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Red Mediterranean Soils in Jordan: New insights in their origin, genesis, and role as environmental archives

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ABSTRACT

It is disputed whether Terrae Rossae form mainly out of the bedrock residue, from allochthonous material like aerosols, or by isovolumetric replacement. Furthermore, whether they are mainly relic soils or are still forming is subject to debate. These questions were addressed by comparing the geochemistry of several limestone and basalt based Red Mediterranean Soils with Lithosols on sandstone and limestone in Jordan. The bedrock residue was included at all test sites. Paleosols and initial soils on the limestone Regolith of historic ruins delivered insights into the possible time frame of soil development. A major reduction of elements in the soils compared to bedrock could be observed for CaO in carbonaceous, SiO_2 in arenaceous, and Fe_2O_3 and MgO in basaltic rocks. All Terrae Rossae, however, are characterised by a significant increase of SiO_2, Al_2O_3, TiO_2, Fe_2O_3, K_2O, and a range of mainly metallic minor elements that cannot be derived from the bedrock. A reasonable explanation could be input via aeolian transfer of minerals, with clay minerals as the major carrier plus quartz. This input probably originates in Egypt and Sudan and has remained largely unchanged over long periods. Growing aridity during the Holocene has apparently increased the share of silt while clay deposition and soil development has been reduced. At some sites, metasomatic processes have contributed to soil development and might help to explain the depth of some profiles. However, formation of red soils during the Holocene seems very limited, and the Red Mediterranean Soils may represent remains of a paleolandscape.

1. Introduction

Many soils in Jordan are characterised by their red colour. Despite the ubiquitous occurrence of these soils, there is no general agreement on their origin, genesis, and age. Discussion centres particularly on their parent material: do these soils mainly represent the non-soluble residue of the underlying bedrocks, or are they largely derived from allochthonous material? Depending on which classification system is used, they are attributed to several soil groups, or are referred to as own group characterised by their colour (Red Mediterranean Soils or Terrae Rossae). The latter terminology was used mainly in older studies (e.g. Moormann, 1959; Reifenberg, 1947), which to some degree is connected to the fact that more sophisticated classification systems had not yet been developed. However, previous studies have demonstrated that the terms "Terra Rossa" and "Red Mediterranean Soil" can still be useful due to their simplicity (Lucke, 2008). "Terra Rossa" is restricted to red soils developed on limestone (Reifenberg, 1947), while "Red Mediterranean Soils" include red soils on any parent material — such as basalt or sandstone — which occur in a Mediterranean climate zone (Moormann, 1959, 23).

This paper evaluates red soils in Jordan with regard to their genesis and parent material. In order to avoid confusion and for the sake of simplicity, we largely use the soil terminology applied by Moormann (1959) and prefer the more general term "Red Mediterranean Soils" (RMS). We decided to use a comparative approach, in which soils developed on limestone are compared with soils and paleosols on basalt, sandstone and other limestone soils in the 150–500 mm annual precipitation zones. The likelihood of allochthonous deposition is evaluated by comparing the rocks and overlying soils. The location of the study sites along climatic gradients and inclusion of paleosols permits some conclusions about the role of climate for RMS development.

The prevailing explanation of the genesis of Red Mediterranean Soils on limestone was first presented by Zippe et al. (1854) and Leiningen (1930), who suggested that the red clay resembles the residue of calcareous rocks. Terrae Rossae could be the result of limestone dissolution by meteoric water, which is supported by studies from Slovakia (Bronger et al., 1984), Italy (Moresi and Mongelli, 1988), China (Ji et al., 2004a, 2004b; Shijie et al., 1999), and Turkey (Temur et al., 2009). At these locations the mineral assemblies and

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geochemistry of the red soils were largely identical to the non-calcareous residue of the underlying limestones.

A purely residual origin of the RMS requires the dissolution of large amounts of limestone (from several metres to many decametres, depending on the purity of the limestone) to form 1 m of soil, which appears questionable at some locations. It has been suggested that Terrae Rossae formed mainly during warm and moist periods, for example under the tropical climate conditions of the Tertiary, and are preserved as Vetusols (Meyer, 1979). However, Skowronek (1978) pointed out that the present occurrence of Terrae Rossae in Spain cannot be associated with earlier geological periods. According to him, a more recent formation of this soil type may have been possible under Garrique vegetation. In addition, there are important differences between the Terrae Rossae in the Mediterranean and current red tropical soils such as Nitisols and Ferrasols. While the latter are characterised by a high kaolinite content and leaching of silicates, the Terrae Rossae in the Mediterranean are characterised by silica enrichment and by clay mineral assemblages which are often dominated by less weathered clay minerals such as smectite.

Already Leiningen (1915) stated that the mineral assemblies of Terrae Rossae often contain allochthonous components. Yaalon and Ganor (1973) suggested that atmospheric Saharan dust settling with precipitation is the main parent material of Terra Rossa in the Near East. This theory was supported by Danin et al. (1982), who found fossil marks of lichen on limestone under a Terra Rossa, indicating that the rock had been exposed to sunlight before it was covered by soil. Studies in Indiana, U.S.A. (Ruhe and Olson, 1980), Croatia (Durn et al., 1999), the West Indies (Muhs, 2001; Muhs et al., 2007; Prognon et al., 2011), Wisconsin, U.S.A. (Stiles and Stensvold, 2008), and Spain (Muhs et al., 2010) also found that the soils were derived from allochthonous material because the geochemical composition of the investigated Terrae Rossae differed significantly from the underlying limestones. However, Jahn (1995) showed that the amount of aerosols in circumsaharian soils varied according to the climate, wind systems, and distance to the desert. In the Golan Heights, which are close to the sites investigated in this study, no more than 20% of the soil mass can be attributed to aeolian deposition.

Other studies found that both of the above mentioned parent materials, allochthonous (aeolian) sediments and residues produced by in-situ weathering of carbonate rocks, have contributed to Terra Rossa development at locations in Spain (Delgado et al., 2003; González Martín et al., 2007), Morocco (Bronger and Bruhn-Lubin, 1997), Mexico (Cabadas et al., 2010; Cabadas-Báez et al., 2010), Jordan (Lucke, 2008; Schmidt et al., 2006) and China (Feng and Zhu, 2009). According to Schmidt et al. (2006), the distribution of Terrae Rossae and Red Mediterranean Soils in Jordan indicates that these soils cannot be the exclusive product of aeolian deposition or carbonate rock weathering, but that the underlying rocks *and* allochthonous sources must play a role in their formation. In this context, a combined contribution of the bedrock and aerosols to the genesis of Red Mediterranean Soils would be present if a metasomatic genesis is assumed. This would significantly reduce the required volume of limestone bedrock for the formation of 1 m of soil. A metasomatic origin was first proposed by Blanck (1915), who suggested that the diffusion of clay-forming elements into the pores of calcareous rocks, and the precipitation of iron out of the soil–water at the rock–soil contact zone, can lead to the replacement of limestone in a pressure-driven reaction. This reaction produces acids that further dissolve calcium carbonate. The soil-forming elements would be supplied from allochthonous sources: overlying soil horizons or aeolian sediments. Using micromorphology, Merino and Banerjee (2008) identified a metasomatic front at the rock–soil transition zone of a Terra Rossa in Bloomington, Indiana, U.S.A., and developed a thermodynamic model describing the replacement reaction. Their model agrees with Blanck (1915), stating that a super-concentration of cations in the rock pore solution triggers clay mineral growth and a subsequent pressure-driven replacement of the limestone. This process also leads to a release of acids, which explains the association between Terra Rossa and karst. Similar replacement features were described for several Terrae Rossae in Jordan by Lucke et al. (2012). Close investigation of the rock–soil contact zones of different limestones with a Scanning Electron Microscope (SEM) equipped with energy-dispersive systems (EDS) made it possible to identify a jelly-like mass of apparently amorphous clay minerals that partially replaced microfossils and calcite plates (Lucke et al., 2012).

According to Blanck (1915, 1926), Terrae Rossae prevail under Mediterranean climate where soils contain little amounts of organic matter, because humus provides a “colloid” that prevents flocculation when the iron-bearing ions come in contact with the calcareous bedrock. Therefore red iron-bearing elements would be more likely to precipitate in soils of Mediterranean climates with lower humus contents. Reifenberg (1927, 1947) argued that the elements driving the growth of clay minerals were not supplied by external sources, but by ascending water from the underlying calcareous rocks. In his model, silicic acids rather than humus provide the “colloid” that prevents flocculation of sesquioxides prior to the ascension of ions into the rock pores and the soil. It is now generally assumed that the red colour of Terrae Rossae is due to strong moisture fluctuations which cause unstable ferrihydrite to form hematite (Cornell and Schwertmann, 2003). Although this process has not yet successfully been simulated in laboratory conditions, there is widespread agreement that the colour of Red Mediterranean Soils is not the result of intense weathering or very moist and warm climates in the past, but is rather typical for Mediterranean climates, and is sometimes the result of limestone dissolution, because the pre-weathered non-soluble residue might be already red. In this context, it could be shown that the rubefication process could be reversed if the soils came under a moister hydroregime, because hematite dissolves preferentially over goethite (Boero and Schwertmann, 1987). Red soil formations on Pleistocene sediments in Germany, however, demonstrate the possibility that Terra Rossa development could have taken place during the Holocene in axeric temperature areas (Schwertmann et al., 1982; Semmel, 1988).

Most soils in the Mediterranean climate zone of Jordan are dominated by red or reddish-brown colours. The distribution of soils in Jordan closely follows the climate and topography. Specific soil orders can be found within the dry and hot subtropical, subhumid–semiarid, semiarid–arid, and arid regions. In addition, the bedrock and relief position play an important role for soil distribution (Schmidt et al., 2006). The climate varies over a distance of less than 100 km from sub-humid Mediterranean conditions in the north-western part of the country to arid desert conditions in the east. The geological structure consists of layered and weakly folded limestone and sandstone, which are at some places capped by basalt flows (Bender, 1974).

Earlier investigations described a diverse pattern of Red Mediterranean Soils that seems closely connected with climate and the geology. Moormann (1959) stated that completely de-calcified Red Mediterranean Soils are only present in areas with precipitation of 600 mm or more, such as the Ajloun mountains. RMS in areas with 350–600 mm annual precipitation show increasing amounts of calcium carbonate. In areas with less than 350 mm rainfall, RMS occur only as paleosols. There are slight differences between RMS on limestone, basalt and sandstone, which are mainly reflected by the skeleton content. The skeleton content consists of limestone and chert fragments on limestones, and basalt and caliche fragments on basalt. Regarding RMS on sandstone, Moormann assumes that these are products of weathered mica-bearing sandstone that were mixed with “limestone dissolution clay” (Moormann, 1959, 23–26).

Schmidt et al. (2006) and Lucke (2008) found a similar connection between the geology and climate in the occurrence of RMS. They noted, however, that completely de-calcified RMS can not only be found in areas with 600 mm or more annual precipitation, but also