

Factors controlling the chemistry and mineralogy of selected soil types of the Czech Republic and Egypt

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Abstract. The geochemistry and mineralogy of selected soil profiles from the Czech Republic and Egypt have been studied using Q- and R-mode factor analysis. This method is used for investigating the element/mineral associations and the distribution of heavy metals in these two very different soils, both of which have been subjected to severe environmental contamination. We consider chemical and mineralogical data from 44 soil samples from the Czech Republic and Egypt.

The results of R-mode factor analysis suggest six geochemical and mineralogical factors that control heavy metal accumulation in the studied soils. Among these are the roles of clay and rock forming minerals in heavy metal accumulation, the alteration of rock forming minerals in the soil profiles, a hematite-phosphate factor, a biotite-plagioclase factor, an orthoclase-muscovite factor, and a depth factor. A similar interpretation holds for the other data sets.

Key words: Q and R-mode analysis, geochemical factor, mineralogical factor, heavy metals

Introduction

With the closure of the High Dam, the annual Nile River floods have ceased to occur. Major power-based industries (e.g., chemical and textile) have developed as a consequence of the availability of abundant, inexpensive electricity. This has resulted in the distribution of untreated or poorly treated industrial wastes, including heavy metals and other chemicals, into the Nile Delta drainage network. The delta water bodies are no longer thoroughly flushed of the wastes discharged into them, and thus became sinks for potentially toxic wastes such as heavy metals.

For the present study, we selected the Bahtim catchment area of Egypt because it is an industrial area. It has been subjected to intense chemical deterioration during the past few decades due to the discharge of various qualities and quantities of waste.

The processes that seem to contribute to the heavy element enrichments in the soil sediments include ion exchange and adsorption on the surfaces of clays, organic particles, colloids from irrigation water, and bioaccumulation (Horwitz 1991, McBride 1994 and Padmalal et al. 1997). Surfactants play also an important role in influencing the degree of mobilization of pollutants in soils and sediments (Schwuger 1994).

The Bahtim area is located on the southern side of the Nile Delta between latitude 30°18' and longitude 31°15' (Fig. 1). The soil of the Bahtim catchment area is heavy and clayey (Vertisol type). The soil samples of this study were taken from depths reaching to 120 cm. The major characteristics of the soils collected from this catchment area are listed in Table 1.

Also studied in the present paper are soils from the Vočadlo (X-7) and Hartvíkov (X-02) catchments (Fig. 2) in the Czech Republic. The Hartvíkov catchment is located

at latitude 49°30' N and longitude 14°50' E, on the Bohemian Massif. The Bohemian Massif is the eastern most outcropping part of the Hercynian (Variscan) orogenic belt in Europe.

The Vočadlo catchment is an agricultural area located in a rural region of the Trnávka River. The soil is of the

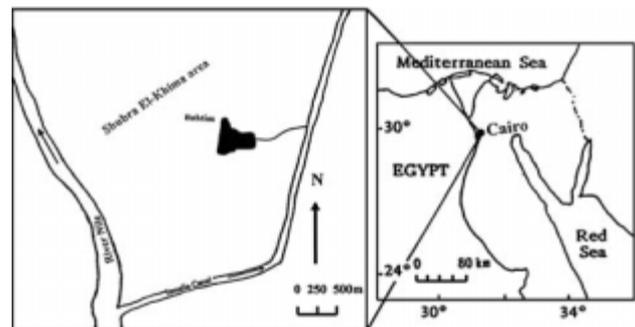


Figure 1. Location map of the Bahtim area, Egypt.



Figure 2. Location map of Vočadlo and Hartvíkov, Czech Republic.

Table 1. Major characteristics of the Bahtim catchment area

Location	Shubra El-Khima City, Cairo
Name of catchment area	Bahtim
Latitude	30°18'
Longitude	31°15'
Altitude (metres)	16.8
Type of catchment	Rural
Landform	Flood plain
Type of countryside	Agricultural and industrial area
Period of monitoring	2000–2001
Drainage area (km ²)	3
Parent material	Nile alluvial deposits
Kind of soil	Vertisol (heavy clayey)
Drainage	Well drained
pH of soil	7.8
Soil depths	Description
0–40 cm	Very dark greyish brown, clay; sticky; plastic; few roots
40–80 cm	Dark greyish brown, heavy clayey soil, some fine roots, very sticky
80–120 cm	Dark brown, heavy clayey soil, no roots

Table 2. Major characteristics of Hartvíkov and Vočadlo catchments (Pačes 1985)

No. of catchment	X-02*	X-07*
Locality	Hartvíkov	Vočadlo
Bed rock	Biotite muscovite gneiss	Biotite muscovite gneiss
Type of countryside	Rural	Rural
Type of basin	Forest	Field
Drainage area (km ²)	0.98	0.59
Forested area (%)	100	1.3
Clear-cut area (%)	0	98.7
Elevation above sea level:		
Maximum (m)	724	635
Minimum (m)	672	570
Mean slope (%)	3.8	4.9
Annual precipitation (mm)	781	736
Annual discharge (mm)	108	171
pH of precipitations	4.27	4.27
pH of runoff	6.84	6.15

Dystric Cambisol type: an acidic, brown soil with varying degrees of podzolization. The fertilizers used in this catchment contain H₂SO₄ and HNO₃, which contribute to the acidification of the arable land. Pačes (1985) has described the location and major characteristics of the Vočadlo catchment (X-7) as listed in Table 2. The bedrocks of the two catchments are mostly biotite gneiss and muscovite-biotite gneiss.

Table 3 shows the comparison between the major characteristics of the studied areas.

For the present study we have selected very different localities with different soil profiles, and which formed under different climatic conditions. The soils were derived from different sources and differ in pH. Moreover, the

Hartvíkov catchment of the Czech Republic is a natural forest (i.e. under control), which features an acidic forest profile not present in Egypt. The main objective of the present work is to investigate the element-mineral associations in these very different soils formed under different climatic conditions, all of which have been subjected to severe environmental contamination. As these soils represent different soil types that were formed under different conditions and are derived from different sources, we will also attempt to determine the factors controlling their chemistry and mineralogy.

Samples and methods

Sampling

A total of forty four soil samples were collected from the soil profiles of the Vočadlo X-7 and Hartvíkov X-02 catchments of the Czech Republic, and in the Bahtim area in Egypt. The Czech soil profiles were excavated to a depth of 160 cm, or until bedrock was encountered. The Bahtim soils were sampled from trenches dug to a depth of 120 cm. Samples selected from the cores and trenches were chosen for representing variations in lithology, colour, and grain size. The samples were dried in air. The weight percentages of sand, silt, and clay particles were determined in accordance with the method of Folk (1968).

Chemistry

The major element chemistry was largely determined by X-ray fluorescence spectrography, using techniques described by Holland and Brindle (1966).

The compositional components determined by these procedures were SiO₂, TiO₂, Al₂O₃, total Fe as Fe₂O₃, MnO, MgO, CaO, Na₂O, and K₂O. A large range of standards was used for calibration. The equipment used was a Philips PW 1540 vacuum X-ray spectrograph. The standard error for the major elements ranged from about 2 % for SiO₂ to 0.04 % for TiO₂, at the average values of these elements in mudstone samples. The rapid methods of Shapiro and Brannock (1962) were used for the determination of CO₂ and H₂O⁺. Trace elements were analyzed by cold vapour atomic absorption spectrometry (AAS). R-mode factor analysis and Q-mode cluster analysis were performed using the SPSS computer programme version 8.0.

Table 3. Comparison between the major characteristics of studied catchments

Locality	Vočadlo	Hartvíkov	Bahtim
Country	Czech Republic	Czech Republic	Egypt
Parent material	Biotite muscovite gneiss	Biotite muscovite gneiss	Nile alluvial deposits
Type of catchment	Rural	Forest	Rural
Type of countryside	Agricultural activities	Forest	Agricultural and industrial activities
Kind of soil	Cambisol	Cambisol	Vertisol (heavy clayey soil)
Type of soil	Acidic	Acidic	Alkaline

Mineralogy

Bulk samples and clay-rich slides were analyzed by X-ray diffraction techniques for identifying the clay and non-clay mineral assemblages.

The mineralogy of the clay fraction of the soils was determined by X-ray diffraction using a Philips diffractometer with a copper target X-ray tube. The clay fraction (taken to be less than 5 μm in size) was obtained from a slurry suspension prepared from the soil samples. Untreated, glycollated and heated (550 $^{\circ}\text{C}$ for 2 hours) clay mounts were prepared for each sample, enabling the identification of individual clay minerals. The clay minerals were identified by the method of Brindley and Brown (1980), supplemented by those outlined by Weaver (1967), and Pierce and Siegel (1969). Semi-quantitative determinations were performed according to Johns et al. (1954). The relative proportions of the clay mineral species were estimated by the intensities of X-ray diffractograms. The peak heights under the (001) basal reflections of the identified clay minerals were used as a measure of their relative abundance. The kaolinite peak was divided by three to compensate its higher degree of crystallinity relative to other clay minerals (Thorez 1976, Moore and Reynolds 1989).

The sand fraction of the Bahtim soil (0.125–0.063 mm) was chosen for mineralogical investigation. Heavy fractions separated by bromoform liquid (sp. gr. 2.89) were mounted with Canadian balsam on glass slides and examined using a polarizing microscope. The percentage of each of the heavy minerals was estimated by counting grains. At least 500 grains were counted in each slide. Mineral identification was undertaken according to the procedures adopted by Milner (1962) and Tickell (1965).

The mineralogy of the Czech soils were evaluated with the use of the RECAI computer program (Ondruš and Veselovský 1995). The calculation of the mineral phases by this model is based on the combination of qualitative and quantitative X-ray analyses, with the data from silicate chemical analysis of four size and density fractions (Ondruš and Veselovský 1995). The results are shown in Table 4a.

Mineral composition

Table 4a shows the average mineralogical composition of all the samples considered in the present paper.

Kaolinite is the dominant clay mineral in both sampled localities of the Czech Republic. It ranges from 0.4 to

27.9 % in abundance, with subordinate amounts of chlorite ranging from 1.1 to 7.1 %. The Bahtim soil is composed mainly of montmorillonite, kaolinite, and illite. Montmorillonite ranges in abundance from 27 to 35 %, kaolinite from 29 to 35.5 %, and illite from 3 to 11 %.

The sand fraction of the Czech soils is composed mainly of quartz, plagioclase, K-feldspar, amphibole (hornblende), muscovite, biotite, anatase, and rarely apatite (Table 4a). The sand fraction of the Bahtim soil is composed mainly of quartz, plagioclase, hornblende, pyroxene, epidote, garnet, biotite, and minor K-feldspar.

The soil samples from the Bahtim catchment are almost entirely of alluvial origin. The presence of both moderately stable minerals and those susceptible to weathering as the major contents of the non-opaque fraction points to a short pedological history. Therefore, the deltaic sediments are geogenic rather than pedogenetic, and the soil forming processes have acted upon these sediments in a delicate way. This interpretation is also supported by the rounded to subrounded shapes of the grains, which indicate aqueous transport over a long distance.

Chemical composition

Major elements

The major element compositions of the Czech and Bahtim soil samples are compared with the average compositions of shale (NASC) in Table 4b. The soil to shale comparison shows close similarity. The lower SiO_2 content in the soils reflects their greater concentration of clay minerals and iron oxide as compared with the average shale.

Silica and aluminum are the most abundant components in all of the soil samples. The concentration of CaO appears to decrease with decreasing particle size, due to the less-resistant nature of Ca-rich plagioclase. CaO was found to be the least abundant basic component of the soils. This leads us to conclude that calcic plagioclases disappear in soil more rapidly than sodic plagioclases, as Ca-rich plagioclase is less resistant to weathering than Na-rich plagioclase.

The high abundance of Mg is probably derived from the weathering of chlorite. The high K_2O contents are due to the abundance of K-feldspar and mica.

The high iron content is due to the dissolution of mafic minerals after the breakdown of primary minerals, and the quick precipitation of oxidized iron in soil.

Table 4a. Average mineralogical compositions of studied soil samples of the Czech Republic and Egypt (data in %)

Locality	Sample	Qz	Ortho.	Plag.	Amph.	Pyro.	Biot.	Musc.	Epid.	Gar.	Anat.	Hema.+ Geo.	Sm.	Kaol.	Ill.	Chlo.	Mud	Sand %
Bahtim catchment	1	11.30	0.15	5.60	3.00	0.75	0.45	0.0	0.5	0.15	0.0	0.01	35.15	30.1	14.8	0.01	78.17	21.83
	2	11.20	0.20	6.30	5.00	1.5	0.80	0.0	0.3	0.2	0.0	0.01	28.31	35.46	11.03	0.01	74.5	25.5
	3	11.00	0.20	6.60	6.00	1.8	1.00	0.0	0.4	0.4	0.3	0.0	1.0	27.63	34.17	10.91	0.01	72.7
Hartvikov catchment	4	20.38	4.00	5.14	0.00	0.01	2.00	13.4	0.0	0.0	0.13	6.29	0.01	18.9	0.02	3.8	11.8	63.04
	5	19.50	1.60	2.00	0.00	0.01	2.60	14.8	0.01	0.0	0.4	6.38	0.02	17.3	0.01	1.4	4.47	62.02
	6	19.70	0.10	0.70	0.00	0.0	1.00	13.0	0.0	0.01	0.5	3.47	0.01	17.3	0.02	2.3	2.9	55.2
Vočadlo catchment	7	12.40	7.20	0.04	2.30	0.01	0.00	14.4	0.01	0.0	0.02	5.63	0.03	27.9	0.01	4.1	1.94	72.06
	8	27.60	4.00	4.80	2.70	0.0	0.00	6.7	0.0	0.01	0.52	0.0	0.02	6.5	0.02	7.1	8.56	52.2
	9	30.80	6.50	4.80	4.11	0.02	0.00	8.4	0.0	0.01	0.75	0.01	0.01	3.8	0.01	0.6	6.19	53.57
	10	29.20	2.10	9.40	3.46	0.0	0.00	8.4	0.01	0.0	0.5	0.0	0.01	9.2	0.02	1.1	4.58	58.76
	11	23.60	3.00	2.10	1.21	0.0	0.00	5.7	0.0	0.0	0.6	0.01	0.02	0.4	0.01	3.7	2.61	37.69

Abbreviations: Qz – quartz, Ortho. – orthoclase, Plag. – plagioclase, Amph. – amphibole, Pyro. – pyroxene, Biot. – biotite, Musc. – muscovite, Epid. – epidote, Gar. – garnet, Anat. – anatase, Hema. + Geo. – hematite + goethite, Sm. – smectite, Kaol. – kaolinite, Ill. – illite, Chlo. – chlorite, Mud – silt + clay.

Table 4b. Average major and trace element chemistry compositions of the studied soil samples of the Czech Republic and Egypt (in %, for Cd, Co, Zn, Mo, Pb in ppm)

Locality	Sample	Depth (cm)	SiO ₂	TiO ₂	Al ₂ O ₃	Fe ₂ O ₃	MgO	CaO	Na ₂ O	K ₂ O	P ₂ O ₅	H ₂ O	CO ₂	Tl ₂ O	ZrO ₂	Cd	Co	Zn	Mo	Pb
Bahtim catchment	1	40.00	49.92	N.D.	16.21	9.94	2.91	4.59	1.28	0.96	0.24	14.57	N.D.	N.D.	N.D.	3.00	41.00	99.00	32.00	31.00
	2	80.00	49.28	N.D.	17.00	10.36	2.76	4.44	1.24	0.93	0.16	13.74	N.D.	N.D.	N.D.	2.00	41.00	94.00	16.00	32.00
	3	120.00	47.98	N.D.	16.95	10.92	2.98	4.87	1.22	0.93	0.10	13.88	N.D.	N.D.	N.D.	3.00	42.00	97.00	70.00	23.00
Hartvikov catchment	4	40.00	49.97	0.76	19.17	8.1	1.87	0.26	0.32	2.53	0.19	8.28	0.16	5.36	0.15	0.80	10.00	42.00	5.00	27.00
	5	70.00	45.14	1.55	20.60	11.40	1.38	0.07	0.17	4.93	0.28	8.12	0.14	1.78	2.65	0.80	7.00	47.00	5.00	30.00
	6	115.00	40.56	1.46	20.35	14.82	2.12	0.09	0.13	2.36	0.47	9.79	0.11	5.76	0.11	0.80	6.00	46.00	5.00	43.00
Vočadlo catchment	7	160.00	43.40	1.38	21.48	10.72	1.65	0.09	0.22	4.52	0.31	8.48	0.11	4.51	0.41	0.80	6.00	17.00	5.00	30.00
	8	30.00	45.79	1.90	16.38	9.43	2.01	0.72	0.43	2.45	0.53	10.59	0.13	6.14	0.20	1.10	17.00	124.00	5.00	68.00
	9	63.00	52.55	2.23	15.22	7.85	1.73	0.56	0.47	2.36	0.28	8.78	0.15	5.27	0.65	1.90	19.00	116.00	5.00	66.00
Vočadlo catchment	10	116.00	49.71	1.80	16.27	8.28	2.13	0.67	0.79	2.17	0.31	9.60	0.13	5.28	0.20	1.10	20.00	132.00	5.00	53.00
	11	150.00	53.86	1.48	17.11	7.55	1.23	0.52	0.99	1.83	0.23	7.42	0.10	3.87	0.74	0.80	13.00	62.00	5.00	34.00
NASC	64.8	0.78	16.9	6.33	2.86	3.56	1.15	3.99	0.11	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.

N.D. – not determined, NASC – North American Shale Composition after Gromit et al. (1984).

Heavy metal concentration

The study of heavy metals in the soil samples is important for demonstrating the chemical interrelationships between soil and irrigation water. The discharging of agricultural and industrial wastes into soils leads to the concentration of heavy metals and As. Siegel et al. (1995) concluded that the clay-size fractions from Holocene samples of lagoonal/marsh, delta front, and pro-delta facies in the northeast sector of the Nile delta are enriched in Fe, Mg, Ni, Cu, and Zn relative to continental crust. Metals may become fixed to solid substances as a result of adsorptive bonding, co-precipitation by hydrous iron and Mn oxides, complexation by organic matter, and incorporation into crystalline minerals (Forstner and Wittman 1983). Abdel Salam et al. (1981) studied the trace element composition of Nile silt, and found concentrations of As, Cu, Cr, Hg, and Zn of 300, 300, 100–300, 100–300, and 300 ppm, respectively.

Cobalt (Co)

Cobalt concentrations in the Hartvíkov and Vočadlo localities of the Czech Republic range from 6 to 20 ppm (Table 4b). The Hartvíkov soil has the lowest Co content (6–10 ppm). This range is similar to the acceptable worldwide limit in soils (1.6–21 ppm, McBride 1994).

The cobalt content in the Bahtim soils was found to be 41 and 42 ppm, which is twice the acceptable limit. The high Co contents in the Bahtim soil are possibly due to its higher pH (7.8) and its textural composition, where silt and clay are 2–3 times richer in Co than is sand (Padmalal et al. 1997). Clay minerals, especially montmorillonite, accommodate most of the Co in place of Mg^{+2} . Moreover, Co is a chalcophile element that is expected to be associated with mafic minerals (pyroxene, biotite, and hornblendes), which are the main components of the Bahtim soil.

Lead (Pb)

Lead concentrations in the Bahtim soil are not indicative of pollution (23–31 ppm), and are within global acceptable range for soils (10 to 84, McBride 1994). The soil of the Vočadlo catchment is more enriched in Pb, with concentrations between 34 and 68 ppm. The high Pb content of the Vočadlo area may be attributed to the application of fertilizers that cause the acidification of arable land: Pb is more soluble under acidic conditions, and is probably leached from its source and then reabsorbed into the soil.

Cadmium (Cd)

Cd concentrations in the Czech soils range from 0.8 to 1.9 ppm (Table 4b), while in the Bahtim soil they range from 2–3 ppm. This element is thus within the acceptable global limits in all the soils considered here (0.01–2 ppm, McBride 1994).

Zinc (Zn)

The Zn content in the Hartvíkov soil ranges from 17 to 42 ppm. It is much higher in the Vočadlo area, where it ranges from 62 to 124 ppm, though it is still within the acceptable range. In the Bahtim soil Zn contents range from 94 to 99 ppm (Table 4b).

Molybdenum (Mo)

The Mo content in the Czech soils is 5 ppm. This is more than double the acceptable global limit for soils (2 ppm, Levinson 1980). The Mo content in the Bahtim soil ranges from 16 to 70 ppm. The anomalous enrichment of Mo in the Bahtim soil may be attributed to industrial discharge. The highest Mo values occur in the Bahtim area, even though this soil has a higher pH (7–8). Disnar (1981) found that the Mo content of recent sedimentary organic matter is inversely pH dependent and becomes negligible where the pH exceeds 7.

Cluster analysis

The cluster analysis carried out in the present work is based on the single linkage method (nearest neighbour), in which the distance metric is the Euclidean distance. Euclidean distances provide a faithful measure of the true similarities between samples (Erez and Gill 1977). The distance coefficients are calculated from numerical data and express the degree of similarity as distance in dimensional space. Thus, as the distance value decreases, the similarity increases (Seyhan et al. 1976).

Q-mode cluster analysis is applied toward classifying the sample areas in the Czech Republic and Egypt according to their chemical and mineralogical characteristics. The resulting Q-mode dendrogram was obtained by treating the non-transported input data matrix of 11 cases (44 samples representing 11 soil profiles: 8 from the Czech Republic, and 3 from Bahtim, Egypt), using their chemical and mineralogical characteristics. The resulting Q-mode dendrogram (Fig. 3) shows an Euclidean distance of 25, indicating a fair degree of similarity between the analyzed samples. This dendrogram is interpreted at a similar level (distance coefficient 14) in which 3 clusters exist (see Fig. 3).

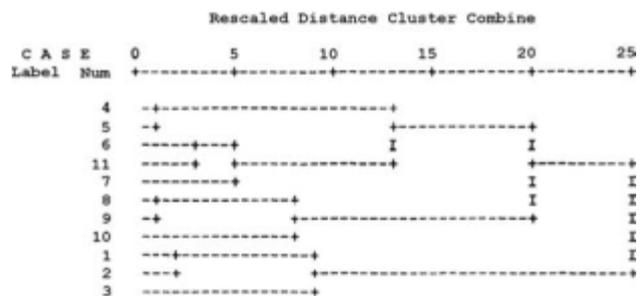


Figure 3. Q-mode dendrogram.

Cluster 1 is represented by soil samples from the Bahtim catchment area of Egypt (cases 1, 2, and 3). Their cluster represents the heavy clayey soil (Vertisol) samples that extend down to about 120 cm. This cluster is characterized by high contents of Ca, Mo, Co, montmorillonite, kaolinite, and illite, and low K₂O relative to the Czech soils. These soil samples have a pH of 7.8.

Cluster 2 is comprised of soil samples from the Vacadlo catchment in the Czech Republic (cases 8, 9, and 10). This cluster is characterized by anomalous Pb and Zn contents, and high contents of quartz, plagioclase, K-feldspar, Ca, and TiO₂. Chlorite is more abundant than kaolinite.

Cluster 3 is comprised of soil samples from the Hartvíkov catchment area of the Czech Republic (cases 4, 5, 6, and 7), which is a forest catchment. This cluster is characterized by high contents of Al₂O₃, K₂O, muscovite, and kaolinite, and by low contents of heavy metals and biotite.

Although it belongs to the Vočadlo catchment, the subindependent case 11 is clustered with the samples from the Hartvíkov catchment. This case is the deepest sample of the soil profile, obtained at a depth between 110–150 cm. At this depth the composition of the soil is close to that of the parent rock, and is further from the sources of contamination. It is therefore similar to the Hartvíkov soil samples, which are from a forested area not affected by rural pollution, and with the same bedrock as at Vočadlo.

Q-mode cluster analysis is applied to the Czech and Egyptian soil samples so as to classify them by their chemical and mineralogical characteristics. The Q-mode dendrogram is obtained by treating the input data matrix of 11 cases, using their chemical and mineralogical components as variables (33 variables). The resulting Q-mode dendrogram shows an Euclidean distance of 25, indicating a fair degree of similarity between the analyzed cases and

their variables. This dendrogram is interpreted as indicative of similarity level a-a' (distance coefficient 5), where two independent cases and two clusters exist (Fig. 4).

The independent cases that are recognized along similarity level a-a' are those of 13 (zinc) and 10 (depth). Element and mineral compositions are apparently not controlled by soil depth. Zinc is an independent case because it is only linked with depth at an Euclidean distance of 16.5. In the two soil profiles from the two Czech localities, the Zn content abruptly decreases to one half or one third of its original content at depths ranging from 115 to 160 cm, while the concentration of Zn in the Bahtim catchment does not change with depth.

Cluster I includes most of the cases in the dendrogram (27 cases): garnet, epidote, P₂O₅, anatase, Na₂O, pyroxene, biotite, amphibole, MgO, Cd, CaO, K₂O, hematite, orthoclase, chlorite, plagioclase, illite, Fe₂O₃, H₂O, muscovite, Al₂O₃, Qz, Co, kaolinite, smectite, and Mo. These variables represent the elements and minerals characteristic for both the Czech soils and the Bahtim soil of Egypt.

Cluster II includes 10 cases: plagioclase, illite, Fe₂O₃, H₂O, muscovite, Al₂O₃, Qz, Co, kaolinite, and smectite. This cluster includes elements and minerals characteristic of the Bahtim soil (except muscovite, which is a characteristic mineral for Vočadlo area of the Czech Republic). The presence of muscovite within this cluster may be attributed to its presence in the Vočadlo soils. The illite is considered to be an alteration product of muscovite.

Sub-cluster II-1 includes 7 cases: Al₂O₃, Qz, Co, kaolinite, smectite, Mo, and a mud fraction. This sub-cluster is characteristic of the mud fraction of the Bahtim soil. Moreover, this cluster includes both the Co and Mo related to the mud fraction (mainly by adsorption to smectite), and the replacement of Mg⁺² by Co in clay minerals.

Cluster III includes 3 cases: SiO₂, Pb and sand. This cluster suggests that Pb may be associated with detrital quartz sand grains. The cluster is linked to sub-cluster III-1 to form a new cluster at an Euclidian distance of 7. This new cluster includes 10 cases: Al₂O₃, Qz, Co, kaolinite, smectite, Mo, mud, SiO₂, Pb, and sand; all of which are represented in the Bahtim soil.

Factor analysis

Chemical and mineralogical data have been included in the factor analysis. Data from 11 soil profiles (44 samples) from the two localities in the Czech Republic and from the Bahtim catchment of Egypt were examined for this study.

The results of the factor analysis suggest six geochemical and mineralogical factors that control heavy metal accumulation in these soils (Fig. 5).

Factor 1: the role of clay minerals and rock forming minerals in heavy metal accumulation

This factor accounts for 49 % of the total variance. It shows high positive loading for MgO, CaO, Na₂O, H₂O, all clay

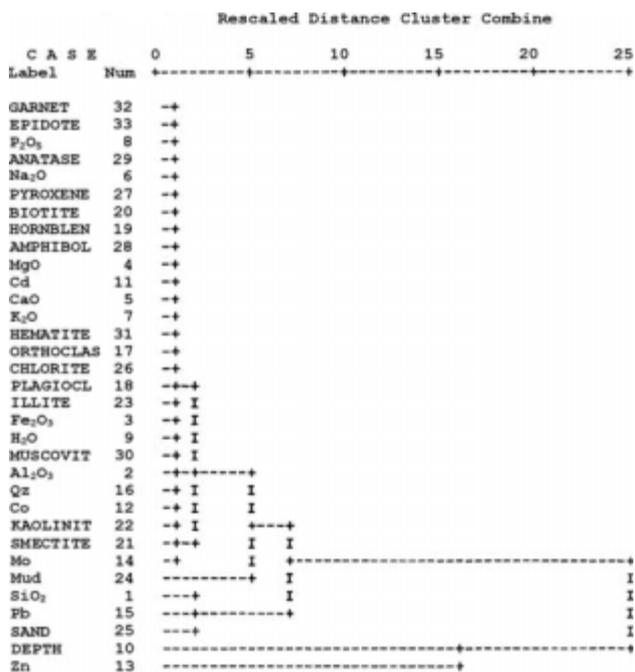


Figure 4. Q-mode dendrogram of variables.

minerals (smectite, kaolinite, and illite), and the mud fraction. This factor also shows high positive loading for Co, Cd, Mo, and low positive loading for Zn (0.17). Concerning the rock forming minerals, there is high positive loading for pyroxene, amphibole (hornblende), garnet, and epidote, and low positive loading for plagioclase. On the other hand, we see high negative loading for K_2O , P_2O_5 , and Pb, and low positive loading for Al_2O_3 . There is also high negative loading for quartz, biotite, orthoclase, chlorite, muscovite and hematite. Depth shows a low negative loading (Fig. 5).

As is shown in Fig. 5, there are very high positive loadings for MgO, CaO, Na_2O , the clay and rock forming minerals, and most of the heavy metals. This indicates the great importance of clay minerals and rock forming minerals in the accumulation of heavy metal elements.

This factor also indicates the significant influence of the fine mud fraction on soil chemistry. These element/mineral associations reflect an aluminosilicate control, probably by the clay fraction. The high positive loading for mud (clay) and the high negative loading for sand (quartz), along with the regional differentiation between the mud and sand fractions, suggest that this factor is largely controlled by the texture or sorting of the mud (clay) fraction.

The significant association of MgO, CaO, Na, and to lesser extent Fe in factor 1 is explained mainly by the geochemical coherence of Mg, Ca, and Fe in various minerals loaded into this factor (pyroxene, epidote, garnet, hornblende, and smectite).

Moreover, this factor is characterized by high positive loadings for clay minerals (smectite, illite, and kaolinite) and low positive loading for Fe_2O_3 , indicating that the clay minerals and hydrous iron are the main sorption surfaces for the accumulation of the heavy metals Co, Mo, Cd, and Zn (clay minerals accommodate Co in place of Mg^{+2}). Middelburg and Comans (1991) concluded that Cd may be readsorbed into the clay fractions. SiO_2 is negatively loaded because it is concentrated in the sand fraction (the latter being also negatively loaded).

The negative loading of depth in this factor indicates that none of the minerals or elements recorded (loaded) in this factor are controlled by depth.

This factor is considered to be the provenance discriminating factor for the Czech and Bahtim soils. It shows high negative loading for K_2O , Al_2O_3 , SiO_2 , quartz, orthoclase, biotite, muscovite, and sand, which are the main components of

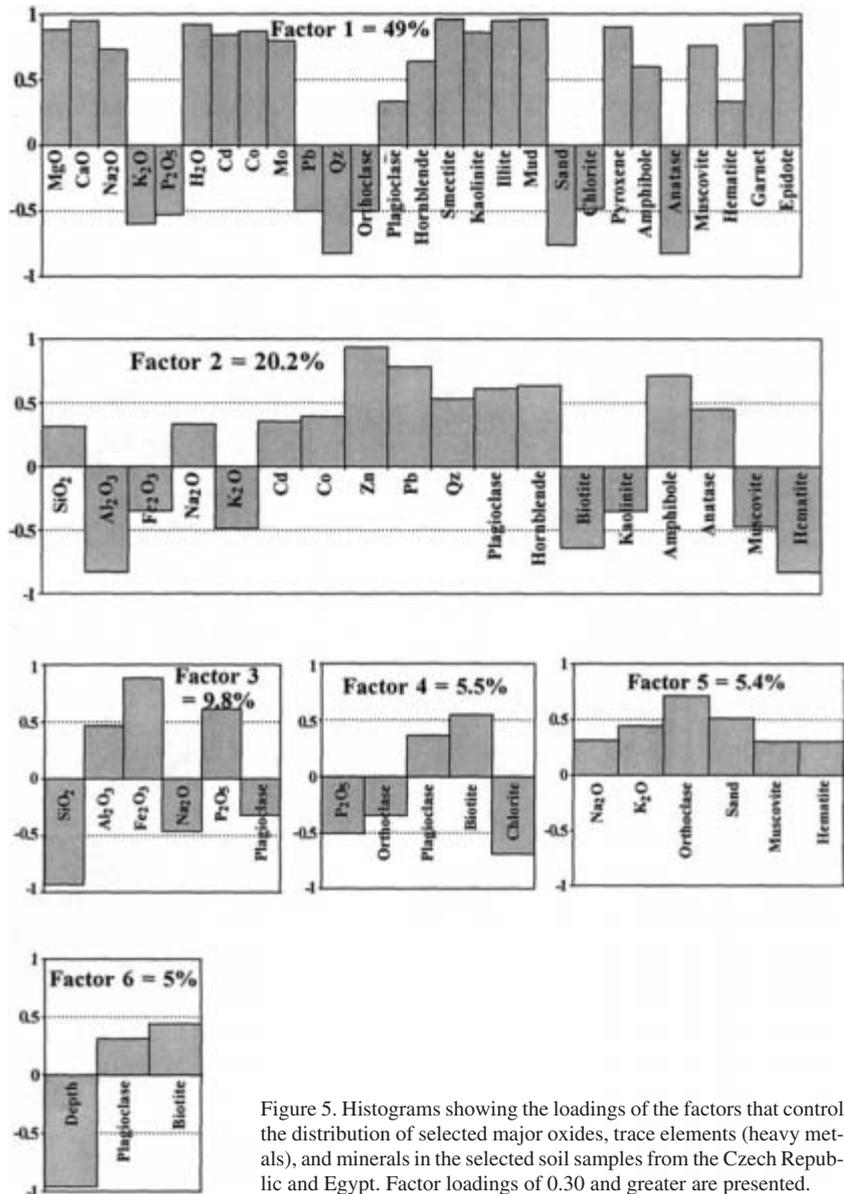


Figure 5. Histograms showing the loadings of the factors that control the distribution of selected major oxides, trace elements (heavy metals), and minerals in the selected soil samples from the Czech Republic and Egypt. Factor loadings of 0.30 and greater are presented.

the biotite muscovite gneiss of the Czech soils. Conversely, the high positive loadings for Mg, Ca, Na, plagioclase, pyroxene, hornblende, garnet, epidote, smectite, and illite match the alluvial soils (Hamdi 1967) and deltaic deposits of the Nile (El Gabaly and Khadr 1962). This suggests that the ancient branches of the River Nile played a major role in supplying delta soils (Bahtim area). The drainage from the Ethiopian highlands (which are composed of basic volcanic rocks) has contributed most of the mineral assemblages.

Factor 2: Zn-Pb versus the alteration products of rock forming minerals

This factor accounts for 20.2 % of the total variance. The positively associated components of factor 2 are plagioclase, hornblende, pyroxene, amphibole, and anatase, while the negatively associated components are smectite, kaolinite, illite, chlorite, hematite, and epidote (see Fig. 5). The

minerals of the negatively associated group could have resulted from the alteration of the minerals that form the positive association.

The elements Zn and Pb are highly loaded in this factor, whereas the other heavy metals such as Cd, Co, and Mo, despite having high loadings in factor 1, show less significant loadings here. These three elements evidently play a dual role by being associated with the high positive loading for plagioclase, hornblende, amphibole, and to a lesser extent pyroxene. Therefore, the heavy metal content of the present soils can not be fully explained in terms of secondary enrichment by adsorption into the clay fraction, as suggested by the high loading of clay in factor 1. It seems reasonable that some of the heavy metal content of the studied soils (especially Zn and Pb) were inherited from detrital rock forming minerals (amphibole, plagioclase, and pyroxene), especially since all of the clay minerals are negatively loaded in this factor.

As in factor 1, the low positive loading for MgO, CaO, Na₂O, and SiO₂ in factor 2 is explained in terms of the geochemical coherence of Mg, Ca, Na, and SiO₂ in sodic and calcic plagioclase, hornblende, and pyroxene. This is demonstrated by the high positive loading for plagioclase and hornblende in this factor.

On the other hand, the high negative loadings for Al₂O₃, Fe₂O₃, and K₂O in this factor are also explained in terms of the geochemical coherence of Al₂O₃, Fe, and K₂O in orthoclase, biotite, muscovite, chlorite, and illite.

Factor 3: the hematite-phosphate factor

This factor accounts for 9.8 % of the total variance. It shows a high positive loading for Fe₂O₃ and P₂O₅, moderate positive loading for Al₂O₃, and low positive loading for hematite, kaolinite, muscovite, and K₂O (see Fig. 5). It is because of the high positive loadings of Fe₂O₃ and P₂O₅ that we designate this as the hematite-phosphate factor.

The moderate positive loading for Al₂O₃ and K₂O with kaolinite and muscovite in this factor is again explained mainly in terms of the geochemical coherence of Al₂O₃ and K₂O in these two minerals. Moreover, it suggests that Fe₂O₃ is related to the clay fraction but not to detrital quartz grains, as indicated by the high negative loading for SiO₂ and quartz in this factor. It is known that P can be adsorbed and co-precipitated with Fe-oxyhydroxides (Berner 1973; Salomons and Foerstner 1984). Koons et al. (1980) has assessed the degree to which trace metals and Fe-oxides become associated during rock weathering and soil formation.

Factor 4: the biotite-plagioclase factor

This factor accounts for 5.5 % of the total variance. It shows a moderate positive loading for biotite and plagioclase, and low positive loading for heavy metals such as Cd, Co, and Mo, as well as Mg and Ca, and minerals such as pyroxene, amphibole, garnet, hematite, and kaolinite.

The positive loadings of these elements and minerals are opposed by moderate negative loadings for P₂O₅, chlorite, and orthoclase (see Fig. 5).

Evidence from this factor suggests that Mo, Cd, and Co are partly inherited from detrital biotite and plagioclase, and are not completely related to clay minerals. As such, we designate this as the biotite-plagioclase factor.

The moderate positive loading for biotite and plagioclase in this factor is opposed by the negative loading of chlorite, which is considered as an alteration product of these minerals.

Factor 5: the orthoclase-muscovite factor

This factor, which accounts for 5.4 % of the total variance, shows high positive loading for orthoclase, and moderate positive loading for muscovite, K₂O and Al₂O₃ and hematite. We thus refer to it as the orthoclase-muscovite factor (see Fig. 5).

The positively loaded association of K₂O and Al₂O₃, in this factor is explained in terms of the geochemical coherence of K₂O, Al₂O₃ in orthoclase and muscovite. These minerals are mainly of detrital origin and are present within the sand-sized fraction.

Factor 6: the biotite-plagioclase versus depth factor

This factor, which accounts for 5 % of the total variance, shows moderate positive loading for plagioclase and biotite, low positive loading for Zn and Pb, and very high negative loading for depth. We have therefore designated it as the biotite-plagioclase versus depth factor (see Fig. 5). The low positive loading for Zn and Pb in this factor suggests that these heavy metals are inherited partly from plagioclase and biotite instead of being related to clay. This result is consistent with the results of factor 2. Moreover, both Zn and Pb are not controlled by depth.

Conclusions

The mineralogical studies of the Bahtim soil of Egypt clearly establishes the dominance of smectite, kaolinite, and illite in the clay fraction; while kaolinite is the dominant clay mineral in Czech soils, with subordinate amounts of chlorite.

The sand fraction of Czech soil is composed mainly of quartz, plagioclase, K-feldspar, amphibole (hornblende), and muscovite, with rare biotite, anatase, and apatite. The sand fraction of the Bahtim soil is composed mainly of quartz, plagioclase, hornblende, pyroxene, epidote, garnet, biotite, and minor K-feldspar.

Chemical studies of these soil samples show that they are broadly similar to average shale. The Czech soils are enriched in Pb, while the Bahtim soil is enriched in Co, both being above the acceptable global limits for soils (McBride 1994). Cd and Zn are within the acceptable limits in the Czech and Bahtim soils.

Factor analysis suggests six geochemical and mineralogical factors that control the accumulation of heavy metals in these soils. These factors may be described as follows:

- 1 The factor characterized by the role of clay and rock forming minerals in the accumulation of heavy metals. This factor accounts for 49 % of the total variance. It shows high positive loadings for MgO, CaO, Na₂O, and clay and rock forming minerals. Co, Cd, Mo and to a less extent Zn are also positively loaded.
- 2 The factor characterized by Zn-Pb versus the alteration products of rock forming minerals in soil profiles. This factor accounts for 20.2 % of the total variance. It shows high positive loading for Zn, Pb, plagioclase, hornblende, pyroxene, amphibole, and anatase, and a corresponding negative loading for smectite, kaolinite, illite, chlorite, hematite, and epidote. The negatively associated group of minerals could have formed from the alteration of those minerals that comprise the positive association.
- 3 The factor characterized by hematite and phosphate accounts for 9.8 % of the total variance. It shows high positive loading for Fe₂O₃ and P₂O₅. P is known to be adsorbed and co-precipitated with Fe-oxyhydroxides.
- 4 The biotite-plagioclase factor accounts for 5.5 % of the total variance. It shows moderate positive loading for biotite and plagioclase, with low positive loading for the heavy metals Cd, Co, and Mo.
- 5 The orthoclase-muscovite factor, accounts for 5.4 % of the total variance.
- 6 The biotite-plagioclase versus depth factor.

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