

Review of Uranium in the Jordanian Phosphorites: Distribution, Genesis and Industry

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Abstract

Phosphorites are well-known, world wide, to accommodate a substantial amount of U relative to other sedimentary rocks. This is due to a great extent to the crystal structure of apatite (carbonate fluorapatite, francolite) where U substitutes Ca. Phosphorites form in shallow marine environments through the accumulation of planktonic fossils debris on the sea floor in areas characterized by upwelling currents. Once the organic-rich sediments are buried below the sea floor and the organic matter is decomposed, PO_4 is released to the interstitial solutions. These PO_4 -rich solutions either precipitate phosphorites directly (authigenic) or the solutions react with pre existing sediments and transform them to phosphorites (early diagenetic). The Jordanian deposits are dominantly of the former type. Consequently, phosphorites are also well known to be associated with high percentage of organic matter which makes them a good source rock for petroleum.

In Jordan, phosphorites are wide spread from its extreme NW to the SE. Uranium contents are not the same in each locality. It is not also the same in each bed in the same locality. In Al-Kora Basin, NW Jordan, U ranges between 60-379 ppm (parts per million or g/ton) with an average of 153 ppm. In Ruseifa, just east of Amman, the range is 132-195 ppm and average of 123 ppm. Central Jordan phosphorites (Al-Abiad and Al-Hasa) have a lower U %. The range is 34-190 ppm with an average of 105 ppm. Eshidiyya Basin has a much less U concentration. The range is 7-125 ppm with an average of 70 ppm. However, a recent work on the uppermost phosphorite horizon, the A0, in Eshidiyya Basin proved the presence of a 3 m thick bed with 242 ppm U. Furthermore, certain phosphorite horizons are known to have much more than the average U in that locality; e.g. in Al-Kora Basin, the average U is 153 ppm while certain horizons have up to 379 ppm U, the uppermost bed in Ruseifa has up to 195 ppm while the average is 123 ppm, and in Eshidiyya the A0 has 242 ppm while the average of the lower horizon (A1-3) average is 70 ppm. Obviously, if the U is to be extracted from the phosphorite, the horizons with higher concentrations of U should be explored and used.

Uranium sticks to francolite in its behavior from precipitation in the marine environment, through mining and beneficiation, and the fertilizer industry. 1) There is a significant high correlation coefficient between CaO and P_2O_5 in the hundreds of samples analyzed. 2) Fines (clays) produced when washing the ore have very little U and consequently, washing water for the last 45 years has not contaminated groundwater with U in central Jordan. 3) Uranium is concentrated in the phosphoric acid then into diammonium phosphate (DAP) in the fertilizer industry and not in the phosphogypsum.

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1. Introduction

Phosphorites are the carrier of uranium, thus the study of them is a prerequisite to the study of U. Phosphorites are widespread in Jordan and cover a relatively large area of the country from the extreme northwest to its south. Low and high grade phosphorites are supposed to have been deposited throughout the country, but subsequent uplift and erosion, from the Oligocene onwards, had removed it from various parts of the country; e.g. Ajlun dome the western parts of the western mountain range, and the extreme south (Bender, 1974; Powell, 1989, Abed,

2000). Furthermore, high grade phosphorites are also present in the subsurface of the eastern desert of Jordan; e.g. Zgaimat Al-Hasat (Abed and Amireh, 1999).

High grade phosphorites were discovered in Jordan in 1908 during the construction of the Hijaz Railway. In 1938, small scale mining from Ruseifa started and was exported by mules through Haifa. The Jordan Phosphate Mines Company (JPMC) commenced its work by 1953 in Ruseifa, 1965 in Al-Hasa, 1979 in Al-Abiad, and 1988 in Eshidiyya (Abed, 2000). Ruseifa mines were closed in 1988 despite the fact that there are several tens of millions of high grade phosphorites south of Amman-Zarqa Highway (Zarqa B area) (Abed, 1989). Central Jordan

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phosphorites (Al-Hasa and Al-Abiad) are near depletion); consequently, Eshidiyya is going to be the centre for phosphorite mining and industry. However, several hundred millions of high grade phosphorites are present in Al-Kora Basin NW Jordan (Mikbel and Abed, 1985; Abed and Al-Agha, 1989), likewise, huge, but not estimated, subsurface deposits in the SE desert continuing into Saudi Arabia are present (Abed and Amireh, 1999). In short, there seems to be no shortage of high grade phosphorites in Jordan even for the distant future.

On the other hand, uranium is well known to be several folds enriched in phosphorites compared with other sedimentary rocks such as sandstones, carbonates and shales. Average U in phosphorite is 120 ppm compared with 3.5, 0.5 and 2.2 ppm in shale, sandstone and carbonate respectively; an enrichment factor of around 30 relative to shale (Altschuler, 1980; Slansky, 1986; McArthur *et al.*, 1987; Krauskopf and Bird, 1995). This is basically due to the nature of the crystal structure of francolite (carbonate flour apatite) where U is substituting for calcium, both having a close radius ($Ca^{+2} = 0.99\text{\AA}$ and $U = 0.97\text{\AA}$ (e.g. Nathan, 1984; McClellan and Van Kauwenberg, 1990). The enrichment of U in phosphorites may also be due to the association of the latter with abundant organic matter in the depositional environment of the phosphorites (Barnett, 1990). Uranium, in the Jordanian phosphorite, was studied by Coopens *et al.*, (1977), Khalid and Abed (1982), Abed and Khalid (1985) and Sadaqah *et al.*, 2005 amongst others).

The aim of this paper is to discuss a) the distribution of U in the various localities and the phosphorite horizons within each locality; b) the genesis of phosphorite formations in Jordan; and c) the behavior of U throughout the processes of mining, upgrading and fertilizers industry.

2. GEOLOGICAL SETTING

The phosphorites of Jordan form part of the Cretaceous-Eocene phosphorite episode which deposited one of the most extensive deposits in the world in the Eastern Mediterranean (Saudi Arabia, Iraq, Syria, Jordan and Palestine) and North Africa (Egypt, Tunisia, Algeria, Morocco, Mauritania, Senegal, ...), and parts of the Caribbean and NE S. America. It is second to the Miocene North American episode (Sheldon 1981; Riggs, *et al.*, 1985; Notholt *et al.* 1989; Abed, 1994; Follmi 1996).

The phosphorites of Jordan are present within Al-Hisa Phosphorite Formation (AHP). Fig. 1 shows the location of high grade phosphorites in Jordan. The age of the AHP is most probably early Maastrichtian, Uppermost Cretaceous (Quennell, 1951; Hamam, 1977; Cappetta *et al.*, 1996). In general, the AHP consists of phosphorites, bedded chert, limestones, oyster buildups, organic-rich marl (oil shale) and other rock types (Powell, 1989; Abed, 2000). However, the lithology and thickness of the AHP are variable from one locality to the other. The total thickness of the AHP is around 10 m in NW Jordan, 30 m in Ruseifa, 40-60 m in central Jordan, 10-17 m in Eshidiyya and 5-6 m in Zgaimat Al-Hasat in the SE desert ((Powell, 1989; Abed, 2000).

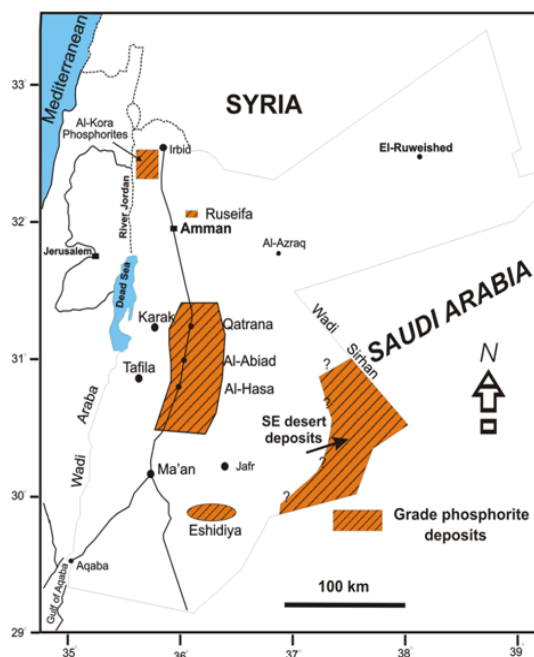


Fig. 1 Location map of the grade phosphorite deposits in Jordan.

The AHP consists of three formal members, from older to younger Sulatani, Bahiyya and Qatrana. The three members are well displayed throughout central Jordan where the terminology was first used by El-Hiyari (1985) (Table 1). In central Jordan, the Sultani Member consists of alternating limestones, bedded chert and minor phosphorites. The Bahiyya Member consists of oyster banks or buildups up to 30 m in thickness that are made of oyster fragment in clinoforms dipping general to the SE (Abed and Sadaqah, 1998). The Qatrana Member is the host of the high grade phosphorites. The grade phosphorites are friable with little calcareous cement. They are present as lenses (small basins) with a diameter ranging up to few kilometers and a thickness up to 13 m.

Table 1. Nomenclature of the Upper Cretaceous rock units in Jordan (Al-Hiyari, 1985)

Age	Group	Formation Member	
		Formation	Member
Tertiary	Belqa	Shallaleh	
		Umm Rijam Chert Limestone	
		Muwaqqar Chalk Marl (MCM)	
Late Cretaceous	Maastrichtian	Al Hisa Phosphorite (AHP)	Qatrana Phosphorite
			Bahiyya Coquina
			Sultani Phosphorite
	Campanian	Amman Silicified Limestone	
	Coniacian	Ghudran	Dhiban Chalk
			Tafila
Mujib Chalk			
Cenomanian	Ajlun	Wadi Es Sir	
		Shueib	
		Hummar	
		Fuheis	
		Na'ur	
Early Cretaceous	Aptian-Albian	Kurnub (Hathira) Sandstone Group	

In Eshidiyya Basin, the three formal members are present only in the northern parts of the basin. The Bahiyya coquina thins gradually towards the SE until it disappears completely. The Sultani Member or the lower

member is hosting the main (high) grade phosphorite deposits. It is divided by the miners into three producing phosphate horizons from top to bottom; A1, A2 and A3, separated by non phosphorite strata like; chert, porcelanite, and minor beds of marl, limestone and dolomite. (Sofremines, 1987; Abed *et al.*, 2007). The A3, at the base,

is rich in quartz sand, while A2 is a friable, high grade phosphorite. The A1 is a low grade indurated by calcite cement (Fig. 2). The Qatrana Member or the upper member is designated A0 and consists of up to 3 m of friable high grade phosphorite in the north thinning to the SE to few centimeters only.

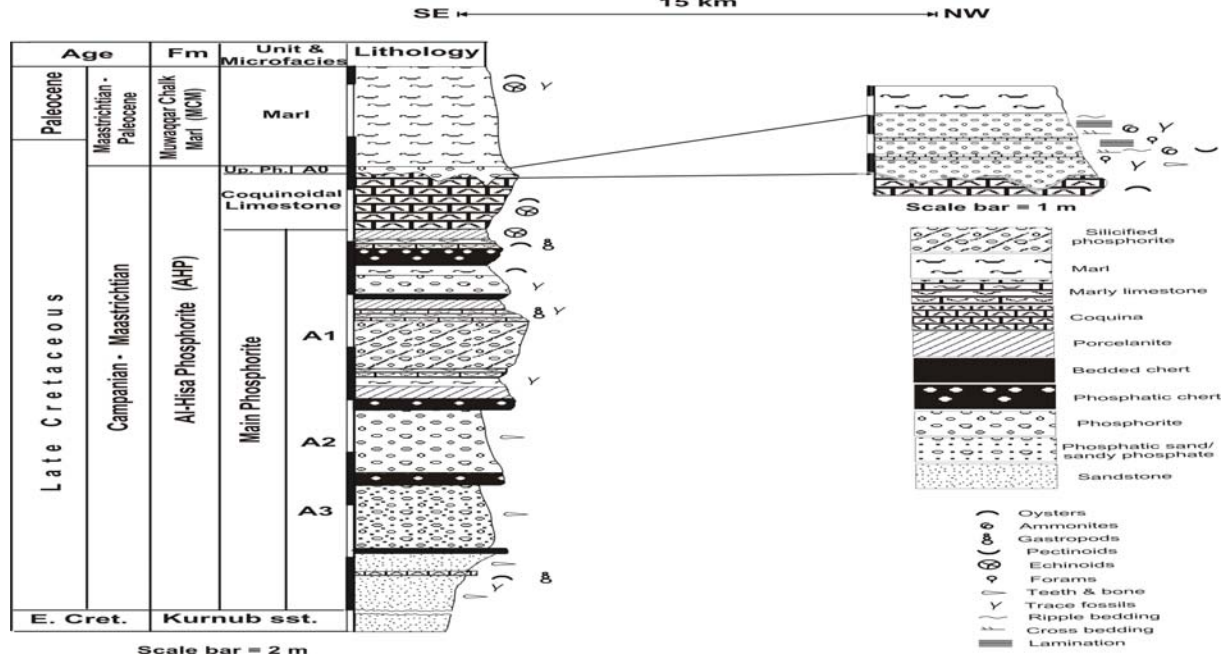


Fig. 2 A columnar section describing the lithology of Eshdiyya phosphorites. A detailed section , right, shows the lithology of the A0 deposits in northern Eshdiyya.

Fig. 3 is a columnar section in central Jordan. The SE desert deposits were discovered by Abed and Amireh (1999). They are deep seated in the subsurface, but crop out as windows at the cores of anticlines such as that of Zgaimat Al-Hasat. Total thickness is 5-6 m consisting of

friable phosphorites with same quartz sand increasing to the SE (Fig. 4). The age, most probably Turonian, seems older than other phosphorites of Jordan (Khalifa and Abed, 2011).

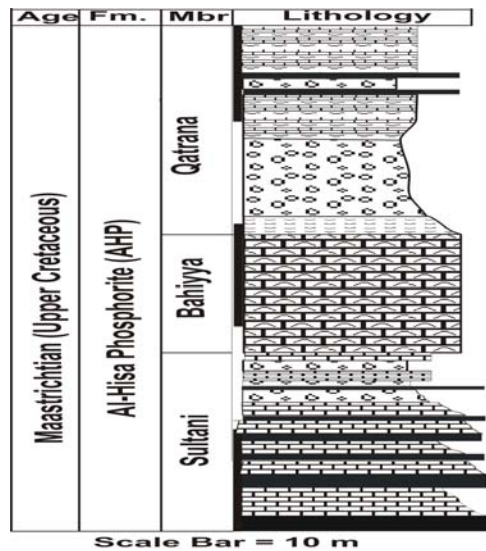


Fig. 3 (left) Generalized lithological section in central Jordan.

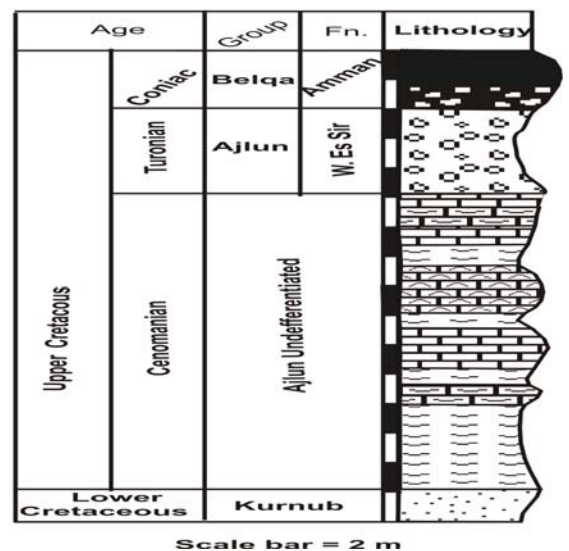


Fig. 4 (right) Detailed columnar section of the Ajlun Group and the phosphorites of the SE desert at Zgaimat Al-Hasat (Khalifa and Abed, 2011). For legend, see Fig. 2.

The Ruseifa mines were closed in 1988, however, the deposits consists of four phosphorite horizons designated from bottom A1, A2, A3, and A4, separated by limestone, trace fossils and some chert (Fig. 5). Al-Kora deposits, NW Jordan, were discovered by Mikbel and Abed (1985) with several million tons of grade phosphorites. The

deposits are up to 10 m thick, the lower part consists of alternating chert and phosphorite capped by about 3 m thick high grade, friable phosphorite horizon rich in organic matter (Abed and Al-Agha, 1989). Fig. 6 shows the lithology near the village of Tobna. These deposits have not been mined yet.

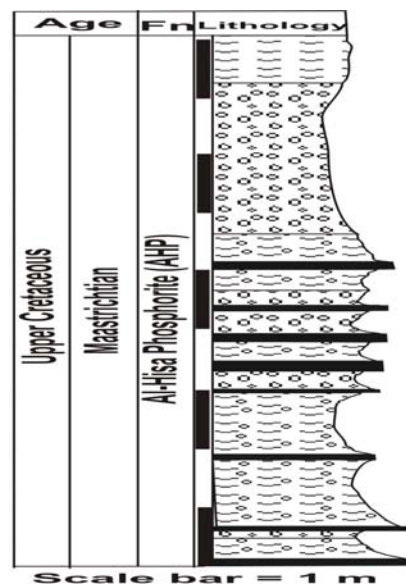
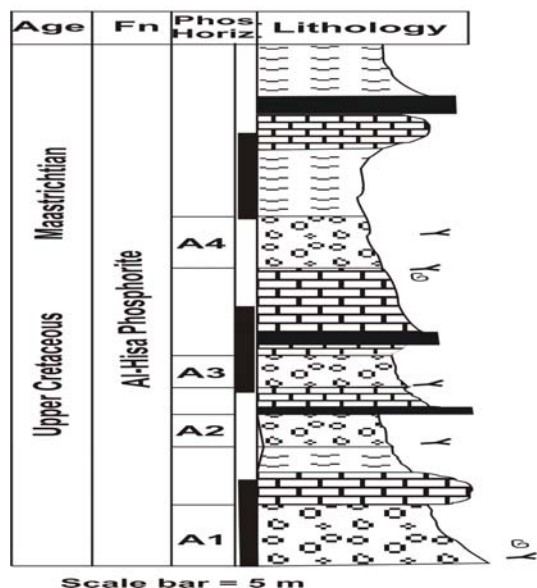


Fig. 5 (left) columnar section describing the phosphorites at Ruseifa Basin.

Fig. 6 (right) Columnar section describing the phosphorites at Tobna, Al-Kora Basin, NW Jordan. For legend, see Fig. 2 .

3. Results and Discussion

3.1. Petrography and Mineralogy

The phosphorites of Jordan are granular in nature with subordinate pristine (primary or not reworked) especially in NW Jordan deposits. Grain types are phosphate intraclasts, peloids, coprolites and skeletal fragments (bone and teeth). The former two types are due mainly to reworking of originally precipitated phosphate material, or may partially be due to the nature of deposition between the pore spaces of pre existing sediments (Riggs, 1979, 1980; Burnett, 1990; Abed and Fakhouri, 1996; Abed et al., 2007 amongst many others).

Phosphate particles or grains, in marine phosphorites, consist of the mineral carbonate flour apatite (francolite), a variety of the mineral apatite. The phosphorites of Jordan have the following chemical formula of francolite $[Ca_{9.86} Mg_{.005} Na_{.14}] [PO_4 4.93 CO_3 1.07 F 2.06]$ (Abed and Fakhouri, 1996). The crystal structure of francolite is rather open, thus enhancing substitution (e.g. McClellan and Van Kauwenberg, 1990). Uranium is one of many elements that substitutes for Ca. Consequently, U is present within the crystal structure of francolite and behaves more similar to Ca than to P, simply because the ionic radii are very close to each other. To shed more light on this relationship, U ppm is correlated with each of CaO%, P₂O₅%, U/ P₂O₅ and U/CaO in 184 samples from the Jordanian phosphorites (Fig. 7). It is clear that a better correlation is present between U and Ca than between U and P, meaning that U is not only present within the

structure of francolite but it occupies same positions of Ca in that structure.

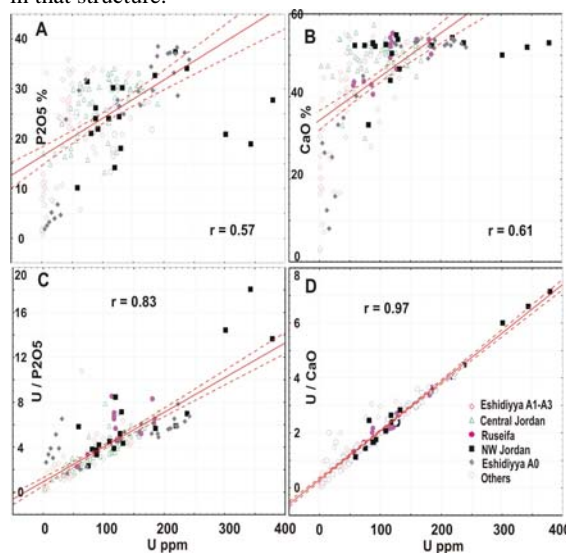


Fig. 7 Correlation between U and A) P₂O₅%, B) CaO%, C) U/P₂O₅ ratio, and D) U/CaO ratio. Solid line is the best fit while dotted lines are for the 95% confidence. Number of samples is 184.

The yellowish-greenish U minerals found on the surface of joints and fractures are due to leaching by groundwater of the original U; i.e. secondary in origin. Consequently, this type occurrence is very limited in abundance, and thus, of minor importance and of no economic value for U exploration.

3.2. Distribution of Uranium

In this title, the distribution of U in the various localities in Jordan is discussed based on data acquired by the author, his coworkers and students since 1980.

3.2.1. Eshidiyya Deposits

Phosphorites are present in two members, the lower member (A1, A2 and A3 horizons) who accommodates the main phosphorite reserves, and the upper member (A0 horizon) with limited reserves (Fig. 2). Tables 2 and 3 display the contents of U in both upper and lower members respectively.

Table 2. Uranium, P₂O₅ and CaO contents and other ratios in the lower phosphorite member in Eshidiyya Basin (Khaled and Abed, 1982; Abed and Khaled, 1985).

	U ppm	P ₂ O ₅ %	CaO%	U/ P ₂ O ₅	CaO/ P ₂ O ₅	U/ CaO		Uppm	P ₂ O ₅ %	CaO%	U/ P ₂ O ₅	CaO/ P ₂ O ₅	U/ CaO
1	45	23.96	41.23	1.88	1.72	1.09	31	63	5.83	39.53	10.81	6.78	1.59
2	96	21.93	37	3.14	1.69	2.59	32	5	9.88	32.05	0.51	3.24	0.16
3	143	33.13	53.12	4.23	1.60	2.69	33	5	10.27	39.35	0.49	3.83	0.13
4	146	23.98	53.3	4.43	2.22	2.74	34	5	6.55	9.17	0.76	1.40	0.55
5	44	27.22	40.4	1.62	1.48	1.09	35	50	30.88	48.04	1.62	1.56	1.04
6	44	23.16	40.78	1.75	1.76	1.08	36	35	31.74	45.96	1.10	1.45	0.76
7	45	25.68	39.04	1.75	1.52	1.15	37	50	22	38.47	2.27	1.75	1.30
8	45	22.18	36.49	2.02	1.65	1.23	38	75	32.84	49.08	2.28	1.49	1.53
9	44	27.63	44.1	1.39	1.60	1.00	39	85	33.96	49.94	2.50	1.47	1.70
10	141	32.63	48.8	4.32	1.50	2.89	40	100	33.76	49.93	2.96	1.48	2.00
11	111	25.33	44.3	4.38	1.75	2.51	41	88	26.6	43.65	3.31	1.64	2.02
12	72	19.99	42.91	3.6	2.15	1.68	42	85	18.27	27.87	4.65	1.53	3.05
13	45	26.14	42.06	1.72	1.61	1.07	43	100	20.7	33.79	4.83	1.63	2.96
14	44	33.82	30.25	1.30	0.89	1.45	44	46	28.25	50.63	1.63	1.79	0.91
15	18	7.45	24.94	2.42	3.35	0.72	45	45	20.05	44.57	2.24	2.22	1.01
16	7	4.1	7.26	1.71	1.77	0.96	46	63	22.92	40.46	2.75	1.77	1.56
17	16	7.7	25.96	2.08	3.37	0.62	47	8	33.13	44.52	0.24	1.34	0.18
18	29	24.15	37.82	1.20	1.57	0.77	48	75	29.91	48.33	2.51	1.62	1.55
19	43	35.91	55.09	1.20	1.53	0.78	49	125	29.7	39.63	4.21	1.33	3.15
20	30	24.21	38.22	1.24	1.58	0.78	50	1	0.83	2.82	1.20	3.40	0.35
21	35	27.78	43.86	1.26	1.58	0.80	51	2	10.89	18.19	0.18	1.67	0.11
22	51	33.66	54.18	1.52	1.61	0.94	52	1	1.5	3.14	0.67	2.09	0.32
23	69	30.34	47.19	2.27	1.56	1.46	53	5	11.38	17.59	0.44	1.55	0.28
24	34	10.68	16.8	3.18	1.57	2.02	54	2	8.8	18.11	0.23	2.06	0.11
25	125	26.71	55.35	4.68	2.07	2.26	55	25	10.1	16.93	2.48	1.68	1.48
26	89	17.07	54.58	5.21	3.20	1.63	65	3	13	20.36	0.23	1.57	0.15
27	175	27.32	52.24	6.41	1.91	3.35	57	1	11.07	16.56	0.09	1.50	0.06
28	34	23	40.84	1.48	1.78	0.83	58	1	7.78	30.47	0.13	3.92	0.03
29	46	33.01	50.55	1.39	1.53	0.91	59	1	2	22.79	0.50	11.40	0.04
30	34	23.94	36.28	1.42	1.52	0.94	60	1	1.66	25.56	0.60	15.40	0.04
Av	51	20.83	36.71	2.24	1.76	1.39	Av. of >11% P2O5 = 70 ppm						

On the other hand, the upper phosphorite member (A0) is much more enriched in U. Table 3 shows the analysis of 28 samples of the A0 with an average U of 133 ppm and a range of 5-242 ppm. If the samples of less than 10% P₂O₅ % are removed, then the average U becomes 172 ppm and

The U average of 60 samples analyzed from the lower member is 51 ppm with a range 1 -175 ppm. If the samples with less than 11 % P₂O₅ % are removed, because they are not typical phosphorites, then the average U will be 70 ppm. The higher U concentrations up to 175 ppm can be found in the calcareous, high grade A2 horizon. The A3 has the lowest U content, partially, because of the high dilution with silica sand which can be present up to 50 % in certain samples. The A1 is slightly higher than the A3 (Khaled and Abed, 1982). Upgrading the lower member will certainly enhance the contents of U in these phosphorites.

the range 40-242 ppm, The data clearly indicates that U is more than twice that of the lower member (Abed and Sadaqah, 2011 in press). The A0 consists of two phosphorite beds up to 3 m thick. The phosphorite beds are calcareous with slight calcite cement, ammonites and trace

fossils. The A0 overlies the coquina member (middle member) with subaerial unconformity. Abed and Sadaqah (2011 in press) concluded that the U enrichment is, at least partially, due to slight leaching of the carbonates and

phosphorites at the unconformity. That is why the lower bed of the A0 has more U compared with the upper bed away from the unconformity.

Table 3. Uranium, P₂O₅ and CaO contents and other ratios in the upper phosphorite member (A0) in Eshidiyya Basin (Abed and Sadaqah, 2011 in press).

	U ppm	P ₂ O ₅ %	CaO% P ₂ O ₅	U/ P ₂ O ₅	CaO/ P ₂ O ₅	U/ CaO		U ppm	P ₂ O ₅ %	CaO% P ₂ O ₅	U/ P ₂ O ₅	CaO/ P ₂ O ₅	U/ CaO
1	220	37.35	54.34	5.88	1.45	4.04	16	158	29.46	53.29	5.35	1.81	2.96
2	162	26.73	53.53	6.06	2.00	3.03	17	207	37.17	52.33	5.58	1.41	3.96
3	220	37.16	54.18	5.91	1.46	4.06	18	125	27.7	52.9	4.51	1.91	2.36
4	223	28.55	53.58	7.81	1.88	4.16	19	21	4.03	25.31	5.14	6.28	0.82
5	190	36.53	51.82	5.20	1.42	3.66	20	31	4.7	33.13	6.55	7.05	0.93
6	180	34.5	49.2	5.21	1.43	3.65	21	72	31.89	45.05	2.26	1.41	1.60
7	210	37.27	52.81	5.64	1.42	3.98	22	12	3.21	12.53	3.86	3.90	0.99
8	127	26.49	52.71	4.78	1.99	2.40	23	40	23.81	34.84	1.66	1.46	1.13
9	242	35.84	51.97	6.74	1.45	4.65	24	5	1.94	28.72	2.63	14.80	0.18
10	135	24.99	52.1	5.40	2.08	2.59	25	61	29.66	40.15	2.05	1.35	1.51
11	234	37.34	52.8	6.28	1.41	4.44	26	27	6.81	15.78	3.89	2.32	1.68
12	182	29.62	52.25	6.15	1.76	3.49	27	16	5.29	7.99	3.04	1.51	2.02
13	190	38.53	53.74	4.93	1.39	3.54	28	9	2.53	26.49	3.36	10.47	0.32
14	216	33.29	52.45	6.49	1.58	4.12	Av	133	25.38	43.55	4.93	2.85	2.73
15	222	38.24	53.52	5.79	1.40	4.14							

3.2.2. Central Jordan Deposits

Central Jordan phosphorites are represented by Al-Hasa and Al-Abiad deposits and their surroundings. The deposits are calcareous, granular, and slightly cemented by calcite and are present in single isolated lenses. Several hundred million tons or high grade phosphorites were

mined since 1965, and consequently these deposits are near depletion. Table 4 shows the chemical results of 34 samples with an average of 105 ppm and a range 60-168 ppm (Abed and Khaled, 1985; Sadaqah et al., 2005; Abed et al., 2008). However, there are no much deposits for future U industry.

Table 4. Uranium, P₂O₅ and CaO contents and other ratios in central Jordan phosphorites, Al-Abiad and Al-Hasa (Abed and Khaled, 1985; Abed et al., 2008).

	U ppm	P ₂ O ₅ %	CaO% P ₂ O ₅	U/ P ₂ O ₅	CaO/ P ₂ O ₅	U/ CaO		U ppm	P ₂ O ₅ %	CaO% P ₂ O ₅	U/ P ₂ O ₅	CaO/ P ₂ O ₅	U/ CaO
1	132	20.82	44.51	6.34	2.14	2.97	24	70	27.67	46.6	2.53	1.68	1.50
2	121	28.16	45.7	4.23	1.62	2.65	25	76	15.55	29.7	4.89	1.91	2.56
3	123	32.04	48.24	3.84	1.51	2.55	26	127	30.2	50.6	4.21	1.68	2.51
4	114	32.95	48.15	3.46	1.46	2.37	27	123	30.64	47.4	4.01	1.55	2.59
5	168	29.52	48.6	5.69	1.65	3.46	28	111	31.9	47.2	3.48	1.48	2.35
6	146	29.83	47.41	4.89	1.59	3.08	29	110	32.81	50.5	3.35	1.54	2.18
7	143	27.92	47.63	5.12	1.71	3.00	30	60	20.97	49.52	2.86	2.36	1.21
8	146	29.67	49.54	5.88	1.67	2.95	31	61	26.96	55.31	2.26	2.05	1.10
9	161	30.44	44.69	5.28	1.47	3.60	32	64	30.93	49.07	2.07	1.59	1.30
10	157	30.66	50.75	5.13	1.66	3.09	33	48	25.92	46.58	1.85	1.80	1.03
11	86	21.19	51	4.06	2.41	1.69	34	190	26.95	53.06	7.05	1.97	3.58
12	165	29.52	51.75	5.59	1.75	3.19	35	39	16.31	33.01	2.39	2.02	1.18
13	158	30.66	53.72	5.15	1.75	2.94	36	63	29.02	46.13	2.17	1.59	1.37
14	160	32.95	52.93	4.86	1.61	3.02	37	83	27.3	52.9	3.04	1.94	1.57
15	160	32.95	52.18	4.86	1.58	3.07	38	57	19.42	43.67	2.94	2.25	1.31
16	168	27	54.02	6.22	2.00	3.11	39	35	18.53	53.72	1.89	2.90	0.65
17	13	31.34	50.72	4.4	1.62	2.72	40	34	22.85	53.92	1.49	2.36	0.63
18	115	30.75	50.8	3.74	1.65	2.26	41	58	25	41.09	2.32	1.64	1.41
19	120	33.98	52.23	3.52	1.54	2.30	42	113	23.92	44.73	4.72	1.87	2.53
20	111	31.72	50.71	3.5	1.60	2.19	43	49	16.59	51.75	2.95	3.12	0.95
21	95	30.21	48.6	3.15	1.61	1.95	44	79	29.86	46.2	2.65	1.55	1.71
22	106	25.6	51.46	4.14	2.01	2.06	45	52	29.74	50.8	1.75	1.71	1.02
23	73	24.44	44.6	2.99	1.82	1.64	46	67	29.8	48.5	2.25	1.63	1.38
								105	27.46	48.52	3.81	1.77	2.17

However, grade phosphorites are present west of Dhiban, near the village of Shgaig. The area is populated and the deposits have not been mentioned by JPMC or other workers (Abed and Khaled, 1985). Reserves are not estimated and the U contents of 14 samples is 79 ppm with a range of 4-118 ppm (Table 5)

Table 5. Uranium, P₂O₅ and CaO contents and other ratios in the phosphorites of the Mujib Area (Abed and Khaled, 1985).

	U ppm	P ₂ O ₅ %	CaO%	U/ P ₂ O ₅	CaO/ P ₂ O ₅	U/ CaO
1	92	22.94	52.41	4.01	2.28	1.76
2	22	16.85	44.7	1.31	2.65	0.49
3	15	14.8	47.29	1.01	3.20	0.32
4	4	16.81	47.4	0.24	2.82	0.08
5	103	13.16	51.13	7.83	3.89	2.01
6	110	18.95	52.47	5.80	2.77	2.10
7	110	23.18	53.79	4.75	2.32	2.04
8	116	29.72	51.8	3.90	1.74	2.24
9	78	26.81	50.24	2.91	1.87	1.55
10	85	23.69	52.18	3.59	2.20	1.63
11	118	30.1	51.3	3.92	1.70	2.30
12	48	17.94	54.64	2.68	3.05	0.88
13	91	24.85	57.31	3.66	2.31	1.59
14	111	22.92	50.17	4.84	2.19	2.21
Av.	79	21.62	51.20	3.60	2.37	1.54

3.2.3. Ruseifa Deposits.

During 1988, Ruseifa mines were closed and the remaining deposits south of the Amman-Zarqa highway are becoming more and more urbanized. Thus, the following lines are of historical value only. The Ruseifa phosphorites consist of four horizons (A1, A2, A3, and A4 topmost) separated by carbonates and chert beds (Fig. 5). Table 6 shows the analysis of 17 samples with an average U of 123 ppm and a range of 57-184. Uranium content increases upwards and the A4 horizon have the highest content of more than 180 ppm (Abed and Khaled, 1985).

Table 6. Uranium, P₂O₅ and CaO contents and other ratios in the phosphorites of Ruseifa (Abed and Khaled, 1985).

	U ppm	P ₂ O ₅ %	CaO%	U/ P ₂ O ₅	CaO/ P ₂ O ₅	U/ CaO
1	123	17.25	52.61	7.02	3.05	2.34
2	121	26.66	55.26	4.55	2.07	2.19
3	113	13.26	52.7	8.52	3.97	2.14
4	56	24.67	42.58	2.27	1.73	1.32
5	86	24.59	42.97	3.5	1.75	2.00
6	57	25.31	43.62	2.25	1.72	1.31
7	183	29.79	52.65	6.11	1.77	3.48
8	184	28.94	50.33	6.53	1.74	3.66
9	127	26.31	46.71	4.82	1.78	2.72
10	73	21.69	43.68	3.37	2.01	1.67
11	119	20.96	53.17	5.68	2.54	2.24
12	117	17.31	49.45	6.76	2.86	2.37
13	161	30.5	53.8	5.28	1.76	2.99
14	162	31.11	53.75	5.21	1.73	3.01
15	181	21.75	53.82	8.32	2.47	3.36
16	117	16.54	54.2	7.07	3.28	2.16
17	117	17.93	52.1	6.53	2.91	2.25
Av.	123	23.21	50.20	5.52	2.16	2.46

3.2.4. Al-Kora Deposits, NW Jordan

The NW Jordan phosphorites are promising future deposits for phosphorites and uranium. There are, at least, several hundred million tons of high grade phosphorites with high U content relative to other deposits discussed earlier. However, the high population (many villages and towns) and the green nature of the area (forests and agriculture) might have been behind the decision not to mine the deposits. Also, the deposits are present within a folded belt which makes open pit mining rather difficult if not impossible in certain localities (Mikbel and Abed 1985).

Table 7 shows the analysis of 18 samples with an average of 153 ppm U and a range of 59-379 ppm U (Abed and Khaled, 1985; Sadaqah, 2000, Sadaqah et al., 2005). The highest U content is around 6 times more than that of Eshidiyya and might be of economic nature if extracted as a byproduct through the fertilizers industry. Detailed field and laboratory work can pinpoint the localities with the high U content.

Table 7. Uranium, P₂O₅ and CaO contents and other ratios in the phosphorites of Al-Kora Basin, NW Jordan. (Abed and Khaled, 1985; Sadaqah et al., 2005).

	U ppm	P ₂ O ₅ %	CaO%	U/ P ₂ O ₅	CaO/ P ₂ O ₅	U/ CaO
1	88	24.09	40.52	3.65	1.68	2.17
2	117	30.23	44.01	3.87	1.46	2.66
3	186	32.7	52.4	5.69	1.60	3.55
4	129	18	53.79	7.16	2.99	2.40
5	120	14.22	50.44	8.44	3.55	2.38
6	132	30.18	46.62	4.37	1.54	2.83
7	127	24.37	54.9	5.21	2.25	2.31
8	81	21.08	33.18	3.84	1.57	2.44
9	75	31.5	52.4	2.38	1.66	1.43
10	238	34.16	52.98	6.97	1.55	4.49
11	88	26.25	52.78	3.35	2.01	1.67
12	89	24.05	53.09	3.70	2.21	1.68
13	301	20.92	50.06	14.39	2.39	6.01
14	343	18.95	51.95	18.10	2.74	6.60
15	109	24.06	52.52	4.53	2.18	2.08
16	59	10.13	52.39	5.82	5.17	1.13
17	379	27.75	53.08	13.66	1.91	7.14
18	92	22	52.23	4.18	2.37	1.76
Av	153	24.15	49.96	6.63	2.07	3.06

3.2.5. Area Comparison

Absolute U content might not be the best way of comparing its abundance in the various localities. For this reason, the U/P₂O₅ ratio is used, meaning the amount of U in ppm present for each 1% P₂O₅. The average U/P₂O₅ ratio for the samples in each locality (not the ratio of averages) is shown in Table 8. It is clear from Table 8 that the ratio increases northwards. It is 2.24 in Eshidiyya; i.e. there is 2.24 ppm U in Eshidiyya deposits for each 1% P₂O₅. It increases to 6.63 in NW Jordan, which clearly shows that the NW Jordan phosphorites are three times

more enriched in U compared with Eshidiyya. The other localities are intermediate between Eshidiyya and NW Jordan. The possible reasons for this northwards increasing trend are discussed further below.

Table 8 The U/P₂O₅ sample averages in the phosphorite deposits of Jordan, n = number of samples averaged.

	U ppm	P ₂ O ₅ %	CaO %	U/P ₂ O ₅	n
Eshidiyya	51	20.83	36.7 1	2.24	60
Central Jordan	105	27.46	48.5 2	3.81	44
Mujib	79	21.62	51.2	3.6	13
Ruseifa	123	23.21	50.2	5.52	16
NW Jordan	153	24.15	49.9 6	6.63	18

4. Behavior of U During Mining and Upgrading.

Mining and upgrading are not discussed here because they are not the subject of this paper. However, mining and upgrading involve the removal of the overburden, obtaining the phosphorite ore, crushing the ore to liberate the suitable grain size, sieving to get a roughly sand-size product, washing with fresh water to get rid of the fines especially clays, and finally drying. Samples from all these stages were analyzed for their U and other elements and the following conclusion was reached (Al-Huwaiti et al., 2005; Abed et al., 2008). Uranium behaves similar to the behavior of P and Ca (Fig. 8a); i.e. U stays fixed in the crystal structure of francolite, as discussed in the mineralogy section.

Environmentally, the discharged washing water has not contaminated the groundwater in Al-Hasa and Al-Abiad mines area despite the fact that the washing process has been ongoing since 1965 and 1979 respectively. Groundwater samples from wells and springs in central Jordan have a U content less than 2 ppb (parts per billion) (Jiries et al., 2004; Abed et al., 2008). See Fig.8b.

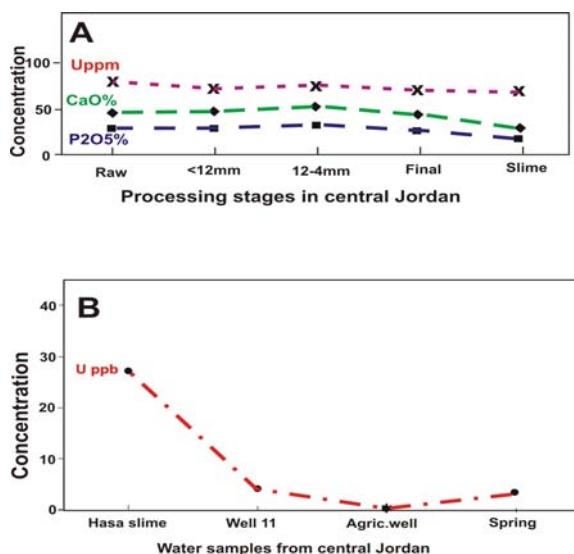


Fig. 8 shows the behavior of U during mining, crushing, sieving and washing (8a upper) and 8b shows the concentration in ppb in the groundwater in central Jordan.

5. Behavior of U in the Fertilizers Industry.

In the fertilizers industry, the upgraded phosphorite ore is reacted with sulphuric acid (H₂SO₄) to produce phosphoric acid (H₃PO₄) and phosphogypsum. The crystal structure of francolite is destroyed through this reaction, its PO₄ forms phosphoric acid, and the Ca of francolite forms the phosphogypsum. Analysis of the two products, the acid, and gypsum, clearly shows that U follows the PO₄ group and is concentrated in the phosphoric acid. The phosphogypsum has no more than 2 ppm U. The phosphoric acid is then transferred to the fertilizer, diammonium phosphate (DAP), and U is found to be concentrated in the DAP. Through these reactions, U is found to be concentrated in the phosphoric acid and the DAP by a factor of 1.5 (Fig. 9). For more details, see Abed et al., (2008).

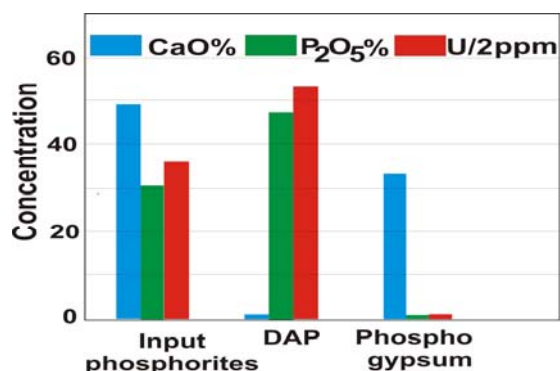


Fig. 9 Behavior of U in the fertilizers industry. Note that the U and P₂O₅ are enriched by a factor of 1.5 in the DAP fertilizer and the U in phosphogypsum is around 2 ppm.

6. Phosphogenesis and the Enrichment of U: Discussion

Why phosphorites have more U compared with other sedimentary rocks? Why U contents increases northwards in the Jordanian phosphorites? Following is an attempt to answer these and others related to phosphogenesis.

Phosphorite, bedded chert, porcelanite and organic-rich sediments, as an association, are known to deposit under upwelling currents regimes (Sheldon, 1987; Iijima, et al., 1994 and the papers within). This is well documented in the recent and subrecent Earth history in shallow continental shelf where upwelling currents are intense and still ongoing; e.g. the coasts of SW Africa (Birch, 1980), the western coast of South America up till California in the north (Froelich et al., 1988; Burnett, 1990; Kolodny and Garrison, 1994), and in the southeastern United States where the Gulf Stream causes upwelling (Riggs et al., 1998). Thus, the association of these facies is usually taken as due to upwelling in ancient phosphorite deposits (Baturin, 1982; Abed and Amireh, 1983; Alomogi-Labin et al., 1993; Glenn et al., 1994; Follmi, 1996). However, some authors had explained the formation of ancient phosphorites without the need of upwelling (e.g. Heggie et al., 1990; Glenn and Arthur, 1990)

Upwelling currents spread deep, cold marine water on the surface of the relatively shallow continental shelves adjacent to the continents (Fig. 10). Deep, cold water, 1000 m or more, is usually rich in nutrients, most important of which are Si and P which are the basic food

for the phytoplanktons (diatoms and dinoflagellates); the lowest step in marine food chains which inhabit the photic zone or the upper 100-200 m of the sea water column. Under such conditions, bioproductivity of the marine food chain is highly increased. Rate of death of these organisms is consequently increased to produce an oxygen minimum zone (OMZ) extending few hundred metres below the photic zone and might reach the shelf floor. The formation of the OMZ reduces the amount of the oxidized soft tissues of the descending organisms, thus giving more chances to the soft tissues (organic matter, OM) to joint the sediments accumulating at the shelf floor. A higher rate of sedimentation will ensure a higher rate of burial for the OM to escape long exposure and oxidation. Consequently, a sediment- rich OM is formed (Baturin, 1982; Salansky, 1986; Glenn *et al.*, 1994; Lucas and Prevot-Lucas, 1995).

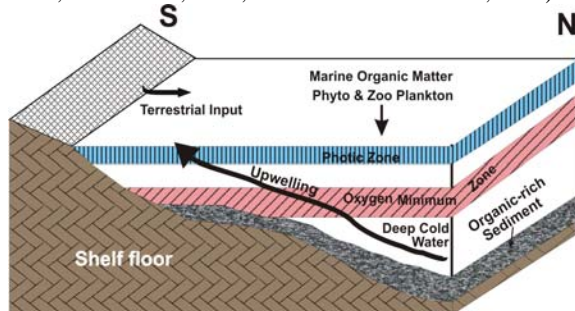


Fig. 10 A schematic model for phosphorite deposition under an upwelling regime.

Decomposition of the sediment organic matter below the water/sediment interface by bacteria and fungi liberates phosphorous to the interstitial pore fluids. Certain minerals form from these fluids like calcite, dolomite and palygorskite before the formation of apatite. This means that P, most probably as PO_4 , is concentrated many folds relative to sea water before its deposition (Riggs *et al.*, 1985). Finally, apatite is either precipitated directly from these interstitial fluids (authigenic origin) or the fluids react with pre existing sediments and transform them into apatite (diagenetic origin) (Price and Calvert, 1978; Birch *et al.*, 1983; Froelich *et al.*, 1983).

Jordanian phosphorites are postulated to have deposited under upwelling cold, deep water from the Tethys Ocean in the north onto its shallow epeiric shelf where Jordan was situated during the upper most Cretaceous. This is evident from the presence of phosphorite, bedded chert, porcelanite (biogenic silica deposits), oil shale and a pronounced negative cerium anomaly indicative of deep oceanic water (Abed and Abu Murry, 1997). Furthermore, Jordanian phosphorites are dominantly authigenic, precipitated from the pore fluid solutions as phosphate mud, which was then reworked into phosphate pellets and intraclasts (Al-Agha, 1985; Abed and Al-Agha, 1989).

Recent pelletal phosphorites off the SW Africa and Peru margins are carbonate fluorapatite (Baturin, 1971; Burnett, 1977; Price and Calvert, 1978; Froelich *et al.*, 1983). The concentrations of P, C, and F in the upper few tens of centimeters of the sediment pore water are high enough to permit their direct chemical precipitation as carbonate fluor apatite. On the other hand, the bone material is made of dahlite; carbonate hydroxyapatite, with F content far less than 1% or even hydroxyapatite which is devoid of F (McConnell, 1973; Altschuler, 1973). Dahlite

is readily converted into carbonate fluorapatite through the interaction with sediment pore water during early diagenesis, incorporating F and possibly CO_3 into its structure. This conversion process takes place contemporaneously with the direct precipitation of pelletal/intraclast material as carbonate fluorapatite (Froelich *et al.*, 1983; Abed and Fakhouri, 1996).

Accordingly, there should be abundant organic matter associated with the phosphorites in their depositional environment. Organic matter is well known as a good scavenger for U and many other trace metals. Most probably, the newly deposited apatite would take up U into its open crystal structure from the engulfing pore fluids which were formed after organic matter decomposition. Uranium, then, becomes part of the apatite occupying some of the positions located for Ca in the apatite structure. It should be emphasized that U in the ancient phosphorites is present within the crystal structure of apatite not adsorbed on the organic matter (Froelich *et al.*, 1983; Burnett, 1990).

In Jordan, the northwards increase of U may be due to higher organic matter associated with the phosphorites in north Jordan. The NW Jordan deposits have around 6% organic matter (Abed and Al-Agha, 1989) with much lower contents further south. The organic matter in the other localities, other than NW Jordan, is to be seen within the phosphate pellets and intraclasts. The dark colour of some of these particles is indicator of organic matter. This is evident from the leaching and oxidation of pellets/intraclasts rims by percolating oxidizing groundwater through these permeable phosphorite deposits throughout the history of these deposits.

7. Conclusions

High grade phosphorites are wide spread in Jordan. Despite the fact that Ruseifa mines were closed and the central Jordan deposits and near depletion, huge reserves are still existing in Eshidiyya Basin (in excess of 1000 million tons), Al-Kora Basin, NW Jordan (several hundred million tons), and the subsurface of the eastern desert.

The phosphorites of Jordan are the main carrier of Uranium in the country. Uranium is present within the crystal structure of francolite (carbonate flour apatite) substituting for Ca. Uranium content varies up 379 ppm in certain phosphorite horizons.

Uranium content in the various localities increases northwards. Eshidiyya deposits lower member (main deposits) has around 70 ppm U while the upper member (A0) 133 ppm, central Jordan 105 ppm, Ruseifa 123 ppm, and NW Jordan 153 ppm. It should be emphasized that certain phosphorite horizons have much more U compared with these averages. Detailed field geology can pinpoint such horizons if U is to be exploited. It is here postulated that organic matter may be one of the main reason for the northwards increase of U.

During mining and upgrading of the phosphorite ores, U sticks to the mineral francolite and thus behaves similar to Ca and P_2O_5 . No groundwater contamination with U is noticed in central Jordan despite the fact that fresh water used in washing the upgraded ore has been discharged to the local environment since more than 45 years.

Throughout the fertilizers industry, U follows P, first into the phosphoric acid and then into the diammonium phosphate (DAP) where it becomes concentrated by a factor of 1.5 relative the fed ore. On the contrary, calcium leaves francolite to phosphogypsum but U does not follow suite, thus phosphogypsum is almost devoid of U with a content up to 2 ppm.

REFERENCES

- [1] Abed, A. M., 1989. On the genesis of the phosphorite-chert association in the Amman Formation in Tel es Sur area, Ruseifa, Jordan. *Science Geologie Bulletin, Strasbourg* 42, 141-153.
- [2] Abed, A. M., 1994. Shallow marine phosphorite-chert-palygorskite association, Upper Cretaceous Amman Formation, Jordan. In: A. Iijima, A. M. Abed, and R. Garrison, (Editors.), *Siliceous, Phosphatic and Glauconitic Sediments in the Tertiary and Mesozoic. Proc. 29th Intern. Geol. Congr., Part C.* VSP, The Netherlands, pp. 205-224.
- [3] Abed, A. M., 2000. Geology of Jordan, Jordanian Geologists Association, Amman (In Arabic).
- [4] Abed, A. M. and Amireh, B., 1983. Petrography and geochemistry of some Jordanian oil shale from north Jordan: *Journal of Petroleum Geology*, 5, 261-274.
- [5] Abed, A. M. and Khalid, H. 1985 Uranium distribution in the Jordanian phosphorite. *Dirasat*, 12: 91-103.
- [6] Abed, A. M. and Al-Agha, M. R., 1989. Petrography, geochemistry and origin of the NW Jordan phosphorites. *J. Geol. Soc. London*, 146: 499-506.
- [7] Abed, A. M. & Fakhouri, K., 1996. On the chemical variability of phosphatic particles from the Jordanian phosphorites. *Chemical Geology* 131, 1-13.
- [8] Abed, A. M. and Abu Murry, O., 1997. Rare earth element geochemistry of the Jordanian Upper Cretaceous phosphorites. *Arab Gulf J. Scient. Res.*, 15, 41-61.
- [9] Abed, A. M. and Sadaqah, R., 1998.. Role of Upper Cretaceous oyster bioherms in the deposition and accumulation of high- grade phosphorites in central Jordan. *Journal of Sedimentary Research*, 68B, 1009-1020.
- [10] Abed. A. M. & Amireh, B. S., 1999. Sedimentology, geochemistry, economic potential and paleogeography of an Upper Cretaceous phosphorite belt in the southeastern desert of Jordan. *Cretaceous Research*, 20, 119-133.
- [11] Abed, A. M., Arouri, K. and Boreham, C., 2005. Source rock potential of the phosphorite-bituminous chalk-marl sequence in Jordan. *Marine and Petroleum Geology*, 22, 413-425
- [12] Abed, A. m., Sadaqah, R. and Al-Jazi, M., 2007 Sequence stratigraphy and evolution of Eshidiyya phosphorite platform, southern Jordan. *Sedimentary Geology*, 198, 209-219.
- [13] Abed, A. M., Sadaqah, R., and Kuisi, M. A., 2008. Uranium and potentially toxic metals during the mining, beneficiation and processing of phosphorite and their effects on ground water in Jordan. *Mine water and the Environment*, 27, 171-182.
- [14] Abed, A. M., Sadaqah, R., 2011. Enrichment of uranium in the upper phosphorite horizon (A0) in Eashidiyya, south Jordan. *Cretaceous Research* (in press).
- [15] Al-Agha, M. R., 1985. Petrography, geochemistry and origin of the NW Jordan phosphorites. Thesis. Univ. of Jordan (unpubl).
- [16] Al-Hwaiti, M., Matheis, G. and Saffarini, G., 2005, Mobilization, redistribution and bioavailability of potentially toxic elements in Shidiya phosphorites, Southern Jordan. *Environmental Geology* 47, 431-444.
- [17] Almogi-Labin, A., Bein, A. and Sass, E., 1993. Late Cretaceous upwelling system along the southern Tethys margin (Israel): Interrelationship between productivity, bottom water environments, and organic matter preservation. *Paleoceanography*, 8: 671-690.
- [18] Altschuler, Z. S. 1973. The weathering of phosphatic deposits: geochemical and environmental aspects. In: G. Griffith, A. Becton, J. M. Spencer and D. T. Mitchell (Editors.). *Environmental Phosphorus Handbook*. Wiley, New York, pp. 33-96.
- [19] Altschuler, Z. S., 1980. The geochemistry of trace elements in marine phosphorites, Part 2: Characteristics, abundances and enrichment. *SEPM Spec publ* 29:19-30.
- [20] Baturin, G. N. 1971. Recent authigenic phosphorite formation on the SW African shelf. In: F. M. Delany (Editor), *The Geology of the East Atlantic Margin*. ICSU/SCOR Working Party 31 Symp. Cambridge. *Inst. Geol. Sci. Rep.*, 70/16, pp. 88-97.
- [21] Baturin, G.N., 1982, Phosphorites on the sea floor.. *Developments in Sedimentology* 33, Elsevier, Amsterdam, 343 p.
- [22] Bender, F. 1974. *Geology of Jordan*. Borntraeger, Berlin.
- [23] Birch, G.F., 1980. A model for penecontemporaneous phosphatization by diagenetic and authigenic mechanism from the western margin of southern Africa. In *Marine phosphorites* (ed Bentor, Y.), *Society of Economic Paleontologists and Mineralogists, Special Publications* 29, 70-100
- [24] Birch, G. F., Thomson, J., McArthur, J. and Burnett, W. C., 1983. Pleistocene phosphorites off the west coast of South Africa. *Nature*, 302: 601-603.
- [25] Burnett, W. C. 1977. Geochemistry and origin of phosphorites deposits from off Peru and Chile. *Geol. Soc. Amer. Bull.*, 88: 813-23.
- [26] Burnett, W.C., 1990. Phosphorite growth and sediment dynamics in the modern Peru shelf upwelling system, In *Phosphorite deposits of the world*, v. 3, *Neogene to modern phosphorites* (eds Burnett, W.C. and Riggs, S.), 62-74. Cambridge University Press, Cambridge).
- [27] Capetta, H., Pfeil, F. Schmidt-Kittler, N. and Martini, E., 1996. New biostratigraphic data on the marine Upper Cretaceous and Paleogene of Jordan. Unpublished report by the, Jordan Phosphate Mining Co, Amman, Jordan.
- [28] Coppens, R., Bashir, S. and Ritchard, P. 1977. Radioactivity of El-Hasa phosphates, a preliminary study. *Mineral Deposita*, 12, 189-196.
- [29] El-Hiyari, M., 1985. The geology of Jabal Al-Mutarammil, Map sheets No 3252, III. National Mapping Project, Bulletin 1, Natural Resources Authority, Amman, Jordan.
- [30] Follmi, K. B., 1996. The phosphorus cycle, phosphogenesis and marine phosphate-rich deposits. *Earth Science Review* 40, 55-124.
- [31] Froelich, P. N., Kim, K. H., Jahnke, R., Burnett, W. C., Soutar, A. and Deakin, M. 1983. Pre water fluoride in Peru continental margin sediments: uptake from seawater. *Geochim. Cosmochim. Acta*, 47: 1905-12.
- [32] Froelich, P., Arthur, M., Burnett, W., Deakin, M., Hensley, V., Jahnke, R., Kaul, L., Kim, H., Soutar, A., and Vathakanoan, C. 1988. Early diagenesis of organic matter in Peru continental margin sediments- phosphorite precipitation: *Marine Geology*, 80, 309-343.
- [33] Glenn, C. R. and Arthur, M. A., 1990. Anatomy and origin of a Cretaceous phosphorite-green sand giant, Egypt. *Sedimentology*, 37: 123-148.
- [34] Glenn, C. R.; Follmi, K. B.; Riggs, S. R.; Baturin, G. N.; Grimm, K. A. Trappe, J.; Abed, A. M.; Galli-Oliver, C.; Garrison, R. E.; Iiyin, A. V.; Jehl, C.; Rohrlch, V.; Sadaqah, R. M.; Schidlowski, M.; Sheldon, R. E. and Siegmind, H., 1994. Phosphorus and phosphorites: sedimentary and environments of formation. *Eclogae Geologicae Helvetica*, 87, 747-788.

- [35] Glikson, M., Gibson, D. L. and Philp, R. P., 1985. Organic matter in Australian Cambrian oil shale and other Lower Palaeozoic shales: *Chemical Geology*, 51, 175-191.
- [36] Hamam, K. A., 1977. Foraminifera from the Maastrichtian bearing strata of Al-Hasa, Jordan. *Jour. Foram. Res.*, 7: 34-43.
- [37] Heggie, D. T.; Skyring, G. W., O'Brian, G. W., Reimers, C., Herczef, A., Moriarty D. J. W., Burnett, W. C. and Milnes, A. r., 1990. Organic carbon cycling and the modern phosphorite formation on the East Australian continental margin: an overview. In: A. J. G. Notholt and I. Jarvis (Eds.) *Phosphorite Research and Development*. Geological Society Special Publication 52, 87-118.
- [38] Iijima, A., Abed, A. M. and Garrison, R., (Editors.), *Siliceous, Phosphatic and Glauconitic Sediments in the Tertiary and Mesozoic*. VSP, The Netherlands.
- [39] Jarvis, I., 1992. Sedimentology, geochemistry and origin of phosphatic chalk: The Upper Cretaceous of NW Europe. *Sedimentology*, 39, 55-97.
- [40] Jiries, A., El-Hasan, T., Al-Hiwati, M., and Seiler, K. P., 2004. Evaluation of the Effluent Water Quality Produced from Phosphate Mines in Central Jordan. *Mine Water and the Environment*. 23 (3): 133-137 Khalid, H., and Abed, A. M., 1982. Petrography and geochemistry of Esh Shidiya phosphates. *Dirasat*, 9: 81-102.
- [41] Khalifa, M. Kh. And Abed, A. M., 2011. Lithostratigraphy and microfacies analysis of the Ajlun Group (Cenomanian to Turonian) in Wadi Sirhan Basin, SE Jordan. *Jordan Journal for Environmental and Earth Sciences (IN press)*
- [42] Kolodny, Y. and Garrison, R., 1994. Sedimentation and diagenesis in paleo-upwelling zones of epeiric sea and basinal settings: A comparison of the Cretaceous Mishash Formation of Israel and the Miocene Monterey Formation of California. In: A. Iijima, A. M. Abed, and R. Garrison, (Editors.), *Siliceous, Phosphatic and Glauconitic Sediments in the Tertiary and Mesozoic. Proc. 29th Intern. Geol. Congr., Part C*. VSP, The Netherlands, pp. 133-158.
- [43] Krauskopf, K. and Bird, D., 1995. Introduction to geochemistry, 3rd Ed. McGraw Hill, Boston.
- [44] Lucas, J. and Prevot-Lucas, L., 1995. Tethyan phosphates and bioproductites. In: Nairn, A. E. et al. (eds), *The ocean basins and margins - The Tethys ocean*. Plenum Press. 8, 367-391.
- [45] McArthur, J. M., Hamilton, P. J., Greensmith, J. T., Walsh, J. N., Boyce, A. B., Fallick, A. E., Birch, G., Benmore, R. A. and Coleman, M. L., 1987. Francolite geochemistry - meteoric alteration on a local scale. *Chem. Geol. (Isotope Geoscience)*, 65: 415-425.
- [46] McClellan, G. H. and Kauwenbergh, S. J. V., 1990. Mineralogy of sedimentary apatite. In: A. J. G. Notholt and I. Jarvis (Editors), *Phosphorite Research and Development*. *Geol. Soc. Lond. Specl. Publ. no. 52*, 23-31.
- [47] McConnell, D., 1973. Apatite, crystal chemistry and mineralogy. Springer, Berlin. 111pp.
- [48] Mikbel, Sh. and Abed, A. M., 1985. Discovery of large phosphate deposits in NW Jordan. *Dirasat*, 12, 125-124.
- [49] Nathan, Y., 1984. The mineralogy and geochemistry of phosphorites. In: Nriagu, J. O. and Moore, P. O. (eds), *Phosphate minerals*. Springer, Berlin, 275-291.
- [50] Notholt, A. J. G., Sheldon, R. P. and Davidson, D. F., 1989. Phosphate deposits of the world, Volume 2, Phosphate rock resources. Cambridge University Press, Cambridge.
- [51] Powell, J. H., 1989. Stratigraphy and Sedimentation of the Phanerozoic Rocks in Central and South Jordan, Part B: Kurnub, Ajlun and Belqa Groups: Bulletin 11, NRA, Amman.
- [52] Quennell, A. M., 1951. The geology and mineral resources of the (former) Transjordan. *Colonial Geology and Mineral Resources, London*, 2, 85-115.
- [53] Prevot, L. and Lucas, J., 1980. Behavior of some trace elements in phosphatic sedimentary formations. In: Y. K. Bendor (Editor), *Marine phosphorites*. SEPM Spec. Publ., 29: 31-41.
- [54] Price, N. B. and Calvert, S. E., 1978. The geochemistry of phosphorites from the Namibian shelf. *Chem. Geol.*, 23: 151-178.
- [55] Riggs, S. R., 1979. Petrology of the Tertiary phosphorite system of Florida., *Econ. Geol.*, 74: 194-220.
- [56] Riggs, S. R., 1980. Intraclast pellet phosphorite sedimentation in the Miocene of Florida. *Journal of the Geological Society, London* 137, 741-748.
- [57] Riggs, S. R., Snyder, S., Hine, A., Snyder, Sc., Elligton, D. and Mallette, P., 1985. Geologic framework of phosphate resources in Onslow Bay, North Carolina continental shelf. *Econ. Geol.*, 80: 716-738.
- [58] Riggs, S. R., Ambrose, W. G., Cook, J. W., Snyder, S. C., & Snyder, St. W., 1998. Sediment production on sediment-straved continental margins: The interrelationship between hardbottoms, sedimentological and benthic community processes, and storm dynamics. *Journal of Sedimentary Research*, A68, 155-168.
- [59] Sadaqah, R. M., 2000. Phosphogenesis, geochemistry, stable isotopes and depositional sequence of the Upper Cretaceous phosphorite formation in Jordan. Unpublished Ph. D thesis , Univ. of Jordan, Amman, 257p.
- [60] Sadaqah, R. M., Abed, A.M., Grimm, K. A. and Pufahl, P. K., 2005. The geochemistry of REE , Yttrium and Scandium in some Upper Cretaceous Jordanian phosphorites, *Dirasat* 32, 32-47.
- [61] Sheldon, R. P. 1981. Ancient marine phosphorites. *Ann. Rev. Earth planet. Sci.* 9: 251-84.
- [62] Sheldon, R. P., 1987. Association of phosphatic and siliceous marine sedimentary deposits. In: J. R. Hein (Editor), *Siliceous sedimentary rock-hosted ores and petroleum*. Nostrand Reinhold, New York, pp. 56-79.
- [63] Slansky, M., 1986. *Geology of sedimentary phosphates*, 210 pp. (Elsevier, Amsterdam).
- [64] Soframines and Consortium Partners, 1987. Feasibility study of Eshidiyya phosphate project. Unpubl. Jordan Phosphate Mines Company, Amman, Jordan.