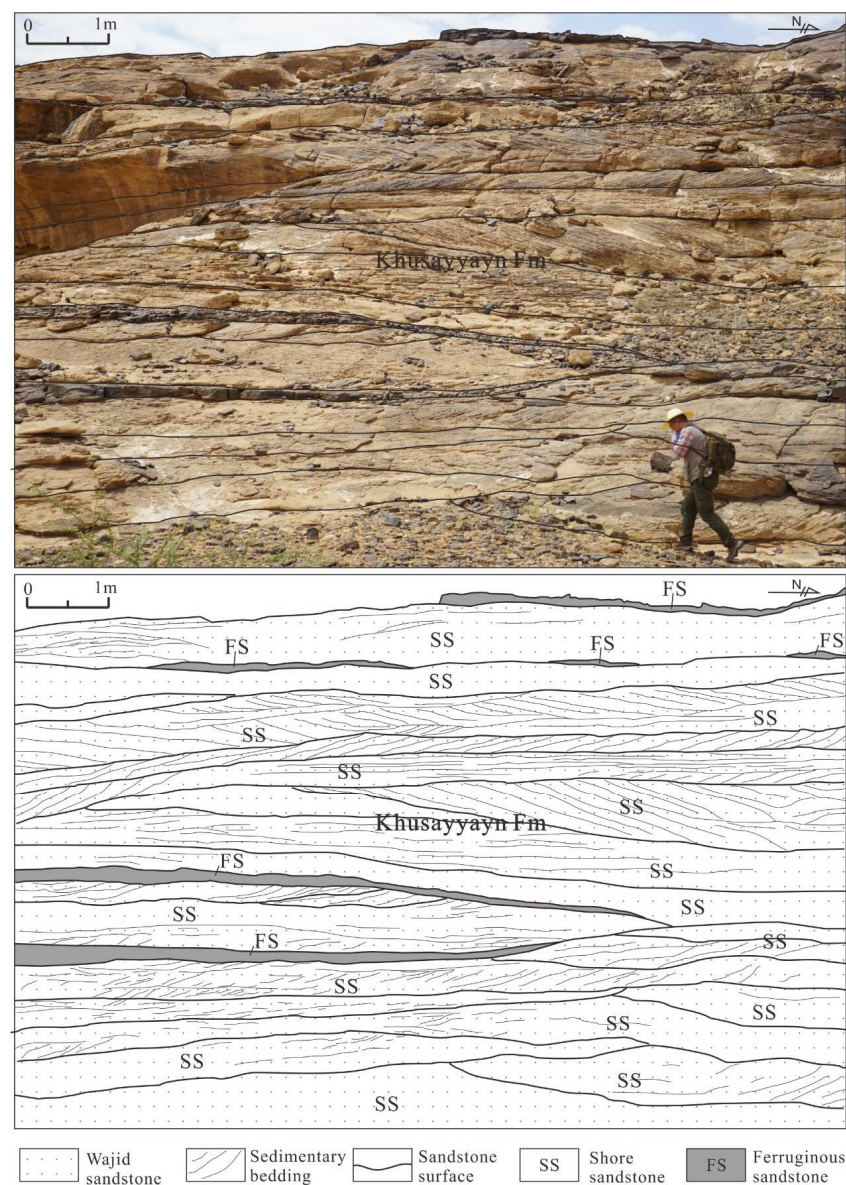


Figure 3. Geological sketch section of the ferruginous sandstone in Khusayyayn Formation of Wajid Group.

3. Sampling and Analytical Methods

Sampling, sample preparation, and chemical analysis were conducted at the Analytical Laboratory of Beijing Research Institute of Uranium Geology (ALBRIUG) in China strictly in accordance with laboratory standards, ensuring the accuracy and precision of the assay.

3.1. Sampling and Sample Preparation

The surface samples of the ferruginous sandstone were collected randomly from the Wajid Sandstone for chemical assay by two of the authors of this article, Dr. Feng He and Xide Li in 2017. The fresh samples were photographed, packed into special cloth bags, and then labeled with the sample codes.

The weathered surfaces were cut and removed, and the samples were then ground to less than 200 meshes with an agate mortar. The dry and coarsely crushed samples were put into a jaw crusher (Retsch BB250XL) and ground until they were less than 4 mm (70% passed through a 4-mm sieve). The samples less than 4 mm were processed in a disk mill (Retsch DM200) and ground to less than 1 mm (95 wt.% passed through a 1-mm sieve). After this process, the quartering milled samples of less than 1 mm were further pulverized with a pollution-free planetary ball mill (Retsch DM400) to 75 μm (85% passed through a 75 μm sieve) and split by quartering. The milled samples were slowly put into disposable plastic bottles with a small, clean plastic spoon. After one sample was processed, fresh quartz sand was used to wash the containers used in the processing.

3.2. Analytical Methods

(1) Petrography

Veins filled with organic matter, pyrite, and clay minerals that were produced by the thin polished sections, were selected for petrographic and mineralogical studies using optical microscopy (transmitted and reflected light) and scanning electron microscopy (SEM) in the backscattered electron mode equipped with an energy dispersive X-ray spectrometer (EDS). The SEM-EDS uses a Nova Nano SEM450\ TESCAN-VEGA\ LMU SEM with a LINK-ISISX alpha particle spectrometer. The SEM analysis was operated at 15 kV in 150 high-vacuum modes, with manual aperture and 4.5 beam spot sizes. All of the SEM thin sections were coated with thin carbon to ensure surface conductivity.

(2) Geochemical composition

The chemical compositions of the selected grains under the thin sections were determined using a JXA-8100 electron microprobe analysis (EMPA). The analytical conditions were a 15 kV acceleration voltage, a 20 nA probe current, a 1~5 microns beam diameter depending on the grain size, a 10 s counting time for the major elements, 20 s for the minor elements, and 40 s for the trace elements.

The samples were powdered below 200 meshes in an agate mill for the whole-rock geochemical composition analysis. The major compositions were measured using AB104L X-ray Fluorescence (XRF) on fused glass beads, and the particular experiment procedures are referred to in reference [49,50]. The trace element compositions were analyzed using the Nexion 300d plasma mass spectrometer (ICP-MS); the detailed steps are illustrated in reference [51–55]. The chemical assay only qualified if the relative standard variation (GBW04131, GBW04132, GBW04133) between the duplicate samples was less than 5% and the accuracy of the CRM was greater than 99.9%.

(3) U and Pb isotope and dating

The U and Pb isotopes were analyzed using an ISOPROBE-T Thermal Ionization mass spectrometer (TIMS). The samples were crushed and milled to fine-grained sand before splitting with a micro splitter to yield representative 5 g fractions for dissolution. The approach of Ludwig et al. (1985) was used in that all of the samples were completely dissolved in hot HF-HNO₃-HClO₄ at 1 atm before small (2–20 μL) liquid aliquots of the 50 mL total solution were employed for U and Pb purification using conventional HBr (Pb) and HNO₃ (U) ion exchange column techniques [56]. The U and Pb concentrations within the aliquots were determined by isotope dilution mass spectrometry before the isotopic compositions

were determined using TIMS. The Pb isotope ratios were corrected for mass discrimination and laboratory blanks, and the uncertainties vary somewhat from sample to sample but are on average 0.01% (on a 2σ basis) for $^{206}\text{Pb}/^{204}\text{Pb}$, $^{207}\text{Pb}/^{204}\text{Pb}$, and $^{208}\text{Pb}/^{204}\text{Pb}$, and $\sim 0.15\%$ for $^{238}\text{U}/^{204}\text{Pb}$ and $^{235}\text{U}/^{204}\text{Pb}$. The acceptable precision for Certified Reference Material (CRM) analyses is $^{208}\text{Pb}/^{204}\text{Pb} = 36.690 \pm 0.004$, $^{207}\text{Pb}/^{204}\text{Pb} = 15.489 \pm 0.001$, and $^{206}\text{Pb}/^{204}\text{Pb} = 16.936 \pm 0.002$ (for NBS9810) and $^{235}\text{U}/^{238}\text{U} = 1.022220 \pm 0.00015$ (for UTB500) [55,57]. Uncertainties and error correlations for the blank-corrected isotope ratios (all blank corrections were negligible) and the resulting concentrations were determined using the equations of Ludwig (1980, 1984) [58,59]. All of the uncertainties are given at the 95% confidence level, and the ore isotopic ratios ($^{206}\text{Pb}/^{238}\text{U}$ and $^{207}\text{Pb}/^{235}\text{U}$) were used to estimate ages using ISOPLOT [60].

Ra226 was conducted on the GMX-50A-Plus High-Purity Germanium Gamma Spectrometer by the standard of GB/T 11743_2013 (Determination of radionuclides in soil by gamma spectrometry).

All of these experiments above were performed at the Geological Analysis and Testing Center, Beijing Research Institute of Uranium Geology (BRIUG), Beijing, China.

4. Results

4.1. Ferruginous Sandstone Petrological Identification

Ferruginous sandstone was primarily found in the Khusayyayn Formation. The lithology is mainly dark grey, black, purple, or brownish-yellow coarse ferruginous sandstone (Figure 4a,d,g). The clastic particles of the ferruginous sandstone were sub-angular, and the cementation mode was primarily contact cementation (Figure 4b,e,h). The clastic materials mainly primarily consisted of quartz, minor feldspar, other heavy minerals, and some organic carbon, mainly containing silicon (Figure 5c). The mainly interstitial material was hematite, limonite, goethite, and a small number of manganese oxides (Figure 4b,c,f,h,i), concentrated with a large number of iron elements (Figure 5a,b). The scanning images of uranium and ferric ions in the electron probe image are consistent with each other (Figure 5a,d). The ferrous oxide observed by SEM in the ferruginous sandstone of the Wajid Group was granular (Figure 6a,c,d), filamentous (Figure 6b), and spherical ferrous oxide aggregate (Figure 6c).

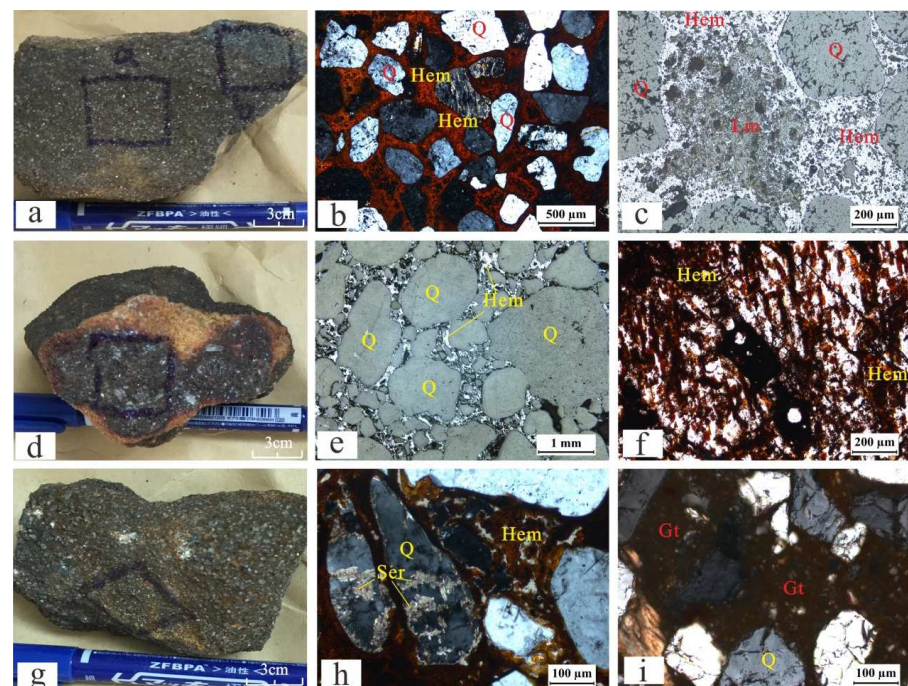


Figure 4. Ferruginous sandstone lithology and alteration features in Wajid Sandstone. (a–c) Y5.1/SR08:

Dark grey coarse ferruginous sandstone. Ferrous cemented quartz sandstone: Quartz is the main mineral particle that contains a small amount of feldspar, hematite, and limonite filling the space between mineral particles. (d–f) Y5.1/SR07: Dark grey and brownish-yellow gravel-bearing coarse ferruginous sandstone. Quartz is the main mineral particle, with a gravel structure. Hematite primarily fills the spaces between the mineral particles and occurs in the intergranular pore and intragranular dissolved pores. (g–i) Y5.1/SR06: Dark grey coarse ferruginous sandstone. Hematite can be seen in the sandstone. Sericite alteration occurs on the surface of the feldspar particles, and goethite fills the spaces between the mineral particles. Q—quartz; Hem—hematite; Lm—limonite; Ser—sericite; Gt—goethite.

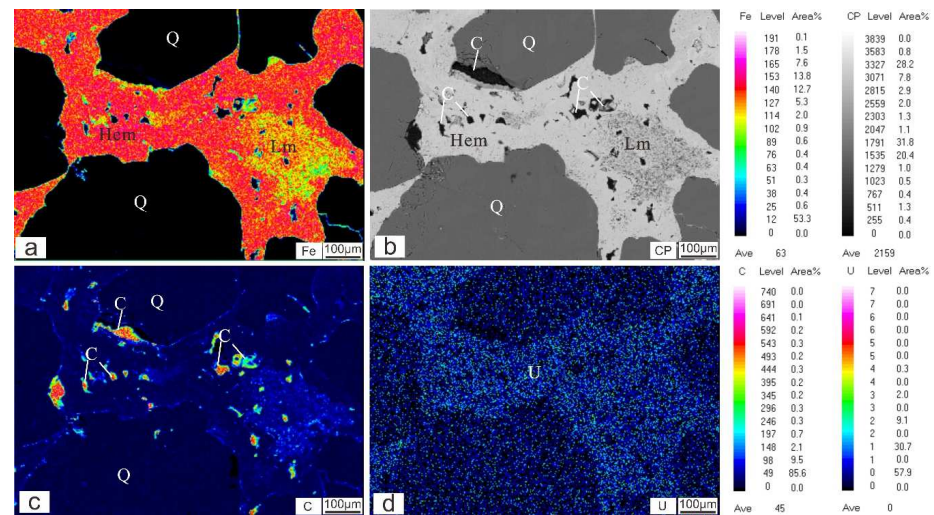


Figure 5. Element distribution of ferruginous sandstone in Wajid Group (Y5.1/SR08). (a) Distribution map of iron element content, including hematite in red area with high iron concentration and limonite with micropores in yellow area; (b) Cathodoluminescent photograph of sample; (c) Distribution map of organic matters; (d) Distribution map of uranium. Q—quartz; Hem—hematite; Lm—limonite; C—organic carbon; U—uranium.

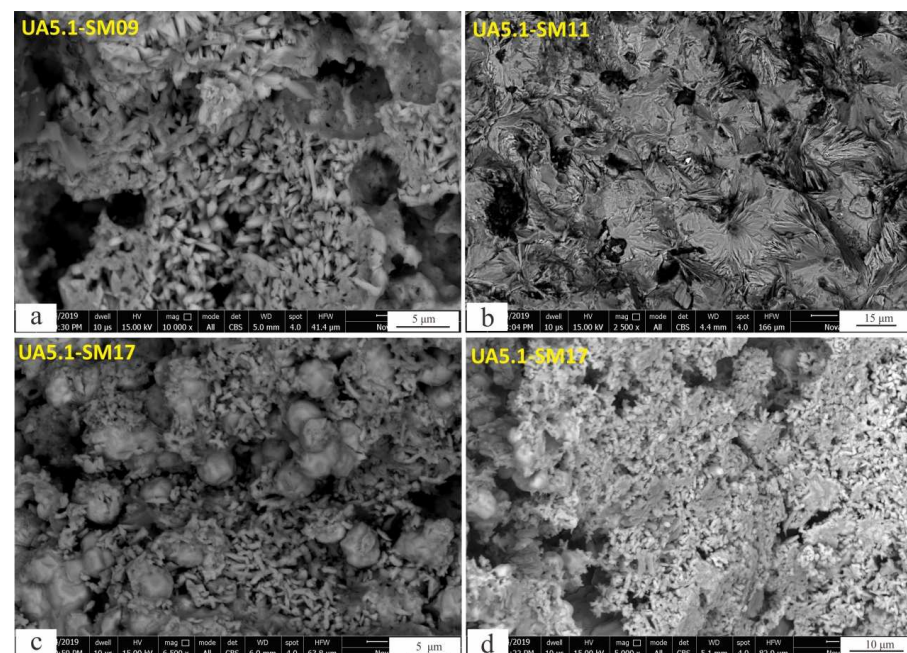


Figure 6. SEM characteristics of ferruginous sandstone of Wajid Group. (a) UA5.1/SM09: granular ferrous oxide aggregate; (b) UA5.1/SM11: filamentous ferrous oxide; (c) UA5.1/SM17: spherical and granular ferrous oxide aggregate; (d) UA5.1/SM17: granular ferrous oxide aggregate.

4.2. Ferruginous Sandstone Chemical Characteristics

(1) Major element content

The SiO₂ content of ferruginous sandstone ranges between 6.67 wt.% and 81.35 wt.% with an average value of 56.73 wt.%. The Fe element in the Wajid ferruginous sandstone basically exists in the form of ferric iron, with Fe₂O₃ content of 12.04~84.97 wt.% and an average content of 28.95 wt.%. The content of FeO is mostly lower than 0.1 wt.% and the highest content is only 0.64 wt.%. The manganese content of some ferruginous sandstone is also high, with an average MnO content of 0.85 wt.% and a maximum of 3.43 wt.% (Table 1).

(2) Organic carbon and sulfur

The organic carbon and sulfur analyses showed that the average content of organic carbon was 0.067 wt.%, and the average sulfur content was 0.045 wt.%. The content of the organic carbon in ferruginous sandstone is not different from other sandstones, with an average of 0.0588 wt.%; the content of sulfur increased significantly, with an average of 0.0672 wt.% (Table 2). The content of sulfur displayed a good correlation coefficient with the uranium content. It indicates that sulfur, as one of the reduce matters, plays a significant role in the concretion of uranium, and the sulfur was always disseminated in the hematite matrix.

(3) pH and Eh

The pH value of the Wajid sandstone in the study area was between 8.49 and 9.80, with an average value of 8.98. This indicated a weak alkaline environment (Table 2). The Eh value was between 192 and 251 mV, and the average value was 226.45 mV. The average pH of the ferruginous sandstone was 8.61, with a higher Eh of 246.25 mV. It was concluded that the Wajid Sandstone, which included the ferruginous sandstone, was in an alkaline oxidation environment.

4.3. Ferruginous Sandstone Uranium Anomaly

(1) Uranium content

The uranium anomaly is only found in the part of the ferruginous sandstone of the Khusayyayn Formation. Uranium anomalies were re-checked or newly discovered within the zonal distribution from north to south in the study area (Figure 7). The anomalies were hosted in ferruginous sandstone, with a uranium content ranging from 50 to 766 ppm in the Khusayyayn Formation of the Wajid Group. The economic value of uranium resources is relatively poor since the uranium anomaly hosted in the thin-bedded and lenticular ferruginous sandstone is less than 1.5 m in thickness and less than 100 m in length. Furthermore, metallurgical tests confirmed that uranium, trapped mainly in the lattice of hematite and goethite, is not easily leachable using conventional methods. Because the uranium anomaly is distributed in the uninhabited area, the uranium content is not particularly high, and its radioactivity has little impact on the environment.

(2) Ra content

The results of the U and Ra contents in subarea 5.1 were preliminarily analyzed, and the U-Ra equilibrium coefficient (Kp) was calculated. Overall, the Kp was relatively stable and was between 0.87 and 1.12, with an average of 0.96. The average Kp value of the ferruginous sandstone was 1.00, and only a small amount of uranium loss or concentration existed. This result indicates that uranium in the ferruginous sandstone was weakly reformed after the uranium concentration. The Kp of the yellow sandstone was less than 1.00, indicating that there was uranium loss in the yellow sandstone at a late stage (Table 3).

Table 1. Contents of major elements (in wt.%) and U, Th (in ppm) in ferruginous sandstone of Wajid Group.

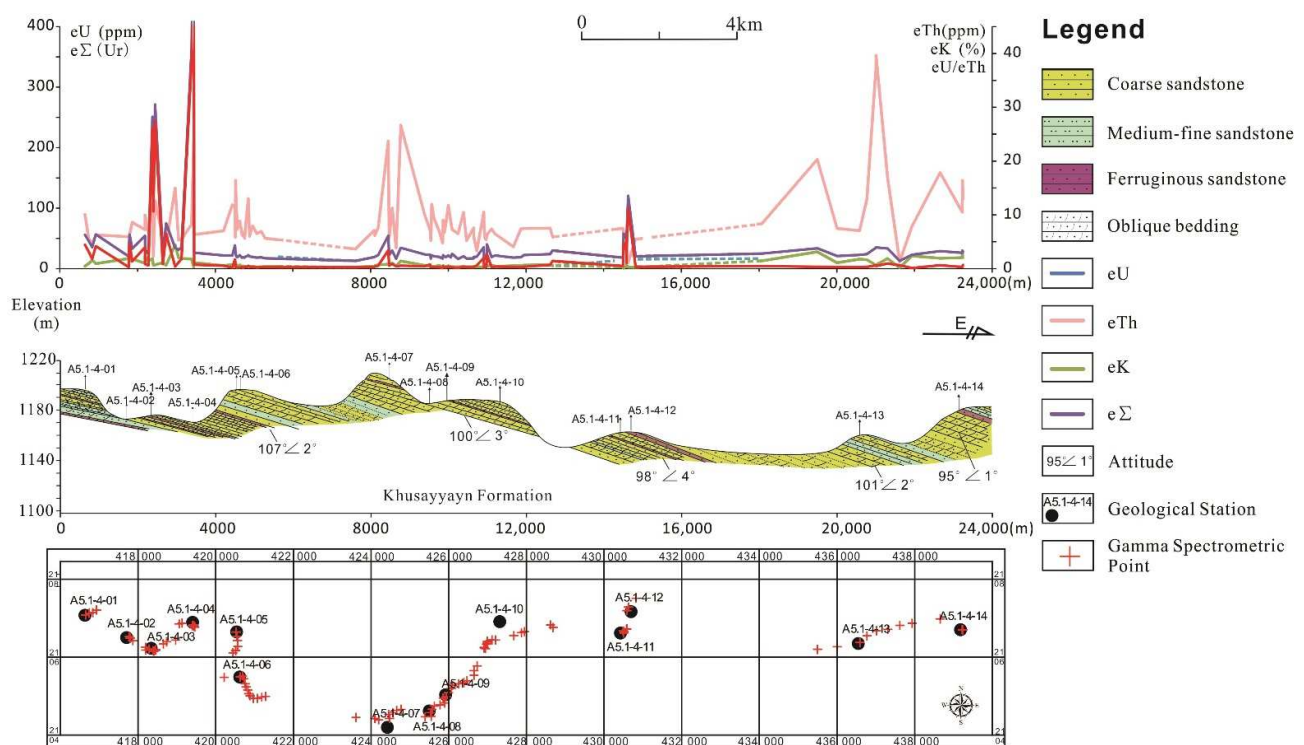
Sample Number	Coordinates			Test Results													
	Longitude	Latitude	Elevation	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	MgO	CaO	Na ₂ O	K ₂ O	MnO	TiO ₂	P ₂ O ₅	LOI	FeO	Th	U
A5.1/SR01	44°14'13.08"	18°58'24.82"	1312	57.80	1.06	31.67	0.18	1.24	0.04	0.22	1.18	0.05	0.22	5.76	<0.10	1.09	107
A5.1/SR02	44°13'42.80"	19°04'30.19"	1312	59.96	1.47	27.89	0.23	2.72	0.06	0.34	0.11	0.06	0.22	6.36	<0.10	1.03	67.4
A5.1/SR05	44°13'50.24"	19°04'28.00"	1184	61.97	2.02	22.85	0.22	3.78	0.03	0.25	1.72	0.11	0.18	6.27	<0.10	1.68	374
A5.1/SR06	44°13'50.25"	19°03'09.06"	1167	63.15	1.51	21.91	0.24	4.29	0.02	0.26	1.43	0.07	0.12	6.44	<0.10	2.13	40.7
A5.1/SR07	44°14'13.08"	18°58'24.8"	1194	64.11	1.07	26.70	0.25	1.41	0.03	0.26	0.59	0.05	0.26	4.72	<0.10	1.39	237
A5.1/SR08	44°14'32.37"	18°57'51.03"	1217	72.67	1.86	17.96	0.16	1.64	0.10	0.25	0.23	0.07	0.12	4.40	<0.10	2.96	76.3
A5.1/SR09	44°16'59.87"	18°57'29.95"	1249	51.89	1.44	32.91	0.30	3.42	0.03	0.29	1.28	0.05	0.13	7.70	<0.10	2.84	10.8
H5.1/SR06	44°13'42.80"	19°04'30.19"	1312	61.77	1.11	27.22	0.20	2.57	0.04	0.26	0.15	0.05	0.22	5.87	<0.10	1.41	52.5
H5.1/SR07	44°13'50.24"	19°04'28.00"	1184	59.90	1.48	22.99	0.18	5.65	0.02	0.24	1.80	0.09	0.19	6.87	<0.10	1.75	766
H5.1/SR08	44°13'50.26"	19°03'09.07"	1167	62.97	0.68	23.29	0.19	3.67	0.02	0.14	1.98	0.04	0.19	6.28	<0.10	3.89	48.5
H5.1/SR09	44°14'13.08"	18°58'24.8"	1194	60.30	1.07	29.69	0.15	0.58	0.04	0.30	2.24	0.06	0.21	4.82	<0.10	1.40	176
W5.1/SR01	44°14'32.33"	18°59'50.22"	1202	58.46	1.42	23.02	0.13	6.22	0.05	0.34	2.23	0.06	0.09	7.76	<0.10	2.33	6.1
W5.1/SR03	44°13'42.80"	19°04'30.19"	1312	60.84	1.49	28.67	0.21	1.95	0.05	0.44	0.09	0.09	0.21	5.77	0.45	11.50	58.6
W5.1/SR04	44°13'50.24"	19°04'28.00"	1184	61.32	1.91	24.63	0.21	3.35	0.07	0.23	1.35	0.11	0.19	6.39	<0.10	2.86	279
W5.1/SR05	44°13'50.24"	19°03'09.05"	1167	62.99	1.52	20.99	0.15	4.67	0.04	0.27	2.67	0.08	0.08	6.35	<0.10	3.91	36.1
UA5.1/SM01	44°13'34.02"	19°06'47.58"	1164	41.27	18.22	29.82	0.24	0.28	0.07	0.54	0.02	1.08	0.39	7.80	0.28	18.10	86.9
UA5.1/SM02	44°13'34.02"	19°06'47.58"	1164	75.43	2.13	16.98	0.35	1.28	0.05	0.13	0.05	0.12	0.16	3.29	0.27	6.67	73.7
UA5.1/SR03	44°10'20.57"	19°26'08.40"	1153	6.67	2.92	84.97	0.08	0.37	0.02	0.07	0.03	0.15	0.71	3.98	0.29	6.31	92.5
UA5.1/SM04	44°14'13.21"	18°57'28.52"	1216	59.57	1.57	32.23	0.11	0.34	0.04	0.46	1.19	0.05	0.13	4.17	<0.10	2.68	39
UA5.1/SM05	44°12'31.04"	19°01'54.38"	1221	68.68	2.32	24.86	0.15	0.69	0.05	0.61	0.07	0.06	0.13	2.29	0.33	1.91	215
UA5.1/SM06	44°12'31.04"	19°01'54.38"	1221	50.65	14.08	23.43	0.18	0.87	0.09	1.81	0.03	0.65	0.20	7.80	0.41	16.70	73.9
UA5.1/SM07	44°12'31.04"	19°01'54.38"	1221	55.94	12.17	22.58	0.25	0.24	0.05	0.71	0.03	0.78	0.14	7.05	0.27	10.80	163
UA5.1/SM08	44°12'27.85"	19°03'17.79"	1173	70.44	2.19	14.22	0.16	5.27	0.04	0.42	0.05	0.21	0.10	6.83	0.39	5.24	36.8
UA5.1/SM09	44°13'27.85"	19°03'17.79"	1173	39.86	6.53	38.63	0.16	1.17	0.09	1.57	3.43	0.45	0.29	7.52	<0.10	6.93	210
UA5.1/SR06	44°13'27.85"	19°03'17.79"	1173	71.08	7.13	12.12	0.10	0.56	0.13	1.97	2.51	0.49	0.05	3.82	<0.10	1.48	7.71
UA5.1/SM10	44°13'27.85"	19°03'17.79"	1173	60.97	0.75	22.31	0.22	6.22	0.03	0.16	1.08	0.04	0.28	7.81	<0.10	2.20	183
UA5.1/SM11	44°14'01.95"	19°03'08.99"	1158	59.35	0.98	31.07	0.18	1.37	0.05	0.07	0.66	0.09	0.58	4.49	<0.10	1.03	320

Table 1. Cont.

Sample Number	Coordinates			Test Results													
	Longitude	Latitude	Elevation	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	MgO	CaO	Na ₂ O	K ₂ O	MnO	TiO ₂	P ₂ O ₅	LOI	FeO	Th	U
UA5.1/SM12	44°16′43.75″	19°01′51.87″	1181	10.38	3.67	70.00	0.38	2.21	0.05	0.23	0.41	0.18	0.25	12.14	<0.10	5.90	58.2
UA5.1/SM13	44°20′21.78″	19°03′06.45″	1141	59.58	1.56	31.55	0.15	1.64	0.03	0.12	0.15	0.07	0.14	4.95	0.46	4.04	11.9
UA5.1/SM15	44°20′26.45″	19°03′25.95″	1137	48.39	0.89	44.66	0.16	2.31	0.02	0.04	0.05	0.02	0.14	3.28	0.64	2.42	642
UA5.1/SM16	44°05′23.54″	18°54′46.68″	1324	81.39	0.76	12.04	0.12	1.72	0.03	0.08	0.30	0.09	0.08	3.35	0.36	2.28	51.9
UA5.1/SM17	44°13′47.42″	18°54′32.57″	1254	50.15	9.05	26.42	0.18	3.76	0.10	1.24	0.35	0.33	0.11	8.14	0.41	17.30	365
UA5.1/SM18	44°13′47.42″	18°54′32.57″	1254	43.91	6.93	33.87	0.36	3.75	0.17	1.28	0.13	0.29	0.13	8.67	<0.10	17.00	627
UA5.1/SR28	44°13′25.24″	18°56′20.08″	1239	37.13	14.86	38.34	0.21	0.33	0.04	0.45	0.01	0.84	0.75	6.62	0.46	18.20	39.1
UA5.1/SR33	44°04′45.93″	18°47′43.83″	1352	74.60	0.55	20.92	0.08	0.34	0.02	0.02	0.09	0.10	0.46	2.80	0.55	1.62	4.34

Table 2. pH and Eh values of sandstone in the Khusayyayn Formation in study area.

Sample Number	Longitude	Latitude	Lithology Name	U (ppm)	Organic Carbon (wt.%)	S (wt.%)	pH	Eh (mV)
H5.1/SR01	44°14'31.38"	20°13'35.46"	Yellow sandstone	1.44	0.058	0.006	9.29	192
H5.1/SR02	44°14'31.38"	20°13'35.46"	Gray sandstone	26.3	0.081	0.029	9.25	206
H5.1/SR03	44°14'32.33"	18°59'50.22"	Light yellow sandstone	2.07	0.094	0.011	9.24	205
H5.1/SR04	44°14'13.08"	18°58'24.82"	Yellow sandstone	11.1	0.078	0.015	9.80	226
H5.1/SR05	44°13'17.90"	19°04'20.03"	Yellow sandstone	3.9	0.061	0.125	8.68	236
H5.1/SR06	44°13'42.80"	19°04'30.19"	Black ferruginous sandstone	52.5	0.069	0.057	8.56	245
H5.1/SR07	44°13'50.24"	19°04'28.00"	Black ferruginous sandstone	766	0.060	0.075	8.69	241
H5.1/SR08	44°13'50.26"	19°03'09.07"	Brownish ferruginous sandstone	48.5	0.054	0.059	8.69	248
H5.1/SR09	44°14'13.08"	18°58'24.80"	Black ferruginous sandstone	176	0.052	0.078	8.49	251
H5.1/SR10	44°30'03.44"	20°21'44.12"	Gray sandstone	0.945	0.062	0.024	9.10	224
H5.1/SR11	43°57'19.82"	19°25'54.81"	Red sandstone	1.65	0.064	0.014	9.03	217

**Figure 7.** Profile location plan and geological section of Wajid Sandstone with ground radiometric surveys profiles.**Table 3.** U-Ra equilibrium coefficient table in study area.

Sample Number	Longitude	Latitude	Lithology Name	U (μg/g)	Ra (Bq/g)	Kp	Up (μg/g)
A5.1/SR01	44°14'13.08"	18°58'24.82"	Yellow ferruginous sandstone	107.00	1.296	0.98	104.43
A5.1/SR02	44°13'42.80"	19°04'30.19"	Black ferruginous sandstone	67.40	0.892	1.07	71.88
A5.1/SR03	44°13'42.80"	19°04'30.19"	Yellow sandstone	2.95	0.036	0.99	2.93

Table 3. Cont.

Sample Number	Longitude	Latitude	Lithology Name	U (μg/g)	Ra (Bq/g)	Kp	Up (μg/g)
A5.1/SR04	44°13'42.80"	19°04'30.19"	Yellow sandstone	3.24	0.035	0.87	2.80
A5.1/SR05	44°13'50.24"	19°04'28.00"	Black ferruginous sandstone	374.00	4.334	0.93	349.23
A5.1/SR06	44°13'50.25"	19°03'09.06"	Black ferruginous sandstone	40.70	0.482	0.95	38.84
A5.1/SR07	44°14'13.08"	18°58'24.8"	Black ferruginous sandstone	237.00	2.607	0.89	210.07
A5.1/SR08	44°14'32.37"	18°57'51.03"	Yellow ferruginous sandstone	76.30	0.826	0.87	66.56
A5.1/SR09	44°16'59.87"	18°57'29.95"	Yellow ferruginous sandstone	10.80	0.118	0.88	9.51
A5.1/SR10	44°13'17.90"	19°04'20.03"	Black ferruginous sandstone	3.49	0.044	1.03	3.58
A5.1/SR11	44°16'59.90"	18°57'29.90"	Black ferruginous sandstone	3.21	0.045	1.12	3.60

4.4. Ferruginous Sandstone Uranium Minerals

(1) Uranium minerals

The EPMA result of the ferruginous sandstone shows that there are two main existing forms of uranium in the study area (Figure 8, Table 4): (1) Part of the uranium minerals are found in the residual heavy mineral. The accessory minerals are primarily zircon, tourmaline, monazite, and barite. (2) The uranium minerals that occur in fissures of quartz, gypsum, and other debris particles displayed star shapes and banded bands. Small amounts of uranium minerals appear to be adsorbed dispersedly by ferruginous cementation, organic matter, pyrite and argillaceous cementation. It was found that the uranium exists in the form of pitchblende, and some REE was found using SEM in the ferruginous sandstone in the study area.

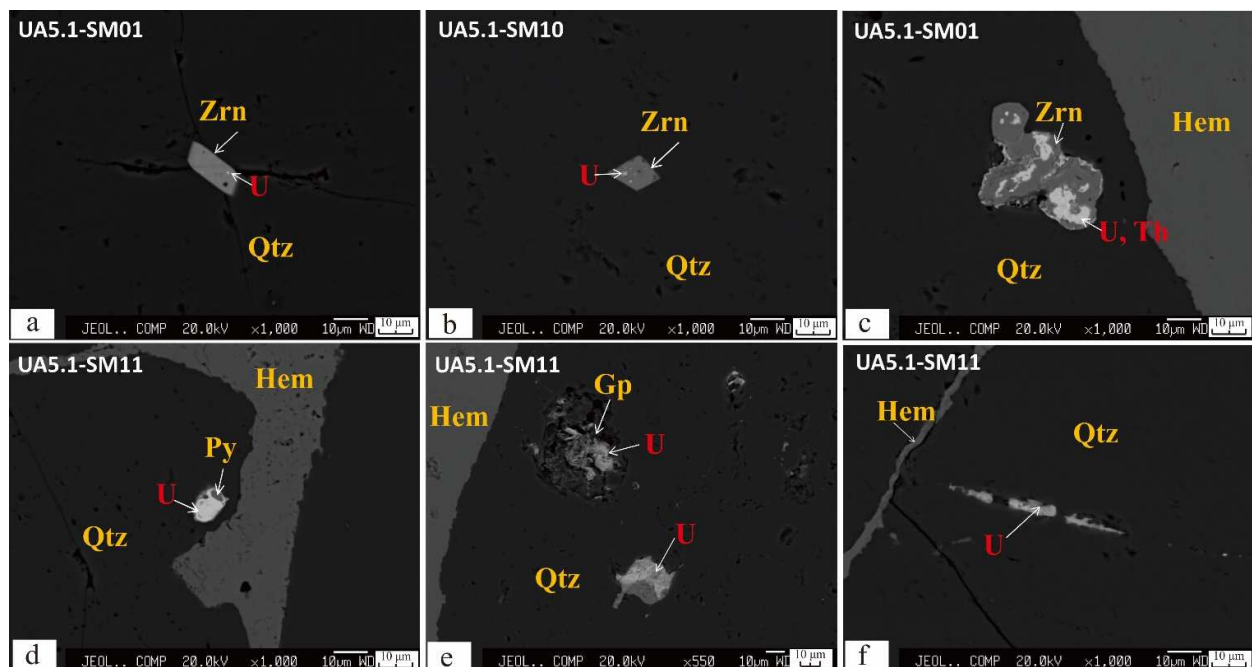


Figure 8. Existence form of uranium minerals in the Wajid Sandstone. (a,b) Zircon minerals contain a small amount of uranium; (c) Uranium and thorium are wrapped in zircon; (d) Uranium is adsorbed by pyrite on the surface of quartz; (e,f) Uranium occur in fissures of gypsum and quartz. Qtz—quartz; Zrn—zircon; U—uranium; Th—thorium; Hem—hematite; Py—pyrite; Gp—gypsum.

Table 4. Contents of elements (in wt.%) of EPMA data in ferruginous sandstone.

Sample Number	Test Results (wt%)												
	Test Point	Y ₂ O ₃	SiO ₂	FeO	UO ₂	MgO	Na ₂ O	TiO ₂	ThO ₂	As ₂ O ₅	Al ₂ O ₃	MnO	PbO
UA5.1/SM01	1	1.15	12.57	0.18	22.83	/	/	/	51.96	/	/	0.13	0.15
	2	/	29.66	0.19	10.81	/	/	/	7.67	0.07	/	0.06	1.16
UA5.1/SM 10	1	1.03	25.01	0.28	5.77	0.04	0.49	/	30.67	/	0.69	/	0.86
UA5.1/SM 11	1	0.19	1.38	1.83	87.86	/	1.04	0.61	/	/	/	1.33	0.28
	2	/	13.41	1.91	60.58	0.14	0.08	0.16	/	0.16	0.04	/	/
	3	/	30.08	2.14	48.46	0.07	0.14	/	/	/	0.01	0.24	/
	4	/	1.20	1.19	91.18	/	0.19	/	/	/	0.07	1.02	0.14
	5	0.30	3.72	2.42	82.09	0.06	1.19	0.16	/	0.29	0.03	0.58	0.28
Sample Number	Test Results (wt%)												
	Test point	V ₂ O ₃	K ₂ O	Nd ₂ O ₃	CaO	Ce ₂ O ₃	SO ₃	La ₂ O ₃	ZrO ₂	Pr ₂ O ₃	P ₂ O ₅	SnO ₂	Total
UA5.1/SM01	1	0.08	0.30	/	0.18	/	/	/	0.23	/	1.88	/	91.64
	2	/	/	/	/	0.30	0.04	0.25	44.26	0.13	1.61	/	96.21
UA5.1/SM 10	1	0.11	0.19	/	0.09	/	/	/	27.21	0.08	0.91	/	93.43
UA5.1/SM 11	1	/	0.26	/	1.38	0.35	0.12	/	0.74	/	1.43	/	98.80
	2	/	1.50	0.26	11.67	/	8.63	/	0.15	0.05	0.27	/	99.01
	3	/	0.51	/	3.55	/	0.09	/	0.15	/	0.60	/	86.04
	4	/	0.20	/	0.55	/	/	0.37	/	/	1.21	/	97.32
	5	/	0.29	/	1.26	0.22	1.48	/	0.47	/	2.73	/	97.57

(2) U-Pb dating

The U-Pb dating data of the ferruginous sandstone indicated that the primary metallogenic age of the uranium is 22.58 ± 0.47 Ma (Figure 9, Table 5). This demonstrated that most of the uranium in the ferruginous sandstone was reformed during a later stage because the age of the mineralization was significantly younger than the age of the host rocks. The uranium mineralization primarily formed in the sedimentary and diagenetic stage and it was concentrated in the later stage. The uranium mineralization age of the later stage occurred during the Neogene.

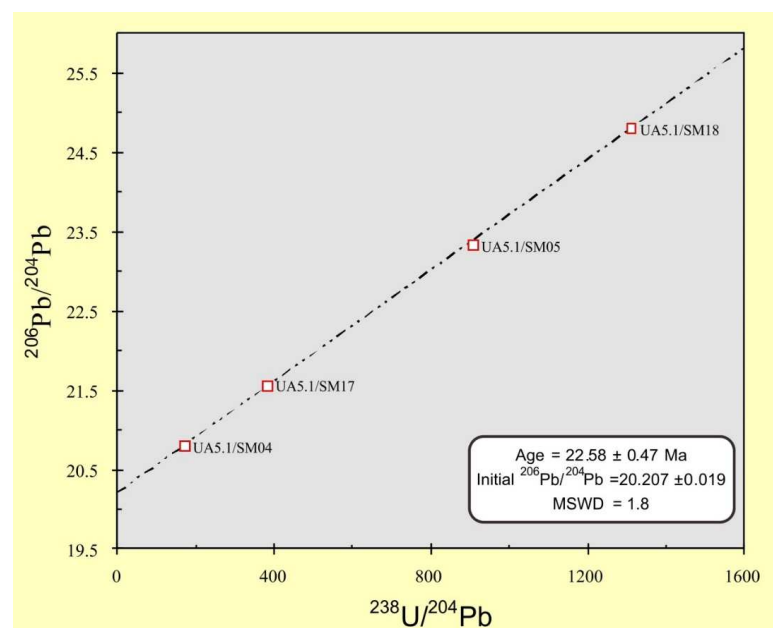
**Figure 9.** Uranium metallogenic age of the ferruginous sandstone.

Table 5. Isochron age of U and Pb of ferruginous sandstone in Wajid Basin.

Sample Number	U ($\mu\text{g/g}$)	Pb ($\mu\text{g/g}$)	$^{238}\text{U}/^{204}\text{Pb}$	$^{208}\text{Pb}/^{204}\text{Pb}$	$^{207}\text{Pb}/^{204}\text{Pb}$	$^{206}\text{Pb}/^{204}\text{Pb}$
UA5.1/SM01	86.9	37.3	160.655	39.767	16.113	23.003
UA5.1/SM04	39	15.5	170.314	39.135	15.956	20.803
UA5.1/SM05	215	16.3	906.008	39.054	16.123	23.333
UA5.1/SM10	183	21.0	625.821	39.128	16.274	26.766
UA5.1/SM11	320	29.5	977.673	39.232	17.347	46.660
UA5.1/SM17	365	64.4	380.684	39.115	16.034	21.565
UA5.1/SM18	627	33.5	1309.290	39.014	16.197	24.807

5. Discussions

5.1. Genesis of Ferruginous Sandstone

Ferruginous sandstone was primarily found in the Khusayyayn Formation. The primary type of cementation was basal cementation, showing that the ferrous cements were primarily formed during the syndiagenetic stage. Occasional porous cementation indicated that the period of the cements was not later than the later diagenetic stage. Ferrous cements of the sandstone were mainly goethite aggregates transformed from limonite. Cracks occurred in the rocks after the early diagenetic stage, and calcium veins filled the cracks. Veins cut through the quartz mineral particles, or surrounded the particles, or were found at the enlarged edges of the particles. After the calcium cementation, limonite and goethite transformed into hematite, and the hematite replaced the calcium cements. Hence, the residual calcium cements appear as rhino horn-like residues.

The formation period of the ferruginous sandstone was in the early synsedimentary and later diagenesis stage in the study area. The ferruginous concretion was found to be formed in the sedimentary period, with an eU content of 30–40 ppm (Figure 10a,b). The preconcentration of uranium existed in the synsedimentary stage, later transformed with the highest eU content of 341.74 ppm (Figure 10c). Part of ferruginous sandstone formed in the later diagenesis period, with low eU content (Figure 10d).

5.2. Mechanism of Uranium Concentration in Ferruginous Sandstone

(1) Ferruginous sandstone sedimentary period (uranium preconcentrated period)

The ferruginous sandstone in the Wajid Group is mainly found in the Khusayyayn Formation of the Early Devonian. The lithology of the Khusayyayn Formation is brownish-yellow and light-yellow medium-coarse sandstone containing lenticular ferruginous sandstone, with large-scale cross-bedding and a small number of parallel laminae, which is a typical littoral continental beach deposit. The humid and hot paleoclimate conditions are conducive to the weathering of the rocks in the Arabian Shield and provide a sufficient source of iron [61]. Ferrous matters were transported to the shallow water environment of the relatively closed or semi-closed inland bay in the Wajid Basin in the form of colloidal and fine suspended gel oxides from the Arabian Shield. With the increased sea level, its hydrodynamic conditions were weaker, which was more favorable for the sedimentation of ferruginous sandstone. The ferrous mineral assemblages are hematite, limonite, and goethite and were mainly formed during the sedimentary and diagenetic periods. Uranium matters were also weathered and transported to the basin from the uranium-rich granite bodies in the Arabian Shield [62], then adsorbed by ferrous cements. The uranium was preconcentrated during the sedimentary and diagenetic periods. A small part of uranium was distributed in heavy minerals, most of which were free stated and adsorbed by the ferrous cement (Figure 5d), and the uranium content was generally 20–50 ppm (Figure 11a).

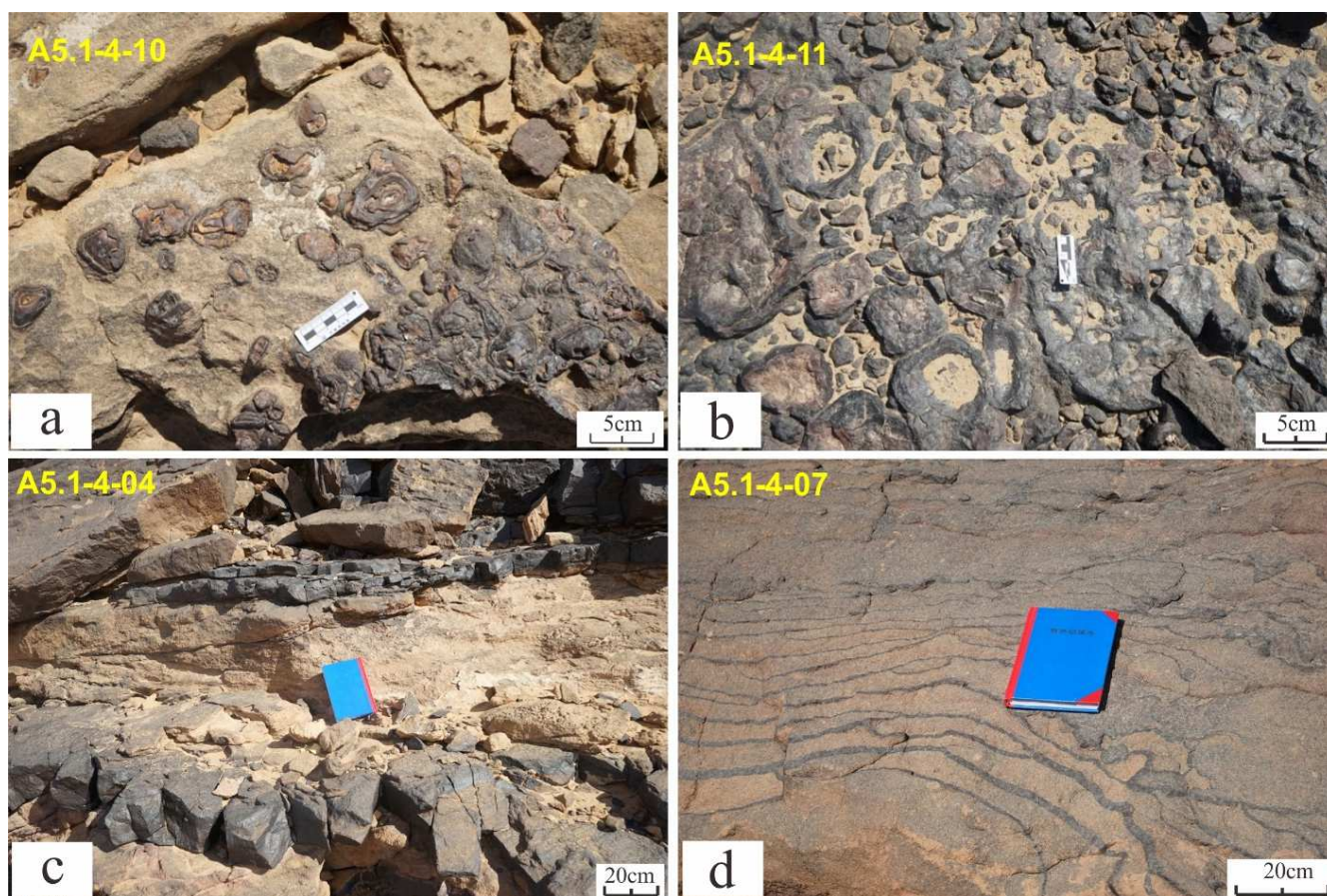


Figure 10. Synsedimentary and later diagenesis ferruginous sandstone in study area. (a,b) Ferruginous concretion formed in the sedimentary period with eU content of 30–40 ppm; (c) Uranium anomaly in ferruginous sandstone formed in the sedimentary period, 15–30 cm thick, later transformed with eU content of 341.74 ppm; (d) Ferruginous sandstone formed in later diagenesis period, 2–4 cm thick, with eU content of 5.2 ppm.

(2) Ferruginous sandstone transformation period (uranium transformation period)

With the slow uplift of the Arabian shield, the ferruginous sandstone of the Khusayyayn Formation was exposed to the surface and denuded. The ferruginous sandstone was transformed, and the uranium deposits were superimposed and transformed by the metallogenic fluid. The main type of uranium mineral was pitchblende, distributed in the fissures, solution pores, and solution fissures of quartz particles. The isochronous uranium metallogenic age given by the whole-rock U and Pb isotope assaying was 22.58 ± 0.47 Ma in the early Neogene. Due to the hot and dry climate in the Neogene, the limonite and goethite in the ferruginous sandstone were further oxidized and dehydrated to form hematite. The uranium preconcentrated in the ferruginous sandstone during in sedimentary period was superimposed and transformed by the oxygen-containing uranium fluid and further concentrated in the cracks or dissolved pores of quartz to form uranium mineralization. The uranium content is generally 80–1000 ppm (Figure 11b).

5.3. Role of Ferric Ions in Uranium Mineralization

Ferric ion is one of the standard ions in the redox environment of natural water. In temperate, tropical climates, Fe is easily taken out of the weathering crust by surface water as $\text{Fe}(\text{OH})_3$ colloid. Under the protection of an appropriate amount of humic acid or combined with humic acid to form a stable complex, Fe is transported by rivers to the catchment basin, distributed in the shallow sea on the continental margin, parallel to the coastline, and occurs in layers or lenticular. The scanning images of the uranium and ferric

ions are consistent with each other, indicating that the ferric ions are closely related to uranium mineralization. The concentration of ferric and uranium ions in water, the acidity and alkalinity of water, chemical composition, temperature, and pressure have effects on the redox reaction between ferric and uranium. Under standard conditions, when the temperature, pressure, uranium, and iron content in the water remain unchanged, Fe^{2+} can reduce U^{6+} in an alkaline medium, and the electrochemical reaction can be carried out spontaneously. The pitchblende–limonite or hematite-type uranium mineralization in the study area is the product of ferrous ion reduction.

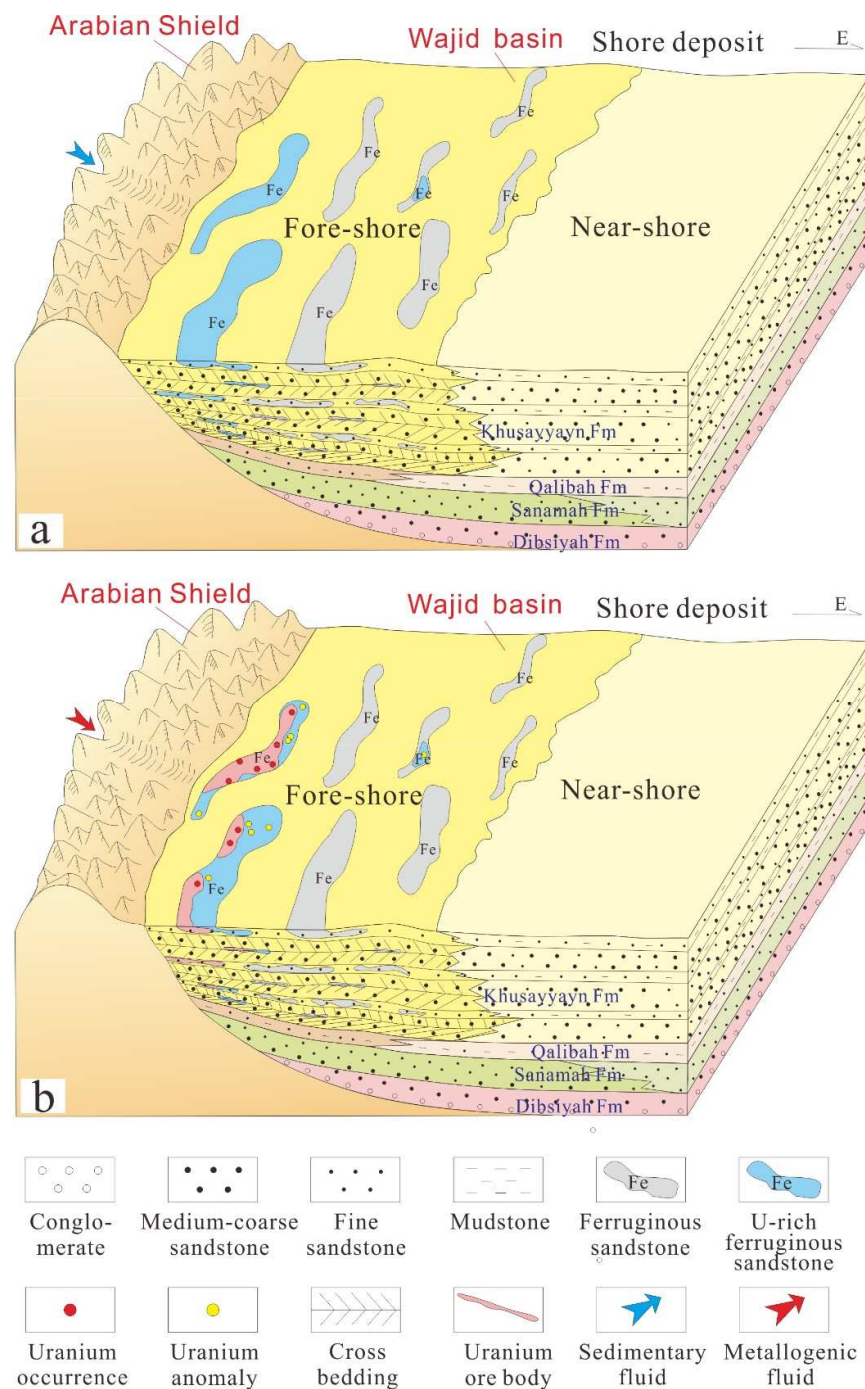


Figure 11. Uranium metallogenic model of Wajid ferruginous sandstone. (a). Sedimentary and diagenetic period of ferruginous sandstone; (b). Ferruginous sandstone transformation period.

The paleoclimate of the Wajid sandstone sedimentary period was a temperate climate. The uranium-rich rock of the Arabian shield was oxidized and denuded, and most of the uranium in the rock was oxidized and dissolved, and migrated to the basin in the form of UO_2^{2+} , $\text{UO}_2(\text{SO}_4)_n^{2(1-n)}$, $\text{UO}_2(\text{CO}_3)_n^{2(1-n)}$. The ferruginous sandstone in the sedimentary period contained a mixed colloidal solution of Fe^{3+} and Fe^{2+} , which was generally a weak alkaline environment. When the oxygenated uranium-bearing water encountered the ferric colloidal solution, most of it was adsorbed by $\text{Fe}(\text{OH})_3$, and part of it was reduced and precipitated by Fe^{2+} , organic carbon, and sulfur, forming the preconcentration of uranium, dispersed in the ferric cementation. During the transformation period of ferruginous sandstone in the early Neogene, the average pH values of the ferruginous sandstone and the surrounding sandstones were 8.98 and 8.49. The alkaline environment caused the dissolution of quartz particles to form a large number of dissolution pores and fissures. When the pH value was greater than 7.5, the uranium adsorbed by early $\text{Fe}(\text{OH})_3$ began to resolve, and the uranium was filled into the corrosion pores and fissures, making the uranium ore further superimposed, transformed, and concentrated.

6. Conclusions

1. The ferruginous sandstone is mainly found in the Khusayyayn Formation of the Wajid Group, mainly distributed along the bottom or bedding of the sandstone, thin-bedded and lenticular, mainly cemented by hematite and limonite. The ferric iron basically exists in the form of Fe_2O_3 in the ferruginous sandstone, and a small amount of reducing substances remains, such as FeO , organic carbon, and sulfur.
2. All of the uranium anomalies were hosted in ferruginous sandstone in the Khusayyayn Formation of the Wajid Group. It indicates that the uranium was weakly reformed after the uranium concentration in an alkaline oxidation environment.
3. It is concluded that there was poor potential for uranium mineralization in the ferruginous sandstone in the work area, and its radioactivity has little impact on the environment. The primary reason is that the uranium mineralization in the ferruginous sandstone was small in size and unfavorable for in situ leaching mining.
4. The formation of the ferruginous sandstone in the study area occurred during the early synsedimentary and later diagenesis stages. The initial concentration of the uranium occurred during the deposition of the ferruginous sandstone.
5. Ferric ions are closely related to uranium mineralization. Most of the uranium was adsorbed by ferric colloidal solutions, and part of it was reduced by Fe^{2+} , organic carbon, and sulfur in the uranium preconcentrated stage during the ferruginous sandstone deposit. The uranium ore was superimposed, transformed, and concentrated due to the change in the pH environment in the early Neogene.

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References

1. Adekoya, J.A.; Aluko, A.F.; Opeloye, S.A. Sedimentological characteristics of Ajali sandstone in the Benin flank of Anambra basin, Nigeria. *Ife J. Sci.* **2011**, *13*, 327–337.
2. Elzien, S.; Abdelateif, F.A.; Mohamed, A.A. Tectonic setting of ferruginous sandstone evidences from petrography and geochemistry, west ed debba, sudan. *Int. J. Eng. Res. -Online* **2013**, *1*, 346–357.
3. Hopson, P.M.; Wilkinson, I.P.; Woods, M.A.; Farrant, A.R. The Lower Albian (Lower Cretaceous) Monk's Bay Sandstone Formation (formerly the Carstone) of the Isle of Wight: Its distribution, litho- and biostratigraphy. *Proc. Geol. Assoc.* **2011**, *122*, 816–830. [[CrossRef](#)]
4. Shen, B.F. Geological characters and resource prospect of the BIF type iron ore deposits in China. *Acta Geol. Sin.* **2012**, *86*, 1376–1395.
5. Konhauser, K.O.; Amskold, L.; Lalonde, S.V.; Posth, N.R.; Kappler, A.; Anbar, A. Decoupling photochemical Fe(II) oxidation from shallow-water BIF deposition—ScienceDirect. *Earth Planet. Sci. Lett.* **2007**, *258*, 87–100. [[CrossRef](#)]
6. Babalola, L.O.; Hussain, M.; Hariri, M.M. Origin of iron-rich beds in the basal Wajid Sandstone, Abha-Khamis Mushayt Area, Southwest Saudi Arabia. *Arab. J. Sci. Eng.* **2003**, *28*, 3–24.
7. Babalola, L.O. Depositional environments and provenance of the Wajid Sandstone, Abha-Khamis Mushayt Area, southwestern Saudi Arabia. Master's Thesis, King Fahd University of Petroleum and Minerals, Dhahran, Saudi Arabia, 1999; p. 239.
8. Abzalov, M.Z.; Paulson, O. Sandstone hosted uranium deposits of the great divide basin, Wyoming, USA. *Appl. Earth Sci.* **2012**, *121*, 76–83. [[CrossRef](#)]
9. Dallwitz, W.B. *Preliminary Laboratory Investigation of Radioactive Ferruginous Sandstone from Madigan's Prospect, Bynoe Harbour, Northern Territory*; Geoscience Australia: Canberra, Australia, 1953.
10. Hayat, H.M.A.; Hussain, S.; Ali, H.M.; Anwar, N.; Iqbal, M.N. Extraction of yttrium from ferruginous sandstone, southwestern sinai, Egypt. *Chem. Technol.* **2015**, *10*, 234–241.
11. Mahmouds, S.M.; Salman, H.M.; Abdelfattah, N.A. Liquid—liquid extraction of uranium from sulfate leach liquor of Ramlet Hemeyir, ferruginous sandstone ore material, Southwestern, Sinai, Egypt. *Phys. Chem. Indian J.* **2014**, *9*, 322–329.
12. MiSchubert, C.; Schüth, C.; Michelsen, N.; Rausch, R.; Al-Saud, M. Investigation and Treatment of Natural Radioactivity in Large-Scale Sandstone Aquifer Systems. *Int. J. Water Resour. Arid. Environ.* **2011**, *1*, 25–32.
13. Rose, A.W.; Wright, R.J. Geochemical exploration models for sedimentary uranium deposits. *J. Geochem. Explor.* **1980**, *13*, 153–179. [[CrossRef](#)]
14. Ministry of Water and Electricity (MoWE), the Kingdom of Saudi Arabia. *Study of Groundwater Natural Radioactive Contamination Phenomena, Volume 1: Main report*; Ministry of Water and Electricity, the Kingdom of Saudi Arabia: Riyadh, Saudi Arabia, 2014.
15. Ministry of Water and Electricity (MoWE), the Kingdom of Saudi Arabia. *Study of Groundwater Natural Radioactive Contamination Phenomena, Volume 4: Sandstone Aquifers*; Ministry of Water and Electricity, the Kingdom of Saudi Arabia: Riyadh, Saudi Arabia, 2014.
16. Johnson, P.R. *Explanatory Notes to the Map of Proterozoic Geology of Western Saudi Arabia*; Saudi Geological Survey Technical Report SGS-TR-2006-4; Scale 1:1,500,000; Saudi Geological Survey: Jeddah, Saudi Arabia, 2006; p. 62.
17. Johnson, P.R.; Andresen, A.; Collins, A.S.; Fowler, A.R.; Fritz, H.; Ghebreab, W.; Kusky, T.; Stern, R.J. Late cryogenian-ediacaran history of the Arabian-Nubian Shield: A review of depositional, plutonic, structural, and tectonic events in the closing stages of the northern East African Orogen. *J. Afr. Earth Sci.* **2011**, *61*, 167–232. [[CrossRef](#)]
18. Kellog, K.S.; Janjou, D.; Minoux, L.; Fourniguet, J. *Explanatory Notes to the Geological Map of the Wadi Tathlith Quadrangle, Sheet 20G*; Kingdom of Saudi Arabia, Ministry of Petroleum and Mineral Resources Deputy Ministry for Mineral Resources: Jeddah, Saudi Arabia, 1986.
19. Edgell, H.S. Aquifers of Saudi Arabia and the geologic framework. *Arab. J. Sci. Technol.* **1997**, *22*, 5–31.
20. Hussain, M.; Babalola, L.O.; Hariri, M.M. Heavy minerals in the Wajid Sandstone from Abha-Khamis Mushayt area, southwestern Saudi Arabia: Implications on provenance and regional tectonic setting. *GeoArabia* **2004**, *9*, 77–102. [[CrossRef](#)]
21. Keller, M.; Amarah, B.; Al Ajmi, F.H. The Wajid Sandstone around Abha/Khamis Mushayt and in its type area: Lithostratigraphic architecture and correlations. *Arab. J. Geosci.* **2017**, *10*, 55. [[CrossRef](#)]
22. Keller, M.; Hinderer, M.; Ajmi, H.A.; Rausch, R. *Sedimentary History of the Paleozoic Wajid Group (Saudi Arabia) and Implications for the Tectono-Stratigraphic Evolution of the Southwestern Arabian Platform*; Workshop of ILP-Task Force on Sedimentary Basins: Abu Dhabi, United Arab Emirates, 2009; Volume 5, pp. 11–12.
23. Abdulkadir, I.T.; Abdullatif, O.M. Facies, Depositional Environments, Reservoir Potential and Palaeogeography of the Cambro-Ordovician Dibsiyah Formation, Wajid Outcrop Belt, Saudi Arabia. *Arab. J. Sci. Eng.* **2013**, *38*, 1785–1806. [[CrossRef](#)]
24. Abdulkadir, I.T.; Sahin, A.; Abdullatif, O.M. Distribution of petrophysical parameters in the Cambro-Ordovician dibsiyah member of the Wajid sandstone, SWSaudi Arabia. *J. Petrol. Geol.* **2010**, *33*, 269–280. [[CrossRef](#)]
25. Ajmi, H.A.; Keller, M.; Hinderer, M.; Rausch, R. *Advances in Understanding the Relation between Reservoir Properties and Facies Distribution in the Paleozoic Wajid Sandstone, Saudi Arabia. Advances in the Research of Aquatic Environment*; Springer: Berlin/Heidelberg, Germany, 2011; pp. 21–28.
26. Al Ajmi, F.H.; Keller, M.; Hinderer, M.; Filomena, C.M. Lithofacies, depositional environments, and stratigraphic architecture of the Wajid Group outcrops in southern Saudi Arabia. *GeoArabia* **2015**, *20*, 49–94. [[CrossRef](#)]

27. Bassis, A.; Hinderer, M.; Meinhold, G. New insights into the provenance of Saudi Arabian Palaeozoic sandstones from heavy mineral analysis and single-grain geochemistry. *Sediment. Geol.* **2016**, *333*, 100–114. [\[CrossRef\]](#)
28. Yassin, M.; Abdullatif, O. Geochemistry of the Lower Paleozoic Wajid Formation in Saudi Arabia—Implications for Tectonic Setting and Provenance. In Proceedings of the 76th EAGE Conference and Exhibition, Amsterdam, The Netherlands, 16–19 June 2014.
29. Dabbagh, M.E.; Rogers, J. Depositional environments and tectonic significance of the Wajid Sandstone of southern Saudi Arabia. *J. Afr. Earth Sci.* **1983**, *1*, 47–57. [\[CrossRef\]](#)
30. Nehlig, P.; Genna, A.; Asirfane, F. A review of the Pan-African evolution of the Arabian Shield. *GeoArabia* **2002**, *7*, 103–124. [\[CrossRef\]](#)
31. McGillivray, J.G.; Hussein, M.I. The Paleozoic petroleum geology of the central Arabia. *AAPG* **1992**, *76*, 1473–1490.
32. Evans, D.S.; Lathon, R.B.; Senalp, M.; Connally, T.C. Stratigraphy of the Wajid Sandstone of Southwestern Saudi Arabia. Paper SPE 21449. In Proceedings of the SPE Middle East Oil Show, Bahrain, 16–19 November 1991; pp. 947–960.
33. Fairer, G.M. *Geologic Map of the Wadi Baysh Quadrangle, Sheet 17F, Kingdom of Saudi Arabia*. Saudi Arabian Deputy Ministry for Mineral Resources Geoscience Map GM-77C, Scale 1:250,000; Ministry of Petroleum and Mineral Resources, Deputy Ministry for Mineral Resources: Jeddah, Saudi Arabia, 1985; p. 40.
34. Janjou, D.; Halawani, M.A.; Memesh, A.; Razin, P.; Jaques, R.; Roobol, M.J.; Shorbaji, H. *Geologic Map of the Jibal al Misma Quadrangle, Sheet 27D, Kingdom of Saudi Arabia*. Saudi Arabian Deputy Ministry for Mineral Resources Geoscience Map GM-138, Scale 1:250,000; Ministry of Petroleum and Mineral Resources, Deputy Ministry for Mineral Resources: Jeddah, Saudi Arabia, 1998; p. 40.
35. Ajmi, H.A.; Hinderer, M.; Rausch, R.; Hornung, J.; Bassis, A. Matrix versus fracture permeability in a regional sandstone aquifer (Wajid sandstone, SW Saudi Arabia), Grundwasser. *Grund. —Z. Der Fachsekt. Hydrogeol.* **2014**, *19*, 151–157. [\[CrossRef\]](#)
36. Kellogg, K.S.; Janjou, D.; Minoux, L.; Fourniguet, F. *Geologic Map of the Wadi Tathlith Quadrangle, Sheet 20G, Kingdom of Saudi Arabia*. Saudi Arabian Deputy Ministry for Mineral Resources Geoscience Map GM-103C, Scale 1:250,000; Ministry of Petroleum and Mineral Resources, Deputy Ministry for Mineral Resources: Jeddah, Saudi Arabia, 1986; p. 27.
37. Dini, S.M.; Wallace, C.A.; Halawani, M.A.; Al-sobhi, S.A.; Kashghari, W.A.; Al-Ghamdi, A.S. *Explanatory Notes to the Geological Map of the As Sulayyil Quadrangle, Sheet 20H, Kingdom of Saudi Arabia*; Saudi Geological Survey: Jeddah, Saudi Arabia, 2009.
38. Senalp, M.; Al-Duaiji, A. Stratigraphy and sedimentology of the storm and tide-dominated shallow marine siliciclastic members of the Qasim formation, Qasim region, Saudi Arabia. *GeoArabia Middle East Petrol. Geosci.* **1996**, *1*, 192.
39. Moshirif, M.A.; El-Hiti, A. Lithofacies and petrography of Wajid sandstone (Cambrian-Ordovician) Saudi Arabia. *J. Afr. Earth Sci.* **1989**, *9*, 401–412. [\[CrossRef\]](#)
40. Mahgoub, M.I.; Abdullatif, O.M. Facies, petrography, reservoir heterogeneity and quality of the late Carboniferous-Permian Juwayl Member, Wajid Sandstone, SW Saudi Arabia. *Mar. Pet. Geol.* **2020**, *120*, 104521. [\[CrossRef\]](#)
41. Wanas, H.A.; Abdel-Maguid, N.M. Petrography and geochemistry of the Cambro-Ordovician Wajid Sandstone, southwest Saudi Arabia: Implications for provenance and tectonic setting. *J. Asian Earth Sci.* **2006**, *27*, 416–429. [\[CrossRef\]](#)
42. Greenwood, W.R. *Explanatory Notes to the Geological Map of the Jibal Al Qahr Quadrangle, Sheet 19G, Kingdom of Saudi Arabia*; Ministry of Petroleum and Mineral Resources, Deputy Ministry for Mineral Resources: Jeddah, Saudi Arabia, 1985.
43. Yassin, M.A.; Abdullatif, O.M. Chemostratigraphic and sedimentologic evolution of Wajid Group (Wajid Sandstone): An outcrop analog study from the Cambrian to Permian, SW Saudi Arabia. *J. Afr. Earth Sci.* **2017**, *126*, 159–175. [\[CrossRef\]](#)
44. Melvin, J.; Norton, A.K. Advances in Arabian stratigraphy: Comparative studies of glaciogenic Juwayl and lower Unayzah strata (Carboniferous-Permian) of Saudi Arabia. *GeoArabia* **2013**, *18*, 97–134. [\[CrossRef\]](#)
45. Nabawy, B.S.; Ibrahim, E.; Kahal, A.; Alfaifi, H.J.; Lashin, A.A. Impact of authigenic iron oxides, clay content and grain size on the aquifer quality properties of the Cambrian-Ordovician Wajid Sandstone, southwest Saudi Arabia. *J. Afr. Earth Sci.* **2020**, *172*, 104000. [\[CrossRef\]](#)
46. Stump, T.E.; Van Der Eem, J.G. The stratigraphy, depositional environments and periods of deformation of the Wajid outcrop belt, southwestern Saudi Arabia. *J. Afr. Earth Sci.* **1995**, *21*, 421–441. [\[CrossRef\]](#)
47. Benaafi, M.; Hariri, M.; Al-Shaibani, A.; Abdullatif, O.; Makkawi, M. Integrated geomechanical, petrographical and petrophysical study of the sandstones of the Wajid Group, SW Saudi Arabia. *J. Afr. Earth Sci.* **2018**, *143*, 162–177. [\[CrossRef\]](#)
48. Benaafi, M.; Hariri, M.; Bertotti, G.; Al-Shaibani, A.; Abdullatif, O.; Makkawi, M. Natural fracture system of the Cambro-Permian Wajid Group, Wadi Al-Dawasir, SW Saudi Arabia. *J. Pet. Sci. Eng.* **2019**, *175*, 140–158. [\[CrossRef\]](#)
49. Finch, R.; Murakami, T. Systematics and paragenesis of uranium minerals. In *Uranium: Mineralogy, Geochemistry and the Environment*; Burns, P.C., Finch, R., Eds.; De Gruyter: Berlin, Germany, 1999; pp. 91–180.
50. Tribouillard, N.; Algeo, T.J.; Lyons, T.; Riboulleau, A. Trace metals as paleoredox and paleoproductivity proxies: An update. *Chem. Geol.* **2006**, *232*, 12–32. [\[CrossRef\]](#)
51. Boynton, W.V. Geochemistry of the rare earth elements: Meteorite studies. In *Rare Earth Element Geochemistry*; Elsevier: Amsterdam, The Netherlands, 1984; pp. 63–114.
52. Mariano, A.N. Economic geology of rare earth minerals. In *Geochemistry and Mineralogy of Rare Earth Elements*. *Mineralogical Society of America Reviews in Mineralogy* 21; Lipin, B.R., McCay, G., Eds.; Mineralogical Society of America: Chelsea, MI, USA, 1989; pp. 309–338.
53. McLennan, S.M. Rare earth elements in sedimentary rocks: Influence of provenance and sedimentary processes. *Rev. Mineral. Geochem.* **1989**, *21*, 169–200.

54. Migdisov, A.A.; Williams-Jones, A.E. A spectrophotometric study of Nd(III), Sm(III) and Er(III) complexation in sulfate-bearing solutions at elevated temperatures. *Geochim. Cosmochim. Acta* **2008**, *72*, 5291–5303. [[CrossRef](#)]
55. Garnit, H.; Bouhlef, S.; Barca, D.; Chtara, C. Application of LA-ICP-MS to sedimentary phosphatic particles from Tunisian phosphorite deposits: Insights from trace elements and REE into paleo-depositional environments. *Chem. Erde Geochem.* **2012**, *72*, 127–139. [[CrossRef](#)]
56. Ludwig, R.K.; Wallace, R.A.; Simmons, R.K. The Schwartzwalder uranium deposit, II: Age of uranium mineralization and Lead isotope constraints on genesis. *Econ. Geol.* **1985**, *80*, 1858–1871. [[CrossRef](#)]
57. Jensen, M.L. Sulfur isotopes and the origin of sandstone-type uranium deposits. *Econ. Geol.* **1958**, *53*, 598–616. [[CrossRef](#)]
58. Ludwig, K.R. Calculation of uncertainty of U-Pb isotope data. *Earth Planet. Sci. Lett.* **1980**, *46*, 212–220. [[CrossRef](#)]
59. Ludwig, K.R. *PB DAT—A Program for Reduction of Pb-U-Th Isotope Data, for Use with HP—86/87 Microcomputers*; Open File Report 83-113; U.S. Geological Survey: Drive Reston, VA, USA, 1984; p. 54.
60. Ludwig, K.R. *ISOPLLOT: A Plotting and Regression Program for Radiogenic Isotope Data*; Open File Report 91-445; U.S. Geological Survey: Drive Reston, VA, USA, 1993; pp. 1–42.
61. Fathy, D.; Wagreich, M.; Ntaflos, T.; Sami, M. Paleoclimatic variability in the southern Tethys, Egypt: Insights from the mineralogy and geochemistry of Upper Cretaceous lacustrine organic-rich deposits. *Cretac. Res.* **2021**, *126*, 104880. [[CrossRef](#)]
62. Fawzy, M.M.; Mahdy, N.M.; Sami, M. Mineralogical characterization and physical upgrading of radioactive and rare metal minerals from Wadi Al-Baroud granitic pegmatite at the Central Eastern Desert of Egypt. *Arab. J. Geosci.* **2020**, *13*, 413. [[CrossRef](#)]