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# Soil and desert varnish development as indicators of landform evolution in central Iranian deserts

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ABSTRACT

Desert varnish (or rock varnish) and soils of Jiroft area, south central Iran play a crucial role in the evolution of landforms in this arid setting containing mantled pediments, rock pediments, inselbergs, alluvial fans, alluvial plains, and flood plains. Mantled pediment contains three stable, semi-stable, and unstable surfaces as indicated by desert varnish and soil development properties. However, alluvial fan could be divided into apex and mid fan settings based on slope position. Mid-fan settings include both stable and unstable surfaces, based on varnish properties. About 100 rocks containing varnish were selected randomly on each geomorphic surface. In addition, a representative soil pedon was described and sampled on each surface for a total of 10 pedons. Results of the study show that brown to black coatings of varnish with the cation exchange capacity (CEC) range of 8.5–21 $cmol_c kg^{-1}$ were composed of <0.2–50 μm particles. Magnetic susceptibility of varnish samples fluctuated between 300 and 1855 $10^{-8}$ $m^3$ $kg^{-1}$ and Si, Ca, Al, Fe, and Mg concentrations were 26.4, 3.9, 3.8, 3.1, and 2.2%, respectively. Age and development indices such as cation-ratio of desert varnish (with the range of 6.14 to 14) and activity ratio of $Fe_o/Fe_d$ (with the range of 0.03 to 0.35) of soils decreased with increasing stability of geomorphic surface and soil development. Chlorite, smectite, illite, palygorskite, and kaolinite clay minerals exist in the clay fraction of studied soils. In addition, chlorite, smectite, vermiculite, sepiolite, illite, palygorskite, kaolinite together with zeolite, quartz, and feldspar tectosilicates were found in desert varnish. Cation-ratio of varnish and activity ratio of $Fe_o/Fe_d$ in different geomorphic positions together with soil properties provide a simple method to study the evolution of landforms in this warm desert setting.



## 1. Introduction

Desert varnish (or rock varnish) is a unique geomorphic phenomenon that forms on the exposed surface of pavements in desert area landforms. Desert varnish is a dark coating with the thickness range of <5 to 600 μm and is composed of about 30% Fe and Mn oxides, up to 70% phyllosilicate clay minerals, and >12 trace and rare elements (Potter and Rossman, 1977; Potter and Rossman, 1979). The dark coating of desert varnish forms slowly (1–40 μm $ky^{-1}$) on stable surfaces by continuous accretion of mineral particles, during the centuries (Watchman, 2000; Liu and Broecker, 2000). Components deposited in desert varnish of an area have external sources and normally are deposited by dust sedimentation from atmosphere (Goldsmith et al., 2014). Local and regional compositional variations in dust storms, climatic fluctuations, and erosional and depositional processes are among the data that could be reflected by desert varnish components (Watchman, 2000). That is why desert varnish has been used as a dating technique by geomorphologists to determine the relative date of landforms in desert regions.

Cation-ratio dating is a relative and correlative age index of landforms used in geomorphologic studies in the past several decades (Dorn, 1983; Harrington and Whitney, 1987; Peterson et al., 1995). The technique was developed as a result of consistent and systematic trends in elemental ratios of desert varnish. The leachable cations including Na, Mg, K, and Ca are gradually either replaced by less mobile cations such as Ti or depleted in some cases. Decrease of (Na + Mg + K + Ca)/Ti or (Ca + K)/Ti cation-ratios could be used as a tool to determine the length of time the desert varnish has been exposed to leaching; hence, this decrease is a time index of the beginning of desert varnish formation at a stable geomorphic surface (Watchman, 2000).

Moreover, Soils that rest underneath varnished surfaces provide an independent perspective for geomorphologists interested in landscape evolution. Abundant research in different geomorphic settings in Iran reveals the power of soil to interpret landscapes. For example, focusing on soil

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landscape relationships in central Iran, Farpoor and Irannejad (2013) and Nadimi and Farpoor (2013) reported that argillic horizon in soils of plain and stable surface of alluvial fan formed during a more humid paleoclimate. Furthermore, Gunal and Ransom (2006) also concluded that clay illuviation and formation of clay coatings in soils of Kansas region is consistent with landscape stability. Moreover, research in Loot Desert, central Iran showed that salic, gypsic, petrosalic, and petrogypsic horizons developed in playa soils, but non-developed Entisols only formed on young pediment surfaces (Nooraee, 2010). Studying soils related to geomorphic positions in Sirjan area, central Iran, Farpoor et al. (2012) found out that developed soils containing petrocalcic horizon were only formed on the stable surface of playa transition. They also reported the presence of petrocalcic horizon in soils of that area as the first report of petrocalcic horizon in Kerman Province, southeast Iran which was formed just on a stable geomorphic surface.

Prior research has sometimes compared varnish chronometric information to soils (e.g. Peterson et al., 1995). However, no prior research has compared cation-ratio results in varnish to soil chemistry. Still, soil chemistry has considerable potential to inform on chronometry and environmental change. For example Layzell and Eppes (2013) reported $Fe_o/Fe_d$ ratio as an index of development for Holocene soils formed on alluvial deposits of Conejos River valley, southern Colorado. Maejima et al. (2002) used crystallinity and activity ratios of free iron oxides to determine age of developed soils on coral reef terraces in southwest Japan; in particular, they showed that the crystallinity ratio of free iron oxides [$(Fe_d\text{-}Fe_o)/Fe_t$] increases and $Fe_o/Fe_d$ activity ratio decreases with increasing the stage of soil development, respectively.

Moreover, clay mineralogy may also be used as an indicator of soil genesis and landform stability. Finding large amounts of palygorskite in different layers of yardangs in Loot Desert central Iran, Farpoor and Krouse (2008) concluded that the old surface of Loot plain was formed under shallow hypersaline water conditions of the past. Similarly, Farpoor and Irannejad (2013) reported a close and mutual relationship between clay mineralogy and stability of geomorphic surfaces of the Aliabbas River alluvial fan, central Iran. Thus, the investigation and mode of formation of smectite, kaolinite, chlorite, illite, and palygorskite clay minerals all show potential to understand the evolution of soils on landforms of different ages.

Given the potential for independent chronometric indicators within varnish and also the underlying soil, the purpose of this research rests in evaluating these two independent chronometric tools in a warm desert setting. In particular, this research offers a unique contribution to the soils and varnish literature by comparing the chemical and mineralogical changes in both varnish and the underlying soil. In particular, hypothesizing the relationship between soil properties and desert varnish characteristics related to geomorphic surface stability, researchers focused on: 1) morphological, physical, and chemical properties and clay mineralogy of desert vanishes in Jiroft area of Iran, 2) capability of using cation-ratios of desert varnish for relative dating and geomorphic surface stability determinations, 3) soil development related to geomorphic surfaces, 4) correlation between desert varnish and soil development and surface stability, and 5) evolution of landforms in study area.

## 2. Materials and methods

### 2.1. Study area

The study area in central Iran, about 10,000 $km^2$, rests in Jiroft area, south of Kerman Province, Iran (Fig. 1). A warm desert climate with mean annual precipitation of 140 mm and an annual mean temperature of 25 °C. Soil moisture and temperature regimes in the area are aridic and hyperthermic, respectively (Van Wambeke, 1986).

### 2.2. Fieldwork

#### 2.2.1. Geomorphic surface investigations

Different landforms in the area were mapped using topographic (1:25,000) and geologic (1:100,000) maps, Google Earth imagery, and field studies. Rock pediments, mantled pediments, inselbergs, alluvial fans, flood plains, and alluvial plains comprise the dominant landforms. Using desert varnish characteristics (varnish color) and soil profile description and development, mantled pediments were subdivided into three geomorphic surfaces including stable, semi-stable, and unstable. Alluvial fans were mapped as surfaces: apex based on slope position and mid-alluvial fan surfaces were subdivided into stable and unstable surfaces according to the characteristics of desert varnish such as color (Fig. 1).

#### 2.2.2. Desert (or rock) varnish sampling

About 100 rocks (igneous felsic origin) containing desert varnish were randomly selected from each of the studied geomorphic surfaces. Desert varnish only forms on the upward face of the rock that shows no displacement and movement during varnish formation (Perry, 2004). The selected rocks were washed with distilled water and ethanol, respectively. The desert varnish was scraped off the rocks using a tungsten-carbide needle with the aid of a hand lens (20×), and the amalgamated desert varnish sample from multiple clasts on a surface were then used for physical and chemical analyses.

#### 2.2.3. Soil sampling

One representative pedon (Fig. 1) on each geomorphic surface was selected, described, and sampled (Schoeneberger et al., 2012) for soil development studies. The air-dried soil samples were crushed and passed through a 2 mm sieve for physicochemical analyses. Soils were classified using World Reference Base (WRB) system (IUSS Working Group WRB, 2015).

### 2.3. Laboratory studies

#### 2.3.1. Desert (or rock) varnish analyses

"Standard Soil Color Charts" (Oyama and Takehara, 1970) determined desert varnish color. A pipette method was used for particle size analyses of desert varnish samples (Gee and Bauder, 1986). Magnetic susceptibility of varnish samples was determined by Barrington Instruments MS2 system with MS2B sensor at 0.46 kHz frequency. Varnish cation exchange capacity (CEC) was investigated by substitution of sodium acetate by ammonium acetate 1 N, pH = 7 (Bower and Hatcher, 1966). Chemical composition of desert varnish samples was determined using ICP-OES, Varian 735 equipment after samples were amalgamated by lithium borate fusion (Delijska et al., 1988). A cation-ratio of (Ca + K)/Ti was then calculated for each geomorphic surface (Dorn, 1983). Citrate-bicarbonate-dithionite (CBD) extractable (sum of crystalline and non-crystalline) iron (Mehra and Jackson, 1958) and ammonium oxalate extractable non-crystalline iron (Schwertmann, 1973) of varnish samples were investigated using an atomic absorption, Varian equipment.

#### 2.3.2. Soil analyses

Volume percentage of coarse fragments (Soil Survey Staff, 2014), pH of saturated paste (Jenway pH meter), and electrical conductivity (EC) of saturated extract (Jenway EC meter) were also determined in soil samples. Pipette method was used for particle size analyses of soil samples (Gee and Bauder, 1986). Equivalent calcium carbonate of soils was determined by back titration method (Nelson, 1982). Gypsum + anhydrite (Nelson, 1982), gypsum (Artieda et al., 2006), and anhydrite (Wilson et al., 2013) were also investigated in soil samples. The same methods were used for CBD and ammonium oxalate extractable iron analyses. Flame photometry (Gammon, 1951) for soluble Na, and complexometry (Ringbom et al., 1958)