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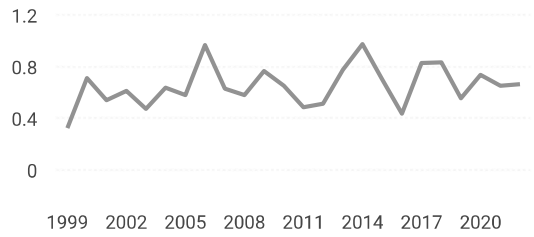

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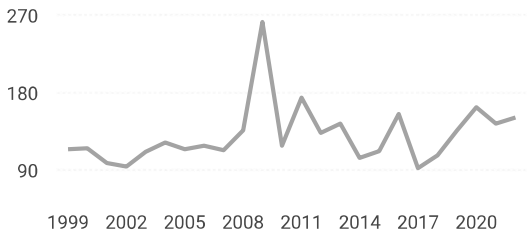

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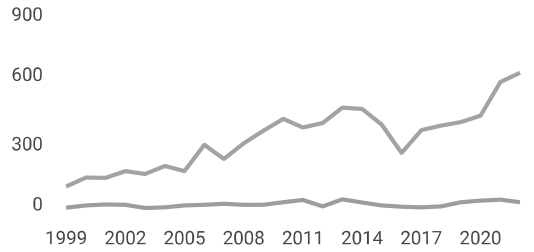

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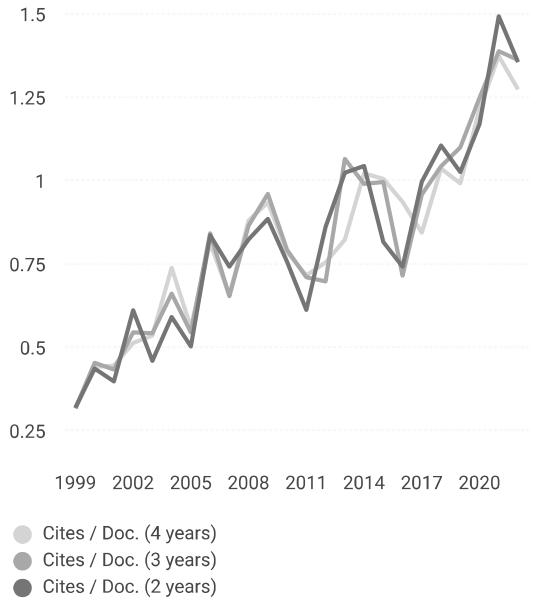

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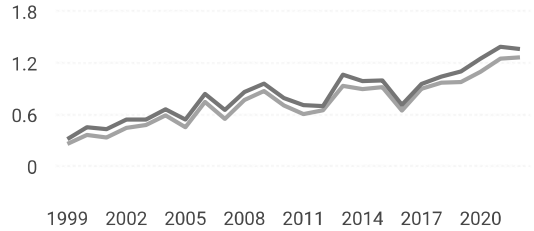

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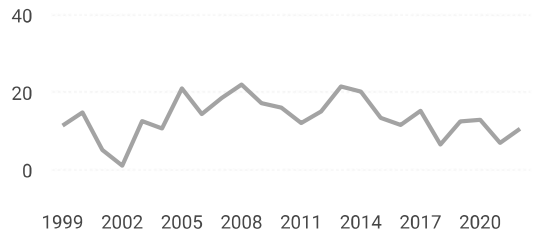

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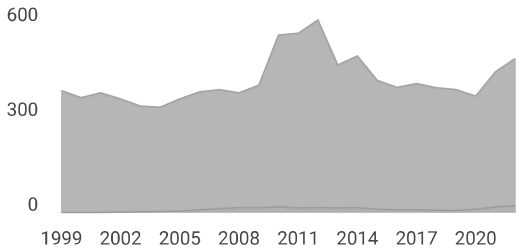

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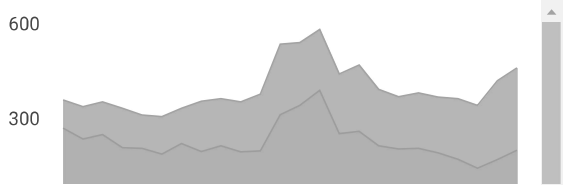

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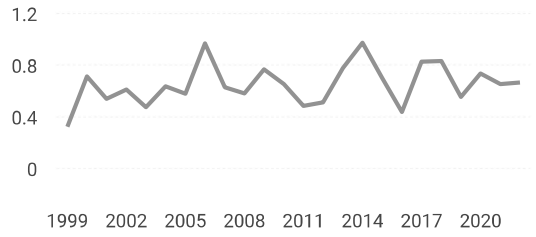

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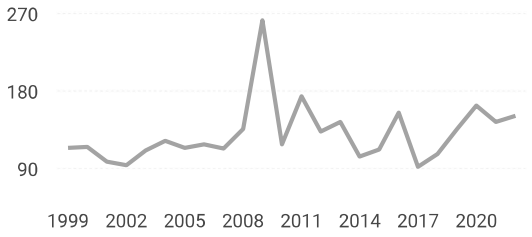

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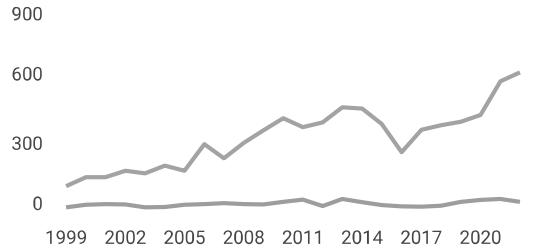

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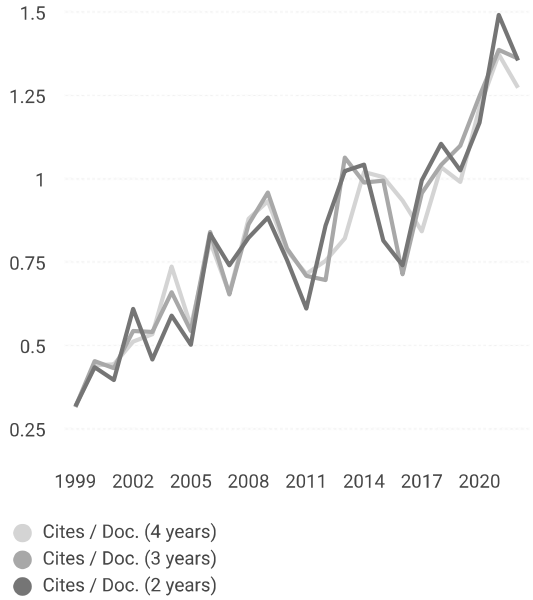

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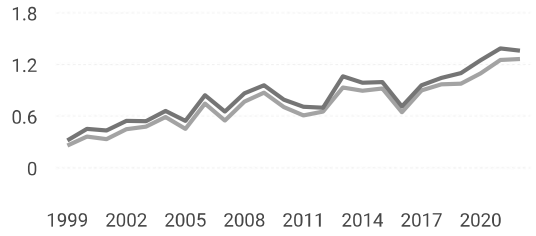

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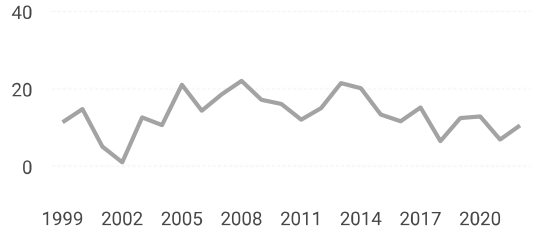

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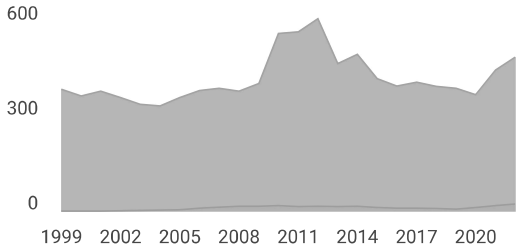

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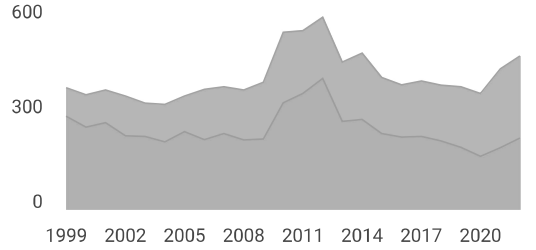

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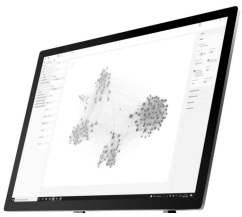

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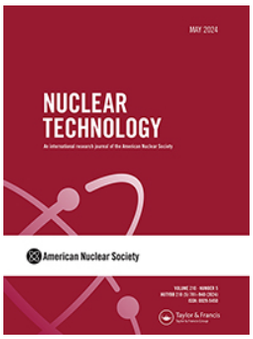

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Javiera Cervini-Silva

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Notes

Bentonites as Natural Sources of Thorium and Uranium

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Abstract — *Bentonites are natural reservoirs of various elements and are of interest because they are sources of thorium and uranium, which are transition elements that provide nuclear energy. The objective of this work was to study the plausible association(s) of these elements with other transition elements of interest. The contents of 18 transition elements (cerium, cobalt, chromium, copper, iron, hafnium, lanthanum, manganese, molybdenum, neodymium niobium, nickel, tantalum, thorium, uranium, vanadium, yttrium, zinc, and zirconium) in 38 bentonites determined experimentally by X-ray fluorescence spectroscopy (XRF) were analyzed.*

The contents of the elements were plotted in (x,y) graphs and then fitted to polynomial functions (orders 1 through 6). According to the coefficient of determination (r^2: $0.5 \le r^2$ strong, $0.3 \le r^2 \le 0.5$ medium, and $r^2 \le 0.3$ weak), the contents of thorium, uranium, niobium, and nickel related strongly, thus the presence of niobium and nickel served to predict the presence of detectable concentrations of thorium and uranium. The equations showing higher r^2 values were

1. $\{Th\} = 1e\text{-}6\{Nb\}^5 - 3e\text{-}4\{Nb\}^4 + 1.9e\text{-}2\{Nb\}^3 - 5.4e\text{-}1\{Nb\}^2 + 7.3\{Nb\} - 6.3,\ r^2 = 0.53.$
2. $\{Th\} = -3e\text{-}8\{Nb\}^6 + 9e\text{-}6\{Nb\}^5 - 1e\text{-}3\{Nb\}^4 + 4.7e\text{-}2\{Nb\}^3 - 1.1\{Nb\}^2 + 11.5\{Nb\} - 16,\ r^2 = 0.54.$
3. $\{Th\} = 5e\text{-}6\{Ni\}^4 - 1.5e\text{-}3\{Ni\}^3 - 1.5e\text{-}1\{Ni\}^2 - 5.8\{Ni\} + 9e{+}1,\ r^2 = 0.49.$
4. $\{Th\} = -7e\text{-}8\{Ni\}^5 + 3e\text{-}5\{Ni\}^4 - 5.1e\text{-}3\{Ni\}^3 + 3.4e\text{-}1\{Ni\}^2 - 9.5\{Nb\} + 1e{+}2,\ r^2 = 0.56.$
5. $\{Th\} = 2e\text{-}9\{Ni\}^6 - 8e\text{-}7\{Ni\}^5 + 2e\text{-}4\{Ni\}^4 - 1.5e\text{-}2\{Ni\}^3 - 7e\text{-}1\{Ni\}^2 - 1e{+}1\{Ni\} + 1e{+}1,\ r^2 = 0.60.$
6. $\{Th\} = -1e\text{-}4\{U\}^5 + 1.3e\text{-}2\{U\}^4 - 4.3e\text{-}1\{U\}^3 + 5.7e\text{-}1\{U\}^2 - 2e{+}1\{U\} + 5e{+}1,\ r^2 = 0.54.$
7. $\{Th\} = 6e\text{-}6\{U\}^6 - 9e\text{-}4\{U\}^5 + 4.5e\text{-}2\{U\}^4 - 1.1\{U\}^3 + 1e{+}1\{U\}^2 - 5e{+}1\{U\} + 1e{+}2,\ r^2 = 0.64.$
8. $\{U\} = 8e\text{-}6\{Nb\}^4 - 1.2e\text{-}3\{Nb\}^3 + 4.8e\text{-}2\{Nb\}^2 - 4.3e\text{-}1\{Nb\} + 6.8,\ r^2 = 0.48.$
9. $\{U\} = 2e\text{-}7\{Nb\}^5 - 4e\text{-}5\{Nb\}^4 + 2.8e\text{-}3\{Nb\}^3 - 7.6e\text{-}2\{Nb\}^2 + 1.1\{Nb\} + 1.9,\ r^2 = 0.5.$
10. $\{U\} = 1e\text{-}8\{Nb\}^6 - 3e\text{-}6\{Nb\}^5 + 2e\text{-}4\{Nb\}^4 - 8e\text{-}3\{Nb\}^3 + 1.3e\text{-}1\{Nb\}^2 - 5.4e\text{-}1\{Nb\} + 5.4,\ r^2 = 0.51.$
11. $\{U\} = 1.8e\text{-}1\{Th\} + 2.6,\ r^2 = 0.49;\ \{U\} = 1.7e\text{-}3\{Th\}^2 - 2.9e\text{-}2\{Th\} + 6.3,\ r^2 = 0.60.$
12. $\{U\} = 2e\text{-}5\{Th\}^3 - 1.7e\text{-}3\{Th\}^2 + 1.4e\text{-}1\{Th\} + 4.5,\ r^2 = 0.58;\ \{U\} = -5e\text{-}7\{Th\}^4 + 2e\text{-}4\{Th\}^3 - 1.5e\text{-}2\{Th\}^2 + 5.5e\text{-}1\{Th\} + 1.5,\ r^2 = 0.6.$
13. $\{U\} = -7e\text{-}9\{Th\}^5 + 2e\text{-}6\{Th\}^4 - 1e\text{-}4\{Th\}^3 - 3e\text{-}4\{Th\}^2 + 2.7e\text{-}1\{Th\} + 2.9,\ r^2 = 0.6.$
14. $\{U\} = 2e\text{-}9\{Th\}^6 - 8e\text{-}7\{Th\}^5 + 1e\text{-}4\{Th\}^4 - 8.1e\text{-}3\{Th\}^3 - 2.4e\text{-}1\{Th\}^2 + 15,\ r^2 = 0.65.$

This study provided a joint experimental and theoretical approach to optimize the recovery of thorium and uranium and to save invaluable onsite and off-site natural resources and work time. The findings might expand on other studies reporting the quantification of transition metals on bentonite matrices. For instance, the concentrations of nickel reported in studies using bench techniques could serve as the basis to calculate the contents of thorium.

Keywords — *Nuclear energy, nickel and niobium as predictors, industrial clays as source, experimental-theoretical study, X-ray fluorescence spectroscopy.*

Note — *Some figures may be in color only in the electronic version.*

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I. INTRODUCTION

In nature, porous media contain large amounts of small clay minerals (clays: ≤2-μm diameter), which are the major sources of transition elements, including those that generate nuclear energy, i.e., thorium (TH) and uranium (U). The justification of this contribution was to assess the contents of thorium and uranium related to the contents of other transition metals present in the clay matrix. The identification of empirical functions relating to the contents of the elements could then contribute to predicting their presence and detectable concentrations in a given matrix, hence providing for better selection of the clay matrix prior to extraction.[1,2] Finally, the predicting equations generated were sought to contribute to future research on nuclear energy.

Here, 38 industrial clays, i.e., bentonites, were studied. The clays were characterized using X-ray fluorescence spectroscopy[3] (XRF). The XRF data were fitted to polynomial functions (orders 1 through 6). Then, the goodness of fit of the functions was estimated from the coefficients of determination (r^2). The closer the values of r^2 were to 1, the better the polynomial function represented the (x,y) data trends.

II. MATERIALS AND METHODS

II.A. Bentonites

The 38 bentonites constituting the collection of the Federal Institute for Geosciences and Natural Resources (Bundesanstalt für Geowissenschaften und Rohstoffe or BGR, Hannover, Germany) were studied (Table I, after Ufer et al.[3]).

II.B. Data Analyses

The contents of selected elements (x in Table I) were plotted against the contents of thorium and uranium (y), and the data were fitted to polynomial functions (orders 1 through 6). Then the relations between x and y were classified based on the r^2 of the functions. The functions with $0.5 \le r^2$, $0.3 \le r^2 \le 0.5$, and $r^2 \le 0.3$ were concluded to be strong, medium, and weak, respectively.

III. RESULTS AND DISCUSSION

Table II lists the obtained functions with y = Th. The functions showing higher r^2 values ($r^2 \le 0.5$) were

$$\{Th\} = 1e\text{-}6\{Nb\}^5 - 3e\text{-}4\{Nb\}^4 + 1.9e\text{-}2\{Nb\}^3 - 5.4e\text{-}1\{Nb\}^2 + 7.3\{Nb\} - 6.3,\ r^2 = 0.53\ , \tag{1}$$

$$\{Th\} = -3e\text{-}8\{Nb\}^6 + 9e-6\{Nb\}^5 - 1e\text{-}3\{Nb\}^4 + 4.7e\text{-}2\{Nb\}^3 - 1.1\{Nb\}^2 + 11.5\{Nb\} - 16,\ r^2 = 0.54\ , \tag{2}$$

$$\{Th\} = 5e-6\{Ni\}^4 - 1.5e\text{-}3\{Ni\}^3 - 1.5e\text{-}1\{Ni\}^2 - 5.8\{Ni\} + 9e+1,\ r^2 = 0.49\ , \tag{3}$$

$$\{Th\} = -7e\text{-}8\{Ni\}^5 + 3e\text{-}5\{Ni\}^4 - 5.1e\text{-}3\{Ni\}^3 + 3.4e\text{-}1\{Ni\}^2 - 9.5\{Nb\} + 1e+2,\ r^2 = 0.56\ , \tag{4}$$

$$\{Th\} = 2e\text{-}9\{Ni\}^6 - 8e\text{-}7\{Ni\}^5 + 2e\text{-}4\{Ni\}^4 - 1.5e\text{-}2\{Ni\}^3 - 7e\text{-}1\{Ni\}^2 - 1e+1\{Ni\} + 1e+1,\ r^2 = 0.60\ , \tag{5}$$

$$\{Th\} = -1e\text{-}4\{U\}^5 + 1.3e\text{-}2\{U\}^4 - 4.3e\text{-}1\{U\}^3 + 5.7e\text{-}1\{U\}^2 - 2e+1\{U\} + 5e+1,\ r^2 = 0.54\ , \tag{6}$$

$$\{Th\} = 6e-6\{U\}^6 - 9e\text{-}4\{U\}^5 + 4.5e\text{-}2\{U\}^4 - 1.1\{U\}^3 + 1e+1\{U\}^2 - 5e+1\{U\} + 1e+2,\ r^2 = 0.64\ . \tag{7}$$

Equations (1) through (7) showed that the concentrations of thorium related strongly with the concentrations of niobium (Nb), nickel (Ni), and U. The empirical Eqs. (1) through (7) were concluded to be useful tools to predict the concentrations of thorium from the concentrations of either Nb, Ni, or U.

Next, Table III lists the obtained functions with y = U. The functions showing higher r^2 values ($r^2 \le 0.5$) were

TABLE I

Contents of the Selected Transition Metals in the 38 Bentonites

Actinides		Lanthanides			Transition Metals													
Th	U	La	Ce	Nd	Y	Zr	Hf	V	Nb	Ta	Cr	Mo	Mn	Fe	Co	Ni	Cu	Zn
(ppm)													(% as Oxide)		(ppm)			
38	3	72	107	50	28	192	7	32	45	6	59	2	0.1	3.3	3	43	27	121
22	3	26	50	50	17	208	6	50	13	5	3	2	0.1	5.5	7	11	49	119
12	4	20	48	50	6	132	5	130	8	5	19	2	0.1	5	18	47	38	210
12	6	26	24	50	20	143	5	153	7	5	41	2	0	8.5	4	22	43	92
13	15	21	41	50	5	155	5	226	9	5	16	2	0	5.5	10	20	17	70
20	14	59	58	50	10	182	5	110	8	5	3	2	0	3.3	4	9	10	79
19	4	43	68	50	13	173	5	35	8	5	3	2	0.1	3.3	3	11	10	92
38	14	25	72	50	16	134	5	5	24	5	5	2	0	4.2	3	9	10	111
40	14	62	103	50	24	121	5	12	22	7	7	2	0.2	3.6	6	8	10	101
5	3	97	201	81	84	191	5	260	32	5	103	2	0	12.1	31	78	177	99
5	3	20	20	50	3	153	8	244	12	5	77	2	0	10.4	46	99	107	189
6	5	20	20	50	16	38	5	49	2	5	195	2	0	8.7	50	84	83	140
18	3	80	107	50	34	256	14	148	73	5	117	2	0.1	11.7	28	163	49	192
13	3	56	59	50	8	254	8	140	75	5	118	2	0	11.2	19	162	40	135
6	6	106	141	111	20	266	7	128	71	8	133	2	0.2	11.6	27	154	34	174
14	19	32	64	50	24	214	5	31	27	5	38	2	0	6.5	10	33	22	188
14	3	49	69	50	15	174	6	57	8	5	3	2	0	3.3	3	9	20	94
19	3	30	55	50	15	145	5	8	10	6	10	2	0	3.4	6	24	14	91
24	4	35	49	50	17	144	5	28	8	5	20	2	0	4	6	29	16	100
43	15	43	91	73	32	142	6	9	27	9	5	2	0	3.6	3	9	10	47
62	6	55	100	71	23	185	8	13	28	5	27	2	0	2.6	4	18	10	71
29	8	52	72	50	6	85	5	34	20	5	5	2	0	1.1	15	17	15	83
33	16	46	66	50	4	76	5	44	20	5	5	2	0	1.3	14	20	21	96
66	4	65	117	58	27	184	6	16	34	5	4	2	0	2.3	5	3	10	67
22	6	34	78	68	25	187	6	53	22	5	40	2	0	7.2	16	46	83	159
33	3	32	40	50	5	95	5	18	9	5	9	2	0	1.3	3	10	28	68
46	11	56	95	72	33	147	5	12	24	5	5	2	0	3.7	3	9	21	44
10	3	20	26	50	5	95	5	22	4	5	3	2	0	2.6	3	20	85	136
5	5	20	20	50	3	100	6	232	2	5	25	2	0	5.2	12	30	105	146
20	6	39	86	50	21	131	5	234	17	5	148	2	0	7.4	21	59	82	141
18	7	34	61	50	9	352	14	8	15	5	5	2	0	5.7	9	19	34	98
150	41	142	276	50	35	293	5	21	93	7	3	2	0	6.5	7	3	10	172
47	11	67	106	50	28	133	7	6	25	5	3	2	0	3.5	3	3	10	26
74	13	20	82	50	22	36	5	141	13	5	35	2	0	0.2	21	11	17	126
65	5	20	58	50	20	135	6	264	32	5	137	2	0	5.5	19	42	10	77
110	12	20	20	50	3	16	5	164	8	5	3	2	0	7.4	3	3	10	262
105	36	55	59	50	12	54	5	5	43	6	3	2	0.1	2.3	6	3	10	71
56	8	30	116	50	32	179	5	25	18	5	6	2	0	2.9	3	3	12	85

TABLE II

Elemental Compositions of the Bentonites and Their Relations, Where the Listed Numbers Between Commas Correspond to the Coefficients (c_6, c_5, c_4, c_3, c_2, c_1, and c_0) and the r^2 Values*

x	Order 1	Order 2	Order 3
	c_1, c_0, r^2	c_2, c_1, c_0, r^2	c_3, c_2, c_1, c_0, r^2
Ce	2.8e-1, 1.3e+1, 0.19	1.7e-3, −1.7e-1, 3.2e+1, 0.24	4e-5, −1.4e-2, 1.4, −6.3, 0.35
Co	−9.2e-1, 4.6e+1, 0.11	5.5e-3, −1.2, 4.7e+1, 0.11	8e-4, −5e-2, −1.9e-1, 4.4e+1, 0.12
Cr	1.9e-1, 4.2e+1, 0.09	1.9e-3, −4.9e-1, 4.6e+1, 0.11	−4e-5, 1.2e-2, −1.2, 5.1e+1, 0.14
Cu	−4.2e-1, 5e+1, 0.24	4.9e-3, −1.1, 6.3e+1, 0.32	−1e-4, 3.2e-2, −2.8, 8.3e+1, 0.39
Fe	−3.1, 5.1e+1, 0.095	1.9e-1, −7.2e-1, 4.6e+1, 0.1	−1.6e-1, 2-8, −1.5e+1, 6.4e+1, 0.12
Hf	−2.5, 5e+1, 0.03	2.8e-1, 7.6, 7e+1, 0.03	−8.9e-3, 5.2e-3, −9.5, 7.4e+1, 0.03
La	3.8e-1, 1.8e+1, 0.1	9.2e-3, −8.3e-1, 4.7e+1, 0.21	8e-4, −6.4e-2, 3.6, −2.3e+1, 0.32
Mn	−3.9e+1, 3.6e+1, 0.0045	−6.3e+2, 6.2, 3.6e+1, 0.008	−6.3e+2, 6.2e+1, 3.6e+1, 0.008
Mo	–	–	–
Nb	5.5e-1, 4.6e+1, 0.19	1e-3, 5e-1, 2.3e+1, 0.14	32.e-3, −1.5e-1, 5.3, −9.6, 0.39
Nd	−3e-1, 5.2e-1, 0.01	−1.8e-2, 2.3, −3.6e+1, 0.03	3.4e-3, −8e-1, 6.1e+1, −1.4e3, 0.06
Ni	−3.2e-1, 4.6e+1, 0.19	6.2e-3, −1.3, 6.1e+1, 0.33	−1e-4, 3.3e-2, −2.7, 7.3e+1, 0.39
Ta	7.8, −6.9, 0.05	−1e+1, −1.4e+2, −4.3e+2, 0.14	3.8, −8.9e+1, 6.6e+2, −1.6e+3, 0.15
U	2.7, 1.1e+1, 0.49	5e-2, 8e-1, 2e+1, 0.52	1.2e-2, −6.3e-1, 1e+1, −7, 0.58
V	−9e-2, 4.3e+1, 0.06	8e-4, −2.9e-1, −4.8e+1, 0.08	−2e-5, 8.8e-3, −1.1, 5.9e+1, 0.12
Y	2.3e-1, 3.1e-1, 0.01	−2e-2, 1.6, 1.5e+1, 0.096	−1.7e-3, 1.8e-1, −3.5, 4.2e+1, 0.19
Zn	−6e-1, 3.5e+1, 0	4e-3, −1, 9.2e+1, 0.15	2e-5, −6e-3, 1.7e-1, 5.1e+1, 0.19
Zr	−6.1e-2, 4e+1, 0.018	1.5e-3, −5.6e-1, 7.9e+1, 0.13	−1e-5, 7.7e-3, −1.5, 1.1e+2,0.29
x	Order 4	Order 5	Order 6
	c_4, c_3, c_2, c_1, c_0, r^2	c_5, c_4, c_3, c_2, c_1, c_0, r^2	c_6, c_5, c_4, c_3, c_2, c_1, c_0, r^2
Ce	5e-7, −2e-4, 3.4e-1, −1.5, 4.4e+1, 0.42	−3e-9, 4e-6, −1e-3, 1e-1, −4.6, 3.4e+1, 8e-5, 0.43	8e-11, 5e-8, −1e-5, 1.4e-3, −5e-2, 4e-1, 3e+1, 0.44
Co	1e-4, −4e-4, −1.5e-2, −5.5e-1, 4.5e+1, 0.12	8e-4, −5e-2, −1.9e-1, 9.4e+1, 0.12	−4e-6, 6e-4, −3.3e-2, 9e-1, 1.2e+1, 6.5e+1, −7.2e+1, 0.19
Cr	−7e-8, −1e-5, 9.7e-3, −1.1, 5.1e+1, 0.14	−3e-8, −5e-2, −1.9e-1, 4.4e+1, 0.12	9e-10, 1e-4, −1e-2, 5e-1, −8.8, 7.7e+1, 0.22
Cu	3e-6, −1.1e-3, 1.3e-1, −6, 1.1e+2, 0.42	−5e-8, 2e-5, −4e-3, 2.9e-1, −9.6, 1.3e+2, 0.43	2e-9, −1e-6, 2e-4, −1.7e-2, 7.6e-1, 1, −1.7e+1, 1.7e+2, 0.44
Fe	3e-2, −9.4e-3, 8.7, −3.1e+1, 7.5e+1, 0.13	1.5e-2, −4.2e-1, 3.9, −1.4e+1, 8.9, 5.7e+1, 0.15	−1.6e-1, 2.8, −1.5e+1, 6.4e+1, 0.12
Hf	3.1e-2, −1, 1e+1, −6.9e+1, 1.8e+2, 0.03	−3e-9, 2e-6, −7e-4, 1e-1, −7e+1, 2e+2, 0.32	3.1e-2, −1, 1.2e+1, −6.8e+1, 1.8e+2, 0.03
La	1e-5, −3.3e-3, 3e-1, −1e+1, 1.5e+2, 0.44	−1e-7, 5e-5, −9e-3, −6e-1, −1.9e+1, 2.3e+2, 0.44	−6e-9, 3e-6, −4e-4, 3e-2, −1, 1.5e+1, −4.4e+1, 0.45
Mn	6.3e+2, 6.2e+1, 3.6e+1, 0.008	−6.3e+2, 6.2e+1, 3.6+1, 0.008	−6e+2, 6.2e+1, 3.6e+1, 0.008
Mo	–	–	–

Nb	3e-5, −4.7e-3, 1.9e-1, −1.5, 2.2e+1, 0.48	1e-6, −3e-4, 1.9e-2, −5.4e-1, 7-3, −6.3, 0.53	−3e-8, 9e-6, −1e-3, 4.7e-3, −1.1, 1.1e+1, −1.6e+1, 0.54
Nd	1e-5, −1.2e-3, −3e-1, 3.6e+3, −9.6e+2, 0.064	−2.9e-2, 4.3, −3e+2, 1e+4, −1.5e-5, 0.08	−4e-5, 1.7e-2, −3, 2.9e+2, −1.5e+4, 4.4e+5, −5e+6, 0.096
Ni	5e-6, −1.5e-3, 1.5e-1, −5.8, 9.1e+1, 0.49	−7e-8, 3e-5, −5.1e-3, 3.4e-1, −9.5, 1e+2, 0.56	2e-9, −8e-7, 2e-4, −1.5e-2, 7e-1, 1.4e+1, 1.2e+1, −5.3e+1, 9e+1, 0.64
Ta	1.7e+1, −4.6e+2, 4.7e+3, −2e+4, 3.3e+4, 0.26	1.7e+1, −4.6e+2, 4.6e+3, −2e+4, 3.3e+4, 0.26	1.7e+1, −4.6e+2, 4-7e+3, −2e+4, 3.3e+4, 0.26
U	−3e-4, 3.6e-2, −1.2, 1.6e+1, −2.1e+1, 0.59	−1e-4, 1.3e-2, −4.3e-1, 5.7, −2.5e+1, 5.5e+1, 0.64	6e-6, −9e-4, 4.5e-2, −1.1, 1.2e+1, −5.3e+1, 9e+1, 0.64
V	2e-7, 3.6e-2, −1.2, 1.6e+1, −2.1e+1, 0.59	9e-9, −6e-6, 1.2e-3, −1e-1, 2.3, 3.7e+1, 0.26	6e-11, −4e-8, 8e-6, −6e-4, 8e-3, −3.8e-1, 5.3e+1, 0.28
Y	−6e-5, 6.4e-3, −1.3e-1, 6e-1, 2-9e+1, 0.19	−2e-5, 2.6e-3, −1.3e-1, 2.6, −2e+1, 8e+1, 0.23	−2e-2, 1.6, 1.5e+1, 0.1
Zn	1e-7, −3e-5, 5e-3, −6.2e-1, 6.9e+1, 0.19	1e-8, −9e-6, 2.2e-3, −2.4e-1, 1.2e+1, −1.4e+2, 0.25	1e-10, −9e-8, 2e-5, −3e-3, 1.4e-1, 5.4e+1, 0.27
Zr	−2e-8, 6e-6, 3.4e-3, −1.1, 1e+2, 0.2	3.1e-2, −1, 1.2e+1, −6.9e+1, 1.8e+2, 0.03	−4e-11, 4e-8, −1e-5, 2.4e-3, −1.8e-1, 4.9, 5.1e+1, 0.47

*The general equation was $y = c_6(x)^6 + c_5(x)^5 + c_4(x)^4 + c_3(x)^3 + c_2(x)^2 + c_1(x)^1 + c_0$. The orders of the functions were 1 through 6.

TABLE III

Elemental Compositions of the Bentonites and Their Relations, Where the Listed Numbers Between Commas Correspond to the Coefficients (c_6, c_5, c_4, c_3, c_2, c_1, and c_0) and the r^2 Values*

x	Order 1	Order 2	Order 3
	c_1, c_0, r^2	c_2, c_1, c_0, r^2	c_3, c_2, c_1, c_0, r^2
Ce	6.7e-2, 3.9, 0.16	6e-4, −8.2e-2, 1e+1, 0.26	1e-5, 4.6e-3, 4.4e-1, −2.5, 0.44
Co	−1.6e-1, 1.1e+1, 0.05	−1.4e-3, −1e-1, 1e+1, 0.01	1.2e-3, −9.1e-2, 1.5, 5.4, 0.12
Cr	−5e-2, 1.1e+1, 0.1	1e-4, −1.4e-1, 1.2e+1, 0.13	−4e-6, 1.7e-3, −2.1e-1, 1.3e+1, 0.13
Cu	−8.4e-2, 1.2e+1, 0.13	1e-3, −2.3e-1, 1.5e+1, 0.19	−2e-5, 7e-3, −5.9e-1, 1.9e+1, 0.23
Fe	−5.1e-1, 1.8e+1, 0.037	−1.1e-1, −4e-1, 9, 0.056	−3.4e-2, 5.1e-1, −2.2, 1.2e+1, 0.07
Hf	−9.4e-1, 1-5e+1, 0.056	3.3e-1, −6.9, 3-7e+1, 0.11	−1.3e-1, 3-7, −3.3e+1, 1e+2, 0.11
La	1.1e-1, 3.9, 0.14	2.5e-3, −2e-1, 1.2e+1, 0.24	1e-4, −2e-2, 1.2, −1e+1, 0.42
Mn	1.9, 9, 0.009	7e+1, −9.3, 9.1, 0.0008	7e+1, −9.3, 9.1, 0.0008
Mo	–	–	–
Nb	1.4e-1, 5.6, 0.13	1.5e-3, 1.4e-2, 7.1, 0.15	3e-4, −3.8e-2, 1.2, −1.2, 0.39
Nd	−6.4e-2, 1.2e+1, 0.009	4e-4, −1.2e-1, 1-4e+1, 0.0085	−6e-5, 1.5e-2, −1.2, 4e+1, 0.01
Ni	−7e-2, 1.1e+1, 0.12	1.2e-3, −2.5e-1, 1.4e+1, 0.20	−2e-5, 6.8e-3, −5.4e-1, 1.7e+1, 0.24
Ta	3.3, −8.8, 0.13	−2.7, 3.9e+1, −1.2e+2, 0.2	6e-6, −2.5e+1, 1.2e+2, −2.9e+2, 0.23
Th	1.8e-1, 2.6, 0.49	1.7e-3, −2.9e-2, 6.3, 0.57	2e-5, −1.7e-3, 1.4e-1, 4.5, 0.58
V	−2.4e-2, 1.1e+1, 0.06	2e-4, −6.6e-2, 1.2e+1, 0.07	−6e-6, 2-5e-3, −2.9e-1, 1-6e+1, 0.12
Y	2e-3, 8.6, 0.002	−3.2e-3, 2-5e-1, 6.3, 0.03	−3e-4, 3.7e-2, −7.6e-1, 1.1e+1, 0.09
Zn	−3.4e-3, 9.5, 0.0004	4e-4, −1e-1, 1.5e+1, 0.02	−3e-6, 1.6e-3, −2.6e-1, 2.1e-11, 0.03
Zr	−4.2e-1, 9.7, 0.001	3e-4, −1.1e-1, 1.7e+1, 0.04	−1e-6, 9e-4, 1.9e-1, 2e+1, 0.09
x	Order 4	Order 5	Order 6
	c_4, c_3, c_2, c_1, c_0, r^2	c_5, c_4, c_3, c_2, c_1, c_0, r^2	c_6, c_5, c_4, c_3, c_2, c_1, c_0, r^2
Ce	3e-8, −5e-6, −1.6e-3, 2.5e-1, 7.6e-1, 0.45	−9e-10, 6e-10, −1e-4, 1.2e-2, 2.9e-1, 7.8, 0.45	4e-11, −3e-8, 9e-6, 1.4e-3, 9.5e-2, 2.9, 3.6e+1, 0.46
Co	−8e-5, 9.2e-3, −3.3e-1, 3.9, −8.4e-1, 0.15	5e-6, −7e-4, 3.5e-2, −8e-1, 7.4, 8.4, 0.17	−2e-7, 4e-5, −2.6e-3, 8.6e-2, −1.4, 1.1e+1, −1.5e+1, 0.13
Cr	5e-9, −6e-6, 1.9e-3, −2.2e-1, 1.3e+1, 0.13	−6e-9, 3e-6, −4e-4, 2.8e-2, −7.8e-1, 1.5e+1, 0.15	2e-10, −1e-7, 2.2e-3, 1e-1, −1.9, 1.8e+1, 0.18
Cu	3e-7, −1e-4, 1.7e-2, −9e-1, 2.1e+1, 0.24	3e-9, −7e-7, 1e-5, 8.8e-3, −7.3e-1, 2e+1, 0.24	7e-10, −3e-7, 5e-5, −3.e-3, −1.4e-1, −2.8, −3.1e+1, 0.24
Fe	1.1e-2, −3e-1, 2.5, −7.6, 1.6e+1, 0.09	4e-3, −1e-1, 9e-1, −3, 2.4, 1.1e+1, 0.1	−8e-4, 3.2e-2, −4.9e-1, 3.4, −1e+1, 1.2e+1, −8.4, 0.11
Hf	2.1e-1, −7.1, 8.6e+1, −4.4e+2, 8.3e+2, 0.13	2e-1, −7.1, 8.6e+1, −4.4e+2, 8.8e+2, 0.12	2e-1, −7.1, 8.6e-1, −4.1e+2, 8.3e+2, 0.12
La	2e-6, −3e-4, 2.5e-2, −6e-1, 1.1e+1, 0.45	−6e-8, 3e-5, −3.5e-3, 2.1, −5.6, 5.8e+1, 0.5	−1e-9, −9.5e-7, −7e-5, 4.2e-3, −1.1e-1, 1.3, 4, 0.47
Mn	7e+1, −9.3, 9.1, 0.0008	7e+1, −9.3, 9.1, 0.0008	7e+1, −9.3, 9.1, 0.0008
Mo	–	–	–
Nb	8e-6, −1.2e-3, 4.8e-2, −4.3e-1, 6.8, 0.5	2e-7, −4e-5, 2.8e-3, −7.6e-2, 1, 1.9, 0.5	1e-8, −3e-6, 2e-4, −8e-3, 1.3e-1, −5.4e-1, 5.4, 0.51

Nd	8e-5, −2.5e-2, 2.7, −1.3e+2, 2.3e+3, 0.03	2e-5, −5.6e-3, 9e-1, −5.6e+1, 1.9e+3, −2.6e+4, 0.04	8e-6, −3.7e-3, 6.6e-1, −6.2e+1, 3.3e+3, −9.1e+4, 1e+6, 0.051
Ni	5e-7, −2e-4, 1.8e-2, −8.5e-1, 1.9e+1, 0.26	−1e-8, 5e-6, −8e-4, −5e-2, −1.5, 2.1e+1, 0.28	3e-10, −1e-7, 3e-5, −2.4e-3, 1.1e-1, −2.25, 2.4e+1, 0.3
Ta	4.5, −1.2e+2, 1.2e+3, −5.5e+3, 9e+3, 0.34	4.5, −1.2e+2, 1.2e+3, −5.5e+3, 9e+3, 0.34	4.5, −1.2e+2, 1.2e+3, −5.5e+3, 9e+3, 0.34
Th	−5e-7, 2e-4, −1.5e-2, 5.5e-1, 1.5, 0.60	−7e-9, 2e-6, −1e-4, −3e-4, 2.7e-1, 2.9, 0.6	2e-9, −8e-7, 1e-4, 8.1e-3, 2.4e-1, 1.5e+1, 0.65
V	1e-8, −1e-5, 3.3e-3, 1.6e+1, 0.13	−3e-10, 2e-7, −6e-5, 7.8e-3, −4.8e-1, 1.8e+1, 0.13	1e-11, −9e-9, 3e-6, −4e-4, 2.8e-2, −9.6e-1, 2e+1, 0.14
Y	−5e-5, 6.9e-3, −2.4e-1, 2.9, −5.1e-1, 0.2	−4e-6, 5e-4, 2.1e-2, 3.3e-1, 1.9, 1.1e+1, 0.18	−5e-7, 9e-5, −4.9e-3, 1.3e-1, −1.6, 9.6, −10.9, 0.21
Zn	−4e-8, 2e-5, −3.1e-3, −8.8e-2, 1.3e+1, 0.04	3e-9, −7e-7, 1e-5, 8.8e-3, −7.3e-1, 2e+1, 0.24	5e-11, −4e-9, 1e-5, 1.3e-3, 8.7e-2, −2.5, 3.8e+1, 0.13
Zr	−4e-8, 3e-5, −6.7e-3, 4.7e-1, 4.8, 0.2	−3e-10, 3e-7, 7e-5, 7e-3, −3.2e-1, 1.8e+1, 0.22	−1e-11, 1e-8, −5e-6, 9e-4, −8.2e-2, 1.3e+1, −2.9e+1, 0.43

*The general equation was $y = c_6(x)^6 + c_5(x)^5 + c_4(x)^4 + c_3(x)^3 + c_2(x)^2 + c_1(x)^1 + c_0$. The orders of the functions were 1 through 6.

$$\{U\} = 8e\text{-}6\{Nb\}^4 - 1.2e\text{-}3\{Nb\}^3 + 4.8e\text{-}2\{Nb\}^2 - 4.3e\text{-}1\{Nb\} + 6.8,\ r^2 = 0.48\,, \tag{8}$$

$$\{U\} = 2e\text{-}7\{Nb\}^5 - 4e\text{-}5\{Nb\}^4 + 2.8e\text{-}3\{Nb\}^3 - 7.6e\text{-}2\{Nb\}^2 + 1.1\{Nb\} + 1.9,\ r^2 = 0.5\,, \tag{9}$$

$$\{U\} = 1e\text{-}8\{Nb\}^6 - 3e\text{-}6\{Nb\}^5 + 2e\text{-}4\{Nb\}^4 - 8e\text{-}3\{Nb\}^3 + 1.3e\text{-}1\{Nb\}^2 - 5.4e\text{-}1\{Nb\} + 5.4,\ r^2 = 0.51\ , \tag{10}$$

$$\{U\} = 1.8e\text{-}1\{Th\} + 2.6, r^2 = 0.49;$$
$$\{U\} = 1.7e\text{-}3\{Th\}^2 - 2.9e\text{-}2\{Th\} + 6.3,\ r^2 = 0.60\,, \tag{11}$$

$$\{U\} = 2e\text{-}5\{Th\}^3 - 1.7e\text{-}3\{Th\}^2 + 1.4e\text{-}1\{Th\} + 4.5,\ r^2 = 0.58\ ;$$
$$\{U\} = -5e\text{-}7\{Th\}^4 + 2e\text{-}4\{Th\}^3 - 1.5e\text{-}2\{Th\}^2 + 5.5e\text{-}1\{Th\} + 1.5,\ r^2 = 0.6\ , \tag{12}$$

$$\{U\} = -7e\text{-}9\{Th\}^5 + 2e\text{-}6\{Th\}^4 - 1e\text{-}4\{Th\}^3 - 3e\text{-}4\{Th\}^2 + 2.7e\text{-}1\{Th\} + 2.9, r^2 = 0.6\ , \tag{13}$$

$$\{U\} = 2e\text{-}9\{Th\}^6 - 8e\text{-}7\{Th\}^5 + 1e\text{-}4\{Th\}^4 - 8.1e\text{-}3\{Th\}^3 - 2.4e\text{-}1\{Th\}^2 + 15,\ r^2 = 0.65\ . \tag{14}$$

These results showed that the concentrations of U related strongly with the concentrations of Nb and Th (U). The empirical Eqs. (8) through (14) were concluded to also be useful tools to predict the concentrations of uranium from the concentrations of either Nb or Th.

IV. CONCLUSIONS

Bentonites are natural reservoirs of Th and U. The objective of this contribution was to generate empirical, fitting functions for predicting the presence and contents of Th and U in the matrices of industrial clay. In this light, 38 chemical compositions of 38 bentonites were fitted to polynomial functions. The contents of 18 transition elements [cerium (Ce), cobalt (Co), chromium (Cr), copper (Cu), iron (Fe), hafnium (Hf), lanthanum (La), manganese (Mn), molybdenum (Mo), neodymium niobium (Nd), Ni, tantalum (Ta), Th, U, vanadium (V), yttrium (Y), zinc (Zn), and zirconium (Zr)], determined experimentally by XRF, were analyzed. The contents of the elements were plotted in (*x,y*) graphs and then fitted to polynomial functions (orders 1 through 6). According to the r^2, the contents of Th, U, Nb, and Ni related strongly; therefore, the presence of Nb and Ni served to predict the presence of detectable concentrations of Th and U. In all, this study provided a joint experimental and theoretical approach to optimize the recovery of Th and U and to save invaluable onsite and off-site natural resources and work time.

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Supplementary Material

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