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Abstract

Paleosols in Iran have received less attention than modern soils, although Quaternary deposits and exposures therein are widespread. The chapter gives a short introduction into the general nature of buried and relict paleosols and on methodological aspects how to recognize, characterize and date paleosols. Examples are given for Pre-quaternary and Quaternary paleosols in Iran. The focus is on paleosols in loess-soil sequences in Northern Iran, which have been studied in more detail. These loess exposures contain paleosols of various development degrees separated by layers of more or less unweathered sediment. Strongly developed argillic horizons of paleo-Luvisols occur as well as very weakly developed brown horizons reflecting syngenetic soil formation. The loess-paleosol sequences are excellent geological archives of climate change, where paleosols mark periods of increased humidity and layers of unweathered loess dry phases. The paleosols most probably correlate with interglacial and interstadial periods of the last glacial cycles suggesting that climate change in Northern Iran was in phase with well-known cycles recorded in the temperate zone of the northern hemisphere. The high potential of paleosols as stratigraphic markers and geological archives of climate change and landscape evolution in Iran is still widely unchallenged.

Keywords

Nature of paleosols • Quaternary • Loess • Pedostratigraphy • Climate archive

8.1 Introduction

While the state of knowledge on modern soils of Iran is advanced, comparatively little information is available on the distribution and properties of paleosols in Iran and adjacent countries. Paleosols are soils formed at land surfaces of the geological past (Ruhe 1956). They may represent excellent stratigraphic markers in geological context and provide important information on paleo-environmental conditions, because the constellation of soil forming factors

such as climate, vegetation or topography can often be deduced from paleosol properties. The formation and preservation of paleosols are closely linked to changes in geomorphodynamic conditions, i.e., changes between stable and unstable land surfaces, providing sufficient time for soil formation on the one hand and burial under protecting sediment covers on the other hand. These changes are often driven by climate change hence sediment-soil sequences may provide excellent records of climate change. Here, we give a brief overview on occurrences of paleosols in Iran in order to demonstrate their general properties and high potential as indicators of climate change and landscape evolution. The focus is on paleosols derived from Quaternary loess and loess-like sediments, i.e., deposits of eolian dust or those showing similar sediment properties including silt as the dominant grain size, homogenous structure, lack

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of bedding, forming stable walls, including carbonate and fossils of land snails etc. Considerable progress has been made in the study of these deposits in Iran during the last decades. Loess forms thick deposits in the North, in particular in the Iranian Loess Plateau and along the Alborz Mountains northern foothills. Other deposits of loess are patchy or consist of dust additions in thin cover beds. Loess-like sediments cover large areas in the Central Iranian highlands for instance in depressions of large basins. Besides representing detailed terrestrial archives of climate and past environmental change, loess itself and the loess-derived modern and ancient soils are of large value for land use, related to the high storage capacity for plant-available water, high nutrient contents and good workability. Loess-derived soils in Iran thus belong to the most fertile lands of the country, which depending on climate conditions and topography are used for grazing, rain-fed or irrigated agriculture as well as forestry as perfectly demonstrated in Golestan Province.

8.2 Nature of Paleosols

The general properties, definition and classification of paleosols have been dealt with in detail previously (e.g., Catt 1990; Yaalon 1995; Retallack 2001; Mason and Jacobs 2007), and a comprehensive discussion would be beyond this chapter. The following remarks shall provide general background information on the descriptions below. Paleosols have either been buried under younger sediments (buried or fossil soils), remained at the land surface during periods of climate change (relict soils) or have been partly exhumed after erosion of overlying sediments. Buried paleosols can easily be distinguished from the modern soil if sediment strata with limited pedogenetic overprint are separating them, which is often the case in unconsolidated sediments and sediment-soil sequences of the Quaternary.

While close similarities between the modern soil and buried paleosols may exist, as is often the case for soils developed from similar parent materials during the present and previous interglacials, there may still be some general differences. Firstly, diagenetic processes including mineralization of organic matter, compaction and loss of soil structure, iron loss by microbial reduction, color changes due to dehydration/recrystallization of hydrous pedogenic minerals, or recalcification from overlying strata may have altered the buried soil. Post-burial alteration may even result in lithification, which is often encountered in Pre-Quaternary paleosols. Secondly, although not necessarily apparent in the field, buried soils may have experienced several phases of soil formation at former land surfaces. Sediment covers on top of the paleosol could have been eroded or the cover was too thin to substantially protect the buried soils from later

soil formation. In these cases, welded or composite paleosols may have formed over one or multiple cycles of climate change. These paleosols can attain several meters in thickness. Thick buried or relict soils may also form by soil formation under more or less continuous dust input or deposition of fluvial deposits. These soils are called syngenetic, accretionary or upbuilding (e.g. Palmer 2007). It is difficult or sometimes impossible to define, when their formation started or ended, in contrast to paleosols formed by top-down pedogenesis on a pristine or pre-weathered substrate. Thirdly, past periods of soil erosion may have considerably truncated the soils at former land surfaces. Paleosols observed today often consist of Bt or Bk horizons, which are more resistant against erosion than top soils. Preservation of complete profiles is the exception rather than the rule and the classification of paleosols is often limited to the horizon level. Fourthly, the climatic conditions and related vegetation and fauna, as well as the paleosols themselves may not have modern analogues in the area of interest, which often holds for interstadial soils formed during short phases of climate amelioration within glacial stages. Examples are the Tundra gley of Central European loess-soil sequences formed above permafrost or the weakly developed but thick accretionary CBb horizons in Iranian loesses. Finally, the duration of paleosol formation may considerably differ from that of modern soils.

Relict soils contain features that have not formed under present-day climatic conditions, implying that they experienced at least one significant change in climate, hence can be defined as polygenetic. Identification of relict soils may be difficult, because (i) morphological imprints of past climates will only be recognizable if the diversity of morphological features in modern soils is well known and (ii) the onset of modern soil formation is often difficult to determine if the timing and magnitude of climate change are not well known. Exhumed paleosols represent a special type of relict soils. The time of exhumation can be deduced if the soil can be traced below layers of younger sediments and if deposition of these sediments can be dated using geochronological methods.

8.3 Recognition, Characterization and Geochronological Dating of Paleosols

In the field, paleosols can be distinguished from sediments by changes in color, intensity of hydromorphic mottling, grain size, development of soil structure, presence of root traces or krotovina, and pedogenic enrichments in soluble salts, gypsum, carbonates, iron and manganese hydroxides or silicate clay. These changes are sometimes subtle and in particular weakly developed paleosols are often not readily

identified in the field. It is of high importance to carefully clean field exposures and to provide detailed field descriptions using pedological field manuals or those suggested for the description of paleosols (e.g., Catt 1990). An important observation is, whether the soil horizon identified consists of redeposited pre-weathered soil material, i.e., can be considered a soil sediment, or if it has formed in situ. Sharp lower contacts with underlying strata provide evidence of soil sediments, but pedogenic processes such as carbonate leaching and reprecipitation may result also in sharp boundaries between Bw or Bt horizons and an underlying Bk. Close inspection of carefully cleaned profiles will help to avoid misinterpretations. Sampling in the field should be as detailed as possible. High-resolution sampling along vertical columns is the basis for detecting sedimentary discontinuities within paleosol horizons and abrupt or gradual transitions from soil horizons to sandwiching sediment layers. Laboratory analyses may involve the whole spectrum of methods available to the soil scientist. However, care has to be taken in interpreting the data, because post-burial alterations may have strongly changed the properties acquired during soil formation. In the past two decades, the use of rock magnetism and geochemical ratios has proven beneficial for characterizing the development degrees of paleosols and stable isotope ratios of carbon and oxygen used to infer information on paleoclimate. In order to reconstruct pedogenic processes, the use of micromorphology is indispensable.

Several geochronological methods are available to determine the age of paleosols and the duration of former soil forming phases. The latter can be assessed if buried paleosol horizons can be sandwiched, i.e., if age estimates can be provided for over- and underlying strata. This approach implies that the time determined for parent material deposition and burial of the paleosol is identical to the onset and end of soil formation, respectively. In case of accretionary soils, this assumption is not valid. In case of top-down pedogenesis, it has to be considered that the time of sediment accumulation within the C horizon can considerably differ from that of the substrate in which the paleosol formed. The different dating techniques have various limitations. Down to an age of about 40,000 years before the present day (40 ka), radiocarbon dating on bulk samples containing humus, or on pieces of charcoal, bone and pollen extracted from soil horizons is feasible. Age estimates down to about 250 ka or even older may be gained by luminescence dating of the time of sediment deposition. This approach has been used to date loess-soil sequences in Northern Iran (Frechen et al. 2009; Karimi et al. 2011; Lauer et al. 2017a, b).

Other approaches are to apply paleomagnetic techniques including polarity changes or intensity variations of the earth magnetic field or to wiggle-match fluctuations in climate proxies such as soil color, pedogenic iron etc. recorded in

sediment-soil sequences with climate proxy data established for well-dated geological archives of paleo-environmental change including ice cores, marine sediments or long limnic records. Both techniques, however, yield relative age estimates and must be combined with numerical dating, otherwise it is impossible to provide reliable age estimates, because complete terrestrial records are rarely to be found and stratigraphic gaps are the rule rather than the exception.

The paleosols can be used as stratigraphic markers to correlate sediment-soil sequences of different eolian, fluvial or colluvial deposits or for correlation with climatic phases known from other climate archives. The legitimate assumption of this pedostratigraphical approach is that weakly developed paleosols—such as Ab, CBb and Bwb horizons in Iranian loess sequences—were often formed during interstadial periods, whereas the well-developed ones (e.g., BA**t**b and B**t**b horizons) formed during interglacials of the climate record. In loess covered areas of Northern Iran, where a B**t** horizon is expressed in the modern soil, the first strongly developed buried B**t** horizon can most probably be correlated with the last interglacial soil, a terrestrial equivalent to Marine Isotope Stage (MIS) 5e. The chronostratigraphic position of the second, third and following B**t**b may represent the penultimate and older interglacials, but age control for this assumption is still lacking. The counting of B**t**b-horizons from the top can only provide a first estimate, since loess deposits often represent discontinuous sediment records due to erosional discontinuities.

8.4 Pre-Quaternary Paleosols in Iran

During the Devonian, large plants began to colonize the continents and roots and root-like structures became more common. If the presence of large plants is considered a prerequisite for soil formation and root traces a key characteristic of soils, paleosols have formed in terrestrial systems since post-silurian times. Using the wider concept of paleosols of Retallack (2001), even Precambrian deposits may contain paleosols. Pre-Quaternary rocks of Iran are also known to include paleosols. For example, Aharipour et al. (2010) described red calcretes, yellowish calcretes, or dolocretes formed in clastic sequences of the lower Devonian Padeha Formation in the Eastern Alborz Mountains. The authors identified alluvial fan, distal fan, and palustrine/lacustrine environments, in which the paleosols formed. Moussavi-Harami et al. (2009) report on several calcrete horizons in Lower Cretaceous fluvial deposits of the Shurijeh formation in the KopehDagh range, which at least partly have a pedogenic origin. In a study of the Miocene Upper Red formation in the Southern Alborz, Ballato et al. (2010) sampled pedogenic carbonates to study changes in stable carbon and oxygen isotopes as indicators of climate change. Recently, a thin

red paleosol (10–15 cm) has been described in the Chehel-Kaman Formation of the Central Kopet-Dagh basin, which probably delineates the Paleocene/Eocene boundary (Rivandi et al. 2013). These examples may illustrate that Pre-Quaternary paleosols can be important stratigraphic markers and paleo-environmental indicators in terrestrial sequences of Iran. They may be difficult to notice in the field, because, after burial, extensive diagenetic alteration may have taken place (e.g., Driese 2009).

8.5 Quaternary Paleosols in Iran

In general, paleosols can be expected in all kinds of unconsolidated Quaternary sediments, which experienced subaerial exposure and stable geomorphodynamic conditions for a sufficiently long period of time to promote soil formation. The preservation of paleosols is promoted in low-energy depositional environments such as floodplains or on elevated land terraces and plateaus where eolian or low-energy fluvial deposition occurred but fluvial erosion,

mass wasting or eolian deflation was limited. If conditions for soil preservation and sediment build-up are favorable, extensive sediment-soil sequences may develop over time. This was the case for loess deposits in Northern Iran reaching several decameters in thickness and containing a large number of weakly to strongly developed paleosols.

8.5.1 Lower to Middle Pleistocene

In the Iranian loess plateau, bivalve conglomerates of the Akchagyl formation mark the final Tertiary dated to about 3 mio years ago (e.g., Forte and Cowgill 2013). The conglomerate is unconformably covered by a series of silty to clayey reddish-brown terrestrial sediments (Fig. 8.1), identified as loess and dated to the lower Pleistocene (~2.4–1.8 Ma ago) as based on palaeomagnetic data (Wang et al. 2016). These deposits show a strong overprint of soil formation and have been interpreted as a thick pedocomplex (Taheri et al. 2017). Diagenetic alteration is indicated by continuous gypsum infillings between large soil prisms and in fissures. The upper

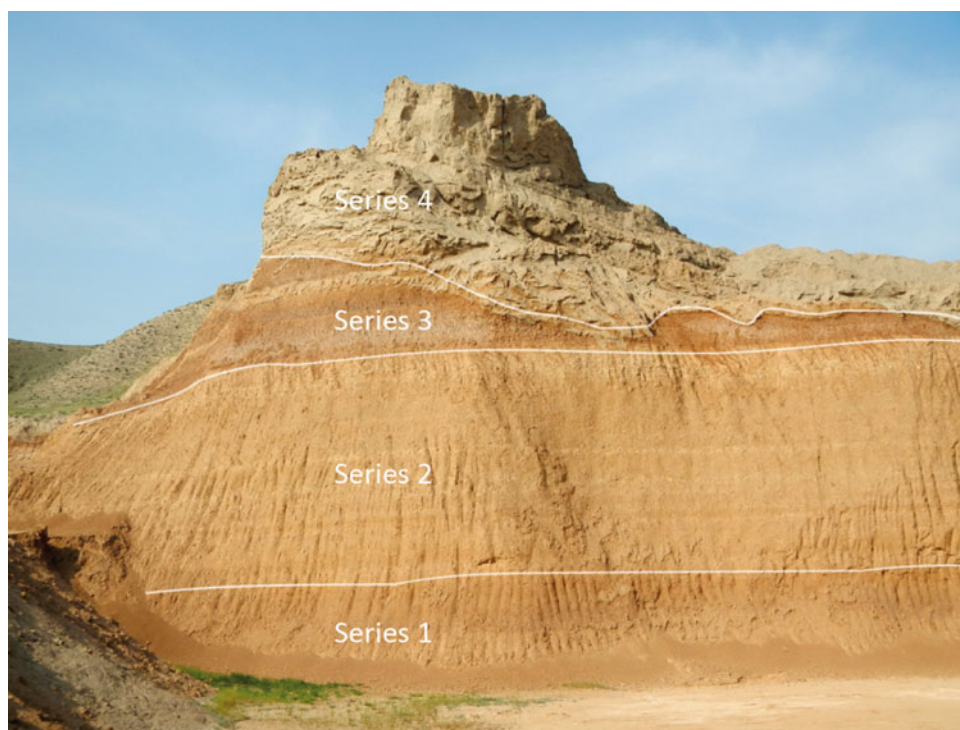


Fig. 8.1 Reddish-brown paleosols in silty to clayey deposits exposed in a limestone quarry near the town of Agh Band, where the underlying bivalve conglomerate of the Akchagyl formation (Pliocene) is exploited (not shown). In the lowest series, a comparatively thick (2 m) well-developed paleosol is visible. In series 2, the light colored sediment is intercalated by a large number of thin weakly developed paleosols which are perfectly aligned. This indicates several short periods of soil formation interrupted by phases of sediment accumulation. Toward the

top, a thick weakly developed paleosol testifies syngenetic soil formation. Series 3 consists of at least three strongly developed paleosols, the lower two being separated by a thin layer of sediment. These soils are strongly enriched in gypsum. Series 1–3 reflect changing dominance of soil formation and sediment accumulation, which could be related to varying eolian inputs. Typical loess (series 4) disconformably covers the soils of series 3. For more information on this section see Taheri et al. (2017) and Wang et al. (2016)

part (series 3 in Fig. 8.1) has an erosional upper boundary and is covered by about 10 m of loess, resembling loess of the nearby key sections of Agh Band where a middle to upper Pleistocene age was determined using luminescence dating (Frechen et al. 2009; Wang et al. 2017; Lauer et al. 2017a, b). The erosional unconformity between the red clay and overlying loess thus probably represents a long stratigraphic gap.

The lower part of several loess profiles in Northern Iran contains reddish-brown, strongly developed paleosols, which consist of Btb- or Bwb-horizons (lower series in Figs. 8.2, 8.3, and 8.4) often showing recalcification from overlying strata. These paleosols can be observed at the section at Rustamabad, located in the Sefid-Rud valley (Kehl 2010), and in several sections situated at the northern foothills of Alborz Mountains, for instance, at loess sections near Neka (Fig. 8.2; Kehl et al. 2005) and Toshan (Vlaminck et al. 2016; Lauer et al. 2017a). Little is known about these presumably middle to early Pleistocene paleosols. They are often welded and polygenetic, and if light colored sediment layers separate them, these are heavily overprinted by pedogenesis. However, it is most likely that these paleosols developed under forest covers similar to the present-day deciduous forest. In comparison with the modern soils under forest (e.g., Khormali et al. 2012), the older interglacial paleosols rarely show dark A-horizons, exhibit a stronger

development of blocky to prismatic soil structure (Fig. 8.3 left), are richer in clay and have a more reddish soil color. Interestingly, some of these old paleosols are distorted, probably resulting from tectonic activity (Fig. 8.4). Another interesting observation is that at the section at Now Deh two weakly developed brown paleosols (Bw horizons over CBk horizons) are intercalated within the loess deposit of presumably MIS 6. These paleosols provide evidence for Middle Pleistocene interstadials in Northern Iran (Kehl et al. 2005; Frechen et al. 2009). Recent evidence for two interstadials of MIS 6 in Northwestern Iran deduced from the $\delta^{18}\text{O}$ record of Lake Urmia (Stevens et al. 2012) corroborates this notion.

While tracing paleosols along exposures, separate paleosol horizons may unify to form a composite or welded paleosol. In Northern Iran, this has been observed for example on the presumably MIS 7 paleosols at the section at Now Deh (Kehl et al. 2005) and at several sections located in brickeries near the city of Gorgan. On the other hand, a single paleosol may fan out into separate horizons, as observed at the section of Rustamabad (Kehl 2010). Both phenomena render the pedostratigraphic correlation of different sections and establishment of a pedostratigraphic framework for the Lower to Middle Pleistocene difficult. As based on “counting Btb horizons from the top” and on



Fig. 8.2 Loess quarry near the town of Neka exposes several series of paleosols. In the lower half of the exposure, at least five strongly developed reddish-brown paleosols can be distinguished (series 1, ~8 m high). The slight curvature of the soils delineates former land surfaces and locally shows former incision of gullies. This sequence is capped by a dark ABt-horizon and two well-developed paleosols of dark color (series 2; ~3.5 m high). These three soils probably represent the pedocomplex of MIS 5. Equivalents of this

pedocomplex can be found in many loess exposures along the Alborz Mountains foothills, which include the sections at Neka 1, Toshan, Now Deh and Mobarakabad (Kehl et al. 2005; Shahriari et al. 2017; Vlaminck et al. 2016). The upper series (~5 m high) includes at least three weakly developed brown paleosols and the modern soil at the surface. At about 3 m below surface, the loess color changes from yellowish brown to grayish reflecting a higher intensity of pedogenic alteration toward the top



Fig. 8.3 Two paleosols in the loess exposure of Fig. 8.2. Left is a presumably Middle Pleistocene, welded paleosol of series 3 with clayey texture, prismatic structure, clay coatings and secondary calcite. Horizon boundaries as well as the lower boundary of the paleosol are difficult to identify, because the loess itself has a strong overprint by pedogenic alteration (spate is 40 cm high). On the right, the

well-developed ABw-horizon in series 2 represents an interstadial paleosol of the last Glacial (presumably MIS 5a). The sharp lower contact is caused by enrichment of underlying loess with secondary carbonate (Bk horizon). The gradual transition toward the overlying loess reflects continuously increasing dust input caused by aridification of the landscape. This loess forms the lowest member of series 3

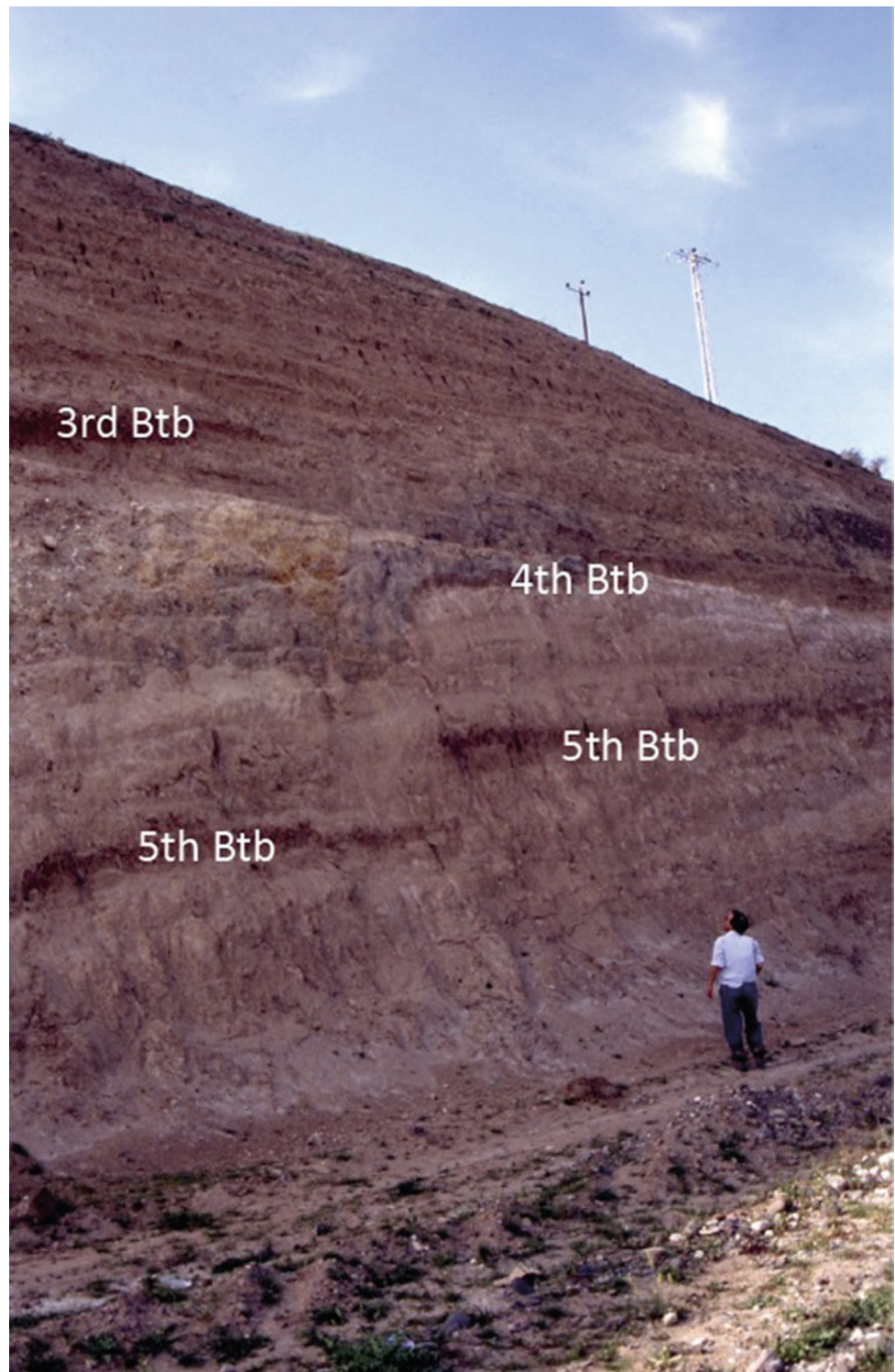
luminescence age estimates for the overlying loess deposits (Frechen et al. 2009; Lauer et al. 2017a), the Btb-horizons below the first buried Btb can be tentatively correlated with MIS 7, 9 and 11 or older interglacials. At least five interglacial soils of this type are exposed in the lower loess series near the town of Neka (Fig. 8.2), indicating, that the loess deposits along the Alborz Mountains foothills may provide a detailed stratigraphy of the Middle Pleistocene.

Observations in many exposures of alluvial fans and fluvial terraces suggest that these deposits also contain paleosols. For example, the fluvial terraces of Sefid-Rud show intercalations of gravel beds, several meters thick, with loess strata including brown paleosols (Fig. 8.5) and road cuts in the alluvial fan within the city of Tehran expose thick gravel sequences with paleosol horizons. In fluvial environments, changes between sediment accretion and erosion can be related to an intrinsic variation of channel courses. In these dynamic systems, erosion of paleosols may take place at the same time like paleosol formation. This leads to limited lateral continuity of paleosols and potentially large gaps in the stratigraphic records. Therefore, chronostratigraphic estimates for these soils are difficult.

8.5.2 Upper Pleistocene and Holocene

The Late Quaternary includes the last interglacial/glacial cycle and the Holocene, i.e., MIS 5 to MIS 1. Loess deposits formed in Northern Iran during this time are considerably thicker than those accumulated within previous interglacial/glacial cycles. The deposits contain a detailed sequence of paleosol horizons (Table 9.1), some of which can be correlated over large longitudinal distances along the loess covered northern foothills of the Alborz Mountains. The sequences start with the last interglacial or Eemian soil (MIS 5e), which consists of strongly developed ABtb horizons near the town of Neka (Fig. 8.2; Kehl 2010) or Btb horizon, as, for example, at the section at Toshan (Vlaminck et al. 2016; Lauer et al. 2017a; Fig. 8.6). Toward the top, about 3–4 m of slightly weathered loess follows in which two well-developed interstadial paleosols have been preserved. These soils consist of ABw- or Bwb-horizons over Bkbs (e.g., Fig. 8.3 right) and are clearly expressed in many loess sections. As based on luminescence age estimates and pedostratigraphic arguments, they probably formed during interstadials of MIS 5, i.e., MIS 5c and 5a, whereas intense

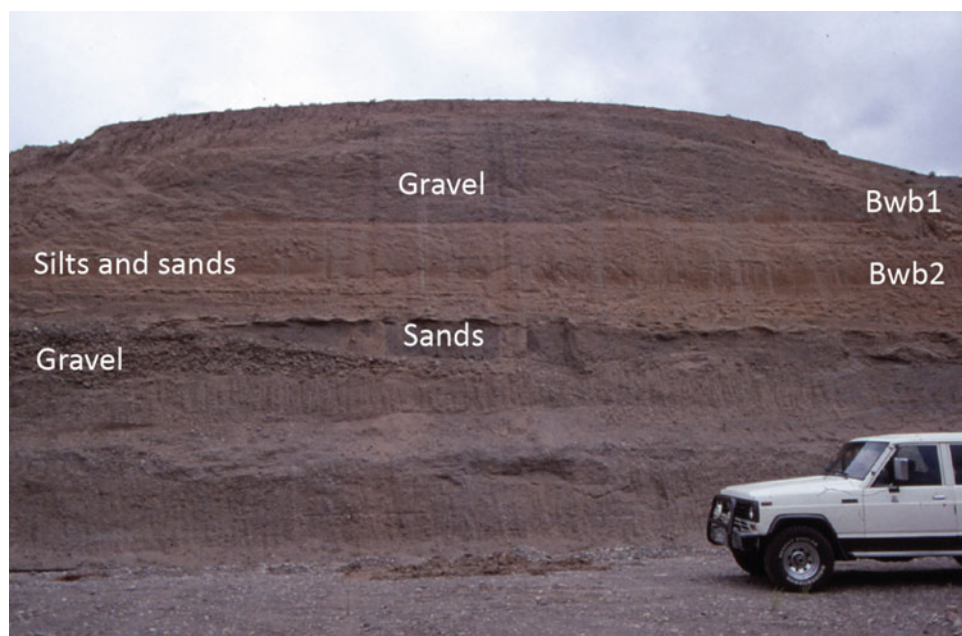
Fig. 8.4 Vertical distortion of the fifth reddish-brown paleosol (Btb) counted from the top at a road cut near the town of Rustamabad, Sefid-Rud valley. The two uppermost Btb-horizons are not shown in the picture. Most probably, the distortion was caused by tectonic activity, which also affected the silty and partly stony slope deposits overlying the paleosol. The third Btb appears to be unaffected, hence distortion occurred before formation of this soil. Reproduced from Kehl (2010, changed)



accumulation of dust took place during the stadials 5d and 5b and after MIS 5a. The three paleosols thus form a pedocomplex (Catt 1998) of MIS 5, which serves as a stratigraphic marker for correlating the loess-paleosol sequences at Neka 1 and Now Deh (Frechen et al. 2009; Kehl 2010) as well as Mobarakabad and Neka 2 (Kehl and

Khormali 2014; Ghafarpour et al. 2016; Shahriari et al. 2017). Interestingly, the upper transition from paleosol horizons into overlying loess is often gradual (Fig. 8.3 right), as clearly shown by the lithological characteristics of the section at Toshan (Fig. 8.6). This suggests that many paleosols in Northern Iranian loess were not truncated before

Fig. 8.5 Fluvial deposits exposed in the valley of Sefid-Rud River near the town of Rustamabad. In between two gravel beds, about 3 m of silty and sandy deposits are intercalated. This unit includes two brown paleosols. The upper one was truncated during accumulation of the upper gravel bed and only a thin remnant of this soil is preserved www.schweizerbart.de/9783443090241



the onset of dust accumulation. The MIS 4 loess deposit at Toshan is the most “typical loess” of this section. It shows coarse texture, low lightness values (L^*) and low redness rating (Fig. 8.6). Toward the top, two weakly developed paleosols at 3–9.5 m depth were detected in the field. In addition, the loess of MIS 3 and MIS 2 at Toshan shows a high degree of pedogenic alteration reflected by frequent calcite concretions, comparatively dark color and elevated redness ratios pointing to syngenetic soil formation during the time of dust accumulation. In the Sefid-Rud valley, sandy loess at the section at Saravan contains two well-developed Ahb-horizons formed during MIS 3 (Kehl 2010).

In Northeastern Iran, Btk horizons were identified within several loess sections (Karimi et al. 2009) possibly dating back to the last interglacial (Karimi et al. 2011). Recently, Karimi et al. (2013) demonstrated that, if taking the high amounts of gypsum and carbonates into account, magnetic susceptibility clearly increases in one of these Btk horizons compared to the parental sediments and overlying layers. The increased magnetic susceptibility of paleosol horizons may represent a valuable indicator of soil development degree (see also Frechen et al. 2009; Ghafarpour et al. 2016) and possibly climatic conditions in the past. A new study of Shahriari et al. (2017) on biomarkers extracted from paleosols of four loess-soil sequences sheds light on the vegetation of the past enabling distinction between semi-arid and forest biomes.

Besides loess, Late Quaternary paleosols are also known from other deposits. Antoine et al. (2006) reported on a well-developed buried paleosol within alluvial deposits of the Caspian lowlands about 25 km southwest of Babolsar. Two radiocarbon ages indicate that the soil is younger than $28,486 \pm 190$ cal BP and older than $12,119 \pm 82$ cal BP. Several studies were carried out on surface soils in the central Iranian Plateau and in the Zagros Mountains. The presence of clay coatings and even argillic horizons in arid regions was related to increased rainfall and edaphic moisture during the past (Khademi and Mermut 2003; Khormali et al. 2003; Ayoobi et al. 2003; Farpoor et al. 2004). Similarly, layered pendants of calcite in coarse-textured soils of the xeric moisture regime probably represent relicts of more humid climate (Khormali et al. 2006). In addition, the stable carbon isotope compositions of gypsum hydration water (Khademi et al. 1997) and pedogenic carbonate (Khademi and Mermut 1999) indicate phases of increased humidity in the past.

In the alluvial plain of the Kor River in Southern Iran, a well-developed paleosol probably formed in loess-like sediments between 27 and 21 ka, as indicated by luminescence age estimates of the underlying and overlying deposits. Several younger weakly developed paleosols were identified in these sediments (Kehl et al. 2009). It is also evident that colluvial deposits on limestone slopes of the Zagros Mountains bear paleosol horizons and that grike-fillings contain argillic horizons formed during moister periods of

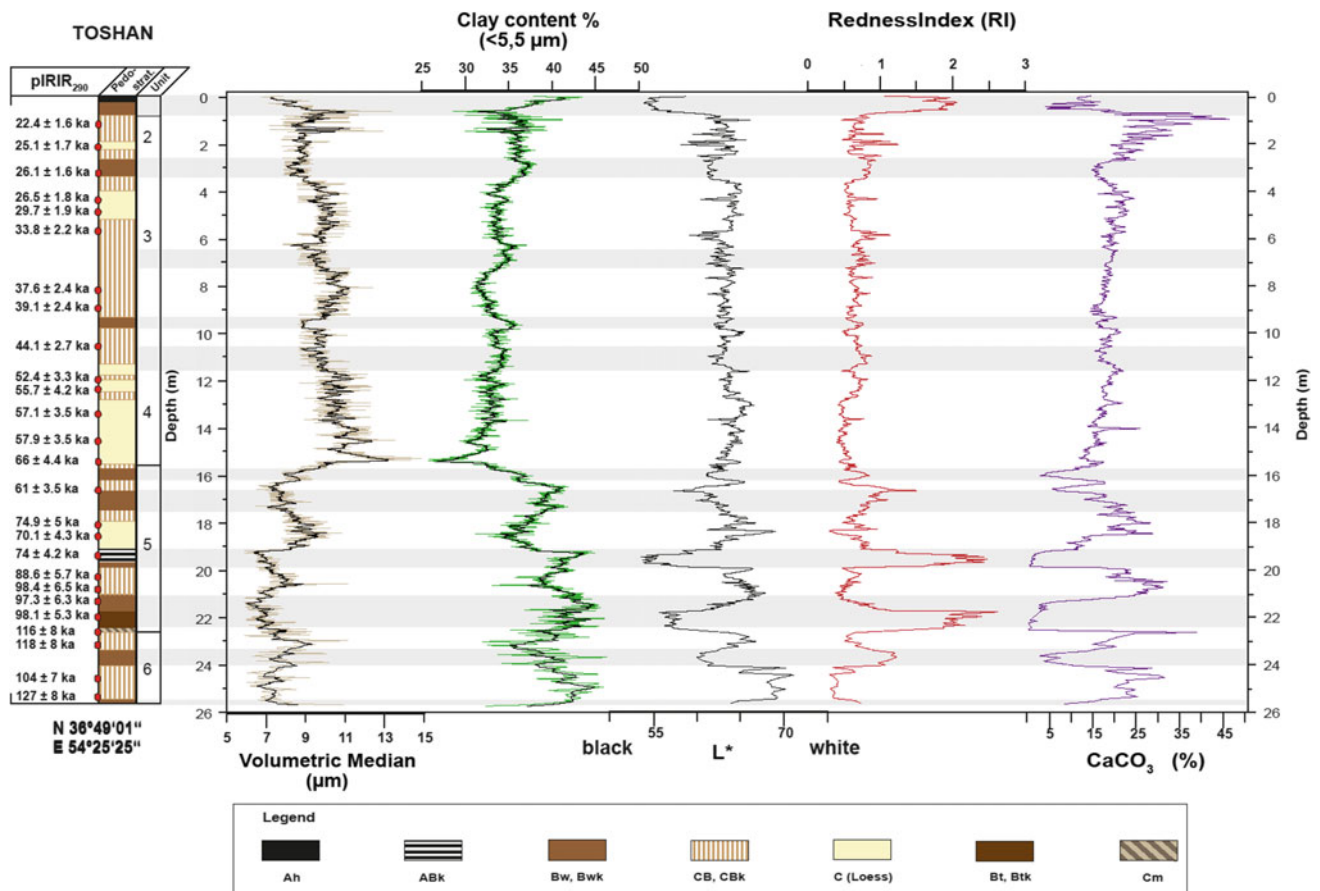


Fig. 8.6 Major stratigraphic units and pedostratigraphic column of the loess-soil sequence at Toshan. The units roughly correlate with MIS 6 to MIS 1 as indicated by results of luminescence dating. The grain size records show finest facies and highest clay content in Btb-horizons and in pedogenically altered loess of the lower part of the sequence. Weakly developed paleosols detected in the field at 3–9.5 m depth below surface show slight increases in the clay fraction in comparison with over- and underlying loess strata. The sediment color reflects

boundaries between more strongly developed soils and loess in the lower part, as well as minor changes within units 4 and 3, where weakly developed soils are present. The CaCO₃ content strongly varies from almost carbonate free in the Bt-horizon at 22 m depth and more than 40% in CBk horizons. In the field, the most typical loess was detected at 15.75 m depth, reflected in high median grain size, moderate L*-values and low redness ratio. Data were taken from Vlamincq et al. (2016) and Lauer et al. (2017a)

the past. In addition, buried paleosols were found in playa deposits near Isfahan (Ayoobi et al. 2003) and in the Yazd-Ardakan plain (Mehrjardi et al. 2009). However, estimates of the timing and duration of pedogenic processes are often insufficient.

8.6 Paleosols as Indicators of Climate Change in Iran

Proxy data such as the $\delta^{18}\text{O}$ or Ca^{2+} concentration in Greenland ice cores for temperature and dust content of the atmosphere, respectively, provide detailed records of climate change on orbital or millennial time scales during the Last Glacial. Rasmussen et al. (2014) defined 26 Greenland

stadials and interstadials between the last and present interglacials (Eemian and Holocene) including subdivisions with shorter changes in climate. Many of these fluctuations can be traced in marine cores, which reach further down in the geological past than ice cores (e.g., Lisiecky and Raymo 2005). The question remains, which cycles and amplitudes of climate change occurred on land and how terrestrial ecosystems reacted to these conditions. Stacked sequences of sediments and paleosols are excellent archives to at least partly answer these questions. Loess deposits are particularly useful because the accumulation of loess involves a series of climate-controlled processes including the production of silt-sized particles, their deflation, eolian transport and deposition as well as syn- and post-depositional transformations including soil formation (e.g., Pécsi 1990; Gardner

and Rendell 1994; Pye 1995; Smalley 1995; Wright 2001). Loess layers with no obvious pedogenic overprint can be correlated with stadial phases, reflecting dry (and cold) conditions during dust accumulation under a sparse vegetation cover. Paleosol horizons represent comparatively moister (and warmer) conditions and steppe or forest vegetation during interstadials or interglacials (e.g., Fink and Kukla 1977; Dodonov 1991; Bronger 2003; Rutter et al. 2003). However, the loess itself has to be understood as a weakly developed paleosol (Bronger 2003), since after the accumulation of dust, initial processes of soil formation such as formation of calcite bridges between grains, precipitation of iron hydroxides and humus accumulation took place.

Climaphytomorphic soils are best suited for paleoclimatic deductions (Bronger et al. 1994). The formation of these soils was governed by climate conditions and related vegetation, while other factors of pedogenesis, such as topography, parent material or time of soil development remained constant over several soils forming periods. This is a theoretical concept, which is difficult to find in nature. However, loess-paleosol sequences in plateau position far above the groundwater table may provide such records. Comparison with a climosequence of modern soils developed under known climate conditions is necessary in order to derive climate proxy data from paleosols. Khormali and Kehl (2011) and Khormali et al. (2012) presented pedons derived from loess, which can serve for comparison. In general, horizon differentiation and degree of soil development increase from the dry northern areas of the Turkmen steppe

toward the more humid areas of the Alborz Mountains foothills, where mean annual rainfall amounts to about 200 mm and 900 mm, respectively. Accordingly, the soil moisture regime (SMR) ranges from aridic in the northern regions to dry xeric, typic xeric and finally udic toward the South (SWRI 2000). In the aridic SMR, an A/C-profile of Typic Torriothents (Haplic Regosols) developed, whereas under dry xeric SMR weakly developed Typic Haploxerepts (Haplic Cambisols) with A/Bw/C and Typic Calcixerepts (Haplic Calcisols) with A/Bk/C-profiles are found. Calcic Argixerolls (Luvi-Calcic Chernozems) have developed an A/Bt/Bk/C-profile (see Chaps. 6 and 7). These soils are common in the typic xeric SMR. Under udic SMR, the intensity of clay illuviation is more pronounced and several Bt horizons could be discerned in the Mollic or Typic Hapludalfs (Haplic Luvisols) developed at the humid side of the climatic gradient (A/Bt1/Bt2/Bk/C). This general picture of soil distribution on loess deposits in Northern Iran is obscured by several factors. In the Iranian loess plateau, soil erosion related with overgrazing has caused truncation of the upper soil horizons such that wide areas in the dryer parts of the climosequence have lost their soils and the raw dust deposit is exposed at the land surface instead. Since erosion may also have truncated paleosols, the mere presence of a certain type of paleosol horizon provides information on the paleo climate (Table 8.1). An attempt was made to compare the paleosol horizons at the three key loess sections at Neka, Now Deh and Agh Band with horizons of the modern soils (Table 8.2). This comparison shows that the horizons of

Table 8.1 Paleosol horizons in Northern Iranian loess and their paleoclimatic implications

Horizon	Main characteristics	Pedological interpretation	Paleoclimatic implications
C	Yellowish brown to yellow orange "unweathered" loess; massive structure	Eolian sediment with incipient soil formation	Comparatively dry and cold climate (during stadials)
CBb	Light brown color; weakly developed subangular blocky structure; root channels, signs of bioturbation, contains primary carbonates, diffuse lower boundary toward Bk or C	Incipient soil resembling a weakly developed Kastanozem or Calcisol, syngenetic soil formation	Slight increase in edaphic moisture (+ temperature rise) during weak (and/or short) interstadials, dry steppe vegetation
CByb	Similar to CBb horizons but enrichment of gypsum as concretions, veins or large crystals	Same as above, but with gypsum enrichment	Same as above
Bwb	Brown color, moderately well-developed subangular blocky structure, root channels, free of primary carbonate, diffuse lower boundary toward Bk	Resembling degraded A-horizons of well-developed Kastanozems or Calcisols with low amounts of humus	Comparatively moist (and/or long) interstadial or dry interglacial, steppe vegetation
ABtb	Dark brown to brownish black color, well-developed subangular to angular blocky structure, partly nut shaped aggregates; some clay skins, sharp lower boundary toward Bk	Phaeozem or degraded Tschernosem	Moist and warm climatic conditions of interglacials with forest steppe or deciduous forest
Btb	Strong brown to reddish-brown, well-developed angular blocky structure, common clay skins, Mn and humus coatings; sharp lower boundary toward Bk	Bt-horizons of Luvisols	Moist and warm climatic conditions of interglacials with deciduous forest
Bkb	Light brown rich in secondary carbonate as concretions or pseudo mycelia, sharp upper boundary, massive structure, partly cemented	Subsurface horizon below Bwb or Btb	

Table 8.2 Modern soils and paleosols at the sections at Neka, Now Deh and Agh Band (Khormali and Kehl 2011). The correlation with MIS is based on pedostratigraphical considerations and luminescence age estimates (Kehl 2009; Frechen et al. 2009)

	Neka	Now Deh	Agh Band ^a
Estimated annual precipitation	750 mm	600 mm	350 mm
Modern soils			
– Subsoil horizons	Bt	BAw, (BAt)	Bk
– Soil units (WRB)	Luvic Phaeozem	Calcic Chernozem	Haplic Calcisol
Paleosol horizons of			
– MIS 5a, 5c	Bw(t)jb	CBkb, Bwkb	CByb, Bwyb
– MIS 5e	ABtb	Btb	Bwyb
– MIS 6	not found	CBkb, Bwkb	not found?
– MIS 7	Btkb	Btb, Bwkb	not found?

^a A new profile near the former section at Agh Band (Kehl et al. 2005) was studied by Lauer et al. 2017b and Wang et al. 2017. It contains a weakly and two moderately well-developed paleosols. Preliminary age estimates suggest that the most strongly developed soil (Bwyb) is older than expected from previous work (Frechen et al. 2009) and could belong to MIS 7 (Lauer et al. 2017b).

interglacial paleosols reflect a climatic gradient similar to that of the modern soils.

Interestingly, more reddish paleosols are typical of the lower strata of loess-paleosol sequences, whereas gray and brown soils are found in the upper parts indicating a trend of aridisation during the in Northern Iran. Shorter aridisation trends are represented by gradual transitions in sediment color and soil structure from paleosol horizons into overlying loess layers. These transitions indicate that at the end of soil forming periods dust accumulation continuously increased and finally outbalanced soil formation. The balance between these two mechanisms changed repeatedly during the Quaternary most probably driven by moisture changes. It appears likely that during interglacials top-down pedogenesis dominated while during transitional periods after interglacials sensu stricto and interstadials syngenetic or upbuilding soil formation was common. Therefore, Iranian loess-paleosol sequences provide excellent geological archives of Late Quaternary climate change.

Overall, earlier hypotheses on repeated Holocene cycles of loess accumulation and soil formation in Northern Iran (e.g., Bobek 1937; Ehlers 1971) must be rejected as based on luminescence dating (Frechen et al. 2009; Lauer et al. 2017a) and pedostratigraphic reasoning. There is convincing evidence that, in Northern Iran, loess deposition and paleosol formation closely followed the climate changes of interglacials, interstadials and stadials of the Northern Hemisphere. In Central and Southern Iran, however, less information is available on the timing of soil forming periods and their relation with past changes in the circulation systems of the Westerlies or the Monsoon. It is to be expected that future studies on sediment-paleosol sequences of Iran will considerably contribute to our understanding of climate change in Western Asia.

8.7 Conclusions and Outlook

There is large potential to improve our knowledge on the properties, genesis, stratigraphic significance and paleoclimate implications of paleosols in Iran. Future investigations could benefit from the large number of exposures available in Quaternary deposits. Pedological characterization and interpretation of paleosols in Iran are still at the beginning and the use of proxy data such as stable isotopes, rock magnetism, or biomarkers for estimating climatic conditions and related vegetation covers during past soil forming periods is quite promising. However, along with this kind of paleoclimatic deductions, more absolute dating of paleosols is needed for sound correlation of paleosols with other records of past climate change and landscape evolution. Future stratigraphic investigations would benefit from paleomagnetic measurements to identify the polarity reversal at the Brunhes-Matuyama boundary or magnetic excursions including the Laschamps or Blake events in loess-soil sequences of Northern Iran. This could provide independent estimates for the age of paleosols. Most information on paleosols in Iran and other places has been gathered by the study of spatially confined exposures. It is an ongoing challenge to describe the catenary relationships of paleosols or their relation with physiographic units widely used in the mapping of modern soils.

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