Magnetic properties and geochemistry of loess/paleosol sequences at Nowdeh section northeastern of Iran

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Abstract

The loess-paleosol sequences in the northeastern part of Iran serve as a high-resolution natural archive documenting climate and environmental changes. These sequences offer evidence of the interaction between the accumulation and erosion of aeolian and fluvial sediments during the Middle and Late Pleistocene periods. In this study, the Azadshar (Nowdeh Loess Section) site was chosen to reconstruct Late Quaternary climate shifts. The 24-meter thick Nowdeh loess/paleosol sequence was sampled for magnetic and geochemical analysis. The sampling involved 237 samples taken systematically at high resolution (10 cm intervals Selected samples, corresponding to peaks in magnetic susceptibility, underwent geochemical analysis to aid in the interpretation of paleoclimatic changes indicated by the magnetic signals. The magnetic susceptibility results of the loess/paleosol deposits revealed low values during cold and dry climate periods (loess) and high values during warm and humid climate periods (paleosol). The magnetic susceptibility at a depth of 22.1 meters (approximately 130 Ka) has significantly decreased, suggesting cold climate conditions at this time. The most substantial changes in magnetic susceptibility occur at depths between 18.6 to 21.3 meters (approximately 100 to 120 Ka). During this period, there are four phases of decrease (indicating cold and dry conditions) interspersed with three phases of increase (signifying warm and humid conditions) in magnetic susceptibility.The comparison of magnetic and geochemical data showed that variations in geochemical weathering ratios corresponded to changes in magnetic parameters. A high level of correlation was observed between the magnetic susceptibility intensity and ratios such as Rb/Sr, Mn/Ti, Zr/Ti, and Mn/Sr. The findings from this research indicate that the sedimentary section of Nowdeh has experienced six distinct climate periods over the last 160,000 years. Notably, three cold and dry

periods occurred between three warm and humid periods. Additionally, during these climate phases, short-term cold (stadial) and warm (interstadial) intervals were also observed.

Keyword: Loess/paleosols sequences, Climate, Magnetic parameters, Geochemical proxies, Northeastern of Iran.

Introduction

Reconstruction of the Quaternary climate is important for the development of climate models that lead to a better understanding of past and present and prediction of future climate development. Loess–paleosol sequences are now recognized as one of the most complete terrestrial archives of glacial–interglacial climate change (Porter, 2001; Muhs and Bettis, 2003, Pierce et al, 2011, Guo et al, 2002) and have been used to reconstruct climate and geomorphological changes during the Quaternary (Karimi et al., 2011; Frechen et al., 2003; Prins et al., 2007).

Loess deposits occur in large areas of the northeast, east central, north and central parts of Iran which is part of the loess belt that covers the Middle East and extends further northward into Turkmenistan, Kazakhstan and Tajikistan (Okhravi and Amini, 2001).The extensive and thick loess deposits in northern Iran have been recently studied in detail establishing a more reliable chronological framework for the last interglacial/glacial cycle (Lateef, 1988; Pashaee, 1996; Kehl et al., 2006; Frechen et al., 2009, Karimi et al, 2009, Karimi et al, 2013, Okhravi and Amini, 2001, Mehdipour et al, 2012).

Paleoclimate studies of loess deposits based on rock magnetism and combined analyses of rock magnetism and geochemistry around the world have attained appreciable advances in the past few decades (Bader et al,2024; Jordanova and Jordanova, 2024; Heller and Liu, 1984; Forster et al., 1996; Ding et al., 2002; Guo et al., 2002; Chlachula, 2011; Bronger, 2003; Baumgart et al., 2013, Guanhua, et al, 2014). These studies comprise loess-paleosol records that cover Chinas loess plateaus, Germany, Poland, Tajikestan, Austrian, Ukraine, and the Danube catchment (Hosek et al, 2015, Ahmad and Chandra, 2013, Chen, 2010; Jordanova et al., 2011; Buggle et al., 2009; Fitzsimmons et al., 2012; Fischer et al., 2012; Jary and Ciszek, 2013; Baumgart et al., 2013; Schatz et al., 2014; Gocke et al., 2014).

Despite its suitable geographical location there is only a limited number of studies of loess deposits from the North of Iran. In this work we explore the potential of loess deposits in northern Iran for reconstructing late quaternary climate/environmental change.

Study area

The Nowdeh section is exposed at about 20 km southeast of Gonbad-e Kavus and east of Azadshahr city. The Nowdeh river dissects a more than 24 m thick sequence of yellowish brown (10 YR 5/4) loess covering northeast dipping weathered limestone.

The study area (37° 05' 50'' N and 55° 12' 58'' E) is part of the Alborz structure and this structure continues beneath the Caspian Sea. This zone includes regions north of the Alborz fault and south of the Caspian Sea. Toward the east, the Gorgan-Rasht zone is covered with thick layers of loess.

The Nowdeh section was selected for this work due to earlier soil studies by Kehl et al (2005) and Frichen et al (2009) combined with the existence 12 dating for this section (Figure1).

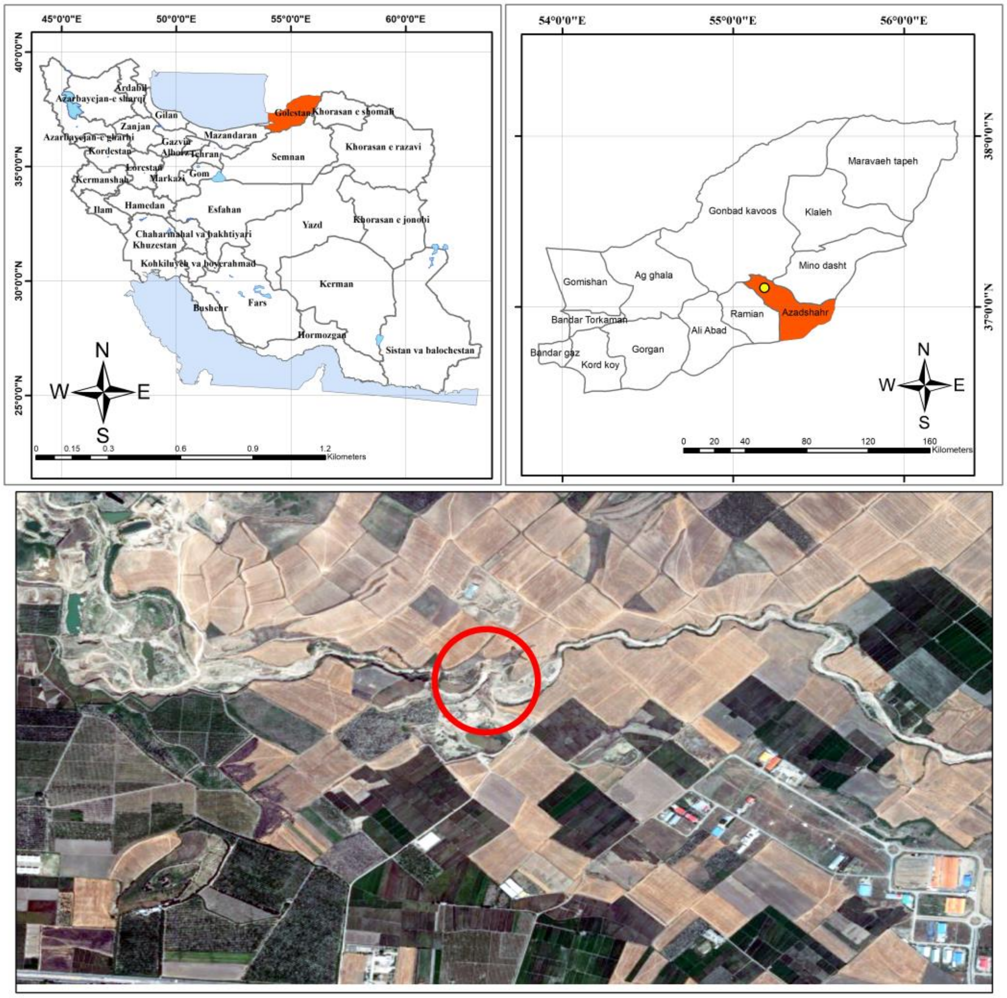

Figure 1: Map of Iran and the location of Nowdeh loess-paleosol sequence.

Figure 2: A view of the sedimentary section of the Nowdeh with its very clear layering.

Methodology

The Nowdeh loess section is approximately 24 meters thick and was sampled at 10 cm intervals for magnetometry and geochemical analysis. The sampling location and method were determined following a detailed study of the area. Magnetic susceptibility measurements of all samples were conducted at the Environmental and Paleomagnetic Laboratory of the Geological Survey of Iran in Tehran. Magnetic susceptibility is indicative of the collective response of diamagnetic, paramagnetic, ferrimagnetic, and imperfect antiferromagnetic minerals present in the samples. Each sample was placed in a 11 cm^3 plastic cylinder for use in magnetic measurement devices. The measurement of magnetic susceptibility was performed using the AGICO Kappabridge model MFK1-A. To ensure the reproducibility of our results, we have meticulously documented all experimental procedures, including the setup, equipment used, and analytical methods. Our findings have been validated by testing multiple independent samples and conducting experiments repeatedly under controlled conditions.

The determination of the Saturation Isothermal Remanent Magnetization (SIRM) was carried out to assess the concentration of ferromagnetic and imperfect antiferromagnetic minerals in the samples. The calculation of the Hard Isothermal Remanence (HIRM) magnetization was performed to identify magnetically significant components such as hematite in the samples using the following formula:

$$HIRM = 0.5(SIRM + IRM{-}0.3T)$$

Where IRM−0.3T is the remanence after application of a reversed field of 0.3 T after growth and measurement of SIRM. The HIRM reflects the contribution specifically of the imperfect antiferromagnetic minerals hematite and goethite (Bloemendal et al., 2008).

The S−0.3T value, or S-ratio, is calculated as

$$S{-}0.3T = 0.5[(-IRM{-}0.3T/SIRM) + 1]$$

and it ranges from 0 and 100%. It reflects the ratio of ferrimagnetic to imperfect antiferromagnetic minerals (Bloemendal et al., 2008).

Based on the magnetic susceptibility results, 70 samples were selected for geochemical analyses (trace elements) to assist the paleoclimatic interpretation of the magnetic signals. Each sample was washed using a sieve with a mesh size of 400 and then dried in an oven. Once dried, the samples were further sieved with a 325-mesh sieve. The very fine sediments were collected, packed, and labeled as the tested material in special containers. A 0.2-gram portion of the powder from each sample was then placed in a 1 molar hydrochloric acid solution. After two hours, the samples were analyzed using an ICP device in the laboratory. The concentrations of the main elements were measured as a percentage, while the minor elements were quantified in milligrams per kilogram. To ensure the reproducibility of the results, we meticulously document all experimental steps, including the setup, equipment used, and analysis methods. The findings of this research have been validated through the use of multiple independent samples and by conducting experiments under controlled conditions.

As explained, the studied area was previously studied by Frichen et al. (2009) and Kehl et al (2005). Therefore, we chose this sedimentary section to investigate climate changes and used their dating data. The infrared stimulated luminescence (IRSL) technique is utilized for this dating. Forty-five samples were taken in light-tight tubes for the IRSL dating study. About 250 g of sediment was sampled. Polymineral fine-graine material(4–11 mm) was prepared for the measurements. The sediment material brought on disc was irradiated by a $^{90}Sr/^{90}Y$ source in at least seven dose steps with five discs each and a radiation dose up to 750 Gy. All discs were stored at room temperature for at least 4 weeks after irradiation. The irradiated samples were preheated for 1 min at 230 ^{0}C. De values were obtained by integrating the 1–10 s region of the IRSL decay curves. An exponential growth curve was fitted to the data and compared with the natural luminescence signal to estimate the De value. Alpha efficiency was estimated to 0.08±0.02 for all samples. Dose rates were calculated from potassium, uranium and thorium contents, as measured by gamma spectrometry (Germanium detector) in the laboratory, assuming radioactive equilibrium for the decay chains. The IRSL ages gradually increase with depth from 20.5± 2.0 to103±10 ka. The stratigraphically oldest sample was collected below the lowermost exposed strongly developed palaeosol (PC2) at a depth of 16.10m below surface. The about 10.50 m thick loess covering the uppermost strong paleosol (PC1) likely accumulated between about 61.9±6.7 and 20±2.0 ka(Frechen et al, 2009).

Results Magnetic properties

In Figure 3, the relationship between susceptibility, NRM (Natural Remanent Magnetization), SIRM, HIRM, and S−0.3T in the Nowdeh section is illustrated. The variability in the magnetic susceptibility signal within the Nowdeh section indicates fluctuations in climate conditions and associated mechanisms during the Late Quaternary period. The values of magnetic susceptibility (χ) in the Nowdeh section range from 28.17 to 203.13 (in units of 10^-8 m^3 kg^-1). The maximum χ values (203.13) are found in the lower paleosol layer at 19.4 meters depth, while the minimum values are observed in the uppermost loess layer at 7.4 meters depth. The rock magnetic records exhibit a strong correlation with the lithology observed in the Nowdeh section. Generally, the paleosol layers exhibit higher magnetic signal intensities compared to the loess layers.

The paleosols exhibit higher magnetic susceptibility (χ) values compared to the loesses, with magnified magnetic enhancement observed in the Bw, Bt, and Btk horizons, while the underlying C (loess) horizon displays lower χ values. This difference probably reflects precipitation of iron oxides in the Bw horizons, resulting in a higher concentration of pedogenetic magnetite in comparison to the C horizons (Jordanova et al., 2013; Hosek et al., 2015). The χ values in the lower and middle sections of the Nowdeh profile, approximately 53-80 and 120-140 thousand years ago (Ka), (respectively at depths of 9 to 15 and 18 to 23 meters), represent intermediate values between unweathered loesses and weathered paleosols.

The results indicate that the Natural Remanent Magnetization (NRM) is consistent with the variance in magnetic susceptibility, particularly notable at lower depths, with the highest recorded value of this parameter observed at 13.1 meters depth in the BW, BWK horizon (figure 3). Variations and discrepancies in magnetic susceptibility align closely with the SIRM values of the Loess sequence. As magnetic susceptibility decreases, SIRM also shows a corresponding decrease. In the interval between 20 to 50 thousand years ago (ka (Depth 2.1 to 8.4 meters), during which much of the upper Loess formation occurred, magnetic susceptibility shows minimal variation, a pattern mirrored in the SIRM diagram for this period. The elevated HIRM values in Figure 3 suggest an increase in the concentration and frequency of magnetic deterrent minerals such as Goethite, maghemite, or hematite.

The comparison between the lower values of saturation (S) (-0.3 T) (between 0.6 to 0.12 Am/m) and the higher values of Hard Isothermal Remanent Magnetization (HIRM) (between 2 to 5 Am/m) indicates that the proportion of minerals with lower saturation, such as magnetite, is significantly lower than the proportion of minerals with higher saturation in paleosols. This pattern contrasts with the composition of loess deposits. This can be clearly seen in loess sediments, for example, at a depth of 1 to 9 meters, representing the time interval between 18 and 52 ka.

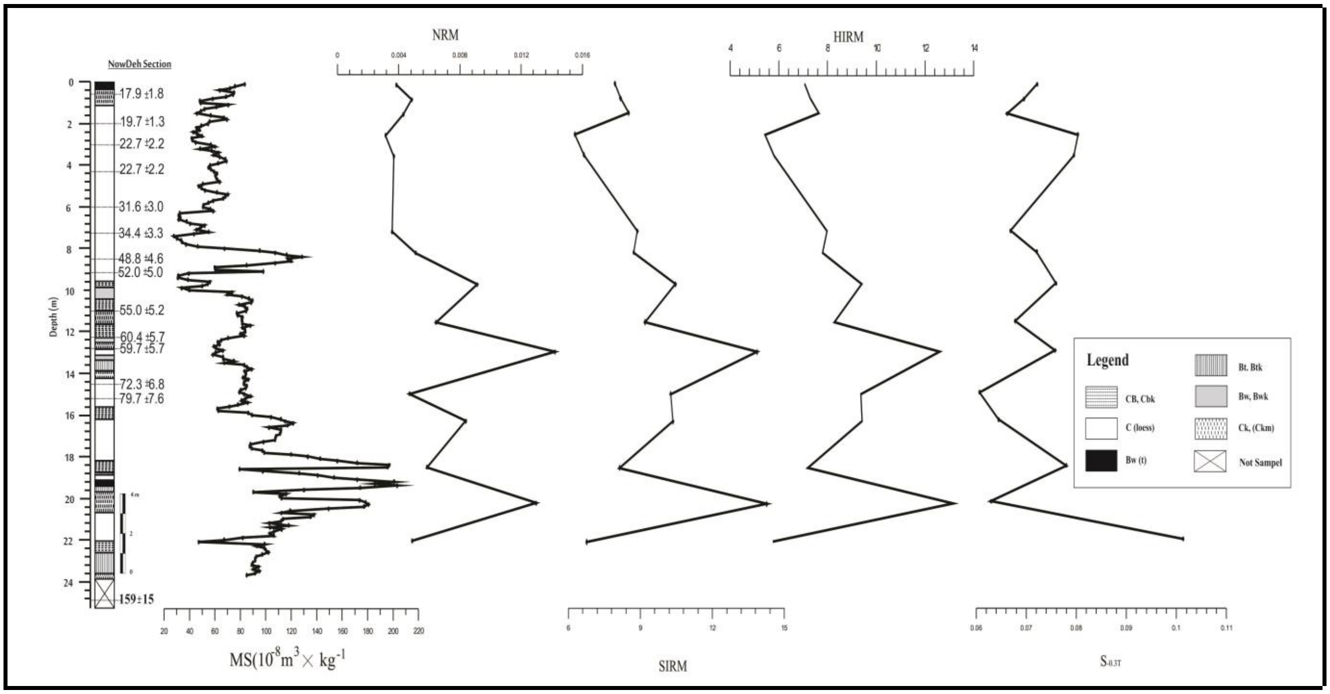

Figure 3: Basic magnetic parameters for Nowdeh section.

Element stratigraphy

Figure 4 illustrates the correlation between the concentration of selected elements (Sr, Rb, Zr, Ti, and Mn) and magnetite susceptibility in the Nowdeh section. The figure indicates significant variations in the concentration of these elements with noticeable differences between them. Sr and Rb exhibit similar trends along the Nowdeh section. At a depth of 2.9 meters, there is a notable increase in the concentration of these two elements, corresponding to an age of 22 thousand years ago (ka). Higher in the section, the concentration of Sr and Rb decreases.

At a depth of 18 meters, the Nowdeh sedimentary section recorded the highest concentrations of elements such as (Sr, Rb, Zr, Ti and Mn). Conversely, the lowest concentrations of these elements were observed at a depth of 8.5 meters, which dates back approximately 48, Ka.

Ti, Zr, and Mn exhibit approximately similar trends in the diagram. These elements show little variation in concentration at the beginning of the section. The changes in element concentrations from the end of the sedimentary section down to a depth of 16.7 meters (approximately 90 ka) display a zigzag pattern. Between the depths of 16.7 and 9.3 meters, the fluctuations in element concentrations are minimal. At a depth of 9.3 meters, corresponding to roughly the last 52 ka, the research indicates the lowest concentrations of the elements measured. However, from this point onward, the concentration of elements begins to rise, peaking at a depth of 8.5 meters, which dates back about 34 ka. This increase suggests a period of hot and humid conditions during that time.

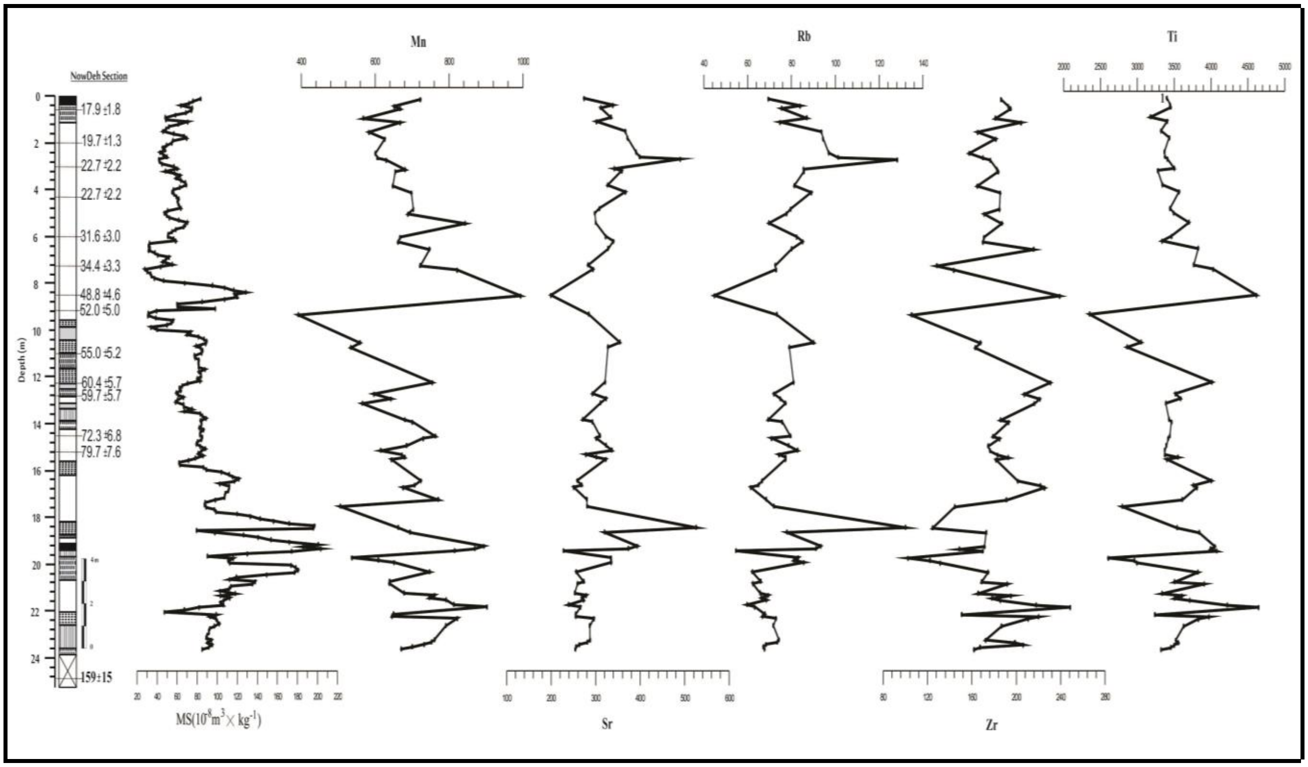

Figure 4: shows depth series of selected element concentrations for Nowdeh section.

Trace element ratio

The variation of the Si/Ti ratio in figure 5 generally follows the magnetic susceptibility pattern (figure 5), except for the lower part of the section (23-24 meters). The ratios of Mn/Sr, Zr/Ti, and Mn/Ti in figure 5 show almost no long-term change, except for at a depth of 8.5 meters, corresponding to an age of 48.8 thousand years. These changes suggest hot and humid climatic conditions, which can be correlated with the high level of magnetic susceptibility. The Rb/Sr ratio exhibits an opposite pattern to the magnetic susceptibility, especially at the depths of 8.5, 16, 19, and 22 meters. The Ba/Rb ratio generally follows the magnetic susceptibility pattern, except at depths of 13, 15, 19, and 22.8 meters where they vary oppositely.

The variation in the Si/Ti ratio does not exhibit a consistent relationship to the sequence of loess/palaeosol layers, as defined by the magnetic susceptibility, in the Nowdeh section. On the other hand, the Mn/Ti ratios tend to show elevated values in the palaeosols, likely due to the concentration of Mn oxide in the finer sediment fraction (Bloemendal et al., 2008). This suggests that the presence of Mn oxide plays a significant role in influencing the Mn/Ti ratio in the sediments, particularly in the palaeosol layers.

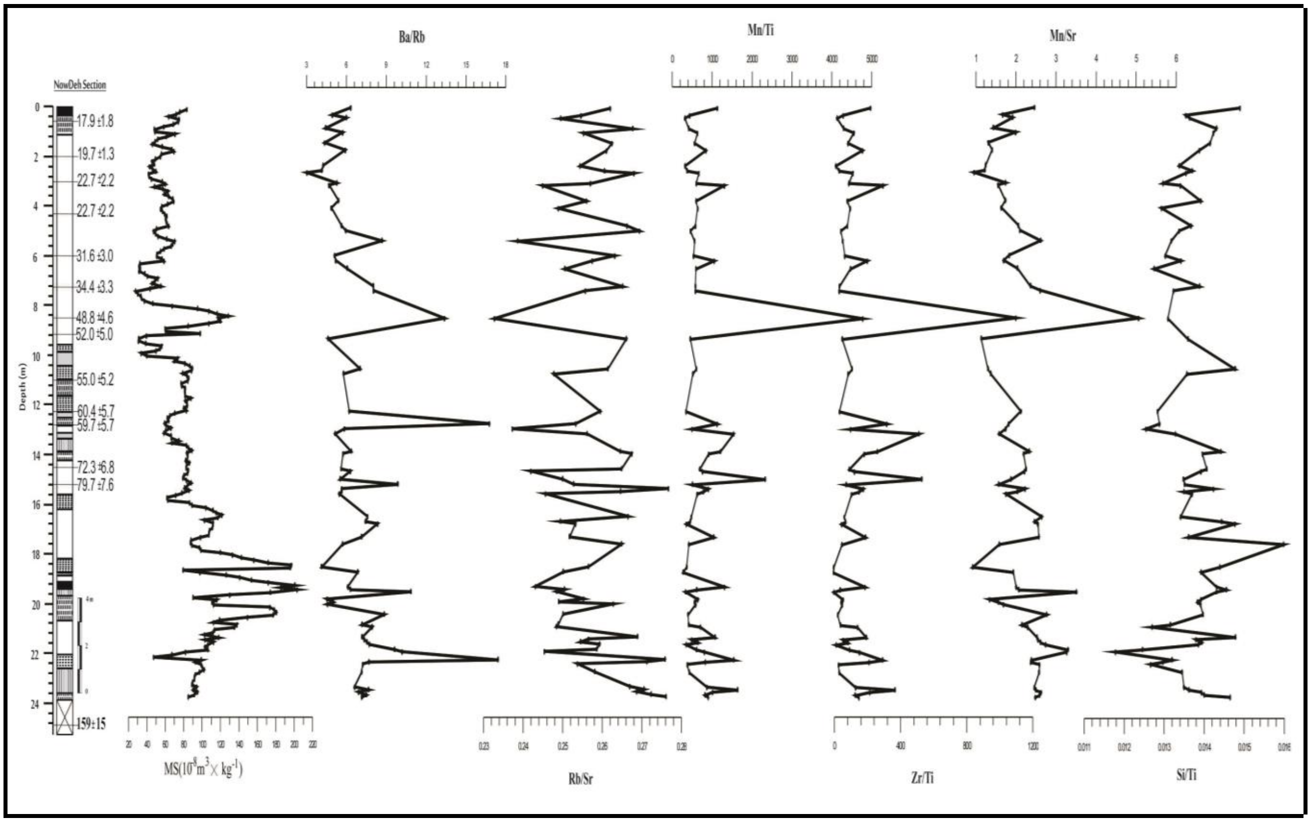

Figure 5: show selected element ratios in Nowdeh section

Discussion

Over the entire 159 Ka sequence at the Nowdeh site, there appears to be a reasonable first-order co-variation between the magnetic and geochemical indicators of weathering and soil formation, particularly with magnetic parameters reflecting variations in ferrimagnetic content and Sr-based ratios. However, upon closer detailed examination based on individual loess and palaeosol layers, an inconsistent relationship is observed between the amplitudes of individual peaks and troughs of magnetic and geochemical parameters (Fig 4 and 5). This suggests that while there is an overall correlation between these indicators at a broader scale, at a finer resolution within specific layers, the relationship becomes more complex and inconsistent. Additional factors or processes may be influencing the variations in magnetic and geochemical parameters within the individual stratigraphic units. This issue can be seen clearly in Figures 4 and 5. As noted by Hosek et al (2015) and Makeey et al (2024), there is a significant relationship between magnetic receptivity, chemical elements, and climatic conditions. Our study reinforces this finding, as indicated by the results obtained.To investigate the relationship between climate change and the magnetic properties of sediments, magnetic susceptibility measurements were conducted on loess sediments in the Nowdeh section. The results of the magnetic susceptibility analysis at Nowdeh revealed distinct sequences corresponding to cold and dry periods as well as warm and humid conditions. These variations in magnetic susceptibility align with the alternating Loess-paleosol sequences, indicating a relationship between the magnetic properties of the sediments and past climate changes in the Nowdeh region.

According to Song et al. (2008), sediment loess is formed under cold and dry climate conditions, leading to lower magnetic susceptibility due to the absence of significant weathering processes. In contrast, in paleosols formed as a result of pedogenic processes, the level of oxidation increases, resulting in an increase in magnetic susceptibility records due to higher concentrations of XYZ elements. It is widely observed, that in a loess/paleosol sequence, paleosols exhibit higher magnetic susceptibility than the adjacent loess layers (Song et al, 2008).The formation of strong magnetic minerals, such as iron oxides, in soils through pedogenesis processes includes minerals like $Fe3O4$, γ-$Fe2O3$, and $Fe2O3$ - $\propto$. In contrast, the mineral magnetism of loess layers is influenced by the grain composition of the aeolian sources depositing the sediments. This distinction in magnetic mineral content between soils undergoing pedogenesis and loess layers sourced from aeolian deposits contributes to the differences in magnetic susceptibility observed between paleosols and loess layers in sediment sequences.

In Fig 3, the brown layer sequences of dark and light paleosols in the loess deposits demonstrate distinct weathering processes that closely resemble the patterns observed during glacial and interglacial periods in the middle and late Pleistocene. The paleosols in the Nowdeh section exhibit higher magnetic susceptibility compared to the surrounding loess layers. This difference is more prominent at lower depths, indicating greater weathering variability during those periods. At a depth of 21 meters (Almost 110 ka), a significant decrease in magnetic susceptibility suggests a cold and dry condition during that timeframe. The magnetic susceptibility chart for the Nowdeh section reveals approximately 8 distinct periods of increasing magnetic susceptibility, reflecting periods of temperature and humidity elevation. In accordance with the standard global loess characteristics, paleosols consistently exhibit higher magnetic susceptibility values compared to adjacent loess layers due to pedogenesis and oxidation processes, as highlighted by Maher (2011) and Spassov (2002). The NRM results suggest a decrease during loess formation and an increase during paleosol formation. This pattern suggests a relationship between NRM and magnetic susceptibility (Bloemendal et la, 2008,). A decrease in NRM indicates dry and cold Climate conditions (The depth of 7.2 meters, which is approximately equal to 34 Ka), consistent with the deposition of loess layers, while an increase in NRM represents warmer and more humid Climate conditions, corresponding to paleosol formation (At depths of 18.6 to 21.3 meters, the highest magnetic receptivity is observed, which aligns with the NRM results; this parameter has also increased during the time range of 100 to 130 ka. The peak of this increase, where the two parameters align, occurs at a depth of 19.4 meters and dates back approximately 120 ka).

The probable justifications for the low alteration in magnetic susceptibility and isothermal remnant magnetization between 20 to 50 thousand years ago can be attributed to two main factors:

1- Decreased Pedogenesis due to cold and dry periods.
2- Reduction in the influx of magnetic particles into loess layers.

During the last 20 ka, there seems to be a correlation between magnetic susceptibility variations in the surface soil layer and climatic conditions. This period coincides with the transition from cold Climate to the current warm and humid climate in the northern region of Iran (Frichen et al, 2009). As a result, the soil's magnetic properties, specifically the saturation isothermal remanent magnetization (SIRM), have likely increased during this time frame. However, since the SIRM samples were only collected at magnetic susceptibility peak points, they may not capture the full extent of variations. Comparing these findings with the research by Antoine et al. (2013) on loess/paleosol sediments in Central Europe reveals a close relationship, particularly around 32 ka.

Geochemical charts can serve as useful indicators of Climate patterns, as they can highlight different levels of weathering severity. In the study of loess deposits, certain chemical ratios can be utilized to reconstruct variations in paleoclimate (Ding et al., 2001). The Zr/Ti, Mn/Ti, Rb/Sr, and Mn/Sr records from the Nowdeh section exhibit a clear pattern of higher values prevailing in the palaeosols, and their high degree of similarity is noteworthy. Rb/Sr has been suggested by several researchers as an indicator of pedogenic intensity in loess, based on the differential weathering of the major host minerals, specifically K-feldspar for Rb and carbonates for Sr (Hosek et al, 2015, makeey et al, 2024). In the case of Mn/Sr, the higher values observed in the palaeosols are likely a result of the combined effects of grain size on Mn concentration, as well as the loss of Sr through solution processes. This indicates that these ratios can serve as important indicators of pedogenic processes and weathering dynamics in the sedimentary record of the Nowdeh section.

In a study by Chen et al. (1999), a comparison was made between the Rb/Sr ratios and magnetic susceptibility values in the uppermost (last glacial/interglacial) sections of the Luochuan and Huanxian regions. The researchers noted a remarkable correspondence between the amplitudes of variation in magnetic susceptibility and Rb/Sr ratios. This finding suggests a close relationship between magnetic susceptibility variations and the Rb/Sr ratios in these regions during the last glacial and interglacial periods. Magnetic susceptibility at a depth of 19.4 meters has recorded high values, which indicates the hot and humid climate conditions at this depth with an approximate age of 120 ka. Variations in the concentrations of manganese (Mn), zirconium (Zr), and titanium (Ti) in the soil reflect a clear stratigraphic pattern, with higher values seen in paleosols and lower values in the loess layers (Bloemendal et al., 2008). This pattern is influenced, in part, by carbonate dilution/concentration effects, as a significant portion of the variability in these elements disappears when expressed on a carbonate-corrected basis.

In the Nowdeh section, the amount of rubidium (Rb) in paleosols was lower compared to its concentration in loess layers. This discrepancy can be attributed to the higher solubility of Rb in warm and humid climates, typical of interglacial periods. Gallet et al. (1996) observed significant depletion of Rb in the paleosols, supporting this interpretation.

Our results indicate that the Mn/Ti, Zr/Ti, and Mn/Sr ratios tend to exhibit higher values in the paleosols. According to Ding et al. (2001), elevated Mn/Ti values in paleosols may result from the concentration of iron (Fe) and manganese (Mn) oxides in the finer sediment fractions. They also noted that the Rb/Sr and Mn/Sr ratios show a clear pattern of elevation in the paleosols, which aligns with the findings of our study. The Rb/Sr ratio has been proposed by various researchers as an indicator of pedogenic intensity in loess deposits, based on the differential weathering of major host minerals such as K-feldspar for Rb and carbonates for Sr. The higher Mn/Sr values in paleosols may be attributed to grain-size effects on Mn concentrations and the solubilization loss of Sr.

Chen et al. (1999) compared Rb/Sr and magnetic susceptibility in the uppermost parts of the Luochuan and Huanxian sections, revealing a significant correspondence between the variations in magnetic susceptibility and Rb/Sr ratios. This suggests a link between weathering intensity and magnetic properties in these sediments. In the context of the Nowdeh sedimentary section, the magnetic parameters were compared with those from other studies conducted in various regions of the world, further contributing to our understanding of paleoclimatic variations and weathering processes in loess deposits.

The comparison of magnetic receptivity results from the Nowdeh sedimentary section with the palynological data from sedimentary cores of Urmia Lake (Djamali et al., 2008) and the ^{18}O analysis from Arabian Sea sedimentary cores (Tzedakis, 1994) has provided valuable insights into past climate conditions (Figure 6). In the analysis, an increase in the AP/NAP index (Arboreal Pollen grains (AP) to that of the Non-Arboreal Pollen grains (NAP)) in the lakes corresponded with the presence of ancient soil layers in the seedling sedimentary section. This increase signifies warmer temperatures and higher humidity levels, conducive to the growth of trees and shrubs. Conversely, a decrease in the AP/NAP index indicates a decline in temperature and humidity, leading to the disappearance of trees and shrubs and changes in surface vegetation cover. This correlation suggests that the climate conditions and their fluctuations in western Iran align with the sedimentary deposition at Nowdeh.

Moreover, the ^{18}O analysis of the Arabian Sea exhibited a strong agreement with magnetic receptivity data. A decrease in the ^{18}O indexes points to warmer climate conditions, while an increase indicates colder conditions (Djamali et al, 2008). The relationship between magnetic susceptibility and ^{18}O levels in the Arabian Sea sediments, as shown in Figure 6, Verifythat an increase in magnetic susceptibility corresponds with a decrease in ^{18}O levels, indicating warmer climate conditions. This alignment further supports the connection between the recorded palynology data of Lake Urmia, ^{18}O data from the Arabian Sea, and the sequence of ancient loess-soil sediments in the Nowdeh sedimentary section.

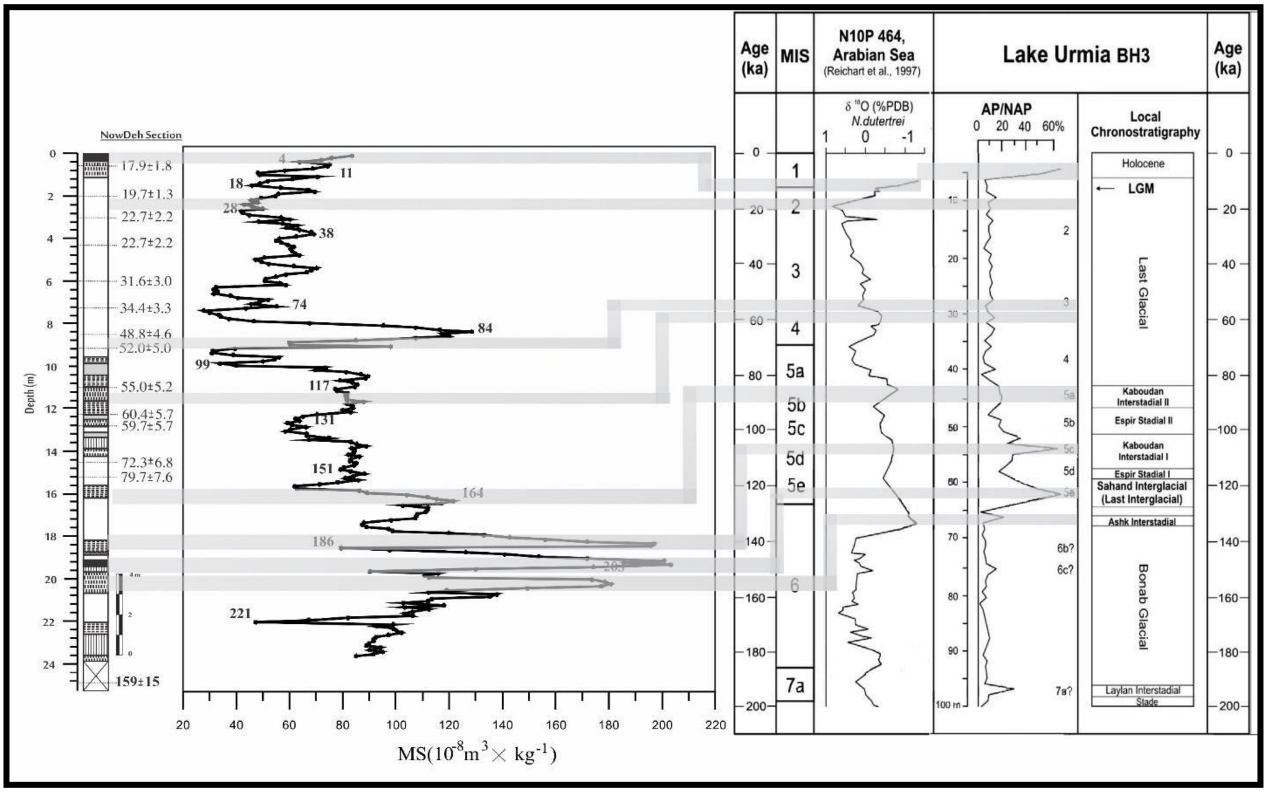

Figure 6: Correlation between recorded palynological data of Lake Urmia (Djamali et al, 2008) and ^{18}O of Arabian Sea sediments (Tzedakis, 1994) with the Loess-Paleosol sediment sequence of Nowdeh sedimentary section.

The results of your current research Verify significant correlation with the studies conducted by Fuchs et al. in 2013 and Hosek et al. in 2015 on ancient loess/paleo soil deposits in Central Europe. Figure 8 depicts consistent patterns in the magnetic receptivity parameter over the past 45, 73, 90, 104, and 108 ka across the study sections. Around 45 and 73 ka, there is a clear increasing trend in magnetic receptivity observed in all analyzed layers, indicating a shift towards warmer and more humid climate conditions compared to earlier periods. This increase in magnetic susceptibility can be attributed to the higher presence of iron oxides in the soil resulting from increased chemical weathering. Conversely, during the periods of 90, 104, and 108 ka, a decrease in magnetic susceptibility is evident across all regions, signifying colder and drier climatic conditions during these time intervals. This issue can also be seen in the amount of $F_{e2}O_3$ in Nowdeh sediments (Figure 7). While the older sediments also show a significant association with climate variations in Central Europe and the Nowdeh area, the absence of radiometric dating in these older sediments introduces some uncertainty when interpreting these findings. Nonetheless, the consistent patterns in magnetic susceptibility across different time periods provide valuable insights into past climate fluctuations and their impact on soil properties in these regions.

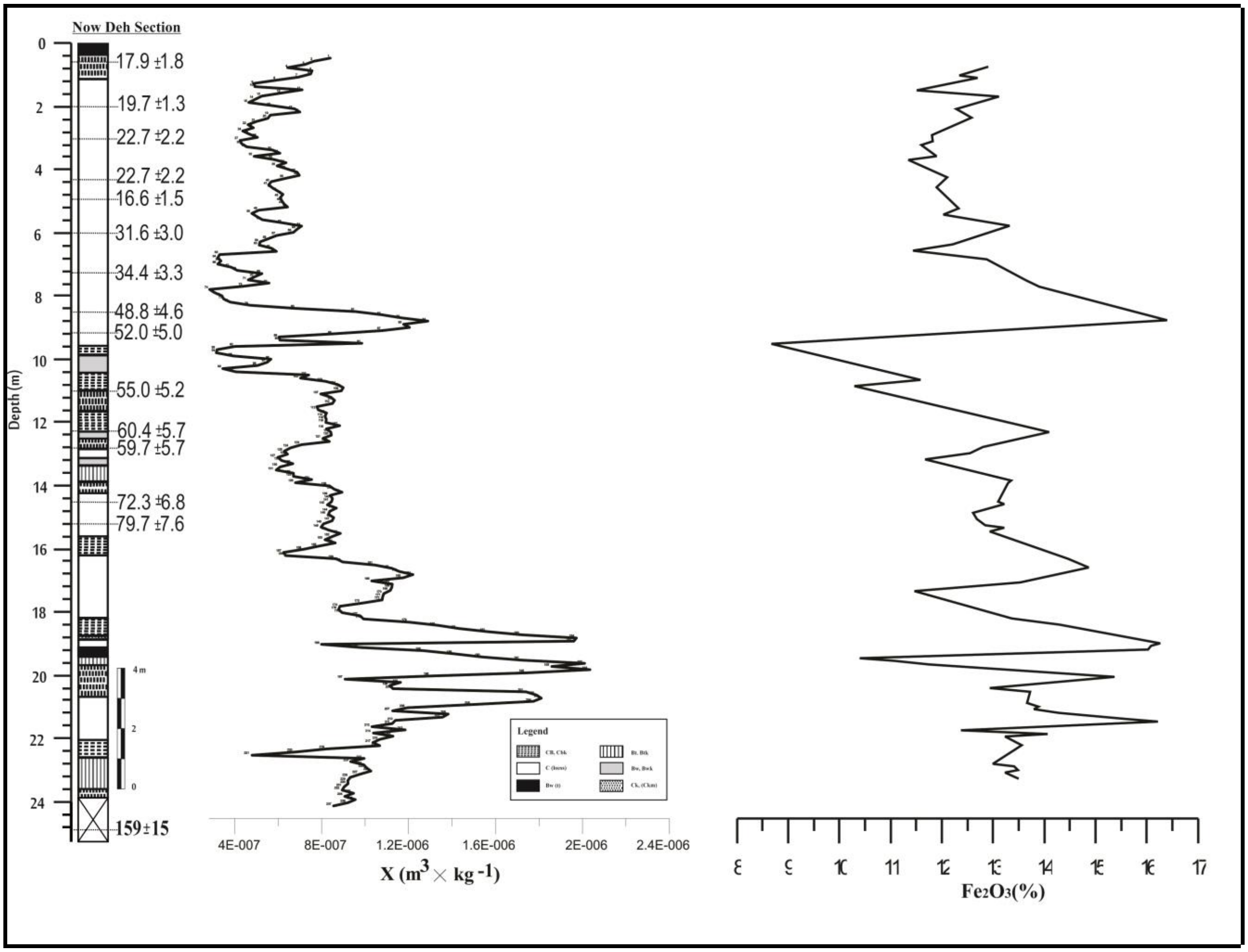

Figure 7: The relationship between magnetic susceptibility and $F_{e2}O_3$

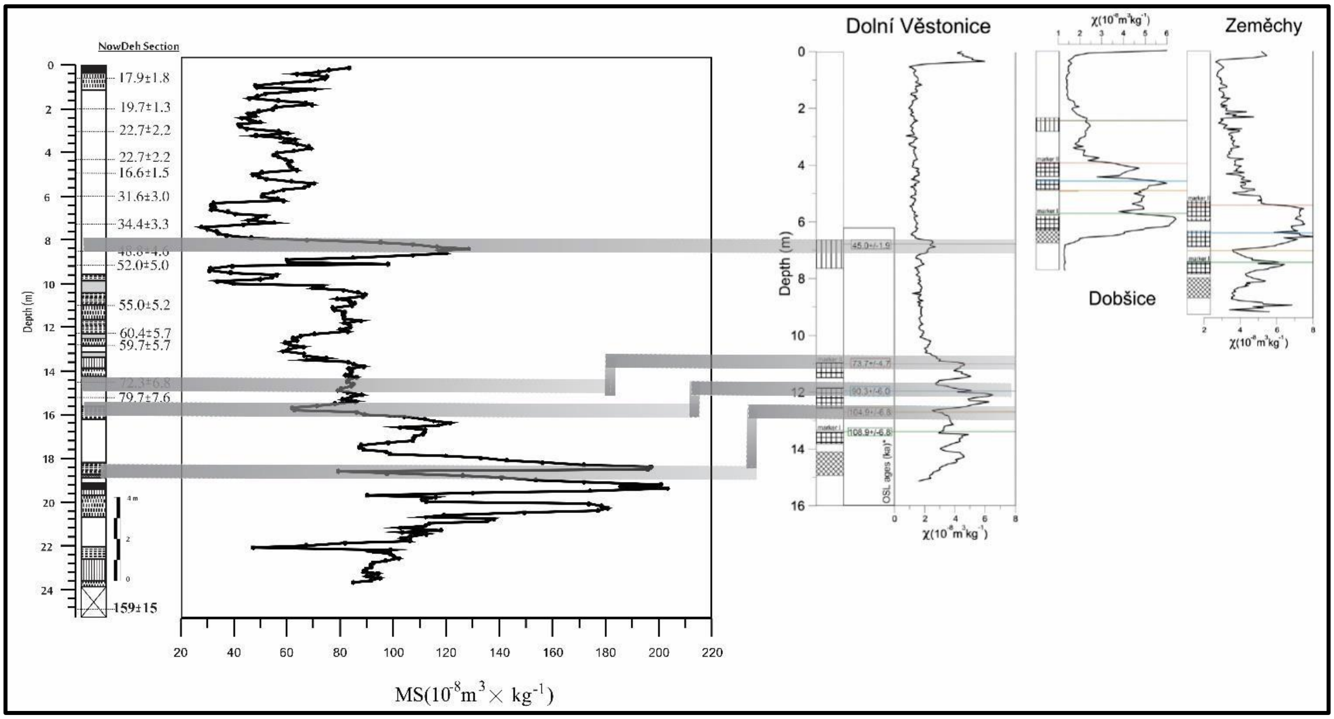

Figure 8: Comparison of changes in magnetic receptivity of Dolní Věstonice sedimentary section, Fuchs et al, 2013, Dobsice and Zemechy section, Hošek et al, 2015, with Nowdehh sedimentary section

The comparison of magnetic receptivity trends as recorded in sedimentary sections of Beiyuan, Heimugou, Biampo, and the ^{18}O records by Imbrie et al. (1984) in Figure 8 reveals a high agreement with the Nowdeh sedimentary section. This alignment indicates similar Climate conditions across different locations in the Northern Hemisphere.

The consistency in magnetic receptivity trends among these various sites suggests a commonality in the climatic conditions experienced during the corresponding time periods. This synchronization in magnetic susceptibility patterns further supports the notion that these regions were subjected to comparable environmental changes and fluctuations in the past.

Additionally, the correlation observed between the magnetic receptivity data and the ^{18}O records underscore the close relationship between climatic factors and sedimentary deposition patterns across these sites (Figure 9). By examining these geological proxies, researchers can gain valuable insights into the past climate dynamics and variations that have affected the Northern Hemisphere over time.

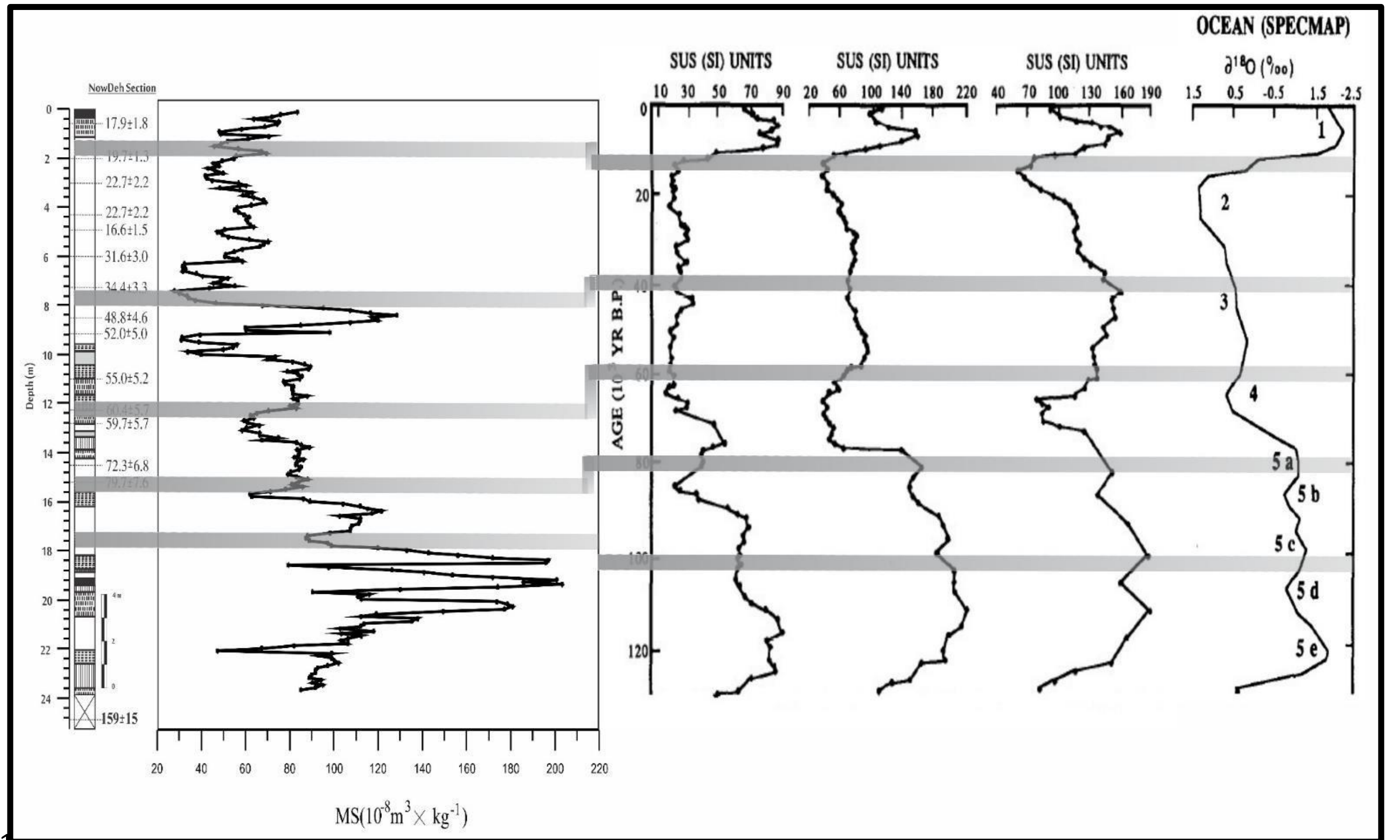

Figure 9: Comparison of magnetic receptivity changes of Beiyuan, Heimugou, Biampo, An et al, 1991, records of ^{18}O Imbrie et al, 1984 with Nowdeh sedimentary section

The findings of Mehdipour et al. in 2012 in the realm of fine loess exhibit a close resemblance to the results presented in our research, as illustrated in Figure 9. In their study, they employed both magnetic and geochemical approaches to assess different climatic periods, and the outcomes align significantly with the findings of Our research. The comparison in Figure 10 reveals a strong consistency in the magnetic receptivity trends between the Nowdeh section and the Neka sedimentary section analyzed by Mehdipour et al (2012). Between 48 and 20 thousand years ago, notable similarities are observed in the fluctuations of magnetic receptivity in both sedimentary sections. Whenever there is an increase in magnetic receptivity, it indicates a warm and humid period with the formation of ancient soil layers. This shared pattern implies a synchrony in climatic conditions between the two regions during this time frame, showcasing the utility of magnetic susceptibility as a proxy for understanding past environmental changes and soil development processes.

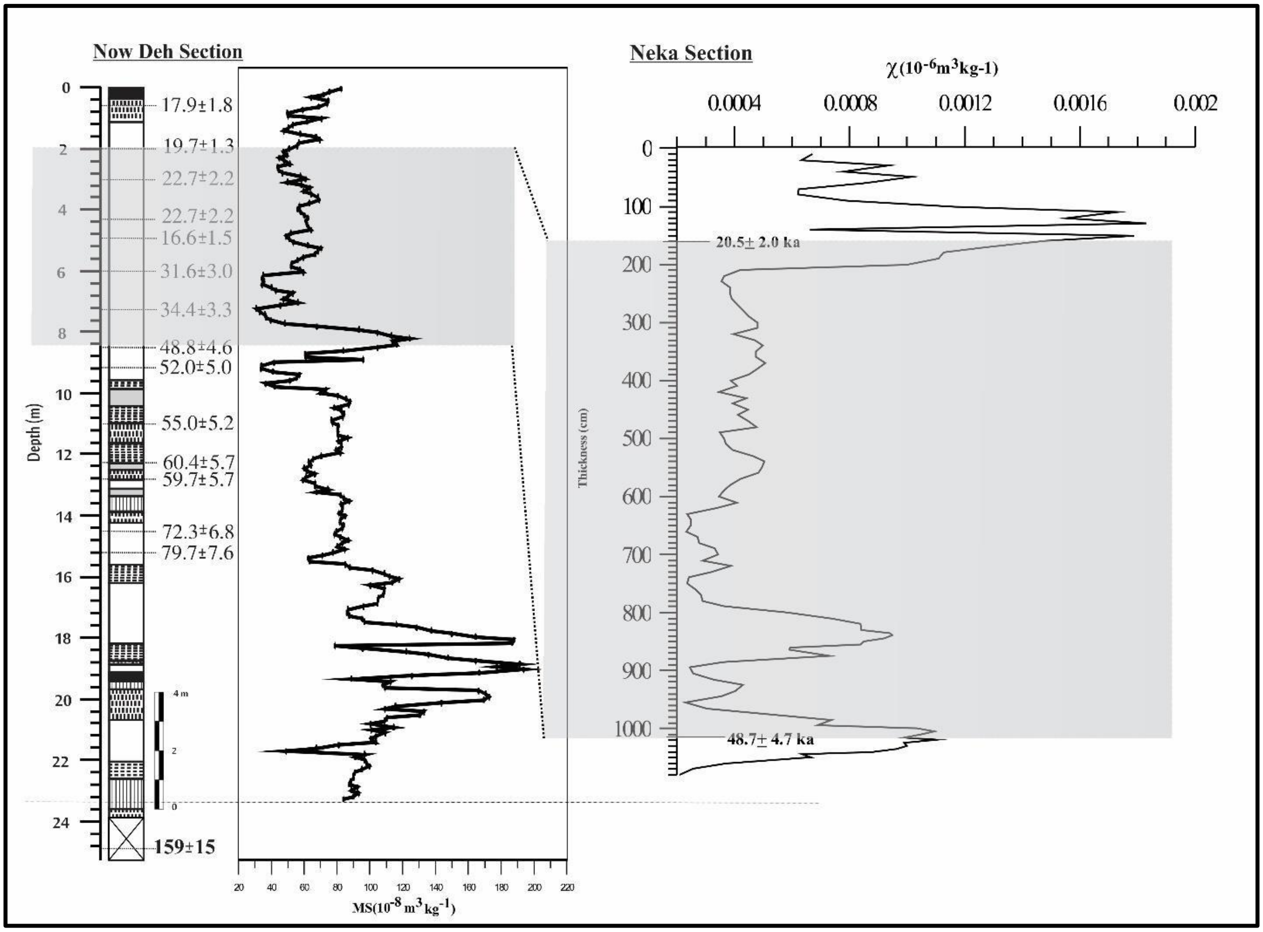

Figure 10: Comparison of magnetic receptivity diagram of Nowdeh sedimentary section with Neka sedimentary section (Mahdi et al., 2012)

The results of this research exhibit a strong consistency with the findings of Beer and Sturm (1995) regarding beryllium saturation in the Zaifang sedimentary section and ^{18}O in marine sediments. In both cases, there is a clear correlation between the fluctuations in beryllium saturation, ^{18}O, and magnetic receptivity.

When beryllium saturation and ^{18}O decrease, there is a corresponding decrease in magnetic receptivity, indicating colder and drier climate conditions. Conversely, an increase in beryllium saturation and ^{18}O is accompanied by an increase in magnetic receptivity, signifying warmer and more humid periods.

The high agreement between the climatic periods identified based on these parameters in the Zaifang sedimentary section and marine sediments, and the magnetic receptivity trends observed in the Nowdeh sedimentary section, highlights the synchrony of similar climate events in the past across different locations. This consistency further supports the robustness of magnetic susceptibility as a proxy for understanding past climate variations and environmental changes (figure 11).

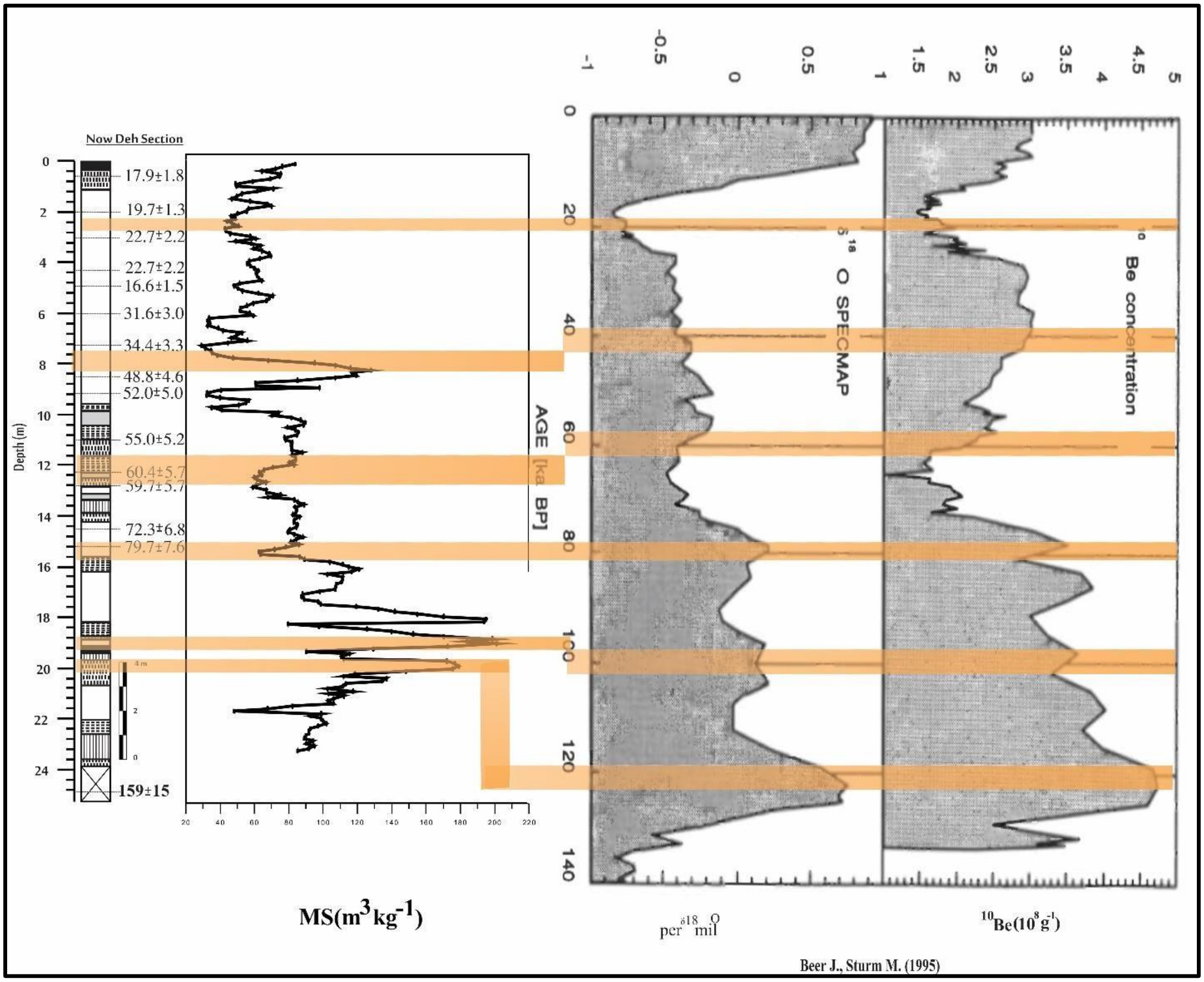

Figure 11: Comparison of magnetic receptivity results of Nowdeh sedimentary section in comparison with ^{18}O and Be 10 isotope results of Xifeng sedimentary section (Beer and Sturm, 1995).

Conclusion

In conclusion, the loess/paleosol sequences from Northeastern Iran serve as a valuable archive for studying the paleoenvironmental changes during the Upper Pleistocene. By employing a multi-proxy approach that integrates sedimentological, magnetic, and geochemical methods, the following key insights have been revealed:

1. The stratigraphy of the studied section aligns well with the typical pattern of Upper Pleistocene loess/paleosol successions in the region, providing valuable insights into the past environmental conditions.
2. Magnetic parameters show a strong correlation with climate conditions, making them effective variables for reconstructing climate change patterns in the region.
3. Comparisons between magnetic and geochemical data indicate that variations in geochemical weathering ratios mirror changes in magnetic weathering parameters, such as magnetic susceptibility, further enhancing our understanding of past environmental dynamics.
4. The high degree of coherence observed between the amplitudes of magnetic susceptibility and various geochemical ratios, including Rb/Sr, Mn/Ti, Zr/Ti, and Mn/Sr, reinforces the reliability of magnetic susceptibility as a proxy for tracking environmental changes and provides additional insights into the interplay between magnetic and geochemical processes.

Overall, this comprehensive multi-proxy analysis enhances our understanding of the paleoenvironmental changes in Northeastern Iran during the Upper Pleistocene period and emphasizes the importance of integrating sedimentological, magnetic, and geochemical data to unravel past climatic fluctuations and environmental dynamics.

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