Research Article

Topographic Effect on the Total Oxides Distribution of Calcareous Soils in Northern Iraq

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Abstract | The formation of soil is thought to be greatly influenced by topography. Understanding topographic variations is thus considered essential since it affects the appropriate management of soil, especially calcareous soils, known for playing a major role in the production of food as well as agriculture. The total oxides for calcareous soils as a topography function have been used for the purpose of characterizing the soils and assessing the application of relevant geochemical data. The physical, morphological, geochemical, and chemical properties of three pedons that have been excavated for a limestone-formed area were evaluated. Although the formation of distinct soils was not sufficiently studied, it has been demonstrated that varied topographic locations affected the soil's physical and chemical characteristics. At lower sites, our findings indicate that the ratio of Al_2O_3, SiO_2, K_2O, Fe_2O_3, P_2O_5, and TiO_2 total oxides rose for both the P1 and A horizons. However, at the same site, the Na_2O, CaO, and MgO ratios are low. Because soil in low-topography sites was subjected to moderate weathering, the geochemical data revealed an incomprehensible trend with topographic locations.

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Introduction

Understanding how topographic variations impact soil properties is essential for putting effective soil management approaches into practice, as topography has a major impact on soil formation. Curvature, slope, and elevation are examples regarding topographic factors that influence a location's hydrological conditions and result in various conditions of soil moisture as well as flow patterns (Al-Salam *et al.*, 2020; Seibert *et al.*, 2007; Salih *et al.*, 2023). Since topography influences how water and other materials are added to and removed from the soil, soil forms have been closely correlated with topographic positions. Through analyzing geochemical data to determine the degree of weathering, differences in classification might be attributed to pedological processes or other factors. The findings demonstrated that the research area's soil physico-chemical, morphological, and mineralogical properties were significantly impacted by the topographic conditions (Dengiz *et al*., 2013). The study examined how soil diversity is affected by altitude differences in semi-arid, forested, and mountainous environments (Badia *et al*., 2013; Razvanchi and Fayadh, 2023). A total of 10 pedons that are found in representative profiles in the limestone rocks have been described in order to do this. The greatest difference among diagnostic horizons in soil is caused by different parent materials. The expected regime of soil moisture shifts from aridic to xeric at the top of the two slopes due to such research's findings regarding soil depth as well as the retention of water, which tend to altitude from top to bottom.

Geochemical weathering indices can help with the understanding of the carbonate processes of weathering in soils; calcareous soil environments had been assessed in this context (Buggle *et al*., 2011; Rahel and Kamal, 2021). Large land areas in semi-humid to arid regions of the world are covered by soils that retain carbonate minerals as a result of their importance in food production and agriculture (Dash *et al*., 2022a). Owliaie *et al*. (2006); Al-Shamary *et al*. (2023); Khormali *et al*. (2003) many studies have been carried out on its pedogenesis. Calcium carbonate makes up calcareous soils, which frequently contain more than 15% $CaCO_3$. It can appear as crusts, nodules, crystals, or powder (FAO, 1990). At almost 90% of the total carbonate, calcite ($CaCO_3$) is the most significant form of carbonate minerals. Aragonite and magnesite ($MgCO_3$) follow. It is most commonly found in sedimentary sediments, followed by dolomite calcium magnesium (CO_3), which is composed of dolomite limestone. Other trace amounts of it can be found in ferrite and anchorites (FAO, 1990; Lindsay, 1991). The amount of carbonate minerals, particularly $CaCO_3$, in Iraqi soils is high 500g/kg. It makes up 5% of minerals in the crust of the earth, and its presence in the soil is crucial because it influences and is affected by a variety of soil physical and chemical characteristics, including soil cluster size, silt and clay separations, and more (Jelic *et al*., 2011). Unexpectedly few researches have employed calcareous soil pedogenesis or total oxides geo-chemistry (Ebeling *et al*., 2016; Chen *et al*., 2011).

A relation between soil geochemical properties and weathering status is established by quantitative models called geochemical indices. As a result, using these indicators provides a quantitative standard for the determination of the extent of weathering and helps identify soil types (Heidari and Osat, 2022). Furthermore, the use of geochemical indicators helps to clarify weathering processes pertaining to the carbonates (Buggles *et al*., 2011). Total oxides represent the outcome of the chemical analyses of the oxides that are produced by the weathering of rocks. Total oxides are mobilized as well as re-distributed throughout weathering as a result of the breakdown of minerals (Hill *et al*., 2000; Eagleton *et al*., 1987; Jin-Long *et al*., 2007; Rigassa *et al*. (2014). The oxides' redistribution and mobility in secondary environment is a popular technique for determining the weathering degree as well as behavior of the oxides throughout the weathering (Beyla *et al*., 2009). The mobile total oxides that are more geo-chemically (i.e., MgO, Na_2O, K_2O, and CaO) will decrease typically with the weathering grade in the case where they're liberated from the host minerals and leached from the parent rock. Al_2O_3, SiO_2, MnO, P_2O_5, TiO_2, and FeO will be among the less prevalent mobile and immobile oxides (Arikan *et al*., 2007; Guann *et al*., 2001). Total oxides, which are often utilized in order to examine the chemical characteristics of the soils, are crucial for the illustration of weathering and determination of soil evolution stage since their spreading presents insight about oxides' movement throughout the weathering (Zhou *et al*., 2015). Numerous researched had shown that the soil oxides represent highly important constituents of soil that are formed by the weathering of rocks and are essential nutrient materials for the growth of the plants as well as the production of food (Huseyin *et al*., 2018; Richter *et al*., 2009; Margany, 2021; Fatah and Ismaeil, 2021; Sahwan *et al*., 2021). The soil oxide concentration is therefore one of the most crucial diagnostic indicators in soil classification and assessment systems worldwide. The concentration regarding elements in the soil is reflected in the losses, gains, or redistribution of primary oxides caused by soil formation processes. Not all oxides are impacted equally. The distribution regarding primary oxides in the soil profile is reflected in pedogenic processes, which most likely mirror the chemical properties of the soil. According to Drever (2005), the distribution of primary oxides in soil can be used to categorize and explain the processes that led to their formation.

In a research, Maniyunda *et al*. (2014) demonstrated that, with the exception of TiO2 and K2O, which varied considerably between the soils, the abundances of the key element oxides were comparable. The proportional retention regarding the major element oxides in the soil varied significantly, and the relative strength of weathering was utilized as a measure of soil development. Therefore, the relative preservation regarding CaO in comparison with other element oxides has been discovered to indicate the intensity of weathering (i.e., the pedogenetic age) in the case compared with soils that originatie on various basic complex rocks. Their findings indicate that the soil pedogenesis process in Bafra Plain is significantly influenced by topographic features on a regional level. According to Tunçay and Dengiz (2016), this finding was corroborated by chemical weathering indicators, like base oxide/R_2O_3 (Fe_2O_3 + Al_2O_3) or R_2O_3 and PIA (i.e., Parker weathering index), chemical alteration index (CIA), and chemical weathering indicators (CIW). Slope location, sometimes referred to as topography, has a major impact on soil growth as well as the incorporation and removal of water and energy from the soil. Therefore, describing and classifying limestone soils based on their topography is the aim of the work that is being presented.

- Determination of ratios of distribution of the total oxides for some of the calcareous soils in the northern region of Iraq.
- Evaluation of soil development extent utilizing specific geo-chemical indications.

Materials and Methods

Area of the study

The research area is located in Sulaymaniyah Governorate of Iraq, in Azmar mountain range (Figure 1). With a mean amount of yearly rainfalls of 736mm and a mean temperature degree of 33.2°C, the area experiences a semi-humid climate, which is classified as Xeric for humidity. Three topographical locations Pedon 1 (i.e., foothill), Pedon 2 (i.e., midland), and Pedon3 (i.e., upslope) were used in order to study the soil. The pedons are located in 35°38’39.98”N, 45°27’54.31”E for Pedon 1, 35° 38’33.5”N, 45°28’30.36”E for Pedon 2, and 35°38’52.84”N, 45° 28’51.87”E for Pedon 3. Pedons are separated by 1,727.44m between Pedon1 and Pedon3, 907.38m between Pedon1 and Pedon2, and 806.27m between Pedon2 and Pedon3. Pedons 1, 2, and 3 have respective elevations of 1,396, 1,270, and 1,167 m. They have been excavated in accordance with the fundamental guidelines provided in the American Soil Survey Manual after being selected at pedons of various altitudes (Soil Survey Staff, 2014). Samples of soil were collected from each horizon and stored for laboratory investigation, and the morphology of the soil profiles of the pedons with various horizons were reported.

Laboratory analyses

A hydrometer has been used in order to determine size distribution of the soil particles (Black *et al*., 1965). Paraffin wax was used to determine bulk density (Black *et al*., 1965), and Jackson (1979) was used to evaluate the pH in water (1:2.5). The procedure outlined by Page *et al*. (1982) was used to measure electrical conductivity (EC). Van Langen (1993) used Walkley-Black wet digestion approach for the determination of organic matter content, whereas Ryan *et al*. (2001) used ammonium acetate to assess the CEC (i.e., cation exchange capacity). The calcimeter method has been used to measure the amount of carbonate mineral (Rowell, 1996). An Inductively Coupled Plasma Mass Spectrometer (ICP-MS) was utilized for determining the chemical determination regarding a few key elements (Burts, 2011).

Calculations of the indicators of weathering

Multiple indices were developed for describing chemical weathering of soils, which include Nesbitt and Young (1982) index. Those indicators have been based on ratio of basic cations (Mg^{2+}, K^+, Na^+, Ca^{2+}) to Al^{3+}, as can be noted in the Chemical Index of the Alteration Equation 1.

$$CIA=\frac{AL_2O_3}{AL_2O_3+K_2O+Na_2O+CaO^*}\times 100 \quad ...(1)$$

CaO^* denotes percentage of silicates that are corrected for apatite and carbonate content. CaO^* percentage is based on CaO/(Na_2O) ratio being <1. In the case where the value of CaO^* is < Na_2O value, CaO^* value is utilized; otherwise, Na_2O is taken (Mc-Lennan *et al*., 1993).

CPA (i.e., Chemical Proxy of Alteration) is viewed a more precise silicate weathering indicator Equation 2. CPA is aimed at avoiding potassium and calcium carbonates’ stabilization, whereas Al and Na represent the most suitable elements for describing the intensity of weathering (Buggles *et al*., 2011).

$$CPA=\frac{AL_2\,O_3}{AL_2\,O_3+Na_2O}\times 100 \quad ...(2)$$

Because potassium-bearing phases, like K-feldspar and clay minerals, are resistant to weathering, K release is minimal in comparison to Na release. According to Baumann *et al.* (2014), this supports the notion that K^+ is secondary in cold climates.

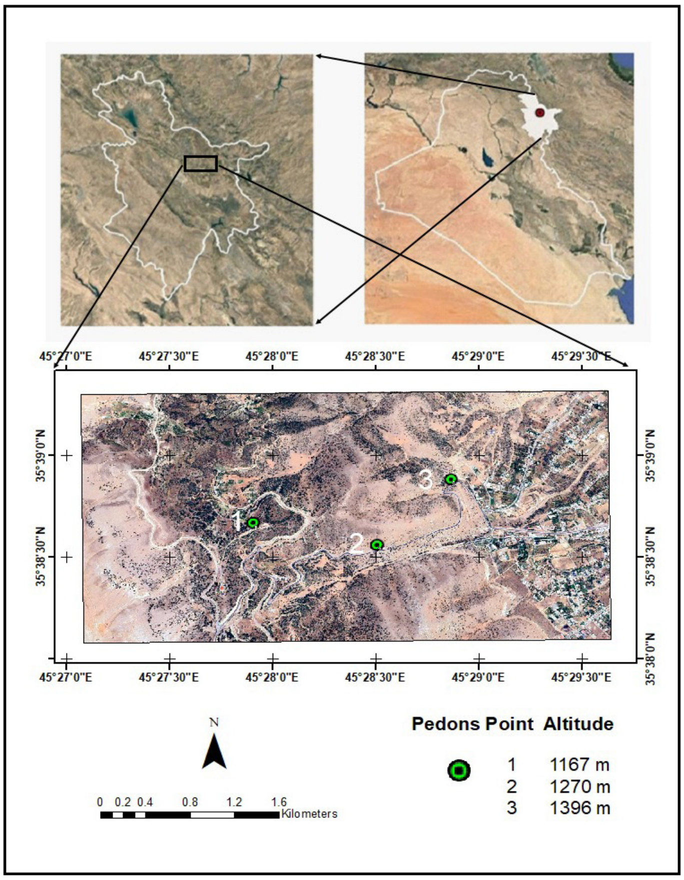

Figure 1: *Location of the study area showing the general transect of the 3 pedons. (Source: Arc GIS software v. 10.50).*

Equation 3 displays FENG index, which was applied to calcareous soils and rises as the weathering process intensifies and the soil develops. To prevent biases from calcium carbonate, Mg and P were substituted for Ca as important determinants. The Weathering Index for Carbonate-rich Soils is the name of this index (Feng, 1997).

$$FENG = \frac{AL_2O_3 + Fe_2O_3}{P_2O_5 + Na_2O + K_2O + MgO} \times 100 \quad ...(3)$$

The alkaline cations' amount that is lost throughout the washing due to metal hydrolysis is indicated by Parker index (PI), which is displayed in Equation 4. As soil development and weathering intensity increase, the Parker Index (PI) decreases (Parker, 1970).

$$PI = \left(\frac{2\,Na_2O}{0.350} + \frac{2K_2O}{0.90} + \frac{MgO}{0.250} + \frac{CaO^*}{0.70} \right) \times 100 \quad ...(4)$$

Results and Discussion

The horizons that make up the pedons of soil that were included in this work are described in morphological detail in Table 1. The soil in the area of the study differs in color, distribution of particle sizes, and top soil horizon thickness. Since top soils were transported from the high altitude P-1 to the low altitude P-3, in which they have collected to create progressively deeper, darker, and finer-textured

Table 1: *Morphological properties of the study area.*

Pedon	Horizon	Depth	Colour (dry)	Colour ((fresh'moisture)	Structure structural and stability	Boundary
	A	0cm-19cm	10 YR 5/6	10 YR 3/6	1mgr	as
	Btk 1	19-43cm	10 YR 4/4	10 YR 3/3	2msbk	gs
P1	Btk 2	43-77cm	10 YR 5/4	10 YR 4/3	2msbk	gs
	Btk 3	77-103cm	10 YR 6/3	10 YR 3/3	2msbk	gs
	Ck	+103	10 YR 5/3	10 YR 4/4	Mas	---
	A	0-17cm	10 YR 5/4	10 YR 3/3	2mgr	as
	Bt	17-25cm	10 YR 4/3	10 YR 3/3	2msbk	cs
P2	Btk 1	25-44cm	10 YR 6/4	10 YR 4/4	2msbk	cs
	Btk 2	44-93cm	10 YR 5/4	10 YR 3/4	2msbk	gs
	Ck	+93cm	10 YR 5/3	10 YR 4/4	Mas	--
	A	0-22cm	10 YR 5/3	10 YR 3/3	3mgr	aw
	Btk 1	22-48cm	10 YR 3/3	10 YR 3/1	2msbk	gs
P3	Btk 2	48-79cm	10 YR 4/4	10 YR 3/4	2msbk	gs
	Btk 3	79-121cm	10 YR 5/4	10 YR 3/3	2msbk	gs
	Ck1	121-150cm	10 YR 4/6	10 YR 3/4	2msbk	gs
	Ck2	+150cm	10 YR 5/3	10 YR 4/4	3csbk	--

Abbreviations: Boundary: a=abrupt; g=gradual; c=clear; w=wavy. s=smooth; Structure: 1=weak; 2=moderate; 3=strong; m=medium; mas=massive; c=coarse; sbk=sb angular blocky; gr= granular.

Table 2: *Some chemical and physical properties of studied soils.*

Pedon	Hori-zon	Depth	pH 1:2.5	ECe (µs.cm⁻¹)	$CaCo_3$ %	O.M. %	CEC (cmolc.kg⁻¹)	B.D (gr. cm⁻³)	P.S.D. (%)			Textural class
									Sand	Silt	Clay	
	A	0-19cm	7.190	0.81	24.90	1.230	42.140	1.580	21.0	30	49	Clay
	Btk 1	19-43cm	7.510	0.53	46.30	1.100	26.10	1.630	10.0	29	61	Clay
P1	Btk 2	43-77cm	7.490	1.14	47.90	1.30	34.80	1.700	15.0	27	58	Clay
	Btk 3	77-103cm	7.360	0.44	48.10	1.340	31.930	1.760	16.0	26	58	Clay
	Ck	+103cm	7.790	0.30	49.30	0.90	32.100	1.490	34.0	35	31	Clay Loam
	A	0-17cm	7.610	0.90	29.20	2.90	40.290	1.410	16.0	33	51	Clay
	Bt	17-25cm	7.720	0.83	30.30	2.70	46.770	1.530	15.0	31	54	Clay
P2	Btk 1	25-44cm	7.350	0.72	41.30	1.10	31.910	1.600	12.0	30	58	Clay
	Btk 2	44-93cm	7.500	0.66	45.20	1.30	23.720	1.510	7.0	32	61	Clay
	Ck	+93cm	7.930	0.37	50.90	0.880	33.830	1.730	10.0	47	43	Clay
	A	0-22cm	7.710	0.29	18.70	4.60	47.130	1.330	17.0	37	46	Clay
	Btk 1	22-48cm	7.950	0.41	39.50	5.20	50.180	1.690	23.0	33	44	Clay
P3	Btk 2	48-79cm	7.830	0.89	44.220	4.70	51.140	1.830	12.0	35	53	Clay
	Btk 3	79-121cm	7.780	0.73	46.50	4.10	33.760	1.620	11.0	30	59	Clay
	Ck1	121-150cm	7.730	0.51	47.30	3.70	31.870	1.430	8.0	53	39	Clay
	Ck2	+150cm	8.020	0.290	41.800	3.800	29.910	1.750	9.00	52.0	39.0	Silty clay

ECe= Electrical conductivity, OM= Organic matter, $CaCo_3$ =Calcium carbonate, CEC= Cation Exchange Capacity. PSD = Particle size distribution; BD = Bulk Density.

soils as elevation decreases, such changes clearly show the effects of soil erosion. All soil pedons have a maximum hue value of 10 YR, which is a strong reflection of the parent material, lime stone. The low-elevation surface soil regarding horizon A in Pedon 3 has a black tint due to the organic matter increase. The calcium carbonate buildup in Pedon3 largely determined the genetic developments that led to colour, texture, and top horizon depth changes. The heavily mottled areas at Pedon3, which have been suggestive of inadequate drainage locally, were influenced by the topography.

With regard to soil pedons, there was a weakly, strongly, or somewhat improved surface (A) horizon with granular structure, a moderately developed pedologic B horizon with subangular blocky structure, and a huge C horizon (with the exception of Pedon 3). There is also the subsurface calcic diagnostic horizon for each pedon. Slope was shown to be one of the most important variables controlling the pedological processes in this pedon. More runoff and the transportation of fine earth particles from the surface downslope through soil movement and surface soil erosion are also encouraged by a slope. The pedon was identified as an old soil since all of its genetic horizons have been categorized as surface soil with limited pedological development as well as developed genetic subsurface horizons. The letters A, Bt (transition), and Ck (parent material) stood for the surface soil.

Table 2 displays findings of the study pedons' physical and chemical characteristics. The soil pedons showed a pH of 7.19 to 8.02, which suggests that the parent material of the limestone is alkaline. According to Rajeshwar and Ramulu (2016) and Khalaf and Hussien (2021), pH values in topographically low places increased, indicating that leaching intensity, which rises with rainfall, has a significant impact on soil formation processes.

There was no significant risk of salinity to crops, as electrical conductivity (ECe) has been< 2dS/m (Salih *et al*., 2023). For pedons 1, 2, and 3, the $CaCO_3$ percentage values varied from 32.40% to 49.30%, 29.20% to 50.90%, and 18.70% to 47.30%, respectively. All pedons showed an increase in $CaCO_3$ percentage with depth, which is indicative of the calcareous parent material's effect and the leaching that occurs during pedogenic processes (Merkli *et al*., 2009; Fattah and Karim, 2021). The annual decomposition and accumulation of crop residues led to an increase in the organic matter content in the surface horizons of the pedons under study (Dash *et al*., 2019c). Reduced oxidation brought on by increased soil moisture is the reason for the rise in organic matter in profile three. Due to the leaching as well as precipitation regarding basic cations from higher sites to lower ones, especially with surface runoff water, a cation exchange capacity (CEC) increase has been noted at lower topographic sites (Abdullatiff and Wheib, 2019; Kishore *et al*., 2020). The three pedons had varying percentages of sand: 10% to 34%, 7% to 16%, and 8% to 23%. On the other hand, pedons 1, 2, and 3 had clay contents ranging from 39% to 59%, 43% to 61%, and 31% to 61%, respectively. The presence of illuviation (clay migration) processes was indicated by the increasing trend in the clay content with the depth observed in Pedon2 and Pedon3 (Dash *et al*., 2022b; Lokya *et al*., 2020; Abdulridha and Essa, 2023). Between the highest and lowest topographies, there was a general reduction in the bulk density in surface horizons. The reason for this decline is that the third pedon has more organic content than the first, which can lower bulk density and boost crop yields (Dash *et al*., 2019b). It has been demonstrated that variations in topographic locations (i.e., altitudes) had an impact on chemical and physical properties of the soils in the area under study, but that the formation of distinct soil types was not significantly impacted. According to the US Department of Agriculture's categorization, all soils were therefore categorized as Typic Calcixerolls (USDA, 2014).

The analysis of each element in the soils under investigation is shown in Table 3. Main element ranges (Si, Al, Fe, Mg, Ca, K, P, Na, and Ti) were consistent with worldwide values in all of the soils studied (Kabata-Pendias, 2011; Tunçay *et al*., 2020). Since quartz is the main component of the majority of soils and the most abundant of the minerals in crust of the earth, Al-Bayati and Al-Obaidi (2023) came to the conclusion that sediments of the Euphrates and Tigris, which are represented by soils of Najaf and Salahal-Din, have a high quartz content. Its specific gravity is low, at 2.65. Additionally, it has a strong resistance to weathering. Its crystal network is hence more stable. All of the soils under study had SiO_2 contents between 29.9% and 53.5%, which was less than 54%. Between 7.99% and 12.17%, the Al_2O_3 content which is strongly correlated with clay distribution showed declining values as depth increased, especially in P1 and P2. In the C horizon, there was a noticeable decrease in Al_2O_3.

In every studied area, there was a reduction in FeO_3 with depth, ranging from 4.12% to 6.13%. The vertical iron oxides' distribution is tightly linked to the amount of the organic matter in surface horizon, according to Kamal and Rashid (2020), who cited Comell and Schwertmann (1979). This is because organic acids that are absorbed on iron oxides' surfaces form a complex bond with iron, increasing iron oxides' amount on surface. With CaO values'

Table 3: *Some total elements analysis concentration levels of studied soil profiles.*

Pedon	Horizon	Depth	SiO_2 (%)	AL_2O_3 (%)	Fe_2O_3 (%)	MgO (%)	CaO (%)	Na_2O (%)	K_2O (%)	P_2O_5 (%)	TiO_2 (%)
	A	0-19cm	35.30	9.180	4.650	5.610	16.60	0.70	1.310	0.140	0.540
	Btk 1	19-43cm	44.40	12.170	6.130	5.710	10.50	0.750	1.670	0.130	0.730
P1	Btk 2	43-77cm	51.00	11.910	6.340	5.450	10.10	0.710	1.710	0.120	0.710
	Btk 3	77-103cm	50.10	10.300	5.870	5.880	8.140	0.650	1.560	0.110	0.630
	Ck	+103cm	48.0	9.140	5.460	5.730	12.80	0.580	1.380	0.110	0.550
	A	0-17cm	36.80	9.410	5.060	4.140	17.010	0.580	1.390	0.160	0.620
	Bt	17-25cm	35.60	9.130	5.070	4.880	20.60	0.570	1.220	0.120	0.590
P2	Btk 1	25-44cm	32.30	8.330	4.800	4.620	23.30	0.420	1.100	0.110	0.560
	Btk 2	44-93cm	31.70	8.010	4.120	4.480	27.10	0.410	0.890	0.080	0.540
	Ck	+93cm	29.80	7.990	4.140	4.530	27.80	0.390	0.860	0.070	0.490
	A	0-22cm	53.50	11.30	5.530	5.450	9.330	0.610	1.870	0.360	0.960
	Btk 1	22-48cm	42.40	10.80	5.030	5.060	18.70	0.510	1.630	0.340	0.780
P3	Btk 2	48-79cm	36.30	10.20	5.040	4.70	21.80	0.510	1.510	0.270	0.620
	Btk 3	79-121cm	34.70	9.60	4.670	4.630	22.10	0.60	1.470	0.740	0.580
	Ck1	121-150cm	34.80	9.40	4.530	4.610	23.20	0.580	1.410	0.230	0.560
	Ck2	+150cm	33.90	9.40	4.610	4.610	23.80	0.570	1.390	0.230	0.560

Table 4: *Some genetic ratios of the pedons.*

Pedon	Hor.	SiO_2/Al_2O_3	SiO_2/Fe_2O_3	Al_2O_3/Fe_2O_3	CaO/MgO	$(K_2O+Na_2O+CaO)/Al_2O_3$	$(K_2O+Na_2O)/Al_2O_3$	$(CaO+MgO)/Al_2O_3$	K_2O/Na_2O
	A	6.520	20.170	3.090	2.12	3.31	0.13	1.840	1.23
	Btk 1	6.190	19.250	3.100	1.32	1.59	0.11	1.370	1.46
P1	Btk 2	7.260	21.370	2.940	1.33	1.57	0.11	1.330	1.58
	Btk 3	8.250	22.680	2.740	0.99	1.46	0.12	1.580	1.57
	Ck	8.910	23.360	2.620	1.60	2.57	0.11	1.810	1.56
	A	6.630	19.320	2.910	2.95	3.31	0.11	1.410	1.57
	Bt	6.610	18.620	2.810	3.03	4.12	0.11	1.710	1.40
P2	Btk 1	6.580	17.880	2.710	3.62	5.10	0.09	1.810	1.72
	Btk 2	6.710	20.440	3.040	4.34	6.16	0.09	1.890	1.42
	Ck	6.320	19.130	3.020	4.41	6.34	0.08	1.930	1.45
	A	8.030	25.710	3.200	1.23	1.53	0.10	1.230	2.01
	Btk 1	6.660	22.400	3.360	2.65	3.17	0.09	1.510	2.10
P3	Btk 2	6.030	19.140	3.160	3.33	3.91	0.09	1.550	1.94
	Btk 3	6.130	19.740	3.210	3.43	4.21	0.11	1.610	1.61
	Ck1	6.280	20.410	3.240	3.61	4.51	0.11	1.650	1.59
	Ck2	6.110	19.540	3.190	3.71	4.62	0.11	1.660	1.60

increase that had been observed in C horizons for all of the pedons as a result of the action of limestone parent material, CaO percentage has been found to range between 8.14% and 27.8%. The recorded MgO values ranged from 4.48% to 5.88%. There was a range of 0.86% to 1.87% for K_2O and 0.399% to 0.75% for Na_2O. To detect chemical changes, titanium, a metal that resists weathering, is utilized. It was found that the soil's TiO_2 percentage ranged between 0.49% and 0.96%, while its P_2O_5 ranged between 0.07% and 0.36%. Those macro-element data may provide further information on indicators of weathering.

Table 4 provides the genetic ratios regarding the sample profiles. Through showing the gain and loss of mineral substances in soil body and predicting formation and modifications of potential types of clay, total chemical analysis aids in identifying direction and degree of soil formation. In addition to being a tool for calculating the proportionate displacements regarding elements, genetic ratios act as a control for inaccurate assessments of substance losses. In an institutional setting, the genetic ratios for weathering pedon were predicted using the molecular dimensions regarding the main element oxides. Throughout the weathering and alteration processes, the index ratio shows stoichiometrical variations (Price and Velbel, 2003). It is easy to estimate each oxide's molecular ratio because of the proportion based on weight. All pedons in the study area, on the other hand, had Si/Al ratios that are greater than 2, which suggests sub-humid or high precipitation with cold locations. This causes a relative rise in Si concentrations by preventing Si from dissolving and leaching from soil profile. The fundamental oxides of K/Na had revealed notable variations amongst pedons. At the same time, compared with the other cases, Pedon I had shown the lowest ratios. In addition to that, Pedon 2 and 3's parent materials made from naturally existing limestone have the highest Ca/Mg ratio. Nonetheless, variations were found between horizons, particularly with regard to the ratios of basic cations, contingent on the parent material's limestone concentration and the existence of the calcic accumulation horizon.

Table 5 illustrates how CPA, CIA, FENG, and PI values change with depth. The pedons' CIA values varied from 71.15% to 78.30%.Ck and A horizons for (P-1 and P-2) had highest and lowest values of CIA, respectively. Subsurface horizons of P-1 and P-3 showed decreasing values of CIA with the value of the depth, whereas subsurface horizons of P-2 showed increasing CIA values with depth. Nesbitt and Young (1982) divided CIA values into five categories: high weathering (80-90%), moderate weathering (70-80%), very high weathering (90-100%), minimal weathering (50-60%), and slight weathering (60-70%).

Table 5: *Weathering rate indices of profiles of studied soil.*

Pedon	Horizon	Depth	CIA	CPA	FENG	PI
	A	0-19 cm	71.150	88.850	72.040	34.660
	Btk 1	19-43 cm	74.000	90.790	91.480	38.560
P1	Btk 2	43-77 cm	73.980	91.060	94.460	37.730
	Btk 3	77-103 cm	72.900	90.590	79.300	36.950
	Ck	+103 cm	72.870	90.540	74.160	34.200
	A	0-17 cm	73.380	90.790	96.870	29.900
	Bt	17-25 cm	74.040	90.680	84.220	30.380
P2	Btk 1	25-44 cm	76.400	92.340	83.480	26.900
	Btk 2	44-93 cm	77.590	92.230	81.660	24.630
	Ck	+93 cm	78.300	62.560	81.270	24.280
	A	0-22 cm	73.700	91.840	86.850	37.930
	Btk 1	22-48 cm	75.830	92.790	89.530	33.670
P3	Btk 2	48-79 cm	75.480	92.390	92.160	31.660
	Btk 3	79-121 cm	72.910	90.670	86.980	32.160
	Ck1	121-150 cm	73.230	90.780	85.900	31.360
	Ck2	+150 cm	73.550	90.920	86.460	31.080

Depending on CIA values, all pedons in this research were as having moderate weathering. For soils grown on various slopes, there was no clear trend towards steadily greater CIA values. The observed range of CPA values was 88.85% to 92.56%. Ck and A horizons for (P2 and P1) had the highest and lowest CPA values, respectively. Salinity-related problems were blamed for the decline in CPA values in the surface horizons across all study profiles, which decreased the degree of weathering seen in these horizons. Given that the CPA index correctly captures the degree of weathering in such pedons, this finding suggests that the CIA and CPA indices behave similarly. Since the CPA index does not include calcium, it can differentiate between calcium and silicates that are combined with carbonates, making it especially appropriate for calcareous soils. Those results are in line with earlier research (Alboz *et al*., 2022; Baumann *et al*., 2014).

With values that range between 72.04% and 96.87%, FENG index showed no clear differential. Ck and Btk1 horizons for (P-2 and P-1) had the lowest and highest PI index values, respectively, with values ranging from 24.28% to 38.56%. In the subsurface horizons of all studied pedons, a decline in PI index values with depth was observed, suggesting a decrease in mobile cations (Ca, Mg, Na, and K) as a result of increased weathering and leaching.

While values of PI index for the same pedon and horizon didn't exhibit a comparable decline, it has been observed that the CPA, CIA, and FENG values did. It was found that the first pedon's Btk 1 horizon had the biggest decline. The PI index's dependence on Al_2O_3, which is inaccurate in representing element mobility to assess relative shifts, is the cause of this discrepancy. It could be inaccurate to assume that silicate minerals are the source of all calcium. As weathering severity and development increase, the PI index falls. The Parker PI is specifically employed for alkaline and extremely alkaline metals (Mg, Ca, Na, and K), despite the fact that it satisfies the requirements for an oxidation index. Vegetation can aid in mineral weathering by holding moisture, changing pH, and sustaining microbial populations that accelerate mineral surfaces' weathering. This could explain the low rates regarding chemical weathering seen in (P3).

Conclusions

Depending on topography (various sites) in northern Iraq, this study aimed to classify soils and assess the application regarding geochemical data (total oxides) for calcareous soils. The physical, morphological, chemical, and geochemical characteristics of three pedons were investigated. The findings indicate that cation exchange, pH, organic matter, and $CaCo_3$ in soil. Along with the clay migration in the 2nd and 3rd pedons with depth, which suggests the presence of illuviation, capacity rose at sites of lower altitude in the first pedon. The physical and chemical characteristics regarding the soils have been found to be influenced by variations in topographic locations, although soil formation was not considerably impacted. However, the transfer of total elements from a high site to a down site of inflow of water for total elements enrichment was the reason for the increase in total oxides (AL_2O_3, Fe_2O_3, K_2O, Na_2O, P_2O_5, SiO_2, and TiO_2) of the A horizon for the first pedon at lower elevations. While PI index decreased for same pedon, the weathering indicators CPA, FENG, and CIA all displayed higher values for the 2nd pedon. As function of topography, the values as well as the rates of geochemical indicators for calcareous soils did not show any discernible trends. In order to evaluate the suitability of soil geochemical indicators for calcareous soils and their efficacy in soil management, more research is advised to examine the spatial variation of these indicators. The topographic features of mountainous areas, particularly in northern Iraq, are influenced by site, which also plays a significant role in soil formation. As a result, soil scientists ought to concentrate their study on this problem.

Novelty Statement

This study delivers the first integrated assessment of how topography controls the distribution of major total oxides in calcareous soils of Northern Iraq by combining full-profile geochemical analyses across three pedons with multiple weathering indices (CIA, CPA, FENG, PI). We demonstrate altitude-linked enrichment of Al_2O_3, SiO_2, K_2O, Fe_2O_3, P_2O_5, and TiO_2—and relative depletion of Na_2O, CaO, and MgO—in surface horizons, providing baseline metrics to inform soil classification and land management in the region.

Author's Contribution

Omar Alsalam (Corresponding author): Conceptualization and study design; field sampling and pedon description; laboratory coordination (particle size, bulk density, pH, EC, OM, CEC, $CaCO_3$); data curation and analysis; calculation of weathering indices (CIA, CPA, FENG, PI) and genetic ratios; visualization; writing—original draft; project administration.

Husian A. Isa: Methodology; field sampling and profile description; oversight of geochemical determinations (ICP-MS) and quality control; data interpretation; writing—review & editing.

Mahmood Ahmed L. Al-Bayati: Contextualization and literature synthesis on Iraqi calcareous/gypsiferous soils; validation of interpretations; writing—review & editing.

Hussein Alserae: GIS and mapping (ArcGIS v10.50; preparation of Figure 1); data organization and tables; writing—review & editing.

All authors read and approved the final manuscript.

Generative AI and AI-assisted technology statement

No generative AI or AI-assisted technologies were used to generate, analyze, or edit the manuscript content (text, figures, or tables). All analyses and writing were performed by the authors; only standard scientific software and instruments were used (e.g., ArcGIS v10.50 for mapping; ICP-MS and conventional soil laboratory methods) as documented in the Methods.

Conflict of interest

The authors have declared no conflict of interest.

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