Catena 119 (2014) 154–165

Contents lists available at ScienceDirect

Catena

journal homepage: www.elsevier.com/locate/catena

Genesis and evolution of the fragipan in Albeluvisols in the Precarpathians in Ukraine

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A R T I C L E I N F O

Article history:
Received 27 March 2013
Received in revised form 18 January 2014
Accepted 21 February 2014
Available online 17 March 2014

Keywords:
Fragipan
Albeluvisols
Quantitative X-ray diffraction
Micromorphology
Precarpathians

A B S T R A C T

The fragipan (Bx) is a subsurface soil horizon restricting the penetration of roots and infiltration of water due to its high bulk density, low total porosity, and discontinuous voids (so-called closed box system). Additionally, the pan is characterized by a hard or very hard consistence when dry, but brittle when moist. The genesis and evolution of the fragipan have been the subject of many research studies, and numerous theories and models concerning these issues can be found in the literature. The principal aims of this study were to: 1) explain the genesis of the fragipan in Albeluvisols in the Precarpathians in Ukraine, basing on micromorphological studies and quantitative mineral composition analyses and 2) propose a model of pan formation and evolution under moderately humid climate conditions. The abundance of clay coatings and clay infillings as well as iron–clay cutans within the studied fragipan indicates that the formation of the pan is related to the translocation of colloids (clay minerals and iron hydroxides) from upper soil horizons. This leads to the filling of voids in the Btx horizon and a decrease in the porosity and hydraulic conductivity of the pan. The enrichment of the fragipan in clay minerals (especially in swelling clay minerals) is responsible for the subsequent degradation of the pan due to wetting and drying, leading to the swelling and shrinking of soil material. The occurrence of many Fe–Mn nodules and a mottled color indicates cyclical wetting and drying within the studied fragipan. In effect, vertical cracks are formed, which serve as pathways for water infiltrating down the soil profile. The water washes out weathering products (iron oxides and clay minerals) from soil material adjacent to the cracks. This leads to the formation and development of bleached tongues along the vertical cracks, which penetrate the fragipan.

1. Introduction

The fragipan (Bx) is a subsurface soil horizon restricting the penetration of roots and infiltration of water due to its high bulk density, low total porosity, and discontinuous voids (so-called closed box system) (Bockheim and Hartemink, 2013; Ciolkosz et al., 1995; IUSS Working Group WRB, 2006; Lindbo and Veneman, 1989; Lindbo et al., 1994; Smeck et al., 1989; Van Vliet and Langohr, 1981). Furthermore, the pan is characterized by a hard or very hard consistence when dry, but brittle when moist (Soil Survey Staff, 2010; Szymański et al., 2012; Witty and Knox, 1989). The fragipan does not exhibit cementation because its air-dried clods slake immediately once immersed in water (IUSS Working Group WRB, 2006; Lindbo and Rhoton, 1996; Soil Survey Staff, 2010). The occurrences of vertical, bleached tongues forming polygonal patterns in the horizontal section, numerous Fe–Mn nodules as well as a mottled color of soil material are all characteristic morphological features of the fragipan (Jha and Cline, 1963; Lindbo and Veneman, 1989; Lindbo et al., 1995; Miller et al., 1971; Szymański et al., 2011).

The genesis and evolution of the fragipan are the subject of many research studies, and numerous theories and models concerning these issues can be found in the research literature. Some of these attribute to the formation of the pan to processes leading to the densification of soil material due to a so-called hydroconsolidation of soil material, because of its oversaturation with water and collapse under its own weight (Assalay et al., 1998; Bryant, 1989; Certini et al., 2007; Scalenghe et al., 2004). Knox (1957), Yassoglou and Whiteside (1960), Hutcheson and Bailey (1964), Lindbo and Veneman (1989), Aide and Marshaus (2002) and Szymański et al. (2011) claim that the main process leading to the formation of the pan is the translocation of clay minerals from upper soil layers to the lower part of the soil profile (so-called lessivage). According to Harlan et al. (1977), Norton and Franzmeier (1978), Steinhardt and Franzmeier (1979), Steinhardt et al. (1982), Franzmeier et al. (1989) as well as Duncan and Franzmeier (1999), the genesis of the fragipan is connected with the translocation of amorphous silica from the upper part of the soil profile and its subsequent accumulation in the lower horizons. Others (e.g. Hallmark and Smeck, 1979; Karathanasis, 1987, 1989; Norfleet and Karathanasis, 1996)

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http://dx.doi.org/10.1016/j.catena.2014.02.011
0341-8162/

indicate that the translocation of amorphous aluminosilicates is responsible for the formation of the Bx horizon. Ajmone-Marsan and Torrent (1989) maintain that fragipans showing the accumulation of silica and goethite are better developed relative to other pans, suggesting that the translocation of SiO_2 with iron hydroxides plays a crucial role in the formation of the pan. Smeck et al. (1989) proposed that the formation of the pan is related to a so-called "weathering front" found along the contact of the two parent materials (showing various stages of weathering) and the precipitation of weathering products (clay minerals, iron and aluminum oxides as well as amorphous silica) within voids of the soil profile. The research literature also provides some theories linking some of the already mentioned processes (e.g. Ciolkosz et al., 1995; Weisenborn and Schaetzl, 2005b).

The principal aims of this study were to: 1) explain the genesis of the fragipan in Albeluvisols in the Precarpathians in Ukraine, basing on micromorphological studies and quantitative mineral composition analyses and 2) propose a model of pan formation and evolution under moderately humid climate conditions.

2. Materials and methods

2.1. Study area

The research was carried out in the Precarpathians in southwestern Ukraine. The study area, which is the outer part of the Eastern Carpathians, is shown in Fig. 1. Interstratified layers of sandstones, siltstones and shales forming the so-called Carpathian flysch are the main bedrock in the study area. The Carpathian flysch is mantled by loess, which does not contain carbonates and serves as the parent material for the studied Albeluvisols. Such loess is often called loess-like deposits due to the lack of carbonates, however in this work it is called loess because this material meets all the criteria of loess (with the exception of carbonate content) (Maruszczak, 2000). The lack of carbonates in the loess, its slightly acidic pH (5.0–6.0), and the domination of swelling clays in the clay fraction are the most important factors (together with humid climate), which are responsible for the translocation of clay fraction down the soil profile (Gunal and Ransom, 2006; Kühn et al., 2006; Quénard et al., 2011; Seta and Karathanasis, 1996, 1997). In many cases, the clay illuviation is observed down to the underlying residue of flysch (Nikorych et al., 2013). The study area is characterized by moderately humid climate conditions with mean annual temperature ranging from 6 to 8 °C, and mean annual rainfall between 650 and 800 mm (National Atlas of Ukraine, 2007). Detailed data for monthly air

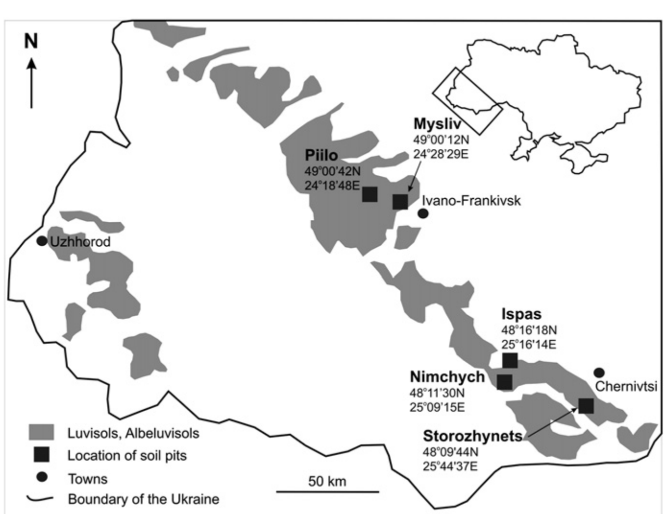

Fig. 1. Location of the investigated soil profiles and occurrence of Luvisols and Albeluvisols in the southwestern part of Ukraine.
Based on Polchyna (2012).

temperature and precipitation is given in Table 1. The study area is largely agricultural, but large parts of the area remain covered by deciduous, mixed and coniferous forests with oak (*Quercus* sp.), beech (*Fagus sylvatica* L.), fir (*Abies alba* Mill.), hornbeam (*Carpinus betulus* L.), lime (*Tilia cordata* Mill.), larch (*Larix decidua* Mill.), and willow (*Salix* sp.) (Nesteruk, 2000).

2.2. Field and laboratory methods

Five representative soil profiles in the investigated area were selected from 20 profiles for a detailed analysis. The location of the pedons studied is shown in Fig. 1 and selected information concerning the study sites is summarized in Table 2. The study profiles are covered by deciduous (Piilo profile), mixed (Nimchych, Ispas, and Mysliv profiles) and coniferous (Storozhynets profile) forests, and formed entirely in loess. The exception is the Storozhynets profile — the lowermost part of which is formed from the residue of Carpathian flysch. All of the studied profiles were excavated on steep or gentle slopes with variable exposure (Table 2).

The soil profiles were excavated and sampled. One large bulk sample was taken from each genetic horizon and subsamples were taken from bleached tongues present within the fragipan. In addition, undisturbed soil samples were taken from each genetic horizon for micromorphological studies. In the laboratory, the samples were air dried, crushed with a wooden rolling pin, and screened through a 2 mm steel sieve. Soil organic carbon content was determined using the Tiurin titrimetric method (Nelson and Sommers, 1996). The pH of the soil was measured using a 1:2.5 soil/distilled water ratio (Thomas, 1996). The total of exchangeable bases was determined using 0.1 M HCl and extractable H and Al in 1 M KCl (Summer, 1992) by titration of extracts (after boiling for 10 s) with 0.1 M NaOH in the presence of phenolphthalein. The concentration of amorphous Fe and Al was determined in ammonium oxalate extracts (prepared according to the procedure given by Van Reeuwijk, 2002) via the colorimetric method using 1.10-phenanthroline (Fe) (Jackson, 1969) and aluminon (Al) (Hsu, 1963). A set of sieves (for sand fractions) and a hydrometer method (for silt and clay fractions) were used for the determination of particle size distribution (Gee and Bauder, 1986). Bulk density and total porosity were determined by means of the core method (Blake and Hartge, 1986). The color of the moist soil material was described using the Munsell color soil charts. Shrinking of soil material was conducted on fine earth soil material (fraction <1 mm). The soil material was placed on a glass plate and moistened with distilled water. Then the soil material was dried at room temperature (~22 °C).

Micromorphological observations and analyses were conducted in thin sections under a polarizing microscope (Nikon Eclipse E600POL). The thin sections were prepared using a standard procedure (e.g. FitzPatrick, 1984) and described according to the terminology given by Stoops (2003).

X-ray diffraction (XRD) was used to determine the mineral composition of the studied Albeluvisols. Quantitative mineral composition analyses were conducted on bulk soil samples (<1 mm), which were ground in a McCrone micronizing mill for 10 min with Baker ZnO (catalog no. 1314-13-2) as an internal standard, under ethanol (2.7 g of soil sample and 0.3 g of ZnO were used). The ground mixtures were side-loaded to obtain random powder mounts and analyzed from 2 to 65°2Θ at a counting speed of 0.02°/5 s. Quantitative XRD analysis was performed using the Seifert Rietveld AutoQuan/BGMN computer program (Taut et al., 1998). XRD data from 15 to 65°2Θ were used for the quantification. In addition to bulk samples, separated clay fractions (<2 μm and <0.2 μm) were also studied. The separation of the clay fractions was done by centrifugation after the removal of carbonates and divalent exchangeable cations using an Na-acetate buffer, organic matter (using 10% hydrogen peroxide) and free iron oxides (using Na-citrate–bicarbonate–dithionite solution) according to a procedure given by Jackson (1969). One part of the separated clay fractions was saturated with K^+ and the second part was