Soil evolution along an alluvial-loess transect in the Herat Plain, western Afghanistan Postprint

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Abstract

Afghanistan is located in the Eurasian loess belt, yet little information exists on soils in the region. Loess covers the Herat Plain in western Herat City, Afghanistan. Despite diverse landforms and parent materials, no information is available on soil and landform evolution in this area. This study identified soils along a transect of different landforms in the Herat Plain and determined the role of geomorphic processes on soil and landform evolution. Five pedons were sampled from an alluvial fan, a depression between the alluvial fan and piedmont plain, saline and non-saline piedmont plains, and the flood plain of the Hariroud River. Physical-chemical properties, mineralogy, and micromorphology were determined. Results showed that soil parent material in the piedmont plain is loess, whereas in the flood plain it is a combination of loess and river alluvial sediments. Calcification, lessivage, salinization, and gleization are the most important pedogenic processes. Calcification and lessivage appear to result from a wetter climate during the late Quaternary, whereas present topography causes gleization and salinization. Clay coatings on carbonate nodules and iron nodules are abundant pedofeatures in the Btk (argillic-calcic) horizon. Iron oxide nodules are common in flood plain soils. Palygorskite formation in both alluvial- and loess-derived soils implies the onset of aridity and increasing environmental aridity in the region. It appears that after formation of a well-developed paleosol on the alluvial fan under a more humid past climate, the piedmont plain was covered by loess deposits, and calcification, gleization, and salinization caused formation of weakly developed surficial soils. This study highlights the role of late Quaternary climatic changes on landform and soil evolution in western Afghanistan.

Full Text

Preamble

Soil Evolution Along an Alluvial-Loess Transect in the Herat Plain, Western Afghanistan

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Abstract: Afghanistan is located in the Eurasian loess belt, yet little information exists on soils in the region. Loess covers the Herat Plain in western Herat City, Afghanistan. Despite diverse landforms and parent materials, no information is available on soil and landform evolution in this area. This study identified soils along a transect of different landforms in the Herat Plain and determined the role of geomorphic processes on soil and landform evolution. Five pedons were sampled from an alluvial fan, a depression between the alluvial fan and piedmont plain, saline and non-saline piedmont plains, and the flood plain of the Hariroud River. Physical-chemical properties, mineralogy, and micromorphology were determined. Results showed that soil parent material in the piedmont plain is loess, whereas in the flood plain it is a combination of loess and river alluvial sediments. Calcification, lessivage, salinization, and gleization are the most important pedogenic processes. Calcification and lessivage appear to result from a wetter climate during the late Quaternary, whereas present topography causes gleization and salinization. Clay coatings on carbonate nodules and iron nodules are abundant pedofeatures in the Btk (argillic-calcic) horizon. Iron oxide nodules are common in flood plain soils. Palygorskite formation in both alluvial- and loess-derived soils implies the onset of aridity and increasing environmental aridity in the region. It appears that after formation of a well-developed paleosol on the alluvial fan under a more humid past climate, the piedmont plain was covered by loess deposits, and calcification, gleization, and salinization caused formation of weakly developed surficial soils. This study highlights the role of late Quaternary climatic changes on landform and soil evolution in western Afghanistan.

Keywords: alluvial fan; loess-derived soils; paleosol; gleization; Hariroud River

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1 Introduction

Afghanistan in western Asia is a landlocked country bordered by the Hindu Kush and Himalaya mountains in the east and the deserts of Iran in the west (Ellicott and Gall, 2003; Ahmadi, 2021). Late Cenozoic tectonic movements and uplift of the Hindu Kush and Himalaya mountains, combined with Quaternary climatic changes, resulted in remarkable landscape diversity. Complex patterns of mountain slopes, valleys, and plains created different bioclimatic regions and associated soils in Afghanistan (Salem and Hole, 1969; Ellicott and Gall, 2003; Rahmani, 2014; Ahmadi, 2021).

Salem and Hole (1969, 1973) studied soil formation factors and physical-chemical properties of major soil groups in eastern and southern Afghanistan, concluding that alluvium, colluvium, and loess deposits are the main parent materials. Rahmani (2014) prepared the first digital soil map for six northern provinces of Afghanistan using artificial neural networks and geostatistical approaches. Similarly, Wali et al. (2021) studied soils in Khost Province, southeastern Afghanistan, developing the first digital map for the region. They found that Khost Province soils are Entisols, Aridisols, and Inceptisols. The main soils in Afghanistan are Entisols, Aridisols, Inceptisols, Alfisols, and Mollisols, with the most developed soils occurring in the eastern part of the country, affected by summer monsoon rainfalls (Ahmadi, 2021).

Loess deposits and associated soils in northern Afghanistan have been investigated by several authors. Soils developed in calcareous loess in the Kunduz region of northern Afghanistan are young (Bal and Buursink, 1976). Shroder et al. (2011) investigated collapse and failure of loess deposits in the Badakhshan region, northeastern Afghanistan, finding these processes were controlled by moisture content, structure, and composition of loess deposits as well as slope of the underlying bedrock.

Based on remote sensing techniques, Evenstar et al. (2018) studied landscape evolution in southern Afghanistan, finding it is chiefly controlled by Quaternary climatic changes. They also found that terraces of the Sistan paleolake correlate well with glacial-interglacial cycles over the last 800 ka. Li et al. (2019) studied relationships between atmospheric patterns, dust activity, and loess deposition in the Afghan-Tajik Basin, finding that differences in air surface pressure between the Caspian Sea and Hindu Kush Mountains controlled dust deposition in the basin during the Quaternary.

Few geomorphological and pedological studies to date have relied mainly on remote sensing techniques without field survey, due to conflicts and socio-political issues. Thus, this study aimed to: (1) identify soils along a topographic transect from alluvial fans to the Hariroud River floodplain in the Herat Plain; (2) determine the role of geomorphic processes on soil and landform evolution; and (3) compare soil status in the study area with similar regions worldwide.

2.1 Study Area

The Herat Plain is located west of Herat City, Afghanistan (Fig. 1 [Figure 1: see original paper]). The Herat Plain in western Afghanistan has extensive agricultural lands, especially around the Hariroud River. The Herat-Frah region is an extension of the Iranian Plateau, consisting of mountain ranges and low hills drained by the Hariroud and Khashroud rivers (Dupre, 1980). Although Paleozoic crystalline and metamorphic rocks with Mesozoic sedimentary deposits (e.g., limestone and sandstone) are the dominant lithologies (Dupree, 1980), most of the region's surface is covered by late Pleistocene loess (Fig. 1b), though alluvium deposits are exposed adjacent to mountains and river banks of the Hariroud River (Bohannon and Lindsay, 2007).

The climate is arid, with mean annual precipitation (MAP) of roughly 210 mm and average annual temperature of about 16.1℃ (Dupree, 1980; Ellicot and Galls, 2003). Rainfall pattern is strongly seasonal, occurring mainly during the cold season. Southwest Asia's climate is influenced by three major systems: the Siberian High, Subtropical High, and Mediterranean Depression, with the latter being the rainfall source during cold seasons (Dupree, 1980; Cullen, 2005). However, the summer Indian monsoon occasionally affects southern and eastern parts of the country (Dupree, 1980).

The soil temperature regime is thermic, and the soil moisture regime is aridic, though areas along water sources may be aquic due to saturation from surface (episaturation) or groundwater (endosaturation).

2.2 Landform and Sampling

Based on the basin and range geomorphic structure, we selected a transect from the Sepidkuh Mountains to the Hariroud River, containing a piedmont, piedmont plain, and floodplain (Fig. 1a). An alluvial fan (Af) extends across the piedmont of the Sepidkuh Mountains. A small depression at the junction of the alluvial fan and piedmont plain accumulates runoff from the alluvial fan, causing temporary ponding and soil saturation. The piedmont plain comprises two different geomorphic surfaces: saline (PP1) and non-saline (PP2) units (Figs. 1a and 2). PP2 is located between the seasonal Karabar River and Hariroud River, where hydrological gradient from a high groundwater table creates aquic conditions. The Hariroud River floodplain is the final landform on the studied transect (Fig. 1a).

Five representative pedons (one per landform) were excavated and described using Schoeneberger et al. (2012) criteria and classified (Soil Survey Staff, 2014). Both bulk and undisturbed samples were collected from genetic horizons for laboratory analyses.

2.3.1 Physical and Chemical Analyses

Soil samples were air-dried and passed through a 2-mm sieve. Soil color of dried <2 mm fraction was determined under natural light using Munsell color charts. Redness rate (RR) values were calculated from dry color using the equation proposed by Torrent and Barrón (1993):

RR = ((10–H) × C)/V, where H is converted Munsell hue (figure preceding YR (yellow-red)), and C and V are chroma and value numbers, respectively. Hematite is a very strong pigmenting agent in soils; therefore, RR usually correlates with hematite content (Torrent and Barrón, 1993; Bech et al., 1997).

pH was measured in saturated paste, and electrical conductivity (EC) in saturation extract (Rhoades, 1996; Thomas, 1996). Calcium carbonate equivalent (CCE) was determined by acid neutralization (Allison, 1960), and organic carbon (OC) by Walkley-Black wet digestion (Nelson and Sommers, 1982). Pedogenic iron (Fed) was extracted by citrate-dithionate (Mehra and Jackson, 1960) and measured by atomic spectrometry. Particle size distribution was determined by hydrometer method (Gee and Bauder, 1986).

2.3.2 Mineralogy and Micromorphology Analyses

For clay mineralogical analysis, samples were washed with distilled water to remove soluble salts, then treated with sodium acetate-acetic acid buffer (pH 5.0) in a water bath at 95℃ to react and destroy carbonates. Organic matter and manganese oxide were removed by 30% H2O2, and iron oxides by dithionate-citrate-bicarbonate method (Mehra and Jackson, 1960). Clay fraction was separated by centrifuge according to Kittrik and Hope (1963), and clay particles were saturated with MgCl2 and KCl solutions. Two slides of oriented clay saturated with Mg and K were prepared. Mg-saturated samples were solvated with ethylene glycol (Mg-EG), and K-saturated samples heated to 550℃ for 2 h (K-550). X-ray diffraction (XRD) patterns were obtained using a Siemens D5000 diffractometer with monochromator and Cu-Kα radiation (30 mA and 40 kV). Clay minerals were identified according to Moore and Reynolds (1997) and Dixon and Schulze (2002). Thin sections were prepared using standard methods, and micromorphological descriptions followed Stoops (2003) and interpretations from Stoops et al. (2018).

3 Results

Soil-landform relationships for the transect and physical-chemical properties are presented in Figure 2 [Figure 2: see original paper] and Table 1 , respectively.

3.1 Parent Materials of the Soils

Based on particle size distribution (Table 1) and landform positions (Figs. 1a and 2), soils developed on three different parent materials: coarse alluvium within the alluvial fan (Af surface), loess deposits in the piedmont plain (PP1 and PP2 surfaces), and a combination of loess and fluvial sediments in the floodplain (Fp surface).

Alluvial fan deposits line the front of the Sepidkuh Mountains toward the Herat Plain (Fig. 1a). Fan deposits are generally coarse-grained and poorly sorted, resulting from depositional events during unstable landscape phases (Blair and McPherson, 2009). Pedon 1 in the alluvial fan contains high gravel contents (45%–73%), with sand as the dominant particle size (40%–77%) in the fine earth fraction (Table 1).

According to the geological map (Fig. 1b), late Quaternary loess deposits cover the piedmont plain. Silt dominates pedons 2 and 3, reaching up to 72% in the <2 mm fraction (Table 1). Sand content in the Az horizon (Fig. 2) of pedon 2 is 59%, considerably higher than underlying horizons, apparently due to transportation from the adjoining alluvial fan. Pedon 4 also formed on loess deposits, characterized by low sand content. However, silt decreases in this soil due to increased clay fraction, likely from changes in depositional setting. In the floodplain, sand content is distinctly higher than in pedons 4 and 5, indicating mixing of loess and floodplain sediments.

To separate alluvial and loess-derived soils, we calculated sand/silt+clay ratios. As illustrated in Figure 3 [Figure 3: see original paper], values in loess-rich pedons (pedons 2, 3, and 4) are about 0.2, except for the A horizon of pedon 2. The higher ratio in this horizon results from surface runoff processes from the upslope alluvial fan. The ratio is highest in pedon 1, containing more sand than other pedons due to its geomorphic position.

3.2 Morphological and Physical-Chemical Properties of the Soils

In pedon 1, we recognized sequences of lithologic discontinuities based on depth variations in amount and size of coarse fragments (Table 1 and Fig. 3). Pedogenic processes created a relatively thick (35 cm) argillic-calcic horizon (Btk) with modest clay increase relative to the A horizon. Secondary carbonate accumulation occurred both as laminations on coarse fragment bottoms and as soft masses in the fine earth fraction. In BC horizons, secondary carbonates accumulated under clasts as carbonate pendants. These correspond to stage II of Machette's (1985) morphogenetic model in pedon 1's lower parts. Carbonate content in pedon 1 varies narrowly between 13.0% and 15.0% (Table 1), with the highest content in the Btk horizon corresponding to the highest clay content. Argillic horizon development is generally time- and climate-dependent (Birkeland, 1999; Ebeling et al., 2016; Bayat et al., 2017b); thus, pedon 1's argillic horizon indicates long-term landform stability and pedogenesis.

Maximum RR values occur in pedon 1's surface layers (Table 1). As RR values strongly correlate with soil hematite content, these suggest hematite formation under aerobic conditions and high soil temperature (Schwertmann, 1993; Torrent and Barrón, 1993).

Pedon 2 was affected by runoff and episaturation (surface water saturation) from upslope alluvial fans. This pedon has an Az horizon with puffy features, a white salt veneer on the surface, and very high EC values (40 dS/m). The Az horizon thickness does not qualify as a diagnostic salic horizon. Episaturation also led to gleyic feature development. Sand content is 59% in the Az horizon, decreasing to 16% in underlying horizons.

Pedon 3, a loess-derived soil, was affected by soluble salts due to its proximity to the depression. EC values are 49 dS/m in the Az horizon, decreasing to 8 dS/m in subsurface layers. This Az horizon, like pedon 2's, is not a diagnostic salic horizon due to low thickness. Secondary carbonates occur as thin filaments. Despite visible secondary carbonates and Bk horizon designation, they are less than 5% by volume and do not meet diagnostic calcic horizon criteria.

Pedon 4 characteristics in PP2 are distinctly different from other loessial pedons. First, groundwater table fluctuations induced gleyic properties (chroma<2 and mottling). Second, EC is considerably lower than in pedons 2 and 3 because this pedon was not affected by saline water from upper surfaces. The water table may be charged by both the Hariroud River and seasonal Karabar River. The difference can be attributed to high clay and low silt content, as well as silt-to-clay transformation.

Pedon 5 is located in the Hariroud River floodplain. Based on particle size distribution, mixing of alluvial materials and loess has occurred. Gleyic and redoximorphic features developed in subsurface horizons. The most important pedogenic processes are structure formation and gleization.

3.3 Free Iron Oxides in the Soils

Free iron oxides or dithionite-extractable iron (Fed) indicate crystalline and amorphous iron oxides (hydroxides) and iron bound to organic materials (Bech et al., 1997; Ortiz et al., 2002; Schaetzl and Thompson, 2015). Fed content is affected by parent material nature and pedogenic process types. Iron oxides are generally released during pedogenesis and accumulate in fine particles (McFadden and Hendricks, 1985; Ortiz et al., 2002).

In pedon 1, Fed content varies between 3.8 and 5.0 g/kg, while other pedons show higher values, especially in gleyic horizons, reaching up to 10.5 g/kg in pedon 2's 2Bg1 horizon (Table 1). Pedon 1's Fed values were produced during aerated pedogenic conditions; these values are similar to weakly developed pedon 3 and lower than most gleyic horizons in other pedons. During gleization, reduction led to Fe release from Fe-bearing minerals and accumulation as amorphous iron (McFadden and Hendricks, 1985; Schaetzl and Thompson, 2015).

Generally, a relationship exists between Fed and clay content in soils developed on homogeneous parent materials (Najafi et al., 2019). Area soils developed on three different parent materials: alluvial (pedon 1), loess (pedons 2–4), and alluvial-loess mixture (pedon 5). The dominant process in pedon 1 is weathering under aerobic conditions, while gleization dominates other pedons. Therefore, no correlation exists between Fed content and particle sizes. As Fe commonly releases from silt and clay, the relationship between Fed and silt+clay content (Fig. 4 [Figure 4: see original paper]) indicates grouping of loessial soils together (pedons 2–4), whereas pedons 1 and 5 form separate groups. This result indicates both parent material and pedogenic process effects on Fed content.

A correlation between Fed content and soil redness is mentioned in some research (McFadden and Hendricks, 1985; Ortiz et al., 2002). However, we found no relationship between Fed content and RR values for Herat Plain soils, likely due to parent material differences and hydric pedogenic processes. Lack of correlation between Fed and RR values was also observed in soils of Southwest Barcelona, Spain (Bech et al., 1997).

3.4 Micromorphology and Clay Mineralogy of the Soils

Clay coatings on carbonate nodules and coarse particles in pedon 1's Btk horizon (Fig. 5a [Figure 5: see original paper] and b) indicate nodule crystallization prior to clay translocation. Carbonate leaching and clay translocation in calcareous materials require sub-humid climatic conditions with annual precipitation of roughly 400–600 mm (Fedoroff, 1997). Therefore, these processes indicate climatic changes in the region and the soil's polygenetic nature.

Moreover, iron nodule accumulation was observed in this horizon (Fig. 5c). In pedon 3, gypsum exists as lenticular euhedral crystals (Fig. 5d).

Thin sections of reduced horizons in pedons 4 and 5 show abundant iron nodules as well as hypocoatings and quasicoatings of iron oxides (Fig. 5e, f and g). These features indicate reduction status that led to iron nodule deposition and coatings related to weathering and iron release from minerals such as biotite during soil formation (Fig. 5g).

The Btk horizon diffractogram of pedon 1 (Fig. 6a [Figure 6: see original paper]) indicates smectite, chlorite, mica-chlorite, kaolinite, and palygorskite occurrence in the clay fraction. Based on the position and climatic conditions, palygorskite and, to some extent, smectite are likely pedogenic products. Neoformation of palygorskite in a Btk horizon in a central Iran alluvial fan occurred under arid/semi-arid and seasonal climatic conditions (Bayat et al., 2017b).

Pedon 4 and 5 clay mineralogy (Figs. 6d and e) shows higher smectite than other pedons, which can be related to silt fraction weathering and increasing clay content and smectite in the clay fraction.

In summary, soil clay mineralogy suggests that palygorskite and, to some extent, smectite are pedogenesis products, while most minerals are inherited from parent materials. Palygorskite is a magnesium-rich aluminosilicate very common in arid region soils where MAP is less than 300 mm (Singer, 1980; Neaman and Singer, 2011), because it is stable only under high Mg and Si ion concentrations with high evaporative and alkaline conditions (Singer, 1980; Kadir and Eren, 2008). Since palygorskite is only stable when MAP is less than 300 mm (Neaman and Singer, 2011), its occurrence is a consequence of aridity onset in the region after calcitic nodule and clay coating development in alluvial soils.

4.1 Soil and Landscape Evolution of the Herat Plain

Alluvial fan sedimentation, loess deposition, and Hariroud River fluvial activities are the main geomorphological processes in the Herat Plain, affecting landscape and soil evolution.

In the Herat Plain, alluvial sediments cover Sepidkuh Mountain slopes as several alluvial fans (Figs. 1a and 2). As tectonic movements are the primary control of fan aggradation (Blair and McPherson, 2009; Bowman, 2019), these sediments were produced during different phases of landscape instability probably induced by tectonic movements (Blair and McPherson, 2009) and climatic oscillations. No data are available for fan deposition and abandonment timing in western Afghanistan. However, studies in eastern Iran revealed intense fan aggradation between 60 and 40 ka in the region (Walker and Fattahi, 2011; Rashidi et al., 2021). On the other hand, loess deposits filled the region's plains (Bohanon and Lindsay, 2007). Afghanistan has extensive loess deposits up to 50 m thick (Bal and Buursink, 1976). The Karakum Desert of Turkmenistan and Amu Darya River alluvial plains are mentioned as dust sources for Afghan loess deposits (Shroder et al., 2011). Loess deposition in Afghanistan generally occurred during the late Pleistocene (Bohannon and Lindsay, 2007) and especially during the last glacial maximum (LGM) (Salem and Hole, 1969). Luminescence dating analyses showed loess sediments in northeastern Iran and near the study area also deposited during LGM until 12 ka (Karimi et al., 2011), then secondary carbonates formed under cool, moist early/mid-Holocene conditions (Bayat et al., 2017a). As loess-derived soil morphology in the Herat Plain is similar to loessic soils in northeastern Iran (Karimi et al., 2011), these soils probably developed along a similar trajectory.

Calcification, lessivage, and gleization are the main pedogenic processes, resulting in different soils across landforms. The most developed soil formed in the alluvial fan's middle part (pedon 1), and the Btk horizon is a remnant of a past humid climate. Generally, Btk horizon existence in calcareous materials of arid regions requires at least three pedogenic sequences: decarbonation, clay production and translocation, and recarbonation (Gvirtzman and Wieder, 2001; Bayat et al., 2017a, 2018). Unlike Btk horizons in Mediterranean soils of Spain (Ortiz et al., 2002) and alluvial soils of central Iran (Bayat et al., 2017a, 2018), which exhibit recarbonation impacts, the Herat Plain's Btk horizon formed without recarbonation, with clay coatings on carbonate nodules as shown by micromorphology analysis (Fig. 1a and b). Clay coatings form under long-term warm and sub-humid/humid climate with strong seasonal rainfall, allowing clay suspension formation and downward particle movement by percolating water during moist seasons and particle precipitation during dry seasons (Fedroff, 1997; Scarciglia et al., 2006; Ebeling et al., 2016). These processes mainly occurred during warm, moist interglacial stages in Mediterranean mid-latitudes (Fedroff, 1997; Scarciglia et al., 2006). Calcification in calcareous soils of mid-latitudes requires MAP between 350 and 450 mm under semi-arid, seasonal climate (Gvirtzman and Wieder, 2001). Therefore, these processes together with illuviation of pedogenic iron in alluvial soils suggest soils experienced at least two periods with more available moisture during the late Quaternary. Clay coatings on carbonate nodules reveal a shift from semi-arid climate (during carbonation) to sub-humid (during clay illuviation) in the Herat Plain. More studies are needed on timing and magnitude of these episodes.

Loess deposits in the Herat Plain can be considered part of a loess belt extending from northeastern Iran (Karimi et al., 2011) to southern Tajikistan (Li et al., 2019). These deposits and associated soils formed in response to atmospheric circulation pattern and strength changes during the late Quaternary (Bayat et al., 2017b; Li et al., 2019). Although loess deposits in the Herat Plain are strongly affected by gleization and redoximorphic processes, calcic horizons in piedmont-plain soils contain paleoclimatic signals. Loess deposition is generally favored by reduced dust-bearing wind velocity, mostly under windy, arid conditions (Karimi et al., 2011; Rhoton and Makewich, 2017). Pedogenic processes modify loess deposits in several ways. Loess deposit modification and calcic horizon formation in the study area's piedmont plain provide strong evidence for post-depositional processes under a moister environment than today. Stable isotopic signals in pedogenic carbonates of northeastern Iran revealed that secondary carbonates in regional loess deposits precipitated in a mixed C3–C4 plant ecosystem and cooler environment (Bayat et al., 2017a).

Authigenic clay minerals can also provide paleoclimatic insights (Galán and Pozo, 2011; Bayat et al., 2017b). Palygorskite, a fibrous clay mineral and Mg-rich aluminosilicate, is very abundant in arid region soils (Churchman and Velde, 2019). Two main palygorskite sources exist in arid soils: inheritance from parent material and autogenesis by neoformation from soil solution or transformation from precursor minerals (Galán and Pozo, 2011). Because palygorskite occurs in both alluvial and loessic soils of the Herat Plain (Table 2), we infer that mineral crystallization in the region is independent of parent material type and formed by authigenic processes. Although saline-alkaline groundwater (especially temporary groundwater) can favor palygorskite crystallization (Churchman and Velde, 2019), the mineral was not detected in Heart Plain gley soils. Thus, mineral formation is controlled by climatic factors. Palygorskite is very sensitive to mean annual precipitation, stable only when MAP is less than 300 mm (Neaman and Singer, 2004). Hence, palygorskite stability in regional soils is evidence of alkaline acidity and high Mg content, implying aridity onset and increasing environmental aridity trends in the Herat Plain.

Based on geomorphological processes and soil formation, we suggest a conceptual sequence for soil-landscape evolution in the Herat Plain during the late Quaternary: (1) alluvial fan formation and development of a well-developed paleosol in a climatic setting favorable for weathering and clay-carbonate translocation, leading to Btk horizon formation; (2) loess accumulation in the Herat Plain and calcic horizon formation during more humid times, likely in the Holocene; and (3) surface salinization and gleization leading to gleyic property development and salic horizon formation.

5 Conclusions

Alluvial and loess-derived soils of the Herat Plain show different morphological and physical-chemical properties in response to parent material diversity, age, and drainage conditions. All studied soils are calcareous. Calcification, lessivage, and gleization are the most important soil-forming processes. Gleization strongly affected Herat Plain soils through episaturation in depression geomorphic surfaces and endosaturation in non-saline piedmont plain and floodplain surfaces. The Btk horizon is characterized by clay coatings on carbonate nodules, evidence of clay and Fed illuviation, and iron nodule formation. Several lines of evidence demonstrate late Quaternary climatic changes in the Herat Plain: (1) Btk horizon development in alluvial soils; (2) loess deposition; (3) calcic horizon formation in loessic soils; and (4) palygorskite formation and preservation in both alluvial and loessic soils. Palygorskite clay mineral crystallization and preservation in both alluvial- and loess-derived soils imply aridity onset and increasing environmental aridity trends.

Finally, as Herat Plain soils provide paleoclimatic proxies, we strongly recommend more detailed studies, especially numerical dating of soils and landforms, for Afghanistan, where soil, landscape, and paleoclimate data are very limited.

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