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Multidisciplinary study of a Holocene sedimentary sequence near Bologna (Italy): insights on natural and anthropogenic impacts on the landscape dynamics

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Multidisciplinary study of a Holocene sedimentary sequence near Bologna (Italy): insights on natural and anthropogenic impacts on the landscape dynamics

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Abstract

Purpose This study investigated a Holocene sedimentary sequence evolved from a small catchment located at San Lazzaro di Savena in the surroundings of Bologna Emilia (Northern Italy), in which different buried soil horizons were detected in order to delineate the physiografic evolution of the area.

Material and methods Several disciplinary/analytical approaches including pedostratigraphy, geochemistry, radiocarbon dating, archaeobotanical investigation and $^{13}C/^{12}C$ stable isotopes analyses that were taken into account for the pedosequence characterization.

Results and discussion This multidisciplinary approach allowed us to identify the main factors that affected the ancient environment along a prolonged time interval (~ 12 ky); starting since 14 ky BP with a paleosoil

ascribed to the Bølling period, cold-arid conditions characterized by a steppic vegetation gradually evolved toward a more humid (and slightly warmer) setting. This climatic change allowed the development of a forest constituted by abundant conifers at ca 10 ky BP. Humans also impacted the environment, at least since 9 ky BP, as indicated by repeated traces of firing (plausibly for deforestation and clear land).

Conclusions The observed data suggest that human impact on the landscape could have been effective starting from the Mesolithic period, earlier than usually considered by previous studies. These anthropogenic activities favoured geomorphological and hydraulic instabilities, accelerating soil erosion within the basin as indicated by the increase of the estimated sedimentation rates and change in the type of geochemical, mineralogical and textural properties of the studied soils. The data allow a comparison with findings provided by other neighbouring sites and contribute to the ongoing debate on the relationships between climatic and anthropogenic impacts on the landscape dynamic.

Key words: Holocene sediments; pedolology and geochemistry; ^{14}C dating and palynology; $\delta^{13}C$ and carbon speciation, climatic changes;

1 Introduction

The interactions between anthropogenic activities and the environment have been correlated throughout the human history. Since the early times, man has modified the environment (e.g. agriculture, grazing, use of fire) (Woodward, 2009 and references within), but in turn anthropogenic activities have been deeply influenced by climatic variability and environmental changes, as demonstrated by paleoenvironmental studies that have shown correlations between climate changes and cultural collapses (Diamond, 2005).

Holocene climate in Europe was punctuated by numerous short-term cold events (Magny et al., 2006; Fleitmann et al., 2007; Yu et al., 2010; Wiersma and Jongma, 2010; Miller et al., 2010; Giraudi et al., 2011; Zanchetta et al., 2012) and these climatic changes were also recorded throughout the Mediterranean region even if their effects varied widely due to local microclimate factors (e.g. Joannin et al., 2013).

According to these climatic variations, during the Middle Holocene, starting from at least 8 ky BP, in many sites of the Northern Apennines the natural vegetation experienced pronounced changes (Branch and Marini, 2013). The initiation and expansion of pastoralism (e.g. leaf foddering) and cultivation further contributed to affect vegetation changes. In several Apennine sites burned biomass were recorded suggesting that burning was the main deforestation approach for land clearing. The record of these changes was however rarely preserved in mountain areas, lacustrine basins, and widespread floodplains. Indeed it can be better recorded in the foothill sedimentary sequences generated by streams having very small catchments. In this study we investigated a Holocene sedimentary sequence evolved from a small catchment located in Emilia Romagna (Northern Italy), in which different buried soil horizons were detected. A multidisciplinary approach was thus carried out in order to assess the relative impact of climatic changes and possible anthropogenic activities in our study area. Our data give new insights for the scientific debate on the early role of human forcing on the environment. The topic is extremely important considering that recent findings highlight the reiterated presence of hominines in the Emilia Romagna Region (Muttoni et al., 2011; Fontana et al., 2013), followed by documented and recurrent settlements of the Bronze age (Vittori-Antisari et al., 2011; 2013). We show that detailed multi-proxies investigations (including pedostratigraphy, geochemistry, radiocarbon dating, pollen and $^{13}C/^{12}C$ stable isotopes analyses) are useful tools for the assessment of the factors that at local scale affected the ancient environment. Results and assumptions were finally compared with those obtained from neighbouring sites in order to delineate hypotheses valid at regional scale.

2 Geological-geomorphological setting and insights on ancient human settlements

The study site, located in the Municipality of San Lazzaro, 5 km eastward of Bologna, covered an area of about 2,000 square meters (44°28’17” N, 11°24’34” E), at an elevation of 62 m above sea level, in a recently urbanized area (Figure 1). It is located at the foothill of the Apennine hills and is crossed by the Via Emilia which is an important route since Roman ages. In particular, the study initiated in connection to a building excavation that reached the depth of ca 5.5 m, allowing careful field observations and sampling (Figure 1). From the geomorphological point of view, the building site is located at the outlet of a little hilly catchment crosscut by a creek known as *Pontebuco stream.* The area consists in a gently sloping alluvial fan (hereon defined *Pontebuco stream* fan: PSF), 0.9 km^2 wide, hosted between the fan apexes of more important rivers such as Savena and Zena.

Although the manmade modifications performed after the II World War prevent a detailed recognition of minor landforms, in general the fan topographic surface doesn’t show traces of bed entrenchment, suggesting an almost continuous aggradation of the fan structure. Another manmade feature is the prominent break in slope (ca 20 m/km) characterizing the northern roadway side of the Via Emilia, located less than 100 m south of the studied stratigraphic site (Fig 1: point 1), due to the diachronic maintenance works performed on the ancient roman route. Upstream, the Pontebuco stream catchment is composed by the little valleys of two tributaries flowing mutually parallel. These tributaries are incised 15-30 m in the foothill and 70 m in the valley head. The whole catchment is on average 3 km long and 0.5-0.6 km large, with local widening related to ancient slide scars (Fig. 1A). It is reasonable to think that the catchment inception could be dated at around 50-100 ky BP (e.g., Farabegoli et al. 1994), but it is unlikely that the most ancient PSF sedimentary phases can be recognized due to the sediment mixing with that of the major fans of neighbouring - more important - rivers Savena and Zena .

From the geological point of view, the PSF apex is precisely located at the foothill hinge, where a vertical tilting is still developing, as result of the mountain chain rising coupled to the alluvial plain subsidence (Amorosi et al. 1996; Stramondo et al. 2007; Cremonini 2014). This narrow belt corresponds at depth to the buried Apennine chain main frontal thrust (Martelli et al. 2009; Boccaletti et al. 2011; Picotti et al. 1997; Picotti and Pazzaglia, 2008).

Lithologically, PSF sediments are generally fine grained and the top of the gravel deposits, ascribed to the Last Glacial Maximum Savena-Zena fluvial system, is lying at ca 9 m below the topographic surface (Martelli et al. 2009). The understanding of sources of the fan sediments requires some information concerning the outcropping lithologies. The upper reach of the Pontebuco stream catchment (Fig. 1) is characterized by the outcrop of Pliocene-Lower Pleistocene marine clays (*Argille Azzurre Formation*: FAA) (Martelli et al. 2009) in turn overlain by a limited thickness of Lower-Middle Pleistocene littoral sands (*Sabbie di Imola* Formation: IMO) (Amorosi et al. 1998) outcropping down valley. In the foothill terraces zone (Fig. 1, point 3) these formations are in turn covered by variously weathered alluvial sediments (*Unità di Bazzano top*) that are 5-7 m thick.

The S. Lazzaro foothill physiographic environment is quite rich in archaeological sites spanning from the Palaeolithic to the protohystory (Nenzioni 1985). No data are known concerning the Roman settlement at S. Lazzaro, but this silent record can possibly be attributed to burial of the ancient topography.

Outcrops preserving ancient traces of human activity have been recorded in the local alluvial sediments (Cremaschi et al., 1987). Moreover, in the PSF, 200 m northward of the studied stratigraphic site (Fig. 1, point 2), a 76000 m^2 wide brick-earth quarry (*Fornace Galotti*) excavation removed the natural sediments up to a depth of more than 5 m allowing to recover archaeological artefacts spanning from the Palaeolithic up to the Villanovan periods, i.e. the first Iron Age (Nenzioni 1985). During the 20th century some scientific excavations were performed in this quarry recording two peculiar archaeo-stratigraphic settings. The first one was a small streambed (3 m large, 1 or 2 m deep), SE-NW directed, found at a depth of 2.5 m below ground level (bgl; Lenzi and Nenzioni 1996, Fig. 1: point 2). Its sandy channel bottom facies contained poorly reworked elements of Clactonian and proto-Levallois lithic industries, probably eroded by the foothill terraces. The second archaeo-stratigraphic setting recorded Villanovan age graves (2800-2600 BP) lying between 2 and 2.7 m of depth, thus referring to a coeval ground surface buried at about 1.5 m of depth (Scarani 1963). These settings represent two stratigraphic benchmarks useful to constrain the stratigraphic log of the studied site.

3 Materials and methods

3.1 Stratigraphic observations and soil sampling

The field observation allowed the distinction of stratigraphic units and buried soil horizons which have been preliminarily characterized in the field for layer morphology, thickness, particle size distribution, colour and other textural characters. From the pedological point of view the buried soils were described according to Schoenebergeret al. (2012) and a sequence of 16 horizons has been recognized and sampled collecting about 1 kg of material from each horizon. A parallel sampling was performed for archaeobotanical (12 samples) and radiocarbon analyses (3 samples) as detailed below.

3.2 Soil analysis

The soil samples were air dried and sieved with a 2 mm mesh sieve. The particle size distribution was determined by the pipette method after dispersion of the sample with a sodium hexametaphosphate solution (Gee and Brauder, 1986). The pH value was potentiometric determined in a 1:2.5 (w/v) soil:distilled water suspension with a Crison pH-meter. The electrical conductivity (EC) was also performed in a 1:2.5 (w/v) soil:distilled water suspension with a Orion conductivity-meter. The carbonate content was measured by volumetric analysis of the carbon dioxide released by a 6 M HCl solution (Loeppert and Suarez, 1996). The total organic C and N has been determined by an elemental CHNS-O EA 1110 Thermo Fisher Scientific; soil samples were weighted in silver pot and treated with HCl to eliminate the inorganic C.

Representative soil samples were selected for mineralogical characterization. The constituent mineralogical phases were identified by X-ray diffraction (XRD) by means of a Philips PW1860/00 diffractometer, using graphite-filtered CuKα radiation (1.54 Å). Diffraction patterns were collected in the 2θ angular range 3–50°, with a 5 s/step (0.02 2θ). Soil samples were also analyzed by X-ray fluorescence spectrometry (XRF) as described by Di Giuseppe et al. (2014). The technique enables the identification and quantification of major (SiO_2, TiO_2, Al_2O_3, Fe_2O_3, MnO, MgO, CaO, Na_2O, K_2O, P_2O_5, expressed in weight percent) and trace (Ba, Ce, Co, Cr, La, Nb, Ni, Pb, Rb, Sr, Th, V, Y, Zn, Zr, Cu, Ga, Nd and Sc expressed in mg kg-1) elements. Samples (~ 10 g) were preliminarily quartered and then finely powdered using an agate mortar. Subsequently, an amount of about 4 grams of powder were pressed with addition of boric acid by hydraulic press to obtain powder pellets. Simultaneously, 0.5-0.6 grams of powder were heated for about 12 hours in a furnace at 1000° C in order to determine the LOI value (Loss On Ignition). This parameter measures the concentration of volatile species contained in the sample. The analysis of the powder pellets was carried out using an ARL Advant-XP spectrometer, properly calibrated analyzing certified reference materials. Precision and accuracy calculated by repeated analysis of numerous international standards having matrices comparable with those investigated, i.e. felsic igneous rocks such as granitoids (AC-E, G-2, GA, GH, GS-N, GSR-1, GSP-1) and rhyolites (JR3, RGM1), and various typology of sedimentary rocks (JDO-1, JLK-1, JLS-1, JSD1, JSD2, JSD3), and were generally better than 3% for Si, Ti, Fe, Ca and K, and 7% for Mg, Al, Mn and Na. For trace elements (above 10 mg kg^{-1}) errors were generally better than 10%.

Further investigations were obtained using a "Elemental, VARIO MICRO cube" analyzer (combustion mode set at 950 °C) for the analysis of the weight percent of carbon coupled with an Isotopic Ratio Mass Spectrometer (IRMS) Isoprime100 for the analyses of the carbon isotope ratios ($^{13}C/^{12}C$). The carbon isotopic composition is given as δ‰ units, with respect to the values of notional standard, which is PDB (Pee Dee Belemnite): $\delta‰=(R_{sample}-R_{standard})/R_{standard}\times1000$. The reproducibility and accuracy of spectrometric measurements were controlled by the repeated analyses of laboratory standards. The average $\delta^{13}C$ standard deviation was ±0.1‰ (Natali and Bianchini, 2015). Analyses were repeated at combustion temperature of 450 °C to measure the carbon content and isotopic signature of the organic matter.

3.3 Radiocarbon datings (^{14}C)

The radiocarbon datings (^{14}C) were performed by high resolution mass spectrophotometry (AMS) technique. The method described by Calcagnile et al. (2005) and Fiorentino et al. (2008) included a preliminary treatment of the samples following a multi-step protocol that removed sources of contamination and converted material in graphite, the form suitable for AMS analyses. The carbon isotopic ratios were then analysed by comparing the ^{12}C and ^{13}C ion beam currents (and in turn the $^{13}C/^{12}C$ ratio expressed as $\delta^{13}C$) and the ^{14}C counts for the investigated samples with those obtained for reference materials (e.g.: the fossil wood IAEA C4) of known isotopic composition supplied by the International Atomic Agency (IAEA). The conventional radiocarbon ages were calculated according to Stuiver and Polach (1977), and then converted to calendar ages by using the latest internationally accepted calibration dataset (INTCAL04; Blackwell et al. 2006) and the OxCal 3.1 software (Bronk and Ramsey 2001).

3.4 Archaeobotanical analysis

3.4.1 *Pollen analysis*

Palynological analyses were carried out applying a methodology already tested for pollen substrates with some minor modifications (Lowe et al., 1996). The method includes the following phases: about 8-10 g were treated in 10% Na-pyrophosphate to deflocculate the sediment matrix. A *Lycopodium* spores tablet was added to calculate pollen concentration (expressed as pollen grains per gram = p/g). The sediment residue was subsequently washed through 7 micron sieves and then re-suspended in HC1 10%for remove calcareous material and subjected to Erdtman acetolysis; heavy liquid separation method was then introduced using Na-metatungstate hydrate of s.g. 2.0 and centrifugation at 2000 rpm for 20 minutes. Following this procedure, the retained fractions were treated with 40% HF for 24 h and then the sediment residue was washed previously in distilled water and after in ethanol with glycerol; the final residue was desiccated and mounted on slides by glycerol jelly and finally sealed with paraffin. This method preserves the slides for many years after preparation and therefore it is suitable for pollen extractions from geological and archaeological samples. Identification of the samples was performed at 1000 light microscope magnification (ocular 10× and objective 100×). Determination of the pollen grains was based on the Palinoteca of our Laboratory, atlases and a vast amount of specific morpho-palynological bibliography. Names of the families, genus and species of plants conform to the classifications of Italian Flora proposal by Pignatti (1982) and European Flora (Tutin et al. 1964-1993). The pollen terminology is based on Berglund and Ralska-Jasiewiczowa (1986), Faegri and Iversen (1989) and Moore et al. (1991) with slight modifications that tend to simplify nomenclature of plants. The term "taxa" is used in a broad sense to indicate both the systematic categories and the pollen morphological types (Beug 2004). Identified pollens (between 300 and 400 grains) have been expressed as percentages of the total.

3.4.2 *Microanthracological analysis*

The same samples prepared for pollen analysis were also investigated for the identification of microcharcoals. Microanthracological analysis has been used to understand past fire events mostly connected to anthropogenic activities. Point count estimation of microscopic charcoal abundance was carried out, and charcoal fragments encountered during pollen counting were recorded in four size classes, based on long axis length (10-50 µm, 50–125 µm, 125-250µm, >250µm) (Whitlock and Millspaugh, 1996; Clark 1982; 1997; Patterson et al. 1987; Whitlock and Larsen 2001). The former two classes are thought to be wind-blown transported hence giving informations concerning the regional fire events, whereas the latter two are considered the result of local vegetation burning.

3.4.3 Anthracological analysis

During the excavation 26 carbonized trunks (from 30 to 50 years old) were found at 3.84 m depth (Fig. 2); in the field were collected subsamples with a size of about 2.5-5.0 cm3 for the identification. In laboratory they were identified using a reflected light microscope with the help to the anthraco-xylological reference collection and on the keys and atlases (Grosser 1977, Hather 2000, Jacquiot et al. 1973, Schweingruber 1990).

3.5 Statistical analysis

A multivariate statistical approach has been useful to investigate the multi-elementary chemical data provided by XRF of the considered horizons highlighting chemical analogies and differences between the samples, and delineating different sample groups. In this study, we used a combination of Principal Component Analysis (PCA) to correlate the measured parameters. A comprehensive mathematical/statistical description of the method is provided by Jolliffe et al. (2002). Through PCA, the observed elemental correlations were grouped in a small number of factors that account for most of the variance of the considered dataset. In particular, this elaboration was carried out by the SPSS (Release 17.0, Lead Technologies, demo version), using Varimax with Kaiser Normalization as rotation method, as suggested by Facchinelli et al. (2001). On the basis of eigenvalues greater than one, four factors were selected for explaining 86.9% of the cumulative total variance.

4 Results

The Figure 2 synthesizes the multidisciplinary results obtained in this study. More detailed information concerning the various type of results were reported in the distinct paragraphs reported below. Although no significant archaeological items were found, the archaeological survey suggested the possible existence of three topographic surfaces characterized by human frequentation, buried at 1.85, 3.47 and 4.75 m of depth, respectively (Figure 2). The former level recorded some sherds probably dating to the Iron Age. The latter two levels did not record any trace of archaeological materials, but are characterized by postholes-like traces.

4.1 Stratigraphy and soil sequences

Down to a depth of 5.5 m below ground level the stratigraphic study highlighted four main distinct sedimentary sets, probably representing different sedimentary phases, where distinct soils have been recognized and described in Table 1 according to Schoeneberger et al. (2012)

From a stratigraphic viewpoint the site showed a horizontal, tabular layering very slightly dipping eastwards. The first set was recognizable down to the depth of 1.85 m, while the other three were separated by marked discontinuities at the depths of 3.65 m, 4.45 m, 5.25 m, respectively.

The uppermost set (including S1-S5 soil samples) consisted in a fining upward sequence with the sandy basal layer (35 cm thick) laterally continuous for tens of metres, possibly related to a splay deposit from an unconfined water current, thus resembling an alluvial fan lobe rather than a lateral crevasse splay. The sand layer contains granules and very small cherty pebbles suggesting that the clastic particles come from the *Sabbie di Imola* formation (IMO; Figure 1B). Some rounded fragments of Roman Age bricks were also found in the sand basal layer. The profile of this set was formed by the following horizons: Apb/ABcb/Bwcb/C1/C2 (from S1 to S5 soil samples; Fig. 2). The Bw horizon was recognized by both root sheaths and prismatic soil structures (Table 1), whereas C1 (S4) was a horizon with a natural high amount (50%) of rounded rock fragment and a coarse (sand) texture. Below the lower limit (C2 soil horizons) of this set a sharp lithological discontinuity was observed.

The second set (samples S6-S10), down 3.65 m, had a quite homogenous silty-clay texture (Table 1) and was characterized by a 2Bcb/2Bcssb1/2Bcssb2/2Bckb1/2Bckb2 sequence of horizons. Almost all the horizons were characterized by many mottles, a blocky angular structure, with sticky consistence, carbonate nodules/concretions and without skeleton. Hard breaking strength distinguished the dried samples, that were also characterized by presence of slickenside (S7 and S8 layers) having at least 4 cm^2 extention; the S9 and S10 soil samples (corresponding to 2Bckb1and 2Bckb2 horizons) were characterized by pedogenetic carbonate nodules. At the boundary between S9 and S10, at the depth of 3.35 m, a bone fragment was found, while a charcoal useful for ^{14}C dating was sampled between 2Bcb and 2Bcssb1 (S6 and S7 soil samples, respectively; Figure 2).

The third set (down to 4.45 m of depth) consisted of variously darkened layers (S12 and S13) and its upper limit was marked by the lithological discontinuity in the 3Bcb horizon (S11 soil sample). The 3Bcb horizon was characterized by the presence of carbonate masses of primary origin (i.e. residues of the parent material). The S12 and S13 layers were coded as 4Ab1 and 4Ab2 due to the textural change with marked increase in the clay content (silty-clay texture; Table 2) with respect the overlying horizon, highlighting the presence of another lithological discontinuity; furthermore, some features like a dark colour (10YR5/3 and 10YR4/2, respectively), hard consistence and plastic character and also carbonate masses and concretions were observed. A burnt tree was sampled between these two horizons.

The fourth set (down to the bottom of the excavation, including S14-S15 samples) was characterized by a change of texture (clay-loam) identifying a further lithological discontinuity. Granular structure, dark colour (10YR3/3) and mottles (10YR5/6) characterized the S14 horizon, whereas S15 showed reddish colour

(2.5Y6/6) with mottles (10YR6/8) and a subangolar blocky structure. These features suggested 5Ab and 5Bwcb horizons sequence, respectively. In the deepest S16 horizon, an additional discontinuity marked by a further change in the texture (loam) was detected. Yellowish brown colour, with presence of mottles (10YR6/8) and carbonate nodules allowed to code this horizon as 6Bwcb (Figure 2 and Table 2).

4.2 Physico-chemical soil properties

The Table 2 shows the main physicochemical soil properties. The pH values ranged from 7.6 to 8.2; generally the total carbonate content was low (from 9 to 60 g kg^{-1}), increasing only in the horizons marking sharp lithological discontinuities (103 and 153 g kg^{-1} for S11 and S16, respectively). The organic C content ranged from 1.4 to 8.3 g kg^{-1}; the C1 and C2 layers had the lowest organic C amount <2 g kg^{-1}, whereas the highest organic C content was detected in the lowest Ab horizons (S12, S13, and S14 samples coded as 4Ab1, 4Ab2 and 5Ab horizons, respectively).

The box plots of Figure 3, obtained for the different sets of samples recognized along the stratigraphy, show an increase of pH values in the second and third sets, associated to a slight increase of carbonate. An increase of organic C and total N along the depth of sequence is also noticed. The sand and clay contents confirmed the existence of lithological discontinuities already observed during the field survey.

The mineralogical composition of the first three sets has been investigated by X-ray diffractometry (XRD). In the most superficial set (sample S2) the dominant mineral phase was quartz, with only minor sporadic amount of calcite and phyllosilicates, whereas in the second (sample S8) and third (sample S12) sets the amount of quartz decreased, while calcite and phyllosilicates progressively increased (Figure 4).

The geochemical composition expressed by the amount of major and trace elements (Table 3) reflected the differences in the mineralogical composition observed in the distinct sets. Elaboration of these data by Principal Component analysis (PCA) allowed to identify the geochemical analogies and differences between soil samples of the distinct sets. In fact, the defined sets broadly corresponded to homogeneous families having distinctive geochemical features (Figure 5), suggesting that the pedological sequence ranging from S1 to S5 had a homogeneous geochemical affinity. A second homogeneous family extended from the layers S6 to S10. The deeper part of the excavation was less homogeneous and from the geochemical point of view differences between S12 -S13 and S14-15 horizons were observed.

High content of quartz fitted with the very high SiO_2 content (65-78 wt%) of the first set, and comparatively low Al_2O_3 (<15.8 wt%) and CaO (<0.95 wt%) percentage confirmed the low amount of phyllosilicates (such as clay minerals) and very low carbonate content. The second set, from S6 to S10 samples, was totally different from the more superficial first set due to the lower SiO_2 content (55.3-61.1 wt%) and higher Al_2O_3 and CaO amount (15.8-17.8 and 1.0-6.1 wt%, respectively), thus confirming the greater content of phyllosicates and calcite that was recorded by XRD. The soil samples of this set were also enriched in many trace elements such as Ni, V, Sc, Rb, Ba, La, Nd, Th, Nb (Table 3; Figure 6) that can be hosted by phyllosicates such as smectite, chlorite and other accessory femic minerals. Within the second set, SiO_2 percentage decreased systematically from the most superficial horizon (2Bcb) to the deepest one (2Bckb2), whereas on the contrary CaO (and Sr) content increased.

The difference in SiO_2, Al_2O_3, CaO between S12-S13 (55.4-58.2 wt%, 17.7-17.8 wt%, 1.6-3.0 wt% for S12 and S13, respectively) and S14-S15 samples (61.9-62.8 wt%, 16.4-16.9 wt%, 1.3-1.5 wt%, for S14 and S15, respectively) suggested that these horizons belonged to distinct sedimentary phases. The trace element distribution (Figure 6) seemed to further support this hypothesis.

The deepest investigated sample (S16) seemed a further independent soil, which reflected a significant presence of geogenic carbonates testified by very high Ca and Sr content.

The elemental-isotopic results of both total C (C_{tot}) and organic C (C_o) carried out on the studied pedostratigraphic sequence are reported in Table 4 and Figure 7. C_o should complement the inorganic carbon fraction C_i (that can be inferable by the $CaCO_3$ content of Table 2) and the sum of two fractions (C_o+C_i) should be conformed to the measured C_{tot} as following: $C_o+C_i=C_{tot}$.

It can be observed that the $C_{tot,}$ content varied between 0.9 and 2 wt%, while the related $\delta^{13}C$ ranged between -11.4 and -24.7 ‰ (Table 4). These C_{tot} isotopic values were the result of mixing between organic matter (usually characterized by strongly negative isotopic values) and carbonates which were characterized by $\delta^{13}C$~ 0 ‰. Coherently, the less negative isotopic values marked perfectly the carbonate-rich horizons. The carbon isotopic composition of the organic fraction had a much more homogeneous $\delta^{13}C$ between -23.6 and -25.2 ‰.

A misfit between the measured C_{tot} and the calculated one (C_o+C_i) was also investigated, and this deficiency (ΔC) was recorded in the most superficial S1 horizon and in the horizons S12, S13, S14. This parameter highlighted the presence of a further carbon fraction that was not recorded, plausibly represented by black (elementary) charred carbon. The elementary carbon detected in the deep S12, S13, S14 was probably related to fires and biomass burning (i.e. burnt trees).

4.3 ^{14}C Datings

The studied stratigraphic sequence contained very few materials suitable for radiocarbon dating: the uppermost sample was represented by charred carbon fragments of the sample S6 (Figure 2); an intermediate sample was a large fragment of mammal bone that was lying between S9 and S10, while the deepest material was represented by combustion residua of tree trunks collected in correspondence of the S12 (Figure 2).

The obtained 1σ confidence level, calibrated ^{14}C datings provided ages of 6660-6530 y BP, 8330-8190 y BP, and 9270-9090 y BP.

At a first instance, these values are positively correlate with a downward trend whose end-member was the deepest paleosol which should have an age of ca 14-15 ky BP (see below). However, the most recent radiocarbon age (6660-6530 y BP) in horizon S6 is diachronic with the finding of Villanovan artefacts which should correspond to ca 2800-2600 y BP. The temporal gap between the radiometric age and the archaeological constraint has to be taken into account and will be discussed in the next section.

4.4 Archaeobotanical analysis

4.4.1 *Pollen analysis*

Pollen grains were found in all samples in a good state of preservation, allowing the identification of most of the cases. In total 3850 pollen grains were counted. Pollen concentrations were variable depending on the richness of organic matter and the preservation conditions. They ranged from 10^2 to 10^3 p/g most samples, and only the samples S15, S14 and S4 were comparatively poor of pollen grains (less than 10^2 p/g).

The pollen flora, consisted of 92 types (31 trees, shrubs, lianes and 61 herbs) and is synthetized in Figure 2. The sample S16 was characterized by high presence of *Compositae* family (81.2%) especially *Cichorioideae* and *Asteroideae*, followed by *Gramineae* spontaneous group (6.7%) with only low percentages of *Pinaceae* (1.8%). *Dryas octopetala* pollen grains were also detected (1.2%). This pollen grains association indicates a landscape developed on steppic conditions (dry and cold) typical of late glacial period.

The samples S15 and S14 revealed a high percentage of *Pinus*, followed by *Cichorioideae* and *Gramineae* spontaneous group which indicates a transition between the steppic condition delineated above and a landscape dominated by conifers, possibly occurred in the Preboreal period.

The sample S13 (the lowest horizon of the third stratigraphic set), containing more pollen grains (and more pollen species), showed a drastic decrease of *Cichorioideae*, a more diversified association of *Pinus* species coupled with the appearance of *Quercus* deciduous (especially *Quercus* cf. *robur*), *Ostrya carpinifolia/C. orientalis*, *Fraxinus excelsior*, *Tilia*, *Ulmus* and *Corylus*. This rich biodiversity suggests an important climatic change with the establishment of more temperate conditions. Noteworthy, this horizon corresponds to the surface where the burnt oak trees were rooted and it can be assigned to the Preboreal (ca. 11.7-10 ky BP).

The samples S12, S9 and S8 were characterized by a further increase of coniferous pollens; in particular S12 corresponded to the part of the sequence where the burned wooden logs (9270-9090 cal y BP) were found. These horizons were characterized by the significant presence of linden and white fir, which plausibly ascribe them to the Atlantic period (Accorsi et al. 1996, 2004).

In the sample S9 and S8 the decrease of *Pinaceae* taxa was connected with an increase of *Corylus*, *Ulmus* and *Tilia*, which could suggest a weak opening in the vegetation cover. This process was accompanied by the presence or expansion of taxa indicative of human impact (e.g. *Cerealia*).

In the sample S6 an increase of *Compositae* (45.8%) coupled with *Plantiginaceae*, *Ranuncolaceae* and *Sparganiaceae*/*Typhaceae* and also *Gramineae* spontaneous group and *Leguminosae* (about 4.2% for each species) has been observed.

The vegetation suffered a further sharp change in correspondence of sample S2 (first stratigraphic set) where it can be observed an additional anthropogenic influence demonstrated by high *Cerealia* diffusion with the presence of pollen grains of both *Hordeum* and *Avena-Triticum* groups, together with pollen grains ascribed to *Triticum* cf, *spelta* and *Secale cereal*. Further proxies of human activities were represented by *Chenopodiaceae, Plantago*, *Rumex, Urtica dioica*, etc.

4.4.2 *Microanthracological analysis*

Among the 12 studied samples, the total micro-charcoal concentration of 10 samples was lower than 0.5 mm^2/g; this concentration plausibly represents representing the local background. Samples S13 and S12 contain a decidedly higher micro-charcoal concentration (8.9 and 4.9 mm^2/g, respectively). Micro-charcoal grains in S13 were characterized by 10-125 μm and is ascribed to a regional fire event, whereas micro-charcoal grains in S12 contain both the 10-125 and >125 μm size classes possibly indicating a local fire event. Therefore the local, direct burning effect is highlighted by sample S12, whereas the evidence of sample S13 could be assigned to an to independent (older) burning effects from a neighbouring area and/or to post-depositional processes reworking the grains of the overlying horizons.

4.4.3 *Anthracological analysis*

The charcoal analysed comes from 26 burnt trunks; generally the charcoal was found in a better state of preservation. The anthracological flora include 2 taxa: *Quercus* cf. *robur* (16 anthracological records) and *Quercus* undiff. (6 anthracological records); 4 anthracological remains are not undeterminable. All of them are regional deciduous oaks.

5 Discussion

The studied stratigraphic suite developed in an alluvial environment along the PSF longitudinal axis generated by a few kilometres scale catchment. The sedimentary record began since the last Late Glacial period, as indicated by the integration of pollen, radiocarbon and soil data. In particular, the pollen analysis can provide clues on the past climatic conditions and chronological thresholds (Orombelli and Ravazzi 1996).

The sedimentation rates in the studied site were calculated using the sediment thickness and the chronological data (Fig. 2; Table 1). In these calculations, we considered the radiocarbon ages, the conventional ages of 14.5 ky BP for the Bølling paleosoil, 3 ky BP for the Iron Age, and 2 ky BP for the top of the natural sequence. The sedimentation rates (mm/y) resulted to be 0.2 during Late-Glacial and Preboreal (samples S15 to S12), 1.2 during Boreal/Atlantic (Mesolithic: samples S12 to S9), 0.8 during the Atlantic (samples S9 to S6), 1.4 during the Late-Antiquity (samples S5 to S1). Although aware that estimations can be influenced by the Sadler effect, implying lowering of the sedimentation rates for investigation of longer/older time spans (Bianchini et al. 2014), we suggest that in the studied sequence a significantly increase of the sedimentation rate occurred since the Mesolithic. The high sedimentation rate recorded during the Boreal/Atlantic period was plausibly due to higher erosion rate within the Pontebuco stream catchment, preferentially affecting the outcropping area of the *Argille Azzurre* Formation (marly-clays). The more marked sediment supply to the Pontebuco stream, in turn favoured a more effective aggradation of Pontebuco stream fan (PSF). These conditions were probably triggered by more marked precipitations.

The basal sample S16 sample characterized by significant amount of geogenic carbonate (high percentage of Ca and Sr) and by the presence of pioneer herbaceous taxa usually considered "aridity markers" (i.e. *Artemisia*) coupled with *Dryas octopetala*, suggest a cold and arid environment. In our view, S16 can be attributed at least to the Older Dryas period (ca. 15 ky BP) for its stratigraphic location below the horizon S15 which is characterized by typical Bølling soil features. This steppic vegetation is recorded in numerous regional pollen records of the same time period (Watts et al. 1996; Magri and Sadori 1999; Ammann et al. 2000; Denefle et al. 2000; von Grafenstein et al. 2000; Allen et al. 2002; Bordon et al. 2009; Kotthoff et al. 2008; Combourieu-Nebout et al. 2009; Fletcher et al. 2010; Desprat et al. 2013) indicating that cold-arid climate conditions were prevailing over the whole Mediterranean basin and especially in the Padanian/Adriatic basin.

In fact, the overlying soil S15 can be considered a benchmark soil assigned to the final part of the the Bølling period (ca. 15-14 ky BP) related to more wet and warm climate conditions (Frisia et al. 2005; Baroni et al. 2006). It is well known that similar climatic conditions have led to the development of Xeralf (Soil Survey Staff 2014) named in Emilia-Romagna Region as *Vignola Unit soil* (Gasperi et al. 1989). These paleosoils were found along the Apennine chain foothill (Cremonini et al. 2012) as well as in the pedealpine plain (Cremaschi 1987; Ravazzi et al. 2012; Cremaschi and Nicosia, 2012). The increase of Pinus indicates a vegetation transition between steppic environment toward a landscape dominated by conifers, that can be associated to the formation of Alfisols under natural wood cover and xeric pedoclimate conditions (Cremaschi and Nicosia 2012).

The dark (S14) and reddish (S15) horizons formed a pedosequence composed by 5Ab and 5Bwcb characterized by few pollen grains. The scarce presence of pollens should indicate a climatic transition occurred in the Younger Dryas/Preboreal period. In spite of a relative paucity of pollens, the very dark S14 sample had high content of elemental C that was detected by a misfit between C_{tot} and that calculated by (Co+Ci). This deficiency (ΔC) can be allocated to black (elemental) charred carbon related to fires and biomass burning. Similar dark soils were found in other sites of the Emilia-Romagna Region (e.g. Alessio et al. 1980; Ravazzi et al. 2006; Cremonini et al 2007), also in distal plain facies such as probably the *Argille di Vedrana*, and although they are not all strictly coeval they could be interpreted as pedomarkers developed between Younger Dryas and Boreal chronozones (Ammann et al., 2000; von Grafenstein et al. 2000). In the city of Bologna a pollen sterile black-soil of similar thickness was dated by radiocarbon at 9300-8650 BP (Cremonini et al. 2007; Cremonini et al 2012; Amorosi et al. 2014).

The S13 sample (4Ab2 horizon) in the third stratigraphic set corresponds to the surface where the burnt oak trees were rooted and can be assigned to the Preboreal/Boreal period, as also suggested by the burned oak trunk of S12 horizon dating ~ 9.1 ky BP. The pollens in the S12 sample suggest that vegetal cover progressively developed during the Holocene (Accorsi et al. 1999) in the Boreal to Atlantic time interval. This horizon also records evidence of charred material, given by the occurrence of relics of combusted oak trees, as also confirmed by the ΔC parameter indicating the presence of elemental carbon. This suggests the occurrence of fires and biomass burning, possibly resulting from man-made deforestation practices, as suggested for other sites of northern Italy (Vescovi et al. 2010).

The above lithological discontinuity (S11 sample), that marked the upper limit of the third set, suggests a sharp variation toward warmer conditions attested by the decline of *Picea* and *Abies* and the increase of Tiliaceae.

This climatic change is coupled with the above mentioned anthropogenic influence testified by several evidence of biomass burning. These findings are in agreement with several anthropogenic indicators of Neolithic settlement (ca. 7950 y BP) in many Italian sites (Bellini et al. 2009; Rottoli and Castiglioni 2009; Joannin et al. 2013).

Noteworthy, in other North Apennines sites, during the mid-Holocene ca. 6450 y BP and ca. 2950 y BP *Abies* declined, even if these vegetation changes in distinct sites were probably not synchronous due to superimposition of local micro-climatic effects on more general climatic changes, and/or to local geological/pedological factors, as well as to human impacts (Vescovi et al. 2010). Similar evidences were recorded at ca. 6650 and ca. 5950 y BP in the stratigraphy of the study-site site Lake Ledro (Joannin et al. 2013).

In the investigated site of S. Lazzaro relatively homogeneous environmental conditions persisted for a long period until the formation of sample S6, which in spite of the radiometric age of ~ 6550 y BP also represented a topographic surface of the first Iron Age (Villanovan). In other words, the existence of charcoal dating to ~ 6550 y BP in this layer implies that this surface could have been exposed to the atmosphere for ~ 3500 years between the Neolithic and the Iron Age. In spite of the long soil development, the complete soil profile is missing and ~ 30 cm of surficial horizons (A) are totally lacking, thus marking a significant erosional process.

This framework is coherent with the paleogeographic reconstruction provided by palynology, which indicates a change of pristine forest condition with appearance of plants introduced by human activities. The stable isotopic values of organic C are similar to those recorded by Vittori Antisari et al. (2013) in a neighbouring excavation (down to a depth of 4.5 m) which recorded soil samples having $\delta^{13}C$ between -23.8 and -26.6 ‰ (Figure 7). These isotopic values on the soil organic fraction are obviously related to the type of existing vegetation, and according to Meier et al. (2014) a similar $\delta^{13}C$ range reflects a clear predominance (~80%) of plants having C3 photosynthetic pathway.

A further abrupt change is testified by the different features recorded in the most superficial horizons between the S5 and S1 samples forming the first set. The textural, mineralogical and geochemical data of these layers indicate that the source of detritus was displaced toward an area dominated by the *Sabbie di Imola* Formation (IMO, quartz-rich sands) and older soils resembling those currently recognized in the terraces of the basin (AES_6, Figure 1B). The related soil profile appears to be very poorly developed, probably indicating continuous sedimentation pulses arriving through the time. During this later period, *Pontebuco stream* possibly experienced high energy, episodical sheet-floods as demonstrated by the S4 sample containing un-classed pebbles and gravel. Subsequently, the PSF area suddenly become quiescent and terminated its aggradation, probably due to human intervention aimed to minimize the flood risks for the human settlement. This happened during Roman times.

6 Conclusion

The presented data emphasize the importance of alluvial sediment and soil investigations to elucidate fluctuations of environmental conditions, including climatic changes and past anthropogenic impacts on the natural landscape. In particular, the considered stratigraphic sequence exposed in the locality of San Lazzaro di Savena (Bologna, Italy) provides information on the Holocene evolution of the northern foot-hill Apennine area, suggesting that at the beginning of this period the climate was quite cold and relatively arid favouring a steppic vegetation growth. With the Holocene inception a slight increase in the temperature and an increase of precipitations favoured the development of forest constituted by abundant conifers. Humans impacted this environment making fires during the Mesolithic to clear the area and during the Neolithic to obtain soils for agriculture and animal farming. The human presence favoured geomorphological and hydraulic instabilities, accelerating soil erosion. Therefore the observed data suggest that human impact on the landscape started to be effective in the Mesolithic period, earlier than usually considered by previous studies. Finally, more recent (probably Roman age) hydraulic works confined the *Pontebuco stream* leading to the inactivation of his alluvial fan area, rendering the surrounding lands stable for settlements.

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Figure captions

Figure 1. A) Geomorphological outline of the S. Lazzaro di Savena surrondings and related foothill. B) Geological and pedological outline of the same area.

Figure 2. Stratigraphic log, soil and horizon sequence coupled with selected chemical parameters of the studied site.

Figure 3. *Box plot showing textural and physicochemical parameters of the different pedostratigraphic sets: I includes samples 1,2,3,4,5; II includes samples 6,7,8,9 10; III includes samples 11,12 13; IV includes samples 14 and 15.*

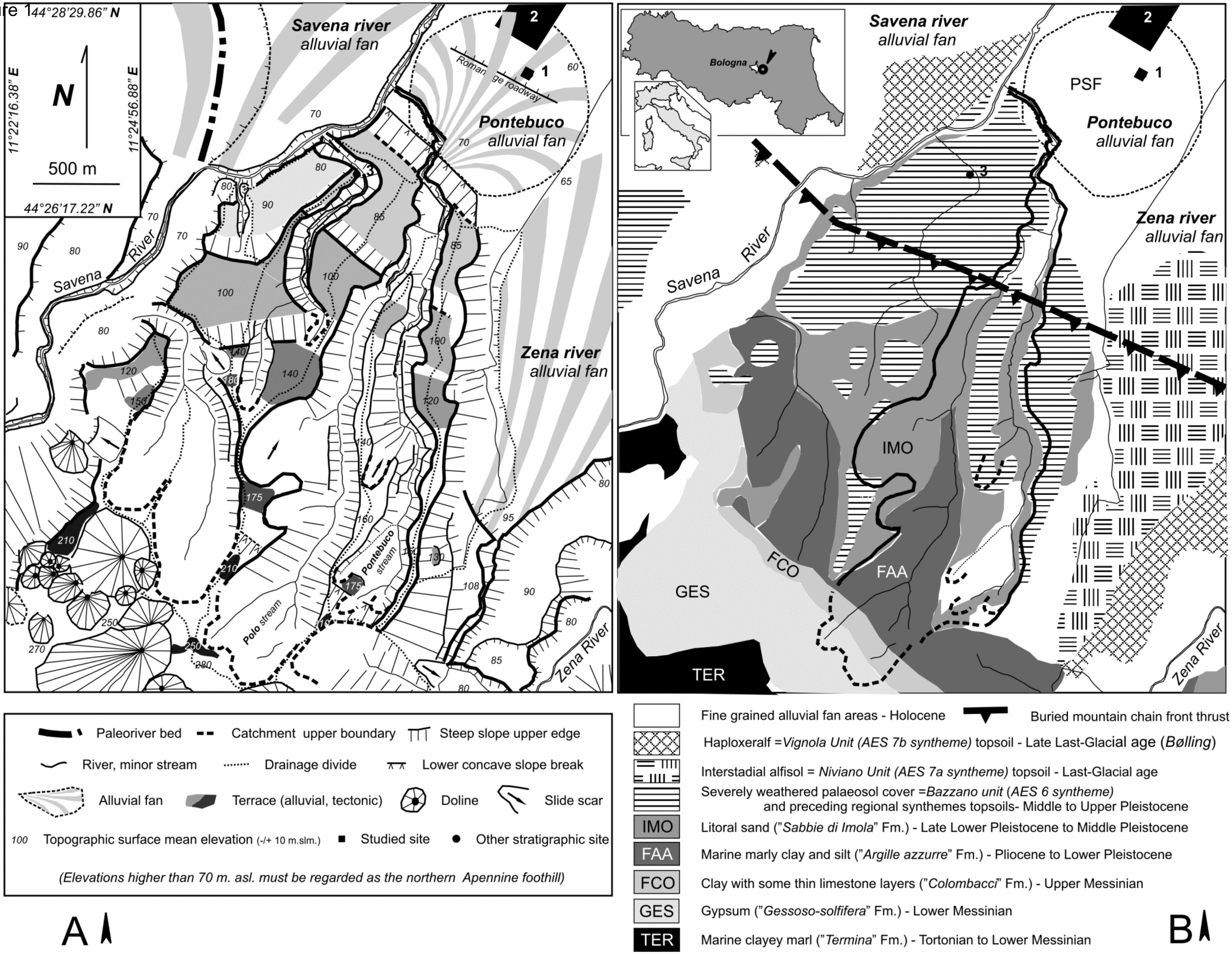
Figure 4. *XRD analyses of soil samples representative of three excavation levels. Note that the more superficial sample 1 records only quartz (preponderant) and feldspar (subordinate), whereas deeper levels (6 and 12 samples) also record the presence of clay minerals. Calcite seems abundant only in the deeper horizons.*

Figure 5. *3D plots of F1-F2-F3 discriminating factors obtained by the statistical elaboration of the X-ray fluorescence (XRF) geochemical data.*

Figure 6. *Trace element content vs depth. The elements have been grouped according to their geochemical affinity and normalized to the UCC (Upper Continental Crust Composition; Rudnick and Gao, 2014).*

Figure 7. *Stratigraphic variation of* $\delta^{13}C$ *of the total C budget and* $\delta^{13}C$ *organic C fraction. The first parameter highlights the horizons containing significant amount of carbonate, whereas the second parameter gives indication on the nature of the existing vegetation that generated the organic matter.*

Figure 1



44°28'29.86" N
44°26'17.22" N
11°22'16.38" E
11°24'56.88" E
N
500 m
Savena river
alluvial fan
Pontebuco
alluvial fan
Zena river
alluvial fan
Savena River
Zena River
Romanage roadway
Polo stream
Pontebuco stream
PSF
IMO
FAA
FCO
GES
TER
Bologna
Paleoriver bed
Catchment upper boundary
Steep slope upper edge
River, minor stream
Drainage divide
Lower concave slope break
Alluvial fan
Terrace (alluvial, tectonic)
Doline
Slide scar
100 Topographic surface mean elevation (-/+ 10 m.slm.)
Studied site
Other stratigraphic site
(Elevations higher than 70 m. asl. must be regarded as the northern Apennine foothill)
Fine grained alluvial fan areas - Holocene
Buried mountain chain front thrust
Haploxeralf =Vignola Unit (AES 7b syntheme) topsoil - Late Last-Glacial age (Bølling)
Interstadial alfisol = Niviano Unit (AES 7a syntheme) topsoil - Last-Glacial age
Severely weathered palaeosol cover =Bazzano unit (AES 6 syntheme)
and preceding regional synthemes topsoils- Middle to Upper Pleistocene
IMO Litoral sand ("Sabbie di Imola" Fm.) - Late Lower Pleistocene to Middle Pleistocene
FAA Marine marly clay and silt ("Argille azzurre" Fm.) - Pliocene to Lower Pleistocene
FCO Clay with some thin limestone layers ("Colombacci" Fm.) - Upper Messinian
GES Gypsum ("Gessoso-solfifera" Fm.) - Lower Messinian
TER Marine clayey marl ("Termina" Fm.) - Tortonian to Lower Messinian
A
B

Figure 2

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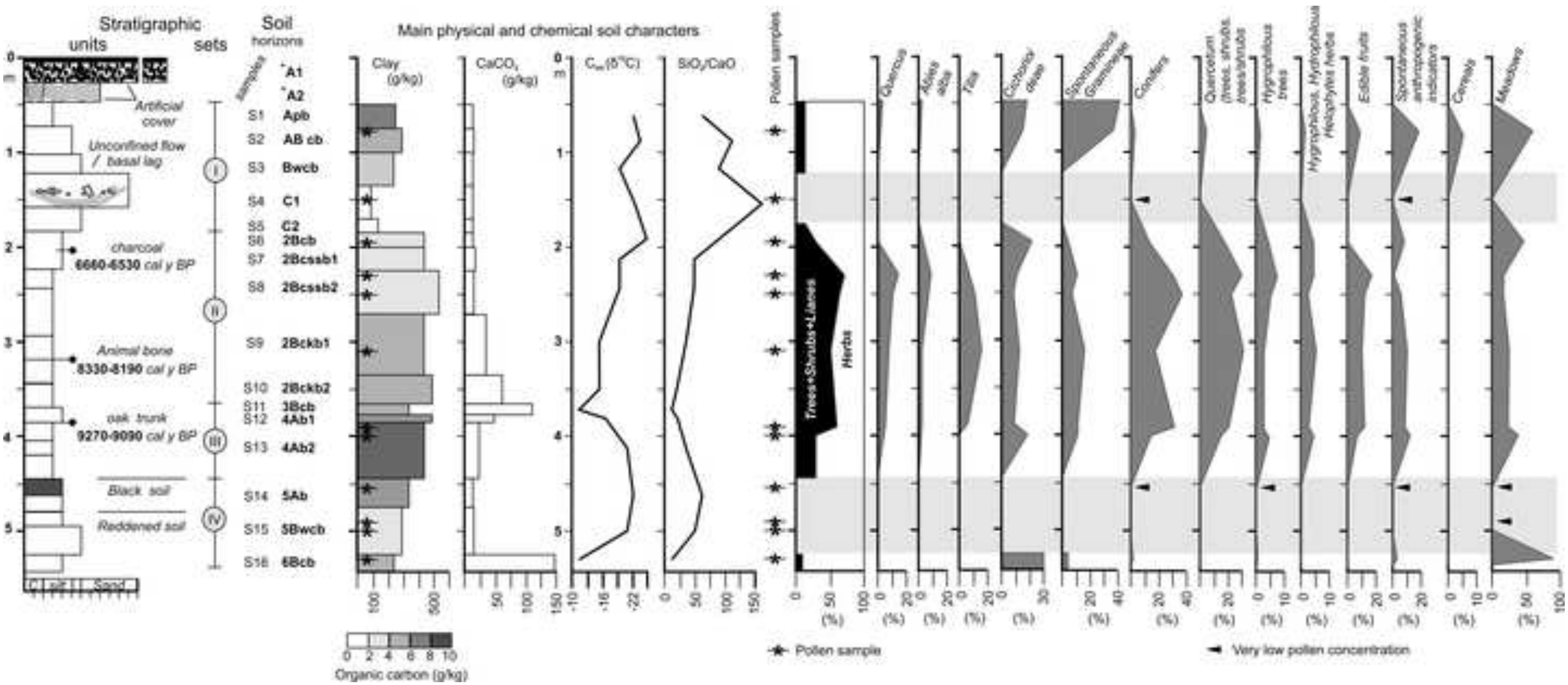

Figure 3
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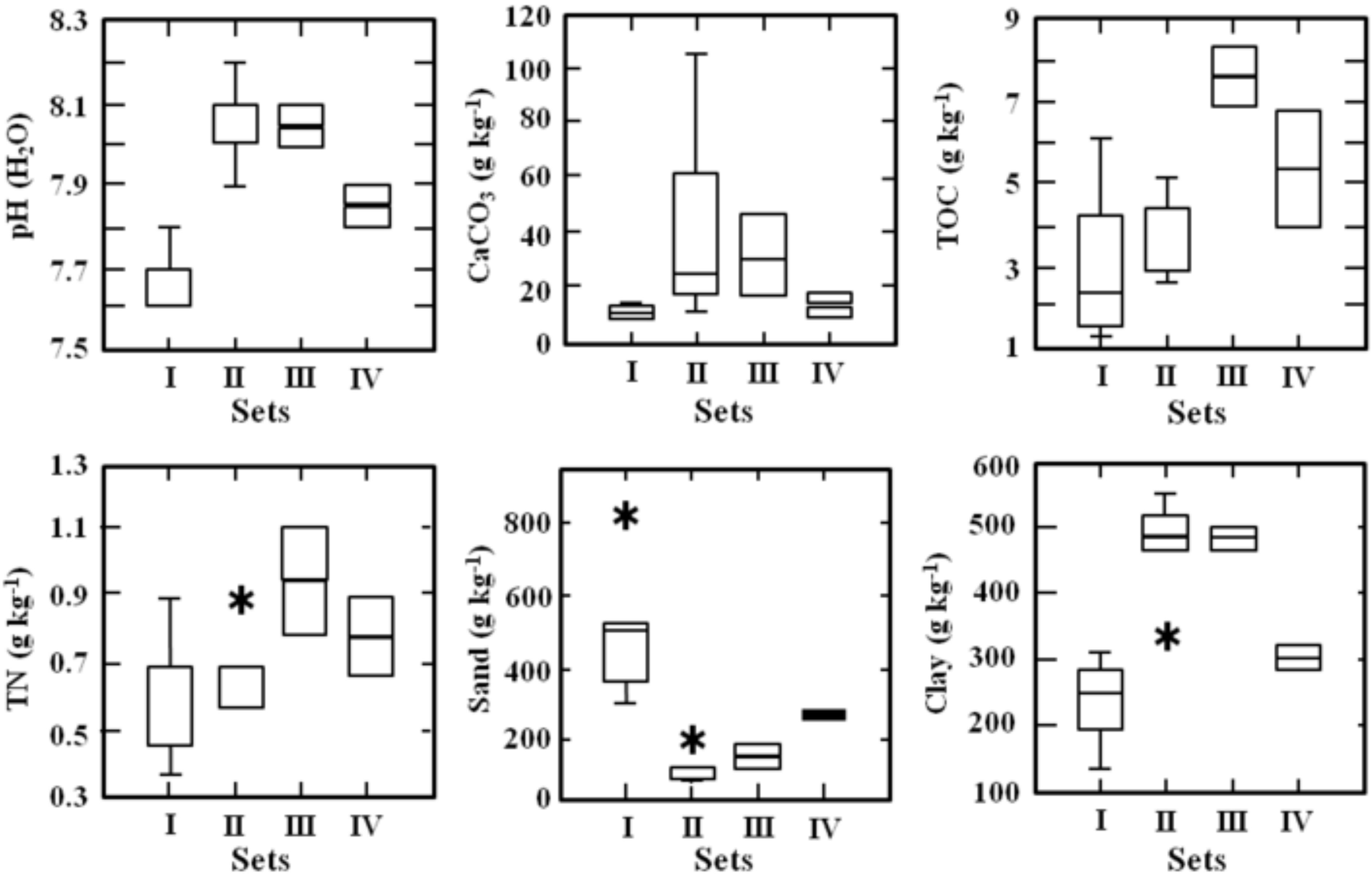

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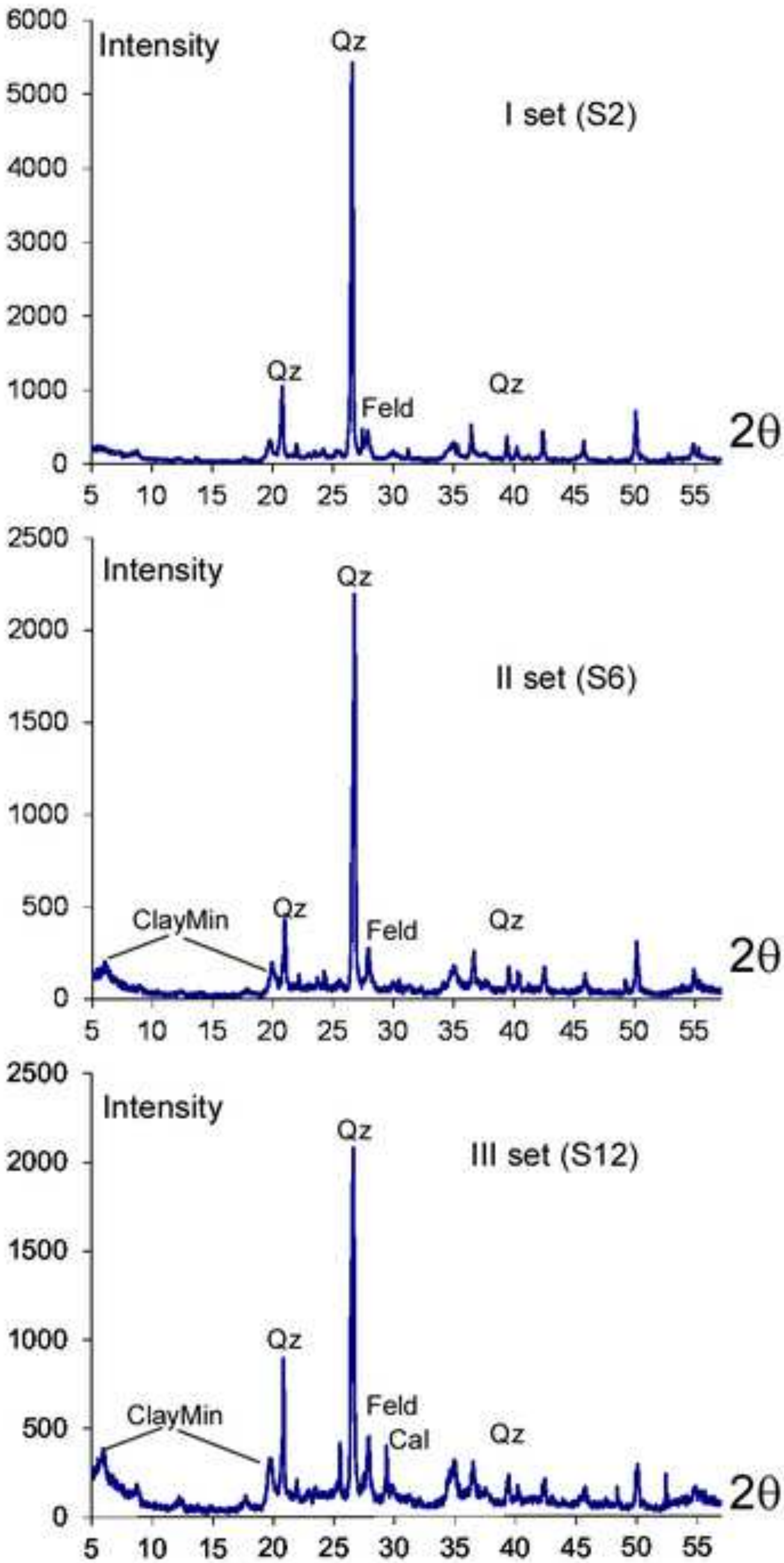

Figure 5
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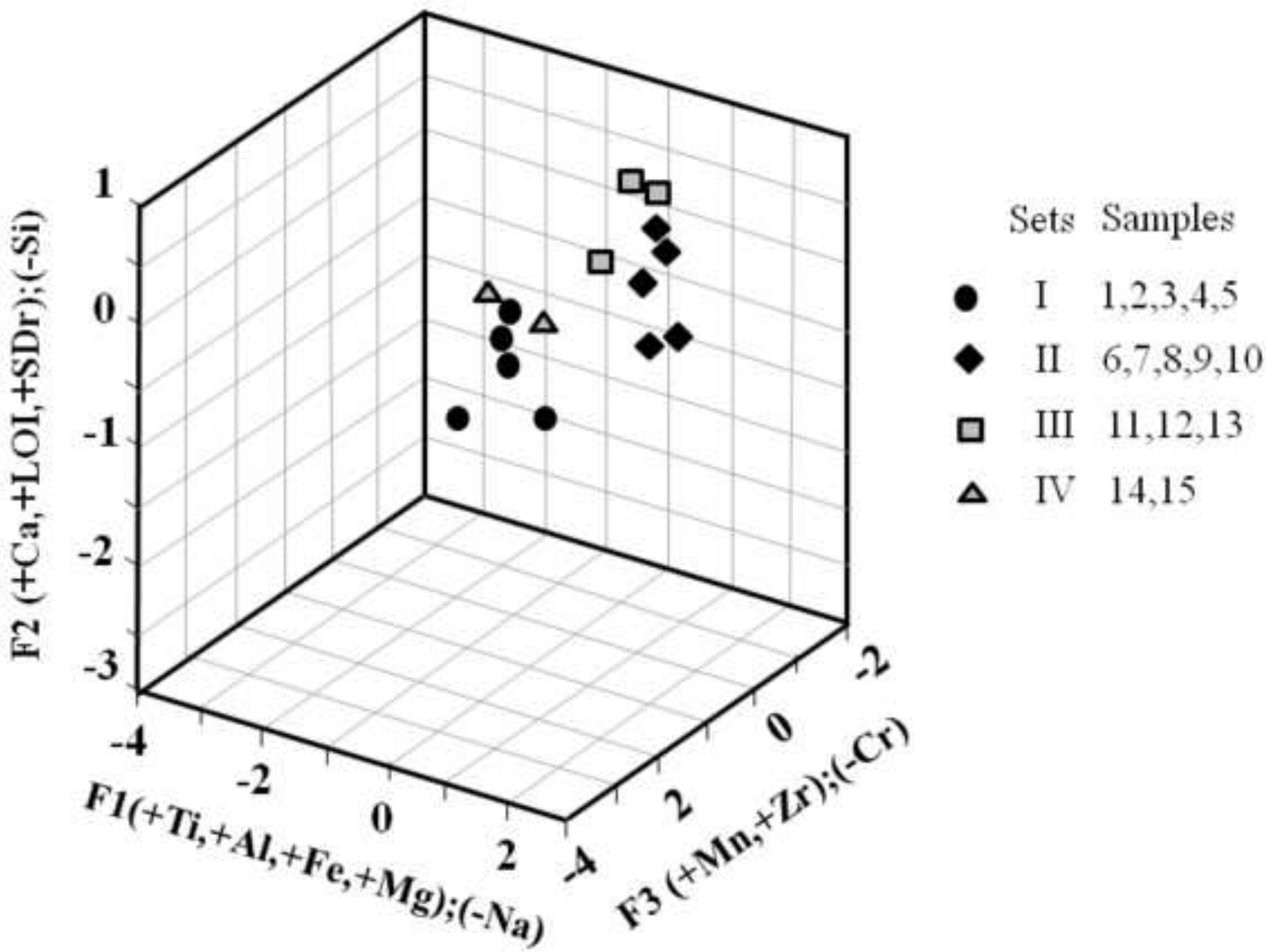

Figure 6

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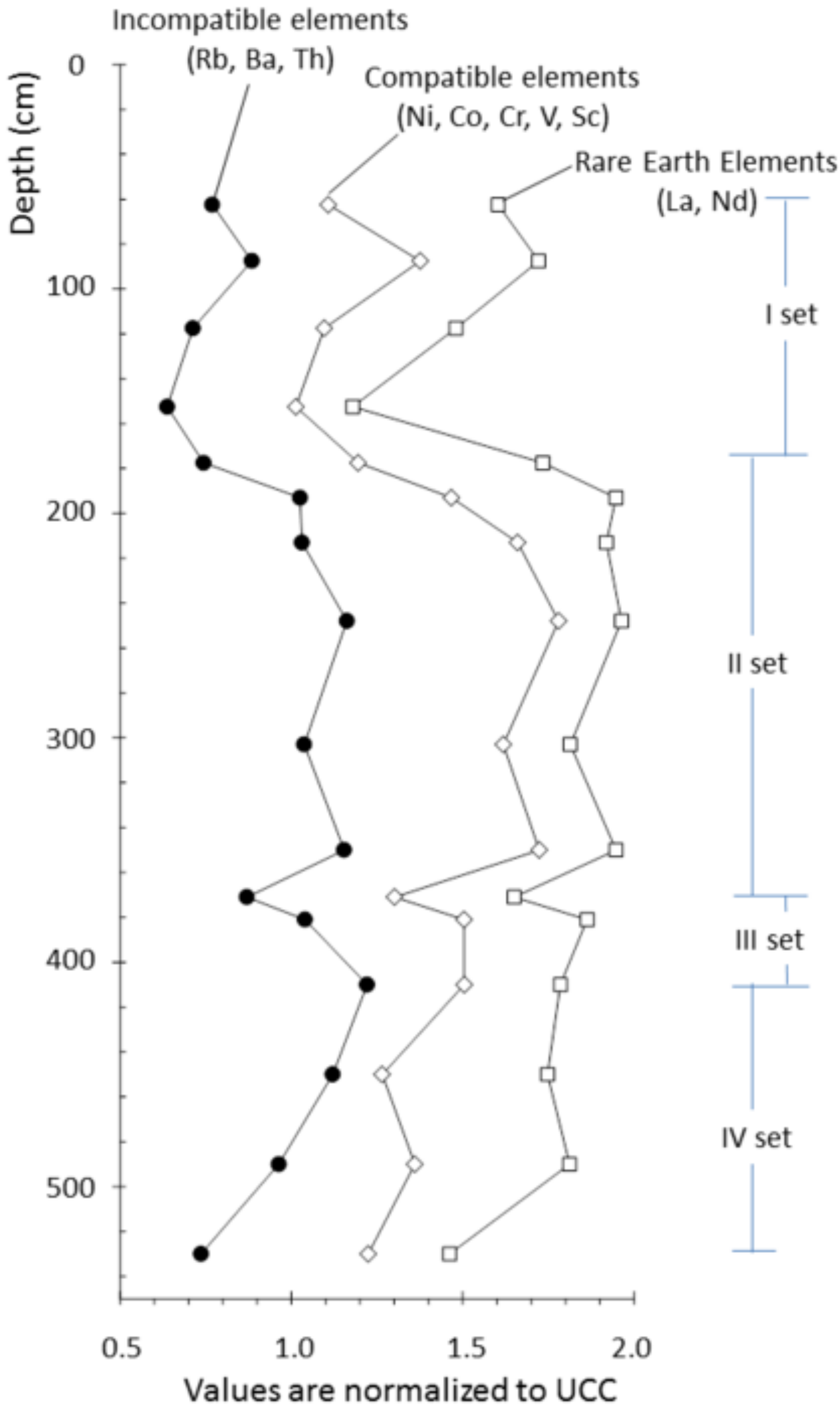

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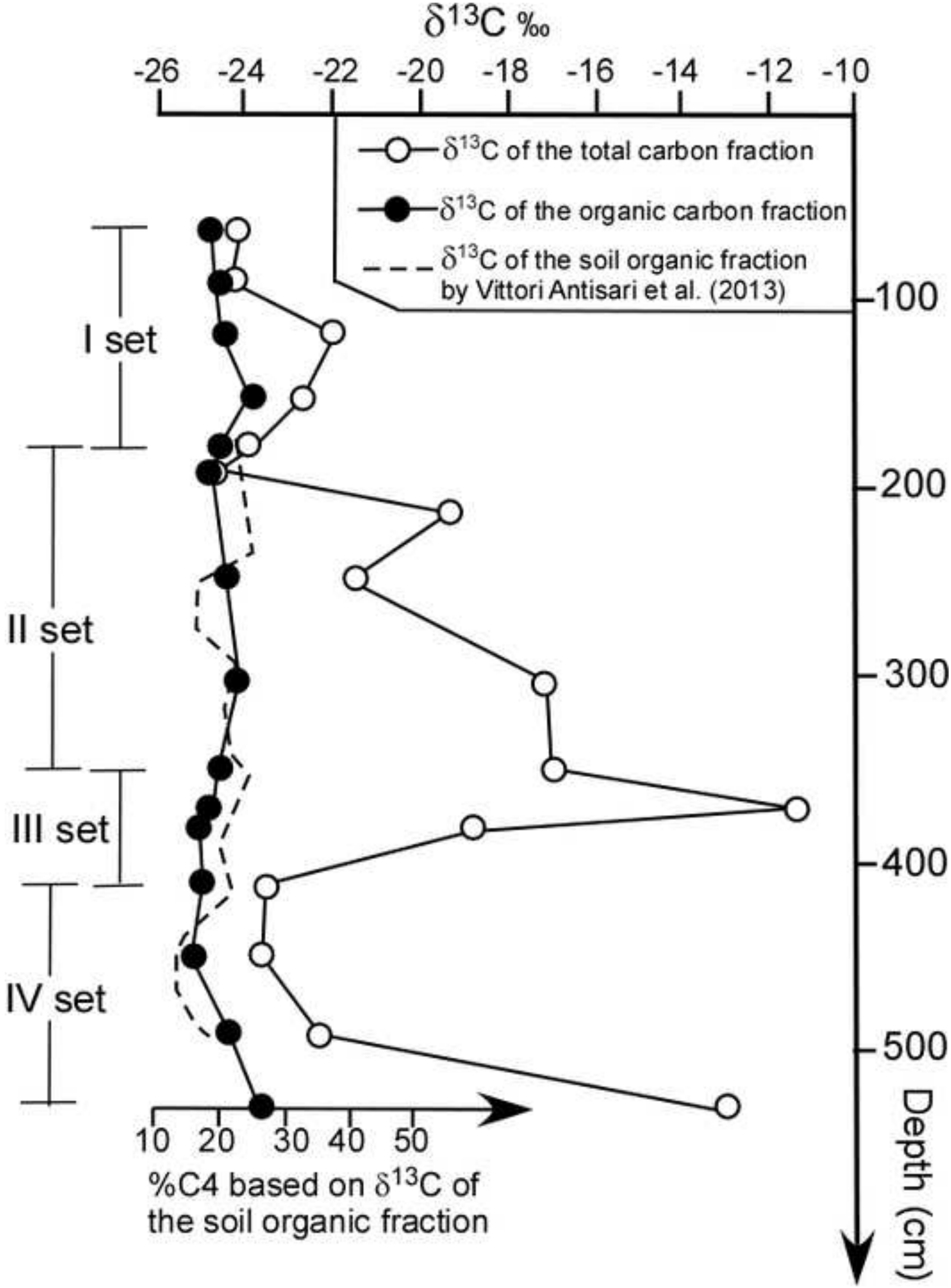

Table 1

Table 1 – *Main descriptive elements of investigated soil profiles. Codes according to Schoeneberger et al. (2012)*

Stratigraphic set	Sample	Horizons				Color Munsell		Mottles					Texture	Structure	Consistence	Concentrations	Rock and other fragments	
		Horizon	Depth (cm)	Boundary D	Boundary T	dry	moist	Q	S	C	Colour	M		G_S_T	D_M_S_P	Q_S_K	V%	R
	Not collected	^A1	0-30	A	S								SL					
		^A2	30-50	A	S								SL					
I	S1	Apb	50-75	C	S	10YR 6/3	10YR 5/3	--	-	-	----	----	L	3_m_pl	SH_FR_(w)ss_(w)ps	------	1	SR
	S2	ABcb	75-100	D	S	10YR 6/4	10YR 5/4	vf	1	F	10YR 5/6	d	CL	3_m_pr	SH_FR_(w)ss_(w)ps	f_1_RSB	0	--
	S3	Bwcb	100-135	A	S	10YR 6/6	10YR 5/4	f	1	F	10YR 5/6	d	L	3_m_pr	HA_FI_(w)ss_(w)ps	f_1_RSB	2	SR
	S4	C1	135-170	G	S	10YR 6/6	10YR 6/8	--	-	-	----	-	SL	0_f_sg	SH_FR_(w)so_(w)po	f_1_CBM	50	RO
	S5	C2	170-185	C	S	10YR 7/4	10YR 6/6	c	1	F	10YR 5/8	d	L	3_m_abk	HA_FI_(w)so_(w)po	f_1_DNN	3	RO
II	S6	2Bcb	185-201	C	S	2.5Y 6/4	2.5Y 4/2	m	1	P	7.5YR 6/8	d	SiC	2_f_abk	VH_FI_(w)ss_(w)vp	c_1_RSB	0	--
	S7	2Bcssb1	201-225	C	S	2.5Y 6/2	2.5Y 4/2	m	1	D	2.5Y 5/4	d	SiC	2_f_abk	VH_FI_(w)ss_(w)ps	c_1_CAN	0	--
	S8	2Bcssb2	225-271	C	S	2.5Y 6/3	2.5Y 4/2	m	3	D	10YR 5/6	d	SiC	2_m_abk	VH_FI_(w)ss_(w)ps	c_1_CAC	0	--
	S9	2Bckb1	271-335	C	S	2.5Y 5/4	10YR 4/3	c	2	F	5YR 3/2	d	SiC	2_m_abk	VH_FI_(w)s_(w)p	c_2_CAN	2	RO
	S10	2Bckb2	335-365	A	W	10YR 5/3	10YR 3/3	m	4	D	G 2 8/5B	d	SiC	3_m_pr	HA_VFR_(w)ss_(w)vp	c_1_CAC/SFB	2	RO
III	S11	3Bcb	365-377	A	W	10YR 7/3	10YR 4/3	--	-	-	----	----	SiCL	2_f_abk	HA_FR_(w)vs_(w)ps	c_2_CAM/RSB	2	RO
	S12	4Ab1	377-385	C	W	10YR 5/3	10YR 3/3	--	-	-	----	----	SiC	3_m_abk	EH_EF_(w)s_(w)p	c_1_CAC	0	
	S13	4Ab2	385-445	C	W	10YR 4/2	10YR 3/2	--	-	-	----	----	SiC	3_f_abk	VH_VFI_(w)ss_(w)vp	m_2_CAM	0	
IV	S14	5Ab	445-475	C	W	10YR 3/3	10YR 3/2	f	1	F	10YR 5/6	d	CL	2_f_gr	SH_VFR_(w)so_(w)ps	m_2_CAM	5	SR
	S15	5Bwcb	475-525	C	W	2.5Y 6/6	2.5Y 4/4	m	2	F	10YR 6/8	d	CL	2_m_sbk	HA_VFR_(w)s_(w)vp	m_2_CAN	2	SR
	S16	6Bcb	525-545	U		2.5Y 6/4	10YR 5/4	f	2	D	10YR 6/8	d	L	2_f_abk	VH_FR_(w)s_(w)p	c_1_CAN	0	

Horizon Boundary. (**D**) Distinctness: A = abrupt, C = clear, G = gradual, D = diffuse (**T**) Topography: S = smooth, W = wavy, U = unknown
Mottles. (Q) Quantity: vf=very few; f=few; c=common; m=many -- (S) Size: 1=fine; 2=medium; 3=coarse; 4=very coarse -- (C) Contrast: F=faint; D=distinct; P=prominent -- (M) Moisture state: d=dry
Texture. Field estimation: SL = sandy loam, L = loam, SiCL=silty clay loam; SiC = silty clay; CL = clay loam,
Structure. (**G**) Grade: 0 = structureless/very weak; 1 = weak; 2 = moderate; 3 = strong -- (**S**) Size: vf = very fine; f = fine; m = medium**;** c = coarse -- **T**) Type: gr = granular, abk = angular blocky, sbk = subangular blocky; pr = prismatic; pl = plat; sg = single grain.
Consistence. Rupture resistence: (**D**) Dry: SH = slightly hard; HA=hard; VH=very hard; EH=extremely hard -- (**M**) Moist: VFR = very friable; FR=friable; FI=firm; VFI=very firm; EF=extremely firm -- (**S**) Stickiness: (w)so = non-sticky, (w)ss = slightly sticky, (w)s = moderately sticky ; (w)vs=very sticky – (**P**) Plasticity: (w) po = non-plastic, (w) ps = slightly plastic, (w)p = moderately plastic; (w)vp=very plastic
Concentrations. (**Q**) Quantity: f= few; c= common; m = many – (**S**) Size: 1 = fine; 2 = medium; 3= coarse – (**K**) Kind: . CAC = carbonate concretions; CAM = carbonate masses; CAN = carbonate nodules; CBM = clay bodies; DNN = durinodes-SiO_2; RSB = root sheaths; SFB = shell fragments
Rock and other fragments. (K) Kind: SHF = shell (**V%**) Fragment content % by volume – (**R**) Roundness: SR =subrounded; RO= rounded

Table 2

Table 2. *Chemical-physical characters of the investigated soil profiles*

Stratigraphic set	Sample	Horizon	Depth	pH (H2O)	EC	Texture: Sand G	Sand F	Silt G	Silt F	Clay	$CaCO_3$	TOC	TN
			cm		mS/cm 20°C	g kg-1					g kg-1		
I	S1	Apb	50-75	7.6	207	87	268	132	264	249	9	6.2	0.9
	S2	ABcb	75-100	7.7	142	60	222	94	328	296	11	4.1	0.7
	S3	Bwcb	100-135	7.7	197	140	347	109	173	231	9	2.4	0.5
	S4	C1	135-170	7.8	164	526	280	33	51	109	10	1.4	0.4
	S5	C2	170-185	7.6	135	124	372	157	170	177	9	1.6	0.5
II	S6	2Bcb	185-201	7.9	157	16	95	99	338	452	11	4.8	09
	S7	2Bcssb1	201-225	8.0	240	26	80	53	381	460	18	3.0	0.6
	S8	2Bcssb2	225-271	8.1	240	15	56	39	365	525	18	3.6	0.6
	S9	2Bckb1	271-335	8.0	244	10	70	44	400	475	33	4.3	0.9
	S10	2Bckb2	335-365	8.0	274	31	51	21	393	503	60	5.2	0.7
III	S11	3Bcb	365-377	8.2	263	41	145	176	312	326	103	4.1	0.6
	S12	4Ab1	377-385	8.1	243	14	96	86	332	472	46	6.8	0.8
	S13	4Ab2	385-445	8.0	243	9	142	113	287	449	19	8.3	1.1
IV	S14	5Ab	445-475	7.8	216	9	241	183	269	297	10	6.7	0.9
	S15	5Bwcb	475-525	7.9	215	20	233	204	271	271	15	4.0	0.7
	S16	6Bcb	525-545	8.2	235	58	230	183	289	240	153	4.1	0.7

Table 3

Table 3. *Concentration of major and trace elements obtained by XRF*

	Sample	Horizon	Depth	SiO_2	TiO_2	Al_2O_3	Fe_2O_3	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	LOI
			cm	%										
I	S1	Apb	50-75	67.81	0.63	14.14	6.33	0.13	1.81	0.94	1.05	2.67	0.28	4.21
	S2	ABcb	75-100	65.47	0.70	15.75	7.31	0.16	2.03	0.61	0.93	2.86	0.11	4.07
	S3	Bwcb	100-135	69.93	0.53	14.38	5.59	0.11	1.55	0.72	1.20	2.82	0.09	3.09
	S4	C1	135-170	77.89	0.29	10.59	4.14	0.09	0.78	0.38	1.28	2.75	0.09	1.72
	S5	C2	170-185	69.99	0.60	14.19	6.02	0.16	1.60	0.65	1.21	2.76	0.09	2.74
II	S6	2Bcb	185-201	61.06	0.79	17.53	8.58	0.07	2.36	1.02	0.68	2.60	0.07	5.24
	S7	2Bcssb1	201-225	59.32	0.78	17.46	8.69	0.12	2.50	1.70	0.63	2.59	0.07	6.14
	S8	2Bcssb2	225-271	57.93	0.80	17.86	9.32	0.11	2.68	1.43	0.56	2.70	0.08	6.53
	S9	2Bckb1	271-335	57.49	0.80	17.30	8.94	0.10	2.65	2.27	0.59	2.68	0.10	7.09
	S10	2Bckb2	335-365	55.35	0.78	17.37	8.92	0.11	2.71	3.02	0.52	2.82	0.11	8.27
III	S11	3Bcb	365-377	55.14	0.73	15.83	7.27	0.10	2.36	6.07	0.69	2.79	0.13	8.89
	S12	4Ab1	377-385	55.43	0.78	17.67	8.67	0.10	2.68	3.00	0.55	3.11	0.15	7.85
	S13	4Ab2	385-445	58.15	0.77	17.77	8.53	0.11	2.68	1.57	0.63	3.18	0.13	6.48
IV	S14	5Ab	445-475	62.81	0.75	16.41	7.44	0.13	2.36	1.34	0.98	3.00	0.12	4.66
	S15	5Bwcb	475-525	61.87	0.73	16.85	7.79	0.12	2.69	1.50	1.02	2.79	0.14	4.50
	S16	6Bcb	525-545	54.75	0.64	13.51	5.85	0.11	2.41	9.29	0.95	2.46	0.14	9.90

Strat. Set	Sample	Horizon	Depth	Ba	Co	Cr	Cu	Ga	Hf	La	Nb	Nd	Ni
			cm	mg kg-1									
I	S1	Apb	50-75	398	21	121	81	16	10	65	11	30	64
	S2	ABcb	75-100	396	22	148	34	18	11	73	12	29	90
	S3	Bwcb	100-135	404	20	139	25	14	9	63	9	26	58
	S4	C1	135-170	373	14	230	23	10	9	56	6	15	37
	S5	C2	170-185	382	22	149	24	15	12	74	12	29	69
II	S6	2Bcb	185-201	439	22	156	37	23	10	81	14	35	83
	S7	2Bcssb1	201-225	449	24	167	39	24	9	83	14	32	110
	S8	2Bcssb2	225-271	440	25	176	44	26	10	81	17	35	123
	S9	2Bckb1	271-335	443	22	164	44	26	11	75	15	33	110
	S10	2Bckb2	335-365	435	22	167	47	27	9	83	19	33	118
III	S11	3Bcb	365-377	422	19	113	40	22	8	72	13	26	77
	S12	4Ab1	377-385	456	22	143	45	26	9	74	13	37	96
	S13	4Ab2	385-445	469	23	138	42	26	11	71	17	34	88
IV	S14	5Ab	445-475	465	20	132	34	20	14	76	15	28	73
	S15	5Bwcb	475-525	461	21	149	33	21	13	77	13	31	88
	S16	6Bcb	525-545	381	19	118	29	18	8	65	13	22	77

Strat. Set	Sample	Horizon	Depth	Pb	Rb	S	Sc	Sr	Th	V	Y	Zn	Zr
			cm	mg kg-1									
I	S1	Apb	50-75	41	112	6	12	111	4	76	19	93	202
	S2	ABcb	75-100	21	119	5	15	93	6	96	22	82	173
	S3	Bwcb	100-135	20	105	6	13	92	3	68	18	84	170
	S4	C1	135-170	20	103	5	8	78	1	40	12	33	131
	S5	C2	170-185	24	110	6	12	109	3	71	27	56	262
II	S6	2Bcb	185-201	21	150	15	19	111	6	120	23	113	162
	S7	2Bcssb1	201-225	21	154	24	20	114	6	132	24	113	145
	S8	2Bcssb2	225-271	24	178	21	21	125	7	139	28	124	146
	S9	2Bckb1	271-335	20	155	26	18	126	6	136	23	120	130
	S10	2Bckb2	335-365	26	185	22	21	156	6	145	28	126	138
III	S11	3Bcb	365-377	22	120	32	19	170	5	117	20	97	123
	S12	4Ab1	377-385	19	155	27	18	129	6	134	20	124	119
	S13	4Ab2	385-445	22	181	19	21	131	8	130	27	116	185
IV	S14	5Ab	445-475	24	159	13	16	131	8	97	33	84	310
	S15	5Bwcb	475-525	23	122	19	15	119	7	96	28	81	260
	S16	6Bcb	525-545	21	95	25	17	158	5	90	28	69	243

Table 4

sample	Total carbon (analyzed at 950 °) wt %	$\delta^{13}C$	Organic carbon (analyzed at 450 °) wt %	$\delta^{13}C$
S1	0.92	-24.15	0.65	-24.73
S2	0.42	-24.22	0.31	-24.63
S3	0.27	-22.02	0.22	-24.45
S4	0.13	-22.70	0.13	-23.83
S5	0.17	-23.97	0.15	-24.58
S6	0.33	-24.66	0.26	-24.65
S7	0.55	-19.35	0.40	-24.76
S8	0.50	-21.53	0.37	-24.36
S9	0.76	-17.10	0.36	-24.13
S10	1.01	-16.96	0.46	-24.54
S11	1.72	-11.46	0.37	-24.78
S12	1.16	-18.78	0.57	-25.05
S13	1.01	-23.50	0.69	-25.01
S14	0.76	-23.65	0.58	-25.18
S15	0.46	-22.33	0.40	-24.41
S16	2.00	-12.99	0.36	-23.59