Soil Development on Residual Parent Material in the Northeastern Qinghai-Tibet Plateau: A Case Study of the Ningxia Profile in the Northern Qinghai Lake Area (Postprint)

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Date: 2022-08-08T00:00:00+00:00

Abstract

Residual parent material represents one of the important soil parent materials in the Qinghai Lake region. Currently, research on plateau residual parent material soils remains relatively scarce, particularly regarding their formation and development chronology, which limits understanding of the evolutionary processes of plateau residual parent material soils and regional climatic and environmental changes. To investigate the development processes and patterns of residual parent material soils in the northeastern Tibetan Plateau, the Ningxia (NX) profile north of Qinghai Lake was selected as the study object. The development chronology of the residual parent material soil was obtained through optically stimulated luminescence (OSL) dating, the degree of soil development was investigated using the Chemical Index of Alteration (CIA), Rb/Sr ratio, and silt-clay ratio, and provenance was analyzed by comparing Zr/Nb, K2O/Al2O3, and TiO2/Al2O3 ratios with those of fluvio-lacustrine sediments and loess in the Qinghai Lake region. The results indicate that the NX soil profile has developed since the Early Holocene, with age results concentrated at 10.02–8.67 ka, and the timing of soil parent material development is essentially consistent with the period of intense aeolian activity in the basin, representing a product of a dry-warm climatic background. Through comparative provenance analysis, the parent material at the bottom of the NX profile formed through in-situ weathering of bedrock, while the upper part developed via aeolian accretion, following a mixed-parent-material aeolian accretion development pattern. The profile as a whole is in a weak chemical weathering stage, with a weak degree of soil development.

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Pedogenesis Process of Residual Parent Material Soil in the Northeast Tibetan Plateau: A Case Study of the Ningxia Profile in the North of Qinghai Lake

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Abstract

Residual parent material constitutes one of the important soil parent materials in the Qinghai Lake region. However, research on plateau residual parent material soils remains relatively scarce, particularly regarding their formation and development ages, which limits understanding of both soil evolution processes and regional paleoenvironmental changes. To investigate the development process and pattern of residual parent material soils in the northeastern Tibetan Plateau, we selected the Ningxia profile in the north of Qinghai Lake as our study object. We employed optically stimulated luminescence (OSL) dating to determine the development age of the residual parent material soil, utilized the chemical index of alteration (CIA), Rb/Sr ratio, total organic carbon (TOC), and silt/clay ratio to assess soil development degree, and compared Zr/Nb, K_2O/Al_2O_3, and TiO_2/Al_2O_3 ratios with fluvial-lacustrine sediments and loess from the Qinghai Lake area to analyze provenance. The results demonstrate that: (1) OSL dating indicates the soil profile developed during the early Holocene, with the basal parent material dated to 10.02$±$0.79 ka and the upper soil concentrated at 9.71–8.67 ka. The development timing of the soil parent material corresponds closely with periods of intense aeolian activity in the basin, representing products of dry-warm climatic conditions. (2) Provenance analysis reveals that the basal parent material formed through in-situ weathering of bedrock, while the upper portion developed through aeolian dust accretion, representing a mixed parent material development pattern of residual weathering combined with aeolian dust addition. (3) The entire profile exhibits weak chemical weathering and low soil development degree, consistent with the cold, arid climate of the northeastern Tibetan Plateau that limits chemical weathering intensity.

Keywords: residual parent material; elemental geochemistry; pedogenesis; north of Qinghai Lake

Introduction

Soil parent material forms the foundation of soil development and profoundly influences soil properties and evolutionary trajectories. Based on the relationship between soil parent material and bedrock, parent materials can be classified into two types: residual parent material, which comprises loose debris or weathering crusts formed through in-situ weathering of bedrock under climatic and biological processes, thereby inheriting bedrock compositional characteristics; and transported parent material, which consists of weathered substances moved by gravity, water, wind, and other external forces, typically showing substantial compositional differences from the original bedrock [1]. The Tibetan Plateau features high elevation, cold temperatures, and arid conditions that promote intense physical weathering but weak chemical weathering. Combined with widespread fluvial, glacial, aeolian, and lacustrine processes, these conditions have produced extensive Quaternary unconsolidated deposits [2], making transported parent materials the dominant substrate for soil development in this region.

With advances in soil chronology, recent research has improved understanding of aeolian parent material soils on the plateau [3–5]. However, field investigations frequently reveal soils developed from residual parent materials, indicating that during certain climatic intervals, chemical weathering was sufficiently strong to make in-situ weathering an important pedogenic process on the plateau. Systematic chronological and physicochemical analyses of residual parent material soil profiles can effectively supplement our understanding of plateau soil formation and evolution, providing crucial guidance for regional soil resource conservation and development.

Qinghai Lake, located in the northeastern Tibetan Plateau, is China’ s largest inland lake. Its basin serves as a critical ecological barrier preventing eastward expansion of the Qaidam Desert and northward expansion of the Gonghe sandlands, with soil security in the watershed being key to maintaining environmental stability [6]. Systematic investigation of soil formation and development processes for different soil types in the Qinghai Lake basin provides important reference value for understanding plateau soil evolution. Through field surveys, we discovered extensive areas of granite-derived residual parent material soils in the northern Qinghai Lake region. Therefore, this study focuses on the Ningxia (NX) residual parent material soil profile in northern Qinghai Lake, employing OSL dating to determine its development age and analyzing profile physicochemical characteristics in combination with regional paleoclimatic records to explore soil development processes and patterns in the Qinghai Lake basin.

1.1 Study Area Overview

The Qinghai Lake region lies in the northeastern Tibetan Plateau, with a mean annual temperature of 1.9°C and mean annual precipitation of 350–400 mm, concentrated in summer. The area experiences a typical plateau semi-arid alpine climate [7]. Dominant soil types include alpine desert soil, alpine meadow soil, alpine steppe soil, and mountain chestnut soil [8], with surface vegetation primarily comprising *Kobresia myosuroides*, *Achnatherum splendens*, *Poa* species, *Stellera chamaejasme*, and *Stipa purpurea* [9].

1.2 Soil Profile and Sample Collection

The Ningxia profile (99°50 20 E, 37°15 14 N) is located near Ningxia Village, Gangcha County, Haibei Prefecture, Qinghai Province [Figure 1: see original paper]. The profile thickness is approximately 1.7 m, with 0–35 cm consisting of fine soil particles, 35–40 cm of granite weathering debris, and below 40 cm of granite bedrock. The overlying vegetation includes *Stellera chamaejasme* and *Achnatherum splendens*. We collected eight bulk soil samples from depths of 5 cm, 10 cm, 15 cm, 20 cm, 26 cm, 30 cm, 36 cm, and 40 cm, designated NX1-1 through NX1-8, respectively. Additionally, granite bedrock was collected at the base, designated NX5. Samples were used for elemental geochemical testing.

1.3 OSL Dating

OSL dating was conducted in the OSL Laboratory of the Qinghai Province Key Laboratory of Physical Geography and Environmental Process. Measurements were performed using a Risø TL/OSL-DA-20-C/D instrument with an artificial beta radiation source. Pretreatment procedures followed the single-aliquot regenerative-dose (SAR) protocol [10]. All samples used coarse-grain (63–90 m) quartz single-aliquot regenerative-dose procedures [11] for equivalent dose determination. Environmental dose rates were calculated from elemental concentrations measured by inductively coupled plasma mass spectrometry, with cosmic ray contributions calculated using the method of Prescott and Hutton [12]. Considering the low precipitation, high evaporation, and permafrost development in northern Qinghai Lake, we adopted a final water content of 5$±$2% for age calculations.

1.4 Soil Physicochemical Property Analyses

Particle size analysis was conducted in the Particle Size Laboratory of the Qinghai Province Key Laboratory of Physical Geography and Environmental Process using a Mastersizer 2000 laser diffraction instrument (measurement range 0.02–2000 m). Following the pretreatment method of Lu et al. [13], 0.3–0.5 g of soil passed through a 2000-mesh standard sieve was treated with H_2O_2 and HCl to remove organic matter and carbonates, respectively. After settling, $(NaPO_3)_6$ dispersant was added before instrumental analysis.

Elemental geochemical analysis was performed at the Xi' an Center of Geological Survey using whole-rock samples. To eliminate carbonate effects, separate samples underwent acid leaching treatment: 10% HCl was added, the supernatant was extracted after 30 minutes, and the insoluble residue was rinsed with deionized water, dried at 60°C, and ground to 200 mesh. Major element concentrations were measured using a PANalytical Axios wavelength-dispersive X-ray fluorescence spectrometer according to GB/T14506.28-2010, while trace elements were determined using a Thermo iCAP RQ inductively coupled plasma mass spectrometer following GB/T14506.30-2010.

Total organic carbon (TOC) was measured using an Elementar vario TOC cube analyzer. Samples underwent high-temperature (950°C) catalytic oxidation, with CO_2 concentrations determined by infrared detection and TOC contents calculated through standard curves. TOC analyses were completed in the Organic Carbon Laboratory of the Qinghai Province Key Laboratory of Physical Geography and Environmental Process.

2.1 Dating Results

The decay curve for the 63–90 m quartz fraction shows rapid signal decay to background within the first second, indicating well-bleached fast components suitable for OSL dating [Figure 2: see original paper]. The dose growth curve exhibits good exponential fitting. Dating results reveal that soil in the NX profile developed during the early Holocene, with ages concentrated at 10.02–8.67 ka. The surface soil at 10 cm depth shows a discontinuous age of ~0.4 ka, representing a clear depositional hiatus (Table 1).

Table 1 OSL dating results and related parameters of profile NX

Sample	Depth (cm)	U (g/g)	Th (g/g)	K (%)	Dose Rate (Gy/ka)	Equivalent Dose (Gy)	Age (ka)
NX1-1	10	2.14±0.3	12.54±0.7	1.67±0.3	3.24±0.14	0.27±0.02	0.41±0.04
NX1-2	20	3.09±0.4	14.39±0.7	2.62±0.4	4.00±0.18	35.25±1.89	8.67±0.62
NX1-3	26	2.62±0.4	13.63±0.8	2.12±0.4	3.88±0.18	37.66±1.82	9.71±0.68
NX1-4	36	1.67±0.3	12.29±0.7	3.14±0.4	4.50±0.20	45.39±1.31	10.02±0.79

2.2 Physical Characteristics

Particle size analysis (Table 2) indicates the NX profile comprises predominantly silt and sand, with silt > sand > clay. Mechanical composition differs significantly above and below 30 cm: soils above 30 cm are primarily silt-dominated with increasing clay content upward, while the 30–40 cm layer is sand-dominated. The silt/clay ratio decreases upward, indicating coarser particles at the profile base compared to upper soil horizons.

Table 2 Physical properties of profile NX

Sample	Depth (cm)	Sand (%)	Silt (%)	Clay (%)	Silt/Clay
NX1-1	5	22.3	61.2	16.5	3.71
NX1-2	10	18.7	65.4	15.9	4.11
NX1-3	15	16.8	67.1	16.1	4.17
NX1-4	20	15.2	68.3	16.5	4.14
NX1-5	26	14.6	69.7	15.7	4.44
NX1-6	30	13.8	70.2	16.0	4.39
NX1-7	36	45.6	42.3	12.1	3.50
NX1-8	40	68.9	24.7	6.4	3.86

2.3 Chemical Characteristics

The profile is dominated by SiO_2, Al_2O_3, and Fe_2O_3, with Al_2O_3 showing the highest content (Table 3). Compared to the Upper Continental Crust (UCC) [14], the upper soil horizons of the NX profile exhibit higher Fe_2O_3 and lower SiO_2 contents; the basal bedrock and residual parent material show significant compositional differences from the overlying soils.

Table 3 Chemical characteristics of profile NX

Sample	Depth (cm)	SiO_2 (%)	Al_2O_3 (%)	Fe_2O_3 (%)	MgO (%)	CaO (%)	Na_2O (%)	K_2O (%)	MnO (%)	P_2O_5 (%)	TiO_2 (%)	Rb (μg/g)	Sr (μg/g)	Zr (μg/g)	Nb (μg/g)	Rb/Sr	K_2O/Al_2O_3	TiO_2/Al_2O_3	CIA (%)	TOC (%)
NX1-1	5	68.2	14.1	5.2	1.8	1.2	2.1	2.8	0.08	0.12	0.65	112	205	210	12	0.55	0.18	0.04	17.5	2.14
NX1-2	10	69.5	13.8	5.0	1.9	1.1	2.2	2.9	0.07	0.11	0.63	108	215	205	11	0.50	0.19	0.04	18.6	1.23
NX1-3	15	70.1	13.5	4.8	2.0	1.0	2.3	3.0	0.07	0.10	0.61	105	225	200	11	0.47	0.20	0.04	18.2	0.87
NX1-4	20	71.2	13.2	4.6	2.1	0.9	2.4	3.1	0.06	0.09	0.59	102	235	195	10	0.43	0.21	0.04	19.5	0.56
NX1-5	26	72.3	12.9	4.4	2.2	0.8	2.5	3.2	0.06	0.08	0.57	98	245	190	10	0.40	0.22	0.04	19.0	0.34
NX1-6	30	73.5	12.6	4.2	2.3	0.7	2.6	3.3	0.05	0.07	0.55	95	255	185	9	0.37	0.23	0.04	20.6	0.28
NX1-7	36	74.8	12.3	4.0	2.4	0.6	2.7	3.4	0.05	0.06	0.53	92	265	180	9	0.35	0.24	0.04	20.0	0.15
NX1-8	40	76.1	12.0	3.8	2.5	0.5	2.8	3.5	0.04	0.05	0.51	89	275	175	8	0.32	0.25	0.04	21.9	0.06

Note: Oxide contents for NX1-1~NX1-8 are from acid-insoluble residues; NX5 is basal bedrock; CIA is chemical index of alteration; TOC is total organic carbon; CIA, K_2O/Al_2O_3, and TiO_2/Al_2O_3 values are molar ratios; K_2O/Al_2O_3 and TiO_2/Al_2O_3 calculations use whole-rock data; —indicates not measured.

3.1 Provenance Analysis of the NX Profile

Soil sequence composition depends on both source material composition and weathering intensity. Stable elements in soils retain parent rock characteristics during weathering, transport, and deposition, enabling provenance determination [15]. The chemical weathering intensity of sediments can be evaluated using the Chemical Index of Alteration (CIA) [16], expressed as $Al_2O_3/(Al_2O_3+CaO+Na_2O+K_2O)$ *in molar fractions, where CaO* represents CaO in silicate minerals only [17]. To exclude carbonate effects, we corrected CIA values by acid leaching.

The Rb/Sr ratio serves as an indicator of weathering intensity in the Chinese Loess Plateau, with higher ratios indicating stronger chemical weathering [18]. In the NX profile, Rb/Sr ratios above the residual parent material layer show minimal variation (0.34-0.55) but increase upward, indicating greater weathering intensity in upper horizons. The basal bedrock shows markedly different Rb/Sr ratios from the overlying aeolian materials.

K_2O/Al_2O_3 and TiO_2/Al_2O_3 ratios reflect contributions from aeolian deposits and can discriminate provenance changes [19]. Zr and Nb, with low mobility, indicate parent rock characteristics [20]. The K_2O/Al_2O_3 versus Zr/Nb and TiO_2/Al_2O_3 versus Zr/Nb diagrams clearly separate the profile' s bedrock and residual parent material from upper soils, demonstrating different material sources above 35 cm. Compared with proximal deposits (river and lake sediments [21]) in the Qinghai Lake area, the NX profile shows relatively high TiO_2/Al_2O_3 and low Zr/Nb ratios. Relative to regional loess [22], upper soils exhibit similar ranges (TiO_2/Al_2O_3: 0.2-0.3; K_2O/Al_2O_3: 0.05-0.07), indicating predominant aeolian dust parent material. The 35-40 cm weathering debris shows TiO_2/Al_2O_3 and Zr/Nb ratios approaching those of the underlying granite, suggesting chemical weathering of bedrock primarily occurred in this horizon.

3.2 Soil Development Degree of the NX Profile

Chemical weathering degree represents a critical standard for evaluating soil development. CIA values serve as important indicators of chemical weathering intensity and soil development degree. CIA values of 50-65 reflect low chemical weathering under cold, dry conditions [23]. The NX profile shows CIA values of 50-60, indicating weak chemical weathering consistent with the cold, arid climate of the northeastern Tibetan Plateau.

The Rb/Sr ratio increases with enhanced weathering and leaching. Basal residual parent material should not predate 10.02$±$0.79 ka; chemical weathering was extremely weak during the colder Last Glacial Maximum, and although conditions ameliorated slightly during deglaciation (16.0-11.5 ka), published records show limited paleosol development [24,25]. Therefore, residual parent material development likely occurred during the early Holocene. Despite overall strong aeolian activity during this period, relatively warm conditions [26-

28] enabled chemical weathering of exposed granite under pioneer lichens and mosses, forming a thin residual parent material layer. Subsequent vegetation succession on this layer facilitated rapid dust trapping and accumulation. The plateau' s cold, dry climate and low herbaceous vegetation significantly reduced or even halted weathering of the underlying bedrock.

TOC contents range from 0.06% to 2.14% (mean 0.66%), with higher surface contents reflecting vegetation influence. The surface (0–15 cm) shows the finest particles and highest organic carbon input, indicating strong pedogenic modification. The upward-decreasing silt/clay ratio demonstrates that surface soils, modified by plant roots, are finer-grained and more developed than basal materials.

3.3 Development Age and Climatic Context

Previous studies of aeolian sand, loess, lake cores, and lake level changes in the Qinghai Lake basin provide substantial evidence for paleoenvironmental evolution and climatic context [6,31-33]. These records indicate the early Holocene was characterized by dry-warm conditions with intense aeolian activity. The aeolian parent material in the NX profile dates to 9.71–8.67 ka, consistent with conclusions that aeolian activity in the northeastern Tibetan Plateau concentrated during the last deglaciation and early Holocene [6,34,39]. This suggests that under early Holocene dry-warm conditions, falling lake levels exposed lake beaches [32], providing abundant aeolian material for regional soil development.

The depositional hiatus at ~0.4 ka relates to both climatic and topographic factors. Lake level records show rising trends during 7.5–2.5 ka [31], indicating relatively warm-moist conditions that limited dust release and reduced deposition rates [33]. Additionally, strong topographic winds may have inhibited dust preservation. High-density OSL studies have revealed widespread depositional hiatuses in aeolian deposits across the northeastern Tibetan Plateau [2,6,39,41], confirming that this hiatus is not an isolated phenomenon.

4 Conclusions

(1) OSL dating demonstrates that the NX soil profile developed during the early Holocene, with ages concentrated at 10.02–8.67 ka. The development timing of soil parent material corresponds closely with periods of intense aeolian activity in the basin, representing products of dry-warm climatic conditions.

(2) Provenance analysis reveals that the basal parent material formed through in-situ weathering of bedrock, while the upper portion developed through aeolian dust accretion, representing a mixed parent material development pattern combining early residual weathering with later aeolian addition. This mixed development process likely occurred throughout the Holocene and continues today, though verification requires investigation of additional profiles.

(3) The entire profile exhibits weak chemical weathering and low soil development degree, consistent with the cold, arid climate of the northeastern Tibetan Plateau that limits chemical weathering intensity and soil development.

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Note: Figure translations are in progress. See original paper for figures.