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Stress features in Terra Rossa soil under traditional olive cultivation: a micromorphological and mineralogical characterization

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Abstract: This study analyzes the micromorphological and mineralogical properties of a Terra Rossa soil under a traditional Mediterranean olive grove. It highlights the microscopic and sub-microscopic features generated by the permanent crop cover. The study area, where the land use has remained unchanged for the last 150 years, is near Sassari (Sardinia, Italy) and is characterized by dominant Terra Rossa developed on Miocene marine limestone. Two soil profiles were opened and described in July 2009, 1 under the canopy of an olive tree and 1 between the trees. Chemical and physical analyses were carried out. Undisturbed aggregates were collected from all the sampled horizons for thin section and scanning electron microscope (SEM) analysis, complemented by mineralogical analyses (X-ray diffractometry, XRD). The results obtained highlighted the effects of vigorous bioturbation and stress actions that have occurred on the pedogenetic features inherited from complex genetic processes.

Key Words: Terra Rossa, traditional olive crop, micromorphology, SEM, XRD, stress coating

1. Introduction

The olive (*Olea europaea*) is a traditional Mediterranean permanent crop and an important component of Mediterranean cultural landscapes (Loumou & Giourga 2003).

In Sardinia (Italy) a considerable proportion of the olive groves is located in the northwestern part of the region, particularly in the Sassari area (Barbera & Dettori 2006). In the middle of the nineteenth century the areas surrounding the town were largely covered by olive groves (Della Marmora 1860).

The olive tree requires relatively little in terms of nutritional elements and water requirements (Dichio *et al.* 2002), and hence was often grown in marginal areas. In many Mediterranean regions it is often associated with Terra Rossa soils (Luvisols or Lixisols, according to FAO/ISRIC/ISSS 2006), where it influenced the development of the soil features.

This study is part of a wider research initiative involving Italian and Turkish teams to address the effects of the traditional Mediterranean tree crops on Terra Rossa soils via micromorphology. Particular attention was given to the oriented clay by stress phenomena occurring at the root-soil interface.

An in-depth micromorphological analysis was carried out to discern between the secondary features developed by a long-term traditional agro-ecosystem and the genetic features of the studied red soil.

Studies of biophysical root-soil interface interactions, with particular reference to small-scale (µm to mm) processes, were reviewed by Young (1998).

Some studies specifically analyzed the mechanical soil compaction caused by root development (Ryan & McGarity 1983; Dexter 1987; Clemente *et al.* 2005), revealing the increase in soil bulk density as the root adjacent to the soil expanded (Clemente *et al.* 2005). Root radial and axial expansion can also create fractures in the soil to prevent excessive energetic expenditure during root elongation (Young 1998). Dexter (1987) created a simplified exponential model to illustrate the soil compression around the roots, showing how much pore space is lost in the soil around the roots as the root volume increases.

A few authors studied the microstructural effects of root development (Blevins *et al.* 1970; Krebs *et al.* 1993; Clemente *et al.* 2005). Clemente *et al.* (2005), studying the effect of *Eucalyptus grandis* roots on a well-structured Oxisol (Kandiudox) in Australia, found: i) a significant

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compaction and porosity reduction to distances greater than 4 cm from soil-root contact; ii) aligned, chiseling fractures, at angles of usually less than 90° to the contact surface, determined by root growth; and iii) clay-oriented features, microfractures, superficial coating by fungi hyphae, and micro-slickenside effects on the root-soil contact surface.

Very few studies specifically address these micromorphological features in the olive rhizosphere, although some articles quantitatively describe the olive root system (Fernandez *et al.* 1991; Dichio *et al.* 2002). Recently, Koçak & Kapur (2010) compared the microstructural development and the root-soil interface of mature olive and carob trees.

2. Materials and Methods

2.1. Study Area and Sampling

The study area is located in an olive grove (about 150 years old) near Sassari (NW Sardinia, Italy; Figure 1), about 110 m a.s.l., with flat to gently undulating morphology. The bedrock is Miocene yellowish-brown compact limestone, containing less than 0.1% of almost colorless, sharp-edged quartz crystals. According to Ginesu (pers. comm. 2011) this formation formed in a shallow marine depositional environment, without significant input of river-transported materials. It is part of a Miocene sedimentary sequence more than 200 m deep including crystalline limestone, sandstone, and compact gray marl, formed during the Miocene in a large, north-south oriented graben, which affected Sardinia (Pietracaprina 1962).

The climate is Mediterranean semi-arid with average annual rainfall around 600 mm, according to Emberger classification.

Two soil profiles were described; the first was under canopy and around the trunk, observed for the main root system growth and subjected to manual farming practices,

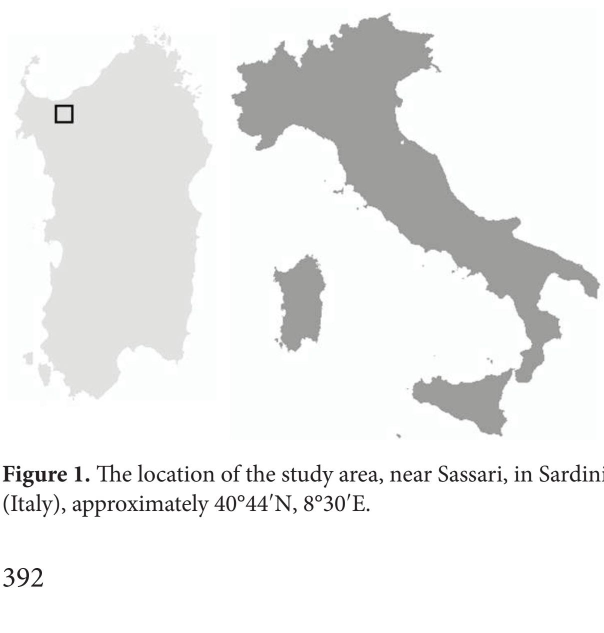

Figure 1. The location of the study area, near Sassari, in Sardinia (Italy), approximately 40°44′N, 8°30′E.

whereas the second was dug between the trees, about 2.5 m from the first, and subjected to annual green manuring.

Both profiles have been described in the field according to Schoeneberger *et al.* (2002) and classified as Haplic Endoleptic Luvisols (Hypereutric, Chromic) according to FAO/ISRIC/ISSS (2006). The profiles consisted of an Ap1-Ap2-Bt1-Bt2-R horizon sequence, to a depth of 80-85 cm under canopy and 80-95 cm between the trees (Table 1). A macromorphological description of the horizons hosting the root system was carried out in the field, in order to compare the root distribution and the presence and location of compacted layers in the 2 profiles. In profile 1 the main roots are mostly active from Ap1 to Bt1, in a horizontal mode. The Ap2 horizon is compacted, most probably because of the anchoring action of the main surface roots, despite vigorous faunal activity. The main roots are horizontal, and in minor areas of the soil, micro-laminations are determined parallel to and in between the roots (compaction of the upper part between roots). In profile 2, part of the Ap1 horizon (0-10 cm) is a compacted layer, with fine roots increasing on and under it.

Horizons were sampled for physical and chemical analysis according to Schoeneberger *et al.* (2002), while undisturbed aggregates, including multiple small aggregates clinging to fine roots, were collected for micromorphological characterization using thin sections and scanning electron microscope (SEM) analysis.

2.2. Physical and Chemical Analyses.

Physical and chemical laboratory analyses were carried out on the fine earth fraction (<2 mm) of air-dried bulk samples, at the Pedology Laboratory of the Faculty of Agriculture, University of Sassari (Italy).

The following chemical analyses were carried out, according to Società Italiana della Scienza del Suolo (2000): organic carbon (OC; Walkley-Black method); total nitrogen (N; Kjeldahl method); pH (in water and in KCl solution; potentiometric measurement); total carbonate content (Carb; by Dietrich-Frühling calcimeter); and cation-exchange capacity (CEC; Cl_2Ba and triethanolamine method).

For particle size distribution analysis, the following granulometric classes were used: 2.0-1.0 mm, very coarse sand; 1.0-0.5 mm, coarse sand; 0.5-0.25 mm, medium sand; 0.25-0.02 mm, fine sand; 0.02-0.002 mm, silt; <0.002 mm, clay. Rock fragments (>2 mm) and coarse sand fractions were determined by wet sieving. The finer granulometric fractions were determined by means of the wet sieving and pipette method of the Società Italiana della Scienza del Suolo (1997).

2.3. Micromorphology

Thin sections (8 × 5 cm) were obtained from undisturbed samples consisting of single, coarse aggregates and small aggregates clinging to the roots.

Table 1. Field description of the studied profiles. The second horizon is named Ap3, in conformity with the field designation. It is actually a ploughed Bt horizon. Classification (FAO/ISRIC/ISSS 2006): Haplic Endoleptic Luvisols (Hypereutric, Chromic).

Horizon and Depth (cm)	Description
Profile 1 (under canopy)	
Ap1 0-10	Brown to dark brown (7.5 YR 4/4), dry, clay loam. Very few, very fine, sub-rounded to rounded, slightly weathered limestone and sandstone rock fragments. Moderate, fine to medium, soft to slightly hard, sub-angular, blocky. Medium porosity for many very fine to few medium pores. Non-calcareous. Well drained. Common fine or medium and very few coarse roots. Common biological activity, for insects and earthworms. Abrupt, smooth boundary.
Ap2 10-20	Brown to dark brown (7.5 YR 4/3), moist. Clay loam. Very few, very fine, sub-rounded to rounded, slightly weathered limestone and sandstone rock fragments. Strong, medium, friable sub-angular blocky. Medium porosity for many very fine and fine pores. Non-calcareous. Well drained. Common, fine, and few medium roots. Common biological activity, for insects and earthworms. Abrupt, smooth boundary.
Bt1 20-49	Yellowish red (5 YR 4/6), dry. Clay loam. Very few, very fine, sub-rounded to rounded, slightly weathered limestone and sandstone rock fragments. Strong, coarse, hard, angular, blocky. Many, distinct, clay coatings on pedfaces and in the voids. Very few, very fine, hard, rounded, bluish black iron-manganese concentrations. Very little porosity for few very fine pores. Non-calcareous. Well drained. Few, fine, and medium roots. Little biological activity. Abrupt, smooth boundary.
Bt2 49-80/85	Reddish brown (5 YR 4/4), dry. Clay loam. Very few, very fine, sub-rounded to rounded, slightly weathered limestone and sandstone rock fragments. Strong, coarse, hard angular blocky. Many, distinct, clay coatings on pedfaces and in the voids. Very few, very fine, hard, rounded, bluish black iron-manganese concentrations. Very little porosity for few very fine pores. Non-calcareous. Well drained. Few, fine, and very few medium roots. Little to no biological activity. Abrupt, smooth boundary.
R >80/85	Miocene limestone.
Profile 2 (between the trees)	
Ap1 0-10	Brown to dark brown (7.5 YR 4/4), dry, clay loam. Very few, very fine, sub-rounded to rounded, slightly weathered limestone and sandstone rock fragments. Moderate, fine to medium, slightly hard, sub-angular, blocky. High porosity for abundant very fine to rare medium pores. Non-calcareous. Well drained. Common, fine roots. Common earthworm biological activity. Abrupt, smooth boundary.
Ap2 10-30	Brown to dark brown (7.5 YR 4/4), moist to dry, clay loam. Very few, very fine, sub-rounded to rounded, slightly weathered limestone and sandstone rock fragments. Strong, medium, hard, sub-angular and angular, blocky. Medium porosity for fine pores. Non-calcareous. Well drained. Common, fine, and medium roots. Common biological activity. Abrupt, smooth boundary.
Bt1 30-50	Yellowish red (5 YR 4/6), moist to dry, clay loam. Very few, very fine, sub-rounded to rounded, slightly weathered limestone and sandstone rock fragments. Strong, coarse to very coarse, hard, angular, blocky. Abundant, distinct, clay coatings on pedfaces and in the voids. Very little porosity for few very fine pores. Non-calcareous. Well drained. Common to few fine roots. Common biological activity. Abrupt, smooth boundary.
Bt2 50-80/95	Reddish brown to orange-red (5 YR 4/5), moist to dry, clay loam. Very few, very fine, sub-rounded to rounded, slightly weathered limestone and sandstone rock fragments. Strong, coarse, hard, angular, blocky. Abundant, distinct, clay coatings on pedfaces and in the voids. Very little porosity for few very fine pores. Non-calcareous. Well drained. Few, fine, and very few medium roots. Little to no biological activity. Abrupt, wavy boundary.
R >90/95	Miocene limestone.

Thin sections were described by amalgamating the basic concepts of Brewer *et al.* (1976), the descriptive approach of Bullock *et al.(*1985), and the enhanced applicative concepts of FitzPatrick's (1993) and Stoops' (2003) systems at the micromorphology laboratory of Çukurova University (Turkey). The micromorphological analysis was focused on the microstructure (MS) and the microstructural units (MSUs) in the different horizons to highlight aggregate development, stress and illuviation coatings, nodule and concretion development, and new mineral formation.

SEM images were obtained with a Philips XLS-30 SEM from small undisturbed lumps, about 1 cm in diameter, at Erciyes University (Turkey).

2.4. Mineralogy

Four horizons (the Ap1 and Bt1 of each profile) were selected to determine the dominant clay mineral in order to confirm the development of the stress phenomena via shrink-swell activity. Clay size fractions were subjected to X-ray diffractometry (XRD) analysis to determine the type of clay minerals. The slides were prepared in 1:4 $MgCl_2$:clay suspensions, where 2 slides were saturated in Mg^{++}, 1 of which was treated with ethylene glycol, and both were scanned from 3 to 13 (2θ).

The slides were prepared at Sassari University and the XRD semi-quantitative analysis was conducted using a Bruker AXS D8 ADVANCE diffractometer at Erciyes University.

3. Results and discussion

3.1. Physical and chemical analyses

The results of the physical and chemical analyses are given in Table 2.

The values of the clay fractions gradually increase with depth in both profiles, and their contents are relatively similar in the A and B horizons, probably as a result of homogenization due to vigorous bioturbation. The somewhat uniform clay fractions in the profile may document the maturity of the profile and the long-standing pedogenic processes determined in the thin section.

OC and N show an abrupt change from the A to the B horizons in both profiles (slightly more gradual in profile 2), where the OC decreases more abruptly from more than 4% in Ap1 to around 1% in Bt2. The same trend is followed by C/N, highlighting a greater degree of humification in the B horizons.

The lower pH of the surface horizon (around 7 in the A horizons compared to around 8 in the B horizons) is most probably due to decalcification (dissolution of the rare primary marine limestone fragments to form rare to moderate secondary nodules at the Bt horizons of both profiles determined in thin sections).

Table 2. Physical and chemical properties of the studied profiles. Profile 1: under canopy. Profile 2: between the trees.

		Profile 1				Profile 2			
		Ap1	Ap2	Bt1	Bt2	Ap1	Ap2	Bt1	Bt2
Lower boundary	(cm)	10	20	49	80/85	10	30	50	80/95
Rock fragments (>2 mm)	(g kg^{-1})	96	4	4	0	92	21	0	2
Very coarse sand (2-1 mm)	(g kg^{-1})	13	12	13	10	15	13	8	9
Coarse sand (1-0.5 mm)	(g kg^{-1})	19	24	18	20	20	31	20	18
Medium sand (0.5-0.25 mm)	(g kg^{-1})	58	65	55	61	62	70	62	61
Fine sand (0.25-0.02 mm)	(g kg^{-1})	331	293	304	282	351	293	305	307
Total sand	(g kg^{-1})	421	394	390	373	448	407	395	395
Silt (0.02-0.002 mm)	(g kg^{-1})	356	288	268	257	354	295	288	254
Clay (<0.002 mm)	(g kg^{-1})	223	318	342	370	198	298	317	351
pH (H_2O)		7.1	7.1	7.7	7.9	7.1	7.1	7.5	8.0
$CaCO_3$ (tot.)	(g kg^{-1})	4	n.d.	n.d.	n.d.	12	8	n.d.	n.d.
OC	(g kg^{-1})	47	41	12	11	44	30	17	9
N (tot.)	(g kg^{-1})	2.2	1.8	1.0	1.0	2.3	1.8	1.2	1.0
C/N		21	23	12	11	19	17	14	9
CEC	(meq 100 g^{-1})	26.7	25.0	22.6	22.6	27.6	26.1	23. 8	21.3
BS	(%)	99	99	99	99	100	100	99	99

n.d. = not detectable.

The CEC slightly decreases with depth in both profiles, because the increase in clay is counterbalanced by the opposite organic matter trend.

3.2. Micromorphology

In both profiles, the macrostructure of Ap1 and Ap2 is prismatic to angular blocky, intergrading to a crumb/granular structure (with a lesser development of the latter in profile 2), with partly compacted consistent structural units. In the Bt1 and Bt2 horizons of both profiles the structure is similar to the upper horizons but is more consistent.

The polarized-microscopic (microstructure) analysis of the 2 profiles was based on the major microstructural features that enabled us to compare the rhizosphere of the olive tree and the soil of the treeless space. These features were particularly related to the presence and abundance of the biofabric together with the stress and illuviation features, as described by Bullock *et al.* (1985), FitzPatrick (1984; 1993), and Stoops (2003).

3.2.1. Microstructure

The MS in both profiles intergrades from Complex/Massive to Massive/Complex with depth indicating similar shrink-swell and natural compaction phenomena.

The 2 profiles have similar MS, characterized by rugrose-welded crumb (Figure 2) intergrading to crumb structure from the Ap to the Bt in each profile. The crumb and granular aggregate development is lower in profile 2 than in profile 1.

The MS of the Ap2 horizons of both profiles is Compact/Massive, probably relating to the macro-observation made in the field on the impact of the anchoring effect of the main roots. However, the sub-angular blocky MS observed in these horizons is more developed in profile 1.

3.2.2. Stress features

Stress phenomena are common in both profiles, and more pronounced and more common in the 2 Bt1 horizons.

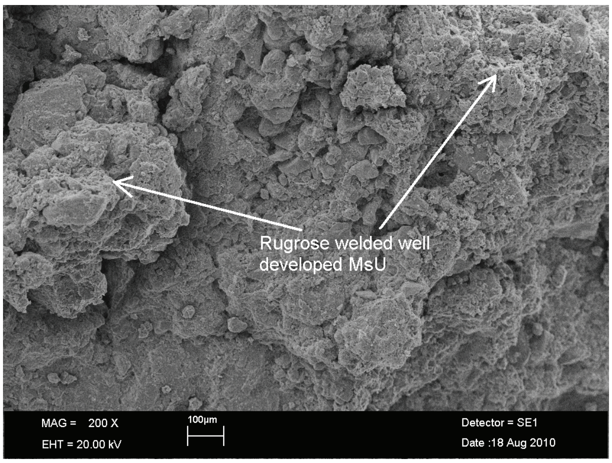

Figure 2. Well-developed rugrose-welded MSU. SEM image.

Rounded to oval MSUs (Figure 3), becoming prominent in Bt1 and Bt2 horizons, have been developed by abundant stress features/linear (linear to reticulate, with crisscross pattern, in Bt2 of profile 1)-oriented clay domains (FitzPatrick 1993) forming faces of the MSUs (Figure 4). They may equate with the permanent microstructural units/aggregates of the S. E. Anatolian Vertisols determined by Kapur *et al.* (1997). Together with stipple-speckled b-fabric (Bullock *et al.* 1985) in red to reddish brown (2.5 YR3/4 Munsell notation) composite colored matrix it occurs in many areas (and may indicate mixed/incorporated presence of earlier and recent stress phenomena in parts of the matrix).

In the Ap1 horizon of profile 1, some MS units/aggregates consist of lignified plant residues and oriented clay/soil aggregates that develop by shrinkage and swelling phenomena (Figure 5).

The Ap2 of profile 1 is the only horizon where stress features were not determined.

The faunal activity is particularly abundant only in Bt2 of profile 2. Here, the permanent MSUs are rare compared to the other horizons, probably as a result of more intense bioturbation. Permanent MSUs are instead prominent in Bt2 of profile 1, along with a lesser development of the stress features compared to Bt1; in other terms, the increase in the permanent MSUs is balanced by a decrease of the temporary MSUs.

3.3. Mineralogy

The clay mineral content of the 2 profiles (Figure 6) is dominantly illite (8.8-8.9 2θ) followed by kaolinite (12.3-12.4 2θ). Smectite is present in all horizons in an interlayered (weathering/transforming to illite) state, but is more visible in the horizons Ap1 (6.10 2θ) of profile 1 and Bt1 (6.20-6.30 2θ) of profile 2. Illite and smectite are the evidence for the stress features determined abundantly in thin sections from both profiles.

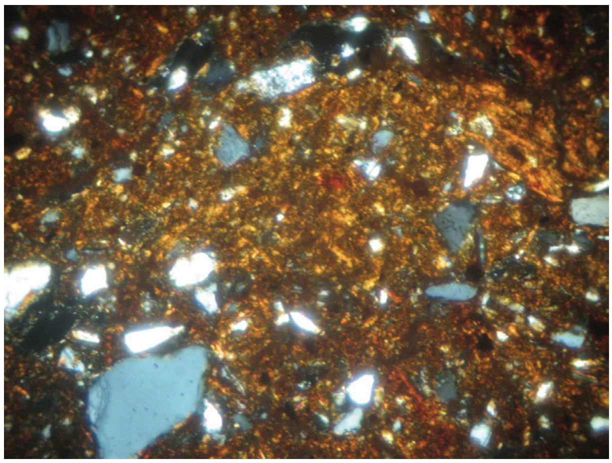

Figure 3. Permanent MSU with reticulate stress features in reddish matrix (XPL, 1 cm = 50 µm).

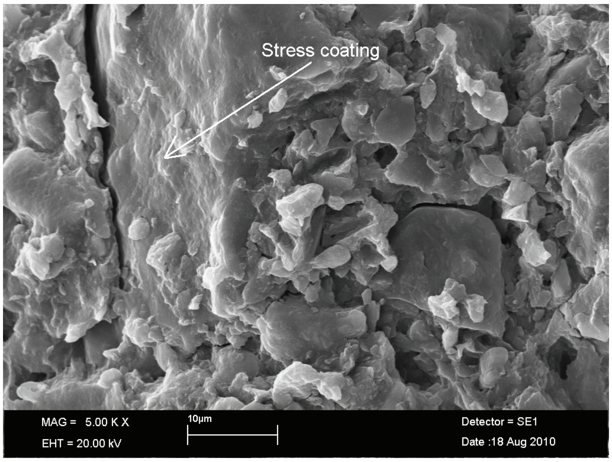

Figure 4. Stress coatings on aggregate surface. SEM image.

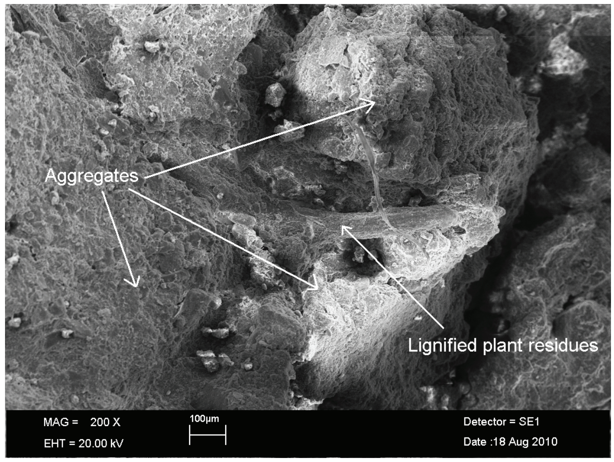

Figure 5. Lignified plant residues and shrink-swell oriented aggregates. SEM image.

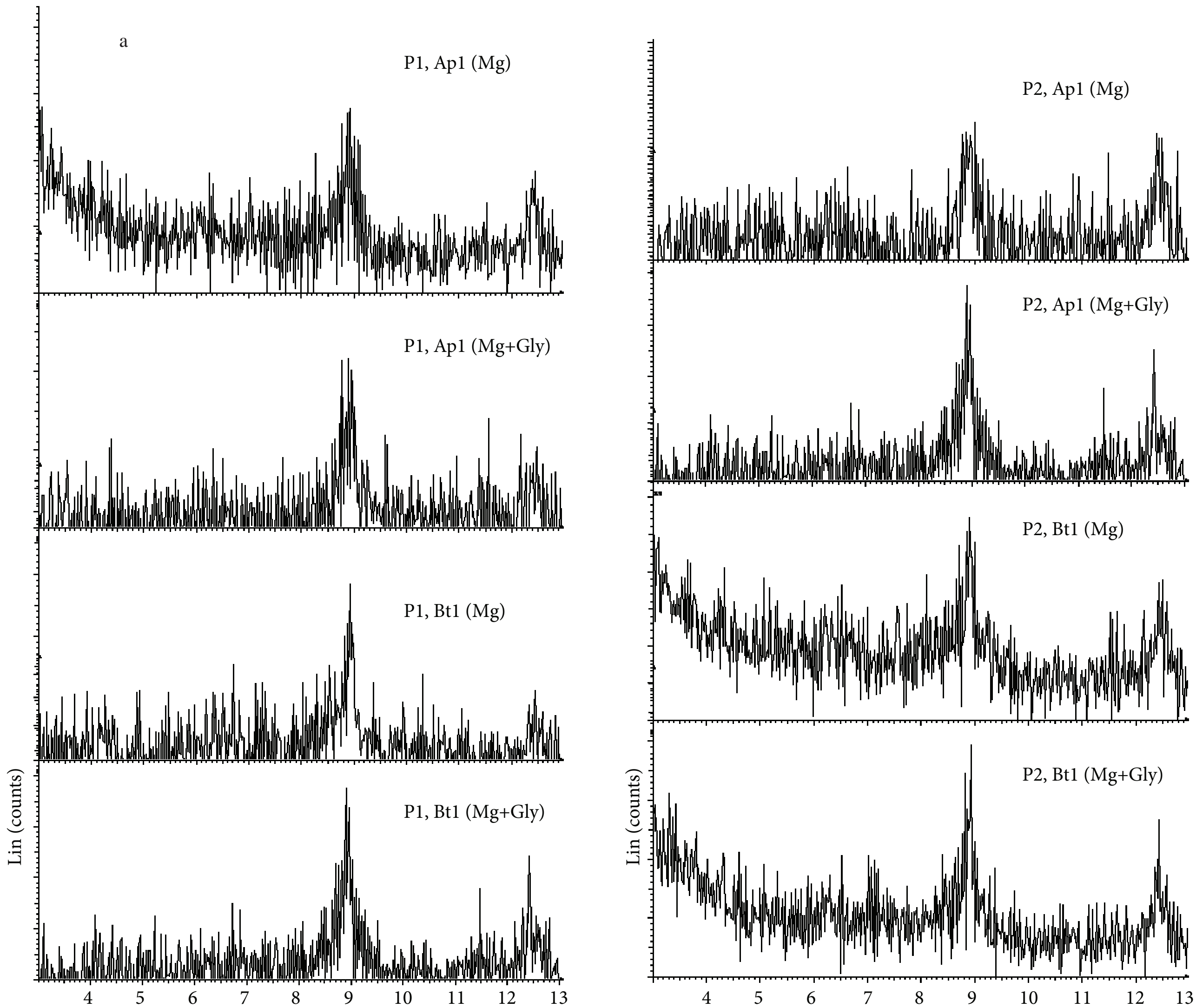

Figure 6. The X-ray diffraction patterns of the clay minerals in horizons Ap1 and Bt1 of a) profile 1 and b) profile 2. Glycolated and Mg++ saturated slides, scanned from 3 to 13 (2θ).

4. Conclusions

The present study, using micromorphological and mineralogical analyses, analyzed the secondary features developed by a long-term traditional agro-ecosystem (a 150-years-old olive grove developed on Terra Rossa soil), and their relation with the genetic features of the studied red soil, which conserves the traces of a complex evolution.

Vigorous bioturbation by soil fauna was observed in both profiles, along with an active mixing action by shrink-swell phenomena, which are responsible for the relatively high profile homogenization. The analysis of the 2 soil profiles, under canopy and between the trees, highlighted that under the canopy the anchoring action of the main olive roots generated a localized soil compaction and partly limited the uniformity of the mixing processes. The effects of this action, macroscopically observed in the field (compaction of the Ap2 horizon), are confirmed by the greater development of the sub-angular blocky MS in Ap2 under canopy.

Oriented clays caused by stress phenomena are common in both profiles, and more pronounced and more common in the 2 Bt1 horizons, where they led to the formation of the permanent microstructural units, becoming prominent in the B horizons. Their relationships with the secondary bioturbation features will be the research subject of a detailed genetic study.

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