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Pedogenic evidence of Urmia Lake's maximum expansion in the late Quaternary

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ABSTRACT

The Urmia Lake recession, and the resulting increase in vast barren area around it, has been rapid in recent decades and thus has attracted attention of environmentalists and geoscientists alike. However, evidence for its different strandlines and the largest extension of the lake during the late Quaternary has not been reported yet. The principal goals of the current research were to figure out pedological evidence of its maximum expansion during the late Quaternary and mapping out the different strandlines along the western shores of Urmia Lake over time. Thirty-two soil pedons at different landscape positions, geomorphic surfaces and distances from Urmia Lake were studied during autumn in 2013 and 2014. Micromorphological and mineralogical studies were performed for some diagnostic horizons. Results showed along the transect under study three different entities diagnostic of the lake's history (1) lithological discontinuities, (2) saline lacustrine sediments, (3) buried soils. However, almost 2 km from the closest pedon to the lake, no evidence of saline playa sediments were detected. Based on previous chronology results from Urmia Lake, which indicated high lake levels with very low salinity since about 180 ky BP, the sediments of this part of the study area were considered to have been deposited at the same period of time, indicating a maximum expansion of Urmia Lake during the late Quaternary. The current results demonstrate that soil pedons which were situated at various distances from Urmia Lake denote different stages of the lacustrine evolution. Along with the distance from the lake the development of soils increases. Due to a longer and more intensive impact of pedogenic processes on the topstratum the overall soil system becomes more "mature". The study of buried soils and their comparison to upper non-buried soils revealed that in some cases, the buried soils were more evolved than their upper soils or vice versa. Through these observations, the periods of exposure to soil-forming processes after each sedimentation period was detected and schematic diagrams illustrating periods of highstands and lowstands (recessions) of Urmia Lake were reconstructed. This study demonstrates that even though multiple episodes of lake recession were apparent, the level of Urmia Lake increased during hydroclimatic events conducive to lake expansion, which affected the soil evolution due to several fluctuations during the late Quaternary.

1. Introduction

Urmia Lake in the northwest of Iran is one of the biggest salt water lakes in the world (Zarghami, 2011). It evolved in a closed basin which has been rapidly drying out during the last three decades, leaving large barren playa deposits. Studies have shown that valuable climate fluctuation data can be found in the soils and stratigraphy of the playa deposits (Smol and Douglas, 2007; Dill et al., 2006; Dill et al., 2003.; Brauer et al., 1999).

A major way to investigate the past history of lakes (e.g., Urmia Lake) is to study the lacustrine sediments exposed due to the lakes' recession and subsequent soil evolutionary processes. Therefore, the study of soils that evolved along the margins of the playa can help us to understand whether they were developed in lacustrine or alluvial sediments and what the characteristics of the lake and climate were at that time.

Soil stratigraphic relationships can provide evidence of drier climates marked by soil development and wetter periods indicated by new lacustrine deposits (Colombo et al., 2016; Farzamnia et al., 2015; Solis-Castillo et al., 2015; Meier et al., 2014; Zucca et al., 2014; Khormali and Kehl, 2011). The presence of deeply buried soils can also indicate a drier climate during soil formation following a lake recession, followed

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by the deposition of new sediments as a consequence of a wetter climate (AhmadDar et al., 2015; Khormali and Kehl, 2011; Dill, 2006; Khormali et al., 2003; Magaldi and Tallini, 2000).

The study and understanding of paleosols that were formed under conditions different from those today (Amit et al., 1993; Ayoubi et al., 2006) could be used as an indicator of paleoclimatic conditions and as a tool to constrain the geomorphological processes prevailing at that time (Retallack, 2001; Tabor and Myers, 2015). Several studies revealed that climatic changes strongly affected the lake water level and were of fundamental significance of the size of lakes, thereby playing a major role in converting them into deserts (Zech et al., 2008; Yan et al., 2016; Lyons et al., 2014; Forzoni et al., 2015; Amman et al., 2001). The incidence of dry climatic periods during the Holocene has been demonstrated through studies of lacustrine sediments (An et al., 2011; Wang and Feng, 2013). Jacobs and Mason (2004) reported three sedimentation and soil formation periods as a consequence of climate change through a micromorphological study of Holocene paleosols in Nebraska, USA. Farpoor et al. (2012) related the presence of clay coatings and infillings in Sirjan Playa, south-central Iran to the wetter climatic conditions during the Holocene. Similar evidence of wetter climates was also reported in Isfahan and Gorgan provinces in Iran by Ayoubi et al. (2006) and Ziyaee et al. (2013), respectively.

Evidence of fluctuations in the Urmia Lake level during the Pleistocene is recorded in several terraces at several locations (Kelts and Shahrabi, 1986). Studies have also revealed the occurrence of lake level fluctuations of 1 to 3.5 m during the Little Ice Age (Kelts and Shahrabi, 1986; Sharifi, 2002; Alipour, 2006). However, no evidence of lake sediments are observed at elevations more than 5 m higher than the present lake level, indicating that the lake has never been much larger than its maximum recorded expansion during the past century (Alipour, 2006).

However, the latest recession of Lake Urmia was so close to the present that there has been little research on the longer-term fluctuations or soil development in the exposed sediments. Therefore, present research aimed at studying (1) the evolution of the soils affected by Lake Urmia's fluctuations of the water level and (2) the evidence of the maximum expansion of Urmia Lake and mapping out its different strandlines through time during the late Quaternary.

2. Materials and methods

2.1. Study area

The study area was located within the western part of the Urmia Lake basin in north-western Iran. It covered approximately 5000 ha of land both parallel and perpendicular to the lake, with varying degrees of salinity and distances. The western boundary of the study area was located on the piedmont plain and continued eastward for almost 11 km towards Urmia Lake with a change in elevation of approximately 25 m. The elevation in the study area (Fig. 1b) varied from 1274 m (close to Urmia Lake) to 1300 m (on the piedmont plain). The elevation variation within the area (Fig. 1c), was only a few meters (1274–1278 m) and topography was mostly flat. The mean annual precipitation was 367 mm. The mean annual temperature for the coldest month was −5.2 °C and for the warmest was 32 °C. The potential evaporation in the area was between 900 and 1170 mm. From the geological and geomorphologial point of view, the landforms in the study area were denominated as playa deposits, modern alluvial terraces and alluvial fans (Geological Survey of Iran, 1995) (Fig. 2). According to previous reports, the soil salinity in the area ranged from 0.7 $dS\,m^{-1}$ in agricultural lands up to 47 $dS\,m^{-1}$ in lands close to the lake (Hamzehpour et al., 2013; Hamzehpour and Bogaert, 2017).

2.2. Field studies

Based on topographic maps, Google earth images of the study area and field observations, five landform types distinguished from each other: (1) playa, (2) plain, (3) lowland, (4) flood plain, (5) piedmont plain (Fig. 3).

To investigate the soil types in the study area and to find out the role of Urmia Lake to have played in soil evolution, 27 soil pedons different as to their landscape positions, geomorphological surfaces, and distances from Urmia Lake were trenched, described and sampled during summer and autumn 2013. Each sample has been taken from diagnostic surface exposures and subsurface horizons. After physicochemical analysis of the soil samples, pedons were classified using the Soil Taxonomy classification system (Soil Survey Staff, 2014). A general landform map and locations of the studied soil pedons are shown on Fig. 4a.

On the basis of the spatial predictions of the boundary line between saline and non-saline soils in previous studies (Hamzehpour et al., 2013) (red line, Fig. 1b), the area for this investigation was chosen to include both sides of the estimated soil salinity boundary (Fig. 1c,). The hypothetical saline-non-saline soil boundary was based on the studies of Stevens et al., 2012. They reported that since 70 ky BP, Urmia Lake has been a saline playa lake. Therefore, one may conclude that all saline soils around the lake formed after 70 ky BP, and non-saline soils are older and were formed when the lake was less saline. With that in mind, five additional soil pedons (2, 4, 5, 6 and 8) close to the soil salinity boundary on different geomorphic surfaces were also studied during autumn in 2014 (Fig. 4b). Out of the soil pedons under study, pedon 1 (puffy ground), pedon 2 (puffy ground-salt crust), pedon 3 (saline clay flat), pedon 5 and pedon 6 (non-saline clay flat), and pedon 7 and pedon 8 (alluvial plain) (all along a transect perpendicular to Urmia Lake) (Fig. 5) were selected for an in-depth study, including the micromorphological and mineralogical features.

Using a satellite image of Urmia Lake from 1998 (the highest level of Urmia Lake during the past 100 years) (Fig. 6a), pedon 1 was chosen as part of the lake surface at that time (Fig. 6b). This could help to better understand the composition of the youngest lake sediments and soil evolution in the western margins of the lake. Pedon 2 was actually located at the shore and the other pedons were far from the lake shore in 1998 (Fig. 6b).

2.3. Laboratory studies

Soil samples were passed through a 2 mm sieve and then routine soil physicochemical properties were investigated. EC and pH were determined in saturated extracts (Rhoades, 1982); analyses of soluble ions (i.e. Na^+, K^+, Ca^{2+}, Mg^{2+}, Cl^-, and CO_3^{2-}) were performed using saturated extracts of soil samples (Rhoades, 1996).

Calcium carbonate equivalent (CCE) was measured using back titration of the remaining HCl (Page et al., 1992). Cation exchange capacity (CEC) was determined with ammonium acetate (1 N NH_4OAc) at pH (CEC-7) (Chapman, 1965). Soil texture was measured using a hydrometer method (Bouyoucos, 1962). Soil organic matter (O.M) was measured with acid digestion (Page et al., 1982). Exchangeable sodium percentage (ESP) and sodium adsorption ratio (SAR) were determined using Eqs. (1) and (2), respectively (Soil Survey Staff, 2014).

$$ESP = \frac{\text{exchangable Na (Cmol(+)}\cdot\text{kg}^{-})}{\text{CEC(Cmol(+)}\cdot\text{kg}^{-})} * 100 \quad (1)$$

$$SAR = \frac{\text{soluble Na(mmol(+)}\cdot\text{l}^{-})}{\sqrt{\frac{\text{soluble(Ca + Mg)(mmol(+)}\cdot\text{l}^{-})}{2}}} \quad (2)$$

Based on field observations and in order to gather evidence of pedogenic processes (e.g., clay coatings, buried horizons or calcic horizons) undisturbed soil samples were collected from seventeen pedogenic horizons of the selected pedons (1, 3, 5, 6, 7 and 8) for follow-up micromorphological studies. Vestpal resin with cobalt as a catalyst and stearic acid as a hardener was used to impregnate the soil