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Terra Rossa in the Mediterranean Region: Parent Materials, Composition and Origin

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Key words: Terra rossa, Parent materials, Composition, Origin, Mediterranean region.

Abstract

In the past, the term "terra rossa" became quite a common indication for all limestone derived red soils in the Mediterranean region. Today, in some classification systems based on the Mediterranean climate as the major soil differentiating criterion, the term terra rossa is used as a name for the soil subclass "Modal Fersiallitic Red soil" when situated on limestones (DUCHAUFOUR, 1982). However, several national soil classifications (e.g. Croatian, Italian, Israeli) retained the term "terra rossa" for the hard limestone derived red soils. The nature and relationship of terra rossa to underlying carbonates is a long-standing problem which has resulted in different opinions with respect to the parent material and origin of terra rossa. Terra rossa is a reddish clayey to silty-clay material, which covers limestone and dolomite in the form of a discontinuous layer ranging in thickness from a few centimetres to several metres. It is also found along cracks and between bedding surfaces of limestones and dolomites. Thick accumulations of terra rossa like material are situated in karst depressions in the form of pedo-sedimentary complexes. A bright red colour is a diagnostic feature of terra rossa and is a result of the preferential formation of haematite over goethite, i.e. rubification. Terra rossa can be considered as soil, vetusol, relict soil (non-buried-paleosol), paleosol or pedo-sedimentary complex (soil-sediments) among different authors. Most authors today believe that terra rossa is polygenetic relict soil formed during the Tertiary and/or hot and humid periods of the Quaternary. However, some recent investigation in the Atlantic coastal region of Morocco (BRONGER & SEDOV, 2002) show that at least some terra rossa previously referred to as polygenetic relict soils should be regarded as Vetusols. In some isolated karst terrain, terra rossa may have formed exclusively from the insoluble residue of limestone and dolomite but much more often it comprises a span of parent materials including, for example, aaeolian dust, volcanic material or sedimentary clastic rocks which were derived on carbonate terrain via different transport mechanisms. BOERO & SCHWERTMANN (1989) concluded that it is of little relevance for the process of rubification whether the primary Fe sources are autochthonous or allochthonous as long as the general pedoenvironment remains essentially suitable for the formation of terra rossa. This pedoenvironment is characterised by an association of Mediterranean climate, high internal drainage due to the karstic nature of a hard limestone and neutral pH conditions. Terra rossa is formed as a result of: (1) decalcification, (2) rubification and (3) bisiallitization and/or monosiallitization. Since Fe_d/clay ratios are relatively uniform in most terra rossa, translocation of clay particles is responsible for the distribution of the red colour throughout the whole profile. However, since terra rossa soils have been exposed to various climatic fluctuations they can be affected by eluviation, yellowing and secondary hydromorphy. Erosion and deposition processes which were superimposed on karst terrains and induced by climatic changes, tectonic movements and/or deforestation might be responsible for both the patchy distribution of terra rossa and thick colluvial or alluvial terra rossa accumulations in uvala and dolina type of karst depressions (pedo-sedimentary complexes, soil-sediments).

1. INTRODUCTION

Thr red colour of many of the soils in the Mediterranean region was the main reason that in the past the broad term "Red Mediterranean soils", occasionally "terra rossa", became quite a common indication for all soils in the region (YAALON, 1997). BRESSON (1993) stated that Red Mediterranean soils resulted from a bisiallitic type of weathering with the release of high amounts of iron oxides closely bound to clay minerals. According to FEDOROFF (1997), the bisiallitic type of weathering is not a specific characteristic of Red Mediterranean soils. He also stated that the concept of clay illuviation is not yet unanimously accepted as a leading soil forming process in Red Mediterranean soils. The colour of the B horizon in Red Mediterranean soils has a hue redder then 5YR and a chroma higher than 3.5 (BECH et al., 1997). Although popular, this geographically based term was not recognized as a good term for a soil group in well defined soil-property controlled systems. Delineation of the Mediterranean region itself is not generally accepted. Generally, the Mediterranean region surrounds the Mediterranean Sea and extends between the latitudes 40 and 30ºN over an area of 4.300,000 km^2 to 7.300,000 km^2 if the drier areas in the Near East are included (LeHOUEROU, 1992). However, the Mediterranean type of climate is not restricted to these latitudes (Fig. 1). Also, similar environmental conditions prevail in all the other continents, but to a lesser extent (YAALON, 1997). Consequently, YAALON (1997) concluded that Red Mediterranean soils are no longer used as a separate classification group in modern soil Taxonomies (Soil Taxonomy; FAO system). In some classification systems based on the Mediterranean climate as the major soil differentiating criterion, they are partally replaced with the term "Fersialitic soils" (DUCHAUFOUR, 1982).

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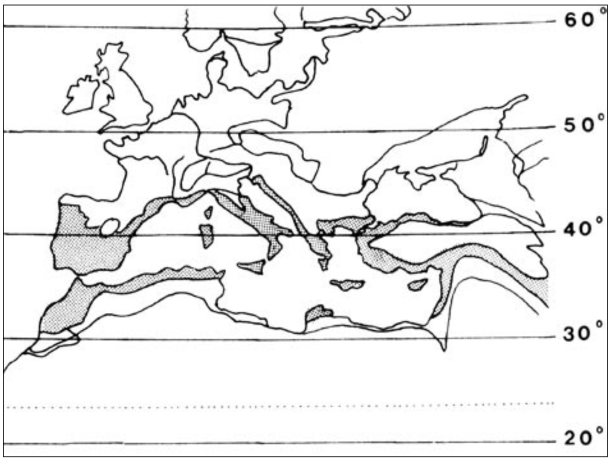

Fig. 1 Distribution of the Mediterranean climate around the Mediterranean and Adriatic sea (modified from The Times Atlas of the World, 1989).

However, the term “terra rossa” remained as a name for the soil subclass “Modal Fersiallitic Red soil” when situated on limestones. Several national soil classifications (e.g. Croatian, Italian, Israeli) retained the term “terra rossa” for the hard limestone derived red soils (Fig. 2).

Terra rossa is a reddish clayey to silty–clayey soil especially widespread in the Mediterranean region, which covers limestone and dolomite in the form of a discontinuous layer ranging in thickness from a few centimetres to several metres. It is also found along more or less karstified cracks and between the bedding surfaces of limestones and dolomites. Thick accumulations of terra rossa-like material are situated in karst depressions in the form of pedo-sedimentary colluvial complexes (DURN et al., 1999). Terra rossa can be covered by Pliocene–Pleistocene sediments of mainly carbonate composition (MORESI & MONGELLI, 1988) or Upper Pleistocene loess (CREMASCHI, 1990a; DURN et al., 1999). Based on the approach, experience and background of authors (e.g. pedology, geology, geography, climatology) as well as field and laboratory methods used, terra rossa can be considered as soil, relict soil (non-buried-palaeosol), palaeosol or a pedo-sedimentary complex. Some authors managed to find evidence that red soils are being created today (VERHEYE & STOOPS, 1973) in areas with certain climatic characteristics (for example, Lebanon). Most authors today believe that terra rossa is a polygenetic relict soil formed during the Tertiary and/or hot and humid periods of the Quaternary (e.g. BRONGER & BRUHN-LOBIN, 1997 and ALTAY, 1997). However, some recent investigations (e.g. BRONGER & SEDOV, 2002) show that at least some terra rossa previously referred to as polygenetic relict soils should be regarded as Vetusols (soils which are marked by a continuity of pedogenetic processes in time), in accordance with the concept of CREMASCHI (1987).

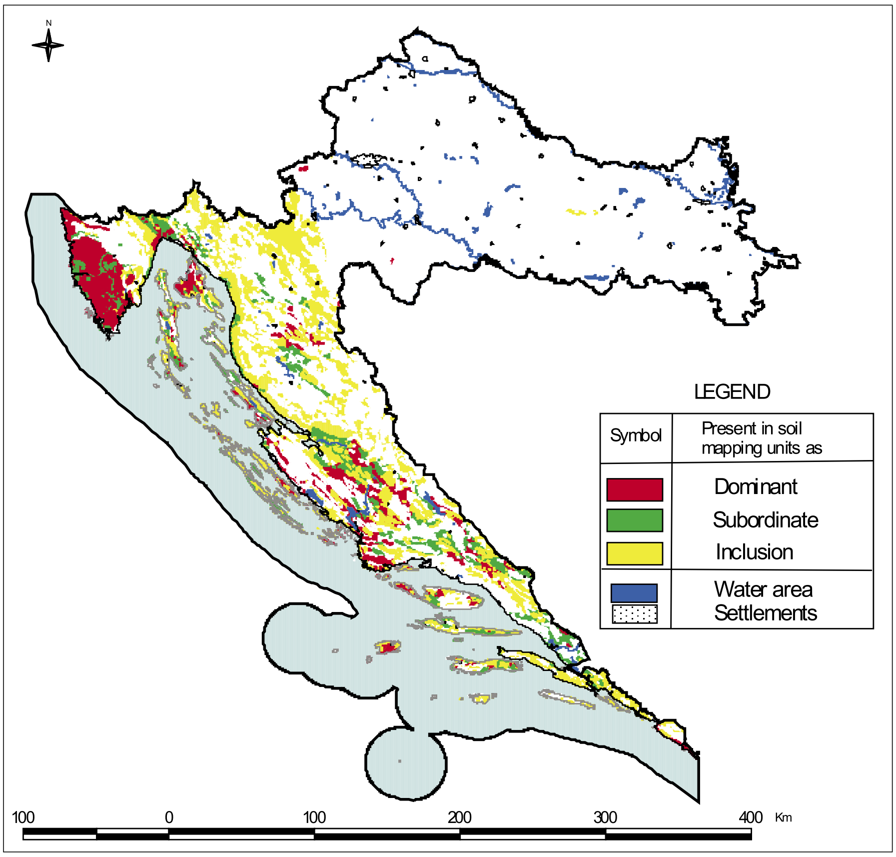

Fig. 2 Distribution of terra rossa soils in Croatia (from BOGUNOVIĆ et al., 2000).

In Soil Taxonomy (SOIL SURVEY STAFF, 1975) terra rossa is classified as Alfisols (Haploxeralfs or Rhodoxeralfs), Ultisols, Inceptisols (Xerochrepts) and Mollisols (Argixerolls or Haploxerolls). According to the FAO system (FAO, 1974) terra rossa is recognised as Luvisols (Chromic Luvisols), Phaeozems (Haplic Phaeozems or Luvic Phaeozems) and Cambisols. The Croatian classification puts terra rossa in the class of Cambic soils (ŠKORIĆ, 1986).

The nature and relationship of terra rossa to underlying carbonates is a long-standing problem which has resulted in different opinions with respect to the parent material and origin of terra rossa. The most widely accepted theory is that terra rossa has developed from the insoluble residue of carbonate rocks (TUĆAN, 1912; KIŠPATIĆ, 1912; KUBIËNA, 1953; MARIĆ, 1964; ĆIRIĆ & ALEKSANDROVIĆ, 1959; PLASTER & SHERWOOD, 1971; ŠKORIĆ, 1979, 1987; BRONGER et al., 1983; MORESI & MONGELLI, 1988). There are two different opinions among these authors. One is that the insoluble residue consists of materials belonging to pre-existing rubified soils, which dissipated and were sedimented as relics within the limestone (e.g. ĆIRIĆ & ALEKSANDROVIĆ, 1959). According to this opinion, the insoluble residue does not have to go through any mineralogical changes in order to create terra rossa. According to this, so called residual theory, the impact of climate on the development of terra rossa is not significant. Its genesis, on the other hand, is significantly influenced by the mineral composition of the insoluble residue. Accordingly, terra rossa belongs to the lithomorphic soils (BRONGER et al., 1983). This conclusion was drawn on the basis of similarities between the chemical and mineralogical composition of terra rossa and the insoluble residue. BRONGER & SMOLÍKOVÁ (1981) for example, failed to find any evidence regarding mineral depletion or clay mineral formation, and this led them to believe that terra rossa soils were lithomorphic as far as the residual theory was concerned. The alternative opinion is that terra rossa is not a lithomorphic soil but that the material (the insoluble residue) was subjected to intense weathering processes during dissolution of the carbonate rock (KUBIËNA, 1953; PLASTER & SHERWOOD, 1971; MORESI & MONGELLI, 1988).

However, other authors have emphasised that the additions of external materials might have diminished the influence of the insoluble residue of limestones and dolomites as the primary parent material of terra rossa (LIPPI-BONCAMPI et al., 1955; BALAGH & RUNGE, 1970; YAALON & GANOR, 1973; ŠINKOVEC, 1974; MACLEOD, 1980; OLSON et al., 1980; JACKSON et al., 1982; DANIN et al., 1983; RAPP, 1984; YAALON, 1997; DURN et al, 1999).

The main objective of this paper is to give an overview of terra rossa soils in the Mediterranean region including the following aspects: (1) iron-oxide phases and distribution of Fet, Fed and Feo in terra rossa, (2) relationships between particle-size distribution in terra rossa and the insoluble residue of limestone and dolomite, (3) bulk and clay mineralogy in terra rossa and the insoluble residue of limestone and dolomite, and (4) possible parent materials other than the insoluble residue of limestone and dolomite, their recognition and significance.

Examples from Istria will be used to demonstrate these aspects. Istria is a typical example of the association between terra rossa and underlying limestones and dolomites. It belongs to the NW part of the Adriatic Carbonate Platform. This part of the platform is composed of a succession of carbonate deposits more than 2000 m thick of Middle Jurassic (Bathonian) to Eocene age, and is overlain by Palaeogene (Eocene) *Foraminiferal limestones*, *Transitional beds (Globigerina marls)* and flysch deposits (Fig. 3). The most important geological structure of the Istrian peninsula is the Western Istrian anticline (POLŠAK & ŠIKIĆ, 1973; MARINČIĆ & MATIČEC, 1991), as shown on Fig. 3.

According to VELIĆ et al. (1995) carbonate and flysch deposits of Istria can be divided into four large-scale sequences. The 1st, 2nd and 3rd large-scale sequences are composed of carbonates, each terminated by important, long-lasting emersions, i.e. type 1 sequence boundaries (TIŠLJAR et al., 1998). Since the formation of flysch, the surface has been affected by tectonics, karst processes and weathering which has led to the development of both surficial and underground features. Different types of sediments, polygenetic palaeosols and soils have been formed. The oldest Quaternary sediments were discovered in the Šandalja cave near Pula and are represented by red breccia with faunal remains of Early Pleistocene age (MALEZ, 1981). Climatic and biotic factors have changed during the Late Tertiary and Quaternary but the pedoenvironment on the hard carbonate rocks of the Jurassic–Cretaceous–Palaeogene carbonate plain of southern and western Istria generally remained suitable for rubification. Terra rossa is found on the Jurassic–Cretaceous–Palaeogene carbonate plain of southern and western Istria (Figs. 3 and 4). It fills cracks and sinkholes, and forms a discontinuous surface layer up to 2.5 metres thick which is, in places, covered by Upper Pleistocene loess. Thick (up to 14 metres) accumulations of terra rossa-like material are found in karst depressions in the form of pedo-sedimentary colluvial complexes.

2. IRON-OXIDE PHASES AND TOTAL, Na DITHIONITE–CITRATE BICARBONATE AND AMMONIUM OXALATE EXTRACTABLE IRON IN TERRA ROSSA

Haematite and goethite are the main pedogenic iron-oxide mineral phases in terra rossa (BRONGER et al., 1983; TORRENT & CABEDO, 1986; BOERO & SCHWERTMANN, 1989; BOERO et al., 1992; DURN

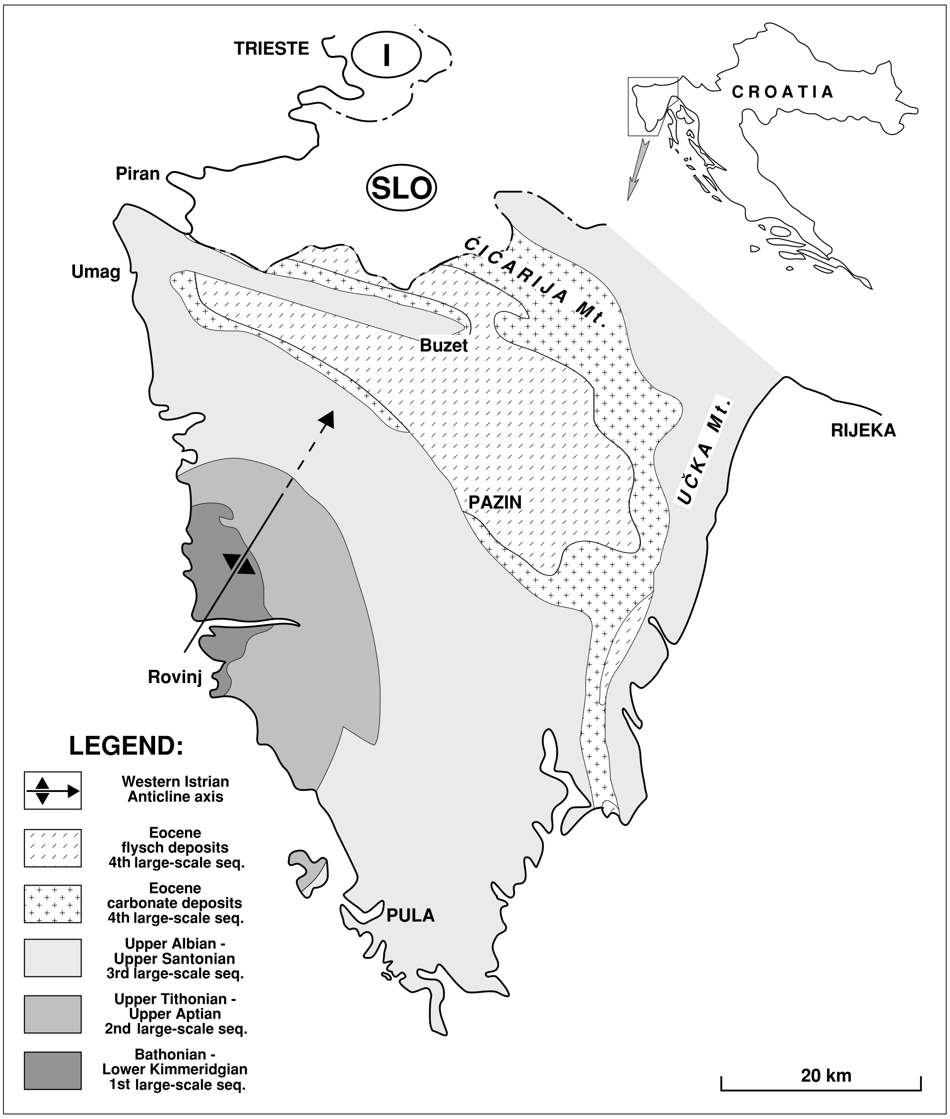

Fig. 3 Map showing schematic distribution of megasequences in Istria and location of the Western Istrian anticline (partly modified after VELIĆ et al., 1995).

et al., 1999). The bright red colour is a diagnostic feature of terra rossa and is a result of the preferential formation of haematite over goethite, i.e. rubification. BOERO & SCHWERTMANN (1989). Namely, in the 30 samples examined (<2 μm fraction) they also estimated that the haematite/(haematite+goethite) ratios averaged 0.62±0.055 i.e. the content of haematite is higher than the content of goethite in terra rossa. SINGER et al. (1998) interpreted the difference in iron oxide mineralogy between terra rossa (dominated by haematite) and rendzina (dominated by goethite) developed on limestones in Israel as a consequence of soil climate, specifically the moisture regime of the two soils. The role of well-lithified limestones below terra rossa in maintaining a haematitic pedoenvironment was also stressed by BOERO et al. (1992). They found that the occurrence of haematite in terra rossa in Italy is irrespective of climate, and haematite may be the dominant iron oxide even in sites with 13°C AAT and up to 1700 mm AAP. Since *in situ* formation of haematite reflects a relatively low water activity, high temperature, good aeration and/or high turnover rate of organic matter, haematite can be considered an indicator of terra rossa formation (BOERO & SCHWERTMANN, 1989). Based on analysis of 48 terra rossa samples from various locations around the world (Italy, Greece, Israel, Spain, Lebanon, France, Mexico, Germany and Australia) BOERO & SCHWERTMANN (1989) found that Fe_d, Fe_d/Fe_t, haematite/goethite ratios and Al substitution in haematite and goethite vary to a rather limited extent which may indicate the specific pedoenvironment under which terra rossa is formed. They suggested this pedoenvironment is characterised by an association of Mediterranean climate, high internal drainage due to the karstic nature of a hard limestone and neutral pH conditions.

XRD analysis showed that the clay fraction of terra rossa samples from Istria contains both haematite and goethite (DURN et al., 2001a; Fig. 5). Broadening of diagnostic haematite and goethite XRD peaks indicates the low degree of their crystallinity and their pedogenic origin. The Munsell hue of dry terra rossa samples ranges between 5YR and 10R, which

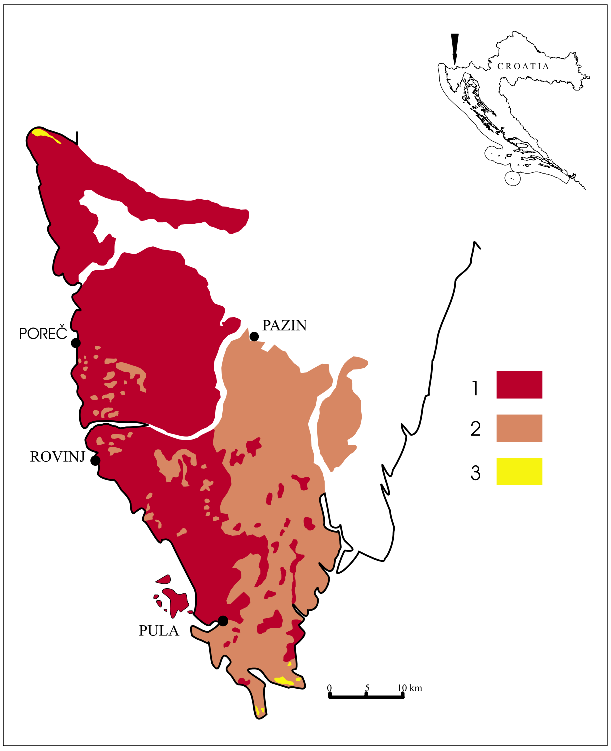

Fig. 4 Distribution of terra rossa in Istria (modified after ŠKORIĆ, 1987). Legend: 1) terra rossa, calcocambiosol, eutric cambiosol, rigosol from terra rossa (area of terra rossa >70%); 2) terra rossa, calcocambiosol, eutric cambiosol (area of terra rossa is 50–70%); 3) eutric cambisol on loess, luvisol on loess, rigosol from luvic and eutric cambiosol (40:30:30).

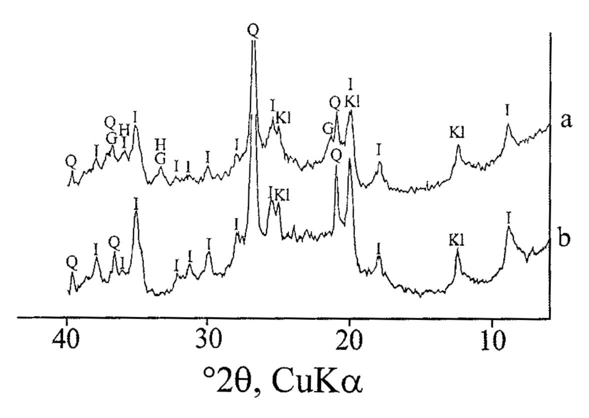

Fig. 5 Characteristic parts of the XRD patterns of terra rossa sample 1 (<2 μm fraction). a) air dried; b) treated with HCl (1:1, 24h). Legend: Kl) Kaolinite; I) Illitic material; Q) quartz; H) haematite; G) goethite (taken from DURN et al., 2001).

indicates that red haematite masks the yellow colour of goethite. Ferrihydrite (which also gives a red colour to soil) was not detected with XRD, probably due to its small amount and poor crystallinity. The results of the analysis of Fe_t (total iron), Fe_d (iron extractable with Na dithionite–citrate bicarbonate) and Fe_o (iron extractable with ammonium oxalate) in samples of terra rossa from Istria are presented in Table 1. The mean value of the Fe_d/Fe_t ratio, which is taken as an index of weathering (e.g. ARDUINO et al., 1984; BOERO & SCHWERTMANN, 1987; BECH et al., 1997) is 0.7, and reflects a quite high degree of weathering of Fe-containing primary silicates. Low values of Fe_o (Table 1) point to the low content of poorly crystalline Fe-oxides (e.g. ferrihydrite). Relatively uniform Fe_d/Fe_t ratios are also shown by the high positive correlation coefficient (Fig. 6) and point to a clear relationship between Fe_d and Fe_t in terra rossa. Fe_d/clay ratios are relatively uniform (Fig. 7) and clearly indicate a predominance of co-illuviation of clay and Fe oxides, i.e. the connection of Fe-oxides with the clay fraction.

The rather limited variation of selected Fe-oxide characteristics in 40 terra rossa samples from Istria (Table 1; especially the average and 95% C.I. values of Fe_d and Fe_d/Fe_t) are very similar to those of BOERO & SCHWERTMANN (1989). While Fe_d in 45 terra rossa samples averaged 3.5% (±0.3) (BOERO & SCHWERTMANN 1989), in 40 samples from Istria, Fe_d averaged 3.68% (±0.28). The arithmetic means of the two sets of data are not significantly different at the 0.05 level (t-test). The two populations are indistinguishable at the 0.05 level, i.e. two arithmetic means represent two independent estimates of the same population (Fe_d in terra rossa). This supports BOERO & SCHWERTMANN's (1989) conclusion, that the rather limited extent of variation of selected Fe-oxide characteristics may indicate a specific pedoenvironment in which terra rossa is formed.

	n	x	s	CV(%)	0.95 C.I.
Fe_t	40	5.19	0.99	19.07	4.88–5.51
Fe_d	40	3.68	0.89	24.18	3.40–3.96
Fe_o	40	0.39	0.09	23.08	0.36–0.42
Fe_d/Fe_t	40	0.70	0.07	10.00	0.68–0.72
Fe_o/Fe_d	40	0.112	0.033	29.46	0.102–0.122

Table 1 Basic statistics for total, dithionite and oxalate extractable iron (%) in terra rossa samples (<2 mm). Legend: n = number of samples, x = arithmetic mean, s = standard deviation, CV(%) = coefficient of variation, 0.95 C.I. = confidence interval (taken from DURN et al., 2001).

3. RELATIONSHIPS BETWEEN PARTICLE-SIZE DISTRIBUTION IN TERRA ROSSA AND THE INSOLUBLE RESIDUE OF LIMESTONE AND DOLOMITE

It is generally accepted that terra rossa is formed on hard and permeable limestones and dolomites with a very low content of insoluble residue (YAALON & GANOR, 1973; MACLEOD, 1980; DANIN et al., 1983; MORESSI & MONGELLI, 1988; YAALON, 1997). However, neither the insoluble residue content of limestone and dolomite nor its particle size distribution is always compatible with the development of terra

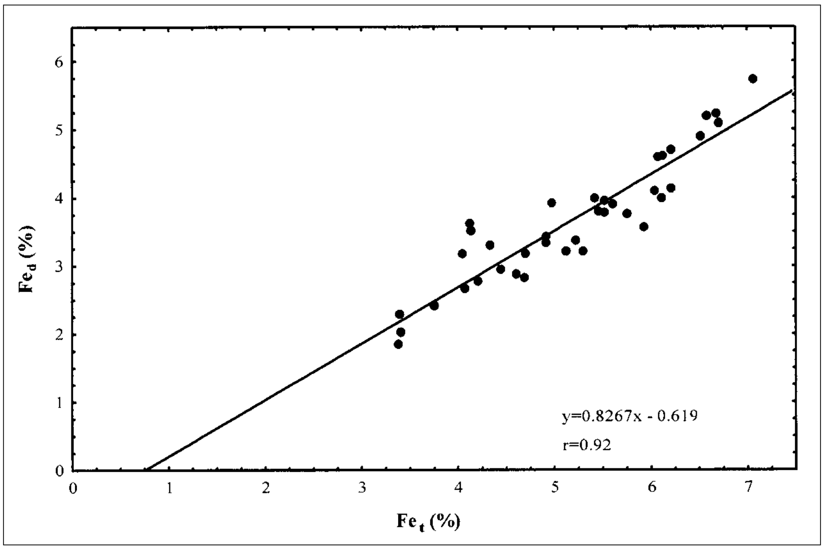

Fig. 6 The ratio of dithionite soluble iron (Fed) and total iron (Fe$_t$) in terra rossa. r is significant at level $p<0.01$ (taken from DURN et al., 2001).

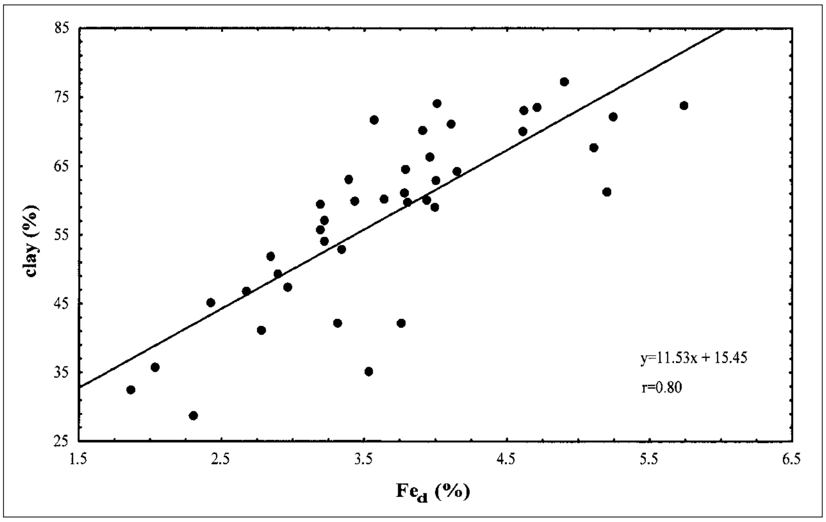

Fig. 7 The ratio of the amount of clay fraction (<2 μm) and dithionite soluble iron (Fe$_d$) in terra rossa; r is significant at level $p<0.01$ (taken from DURN et al., 2001).

rossa entirely by the dissolution of carbonate rock. The average insoluble residue content of limestones in Epirus, Greece was found to be 0.15% (MACLEOD, 1980). According to DANIN et al. (1983) dolomites near Jerusalem, Israel contain on average 1% insoluble residue. The insoluble residue content of limestone and dolomite from Istria, Croatia, averages 0.86% (DURN et al., 1999). Based on: (1) a conservative mean content of 1% of insoluble limestone residue, (2) the annual rate of dissolution of 10 to 40 μm limestone and (3) a high extent of preservation of residue (not counting any loss by corrosion), YAALON (1997) concluded that it would be necessary to dissolve 50 m of limestone to accumulate half a metre of soil, which would require some 2.000,000 years (±50%). Higher silt/clay ratios in terra rossa compared to the insoluble residue of underlying limestones and dolomites was observed in Israel (YAALON & GANOR, 1973), Greece (MACLEOD, 1980) and Croatia (DURN et al., 1999) which indicates that the additions of external materials might have diminished the influence of the insoluble residue of limestones and dolomites as the primary parent material of terra rossa.

According to DURN et al. (1999) terra rossa in Istria is composed predominantly of clay (<2 μm) and silt (2–63 μm) sized particles, with sand (>63 μm) particles forming less than 4% (Fig. 8). The clay content ranges from 32.1 to 77.2% and generally increases with depth in the profiles. The higher content of sand sized particles observed in a few samples is attributed to rhizoconcretions which formed in terra rossa as the result of palaeopedological processes which post-date terra rossa formation (recalcification of terra rossa following its burial) or to the recent colluvial additions of flysch. The insoluble residue content of the underlying limestones and dolomites ranges from 0.08 to 2.23 wt.% and is dominated by clay sized particles (DURN et al., 1999). The clay content in the insoluble residues ranges from 63.8 to 87.5%. An average silt/clay ratio in terra rossa (0.81) is higher than that in the insoluble residue of limestone and dolomite (0.25). If terra rossa has developed only from the insoluble

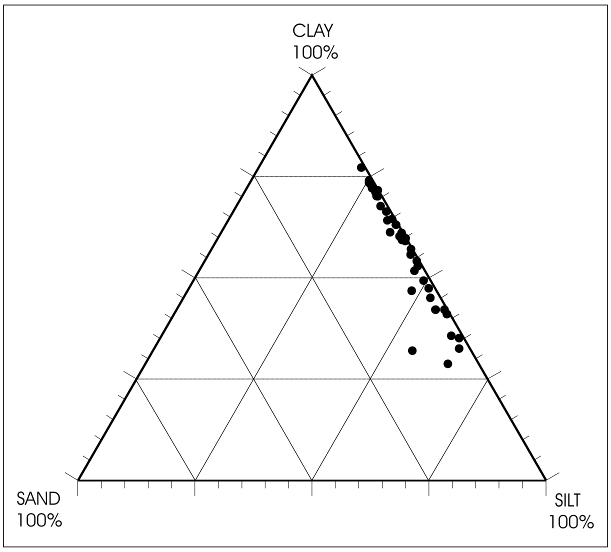

Fig. 8 Particle size analysis of terra rossa (taken from DURN et al., 1999).

residue of limestone or dolomite, its clay content, due to weathering, should be higher than that in the insoluble residues which is not the case, which supports the influence of external material in the genesis of terra rossa in Istria.

4. BULK AND CLAY MINERALOGY IN TERRA ROSSA AND INSOLUBLE RESIDUE OF LIMESTONE AND DOLOMITE

The mineral composition of terra rossa in the Mediterranean area may be very variable. MACLEOD (1980) found that the clay fraction of terra rossa from Epirus (Greece) consists of kaolinite, micaceous minerals, vermiculite, quartz and Fe-oxides. According to MORESI & MONGELLI (1988) terra rossa from Apulia (Italy) is composed of kaolinite, illite, Fe-oxides, quartz, feldspar, mica, Al-oxides and hydroxides, and Ti-oxides. The clay fraction of terra rossa from Spain contains kaolinite, illite, vermiculite, montmorillonite, interstratified clay minerals and goethite (GARCIA-GONZALES & RECIO, 1988). The chief constituents of the clay fraction of terra rossa from Sardinia are illite and kaolinite, while hydroxy-interlayered vermiculite is the dominant phase in NE Italy (BOERO et al., 1992). Terra rossa soils from the Karbum Peninsula of Izmir province (Turkey) contain a clay fraction comprising smectite, palygorskite, kaolinite, Fe-oxides and quartz (ATALAY, 1997). BRONGER & BRUHN-LOBIN (1997) found considerable to extensive formation of clay minerals, mainly kaolinites in terra rossa from NW Morocco.

Data on the mineral composition of the insoluble residue of limestone and dolomite are quite scarce in the region. Insoluble residues of limestones from Epirus (Greece) are dominated by micaceous clay minerals while quartz and kaolinite are sporadically present in the clay fraction and of local importance (MACLEOD, 1980). MORESI & MONGELLI (1988) stated that the insoluble residue of Cretaceous carbonate rocks from the Murge and Salento areas (Italy) is composed of kaolinite, illite, Fe-oxides, quartz, feldspar, mica, Al-oxides and hydroxides, and Ti-oxides. Terra rossa soils situated on those carbonate rocks consist of the same minerals, but the amount of kaolinite is higher than the illite content.

In general, the bulk and clay mineralogy in terra rossa and the insoluble residue of underlying limestone and dolomite indicate that: (1) terra rossa formed from re-working of the insoluble residue of underlying carbonate rocks (e.g. MORESI & MONGELLI, 1988) or (2) the additions of external materials may have diminished the influence of the insoluble residue of limestones and dolomites as the primary parent material of terra rossa (e.g. MACLEOD, 1980).

Istrian terra rossa is composed of quartz, plagioclase, K-feldspar, micaceous clay minerals (illitic material and mica), kaolinites (Kl_D and Kl), chlorite, vermiculite, low-charge-vermiculite or high-charge smectite, mixed-layer clay minerals (other than illitic material), haematite, goethite and an XRD-amorphous inorganic compound (DURN et al, 1999). Calcite, dolomite and boehmite are sporadically present and are of local importance. The results of semiquantitative phase analysis of selected terra rossa samples are given in Table 2.

Dominant mineral phases in the clay fraction of all terra rossa from Istria are kaolinites (Kl_D and Kl), illitic material, Fe-oxides and XRD amorphous inorganic compounds, while vermiculite, low-charge-vermiculite or high-charge smectite, chlorite, mixed-layer clay minerals and quartz are present in subordinate amounts (Fig. 9). The clay fraction of terra rossa also contains boehmite (only those samples which were taken in the vicinity of bauxites of Jurassic and Palaeogene age). The results of XRD analysis of the clay fraction separated from selected terra rossa samples are presented in Table 3.

In all terra rossa samples the content of kaolinite which does not form intercalation compounds with DMSO (Kl) is higher than that of kaolinite which intercalates with DMSO (Kl_D). Fine clay (<0.2 μm fraction) contains only kaolinite which does not form intercalation compounds with DMSO (Kl) (Table 4). This mineral is the dominant mineral phase in fine clay. Coarse and medium clay (2–0.2 μm fraction) contains both kaolinite which does not form intercalation compounds with DMSO (Kl) and kaolinite which intercalates with DMSO (Kl_D), the former being more abundant (Table 4). Low-charge vermiculite or high-charge smectite was detected only in the fine clay of samples 47 and 52 (Table 4).

The insoluble residues of limestone and dolomite are greyish-brown in colour and contain quartz,

Sample	Quartz	Plagioclase	K-feldspar	Hematite+Goethite	Phyllos.+am.	Calcite	Dolomite	Boehmite
15	23	2	1	6	68			
22	33	5	2	3	57			
25	21	2	1	6	70			
47	32	4	1	3	52	5	3	
52	29	1	1	5	64			
60	18	3	1	7	62			9
100	13	2		8	67			10
131	25	3	1	5	66			
136	15	1	1	7	76			

Table 2 Mineral composition of the <2 mm fraction of terra rossa (wt.%). Legend: Phyllos.+am. = Phyllosilicates and amorphous inorganic compound (taken from DURN et al., 1999).

Sample	Illitic material	Kl_D	Kl	Vermiculite	L.c. vermiculite	Chlorite	Mc	Quartz	Boehmite
15	+	+	+	+			+	+	
22	+	+	+	+		+	Ch/V	+	
25	+	+	+	+			+	+	
47	+	+	+	+	x	+	+	+	
52	+	+	+	+	x	+	+	+	
60	+	+	+	+		+	+	+	+
100	+	+	+	+		+	+	+	+
131	+	+	+	+			+	+	
136	+	+	+	+			+	+	

Table 3 Mineral composition of the < 2μm fraction of terra rossa after the removal of carbonates, humic materials and iron-oxides. Legend: Kl_D = Kaolinite which forms intercalation compounds with DMSO, Kl = Kaolinite which does not intercalate with DMSO, L.c. vermiculite = Low-charge vermiculite or high-charge smectite, Mc = Mixed-layer clay mineral, Ch/V = chlorite/vermiculite, x = mineral present only in the <0.2 μm fraction (taken from DURN et al., 1999).

micaceous clay minerals (illitic material and mica), mixed-layer clay minerals, goethite and amorphous organic and inorganic compounds (DURN et al., 1999). K-feldspar, plagioclase, and kaolinite which forms intercalation compounds with DMSO and chlorite occur sporadically. The dominant mineral phase of the clay fraction of the insoluble residues is illitic material. The results of semiquantitative phase analysis of selected insoluble residues are shown in Table 5. The results of XRD analysis of the related clay fraction, based on the patterns of oriented samples, are given in Table 6.

The bulk and clay mineral assemblage in the insoluble residue of limestones and dolomites does not support development of terra rossa entirely by the dissolution of carbonate rock.

5. POSSIBLE PARENT MATERIALS OTHER THAN INSOLUBLE RESIDUE OF LIMESTONE AND DOLOMITE, THEIR RECOGNITION AND SIGNIFICANCE

Soil geomorphic studies made by OLSON et al. (1980) in southern Indiana, USA, indicate that the terra rossa is mainly debris, derived from the erosion of higher lying clastic sedimentary rocks, transported and deposited on pediments cut into lower lying limestone. LIPPI-BONCAMPI et al. (1955) and YAALON & GANOR (1973) mention the role of aeolian materials from volcanoes in the surrounding area in the formation of terra rossa. CHIESA et al. (1990) concluded that in the Marche region (Italy), aeolian deposits formed during the Pleistocene were affected by pyroclastic materials from the Tyrrenian area. ŠUŠNJARA et al. (1994) found vitric tuff interstratified within terra rossa near Gljev in central Dalmatia (Croatia). RAPP (1984) suggested that the terra rossa soils of Southern Europe might be wind-borne material from Africa. According to JAHN et al. (1991), 10% of the soil material in terra rossa from southernmost Portugal is of aeolian origin. Aeolian contributions have also been recognised due to the similarities in clay mineralogy (BALAGH & RUNGE, 1970), similarities in heavy mineral fraction (ŠINKOVEC, 1974; DURN et al., 1992; DURN & ALJINOVIĆ, 1995), particle size distribution (MACLEOD, 1980) and the divergence of oxygen isotopic ratios of associated fine quartz (JACKSON et al., 1982; NIHLEN & OLSSON, 1995). Given the fact that the "cryptogamic imprint" on the rocks

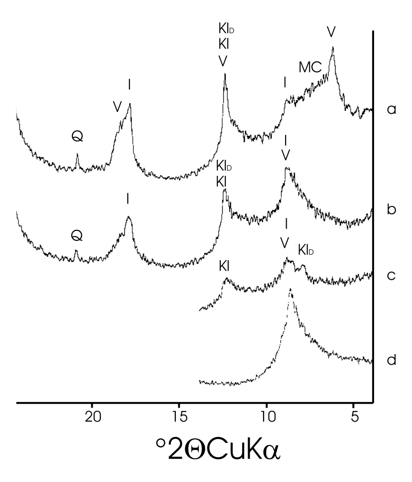

Fig. 9 Characteristic parts of the XRD patterns of terra rossa sample 52 (<2 µm fraction) after removal of Fe-oxides (oriented preparations): a) Mg-saturated; b) K-saturated; c) K-saturated and DMSO solvated; d) heated for 1 hour at 550°C. Legend: V) vermiculite; MC) mixed-layer clay mineral; I) illitic material; KlD) kaolinite which intercalates with DMSO; Kl) Kaolinite which does not intercalate with DMSO; Q) Quartz (taken from DURN et al., 1999).

can be detected on the rock faces under the present soil surface, DANIN et al. (1983) concluded that the principal contributor to the formation of the upper soil layer of terra rossa in the studied area in Israel is from an aeolian source.

Previous statements imply a polygenetic nature for terra rossa. In some isolated karst terrains it may have formed exclusively from the insoluble residue of limestone and dolomite but much more often it comprises a span of parent materials which arrived on the carbonate terrain via different transport mechanisms (DURN et al., 1999). For example, YAALON (1997) concluded that practically all terrestrial soils in the Mediterranean region were influenced by the addition of aeolian dust.

Four different aspects regarding the parent material of terra rossa in Istria will be presented: (1) particle size, (2) mineralogy, (3) geochemistry and (4) micromorphology.

5.1. Particle size

The insoluble residue content of limestone and dolomite from Istria, Croatia averages 0.86% (DURN et al., 1999). The content of the insoluble residue indicates that an excessive thickness of limestone and dolomite must have been dissolved to form terra rossa, and that the extent of the preservation of that residue through the Quaternary must have been unusually high. Also, the average silt/clay ratio in terra rossa (0.81) is higher than that in the insoluble residue of limestone and dolomite (0.25) which indicates that coarser material must have contributed as parent material for terra rossa. When we compare the particle size of the insoluble residue of limestone and dolomite, loess and marl (Fig. 10) with that of terra rossa (Fig. 8), it does not exclude loess and flysch as possible parent materials for terra rossa formation. Namely, both the insoluble residues of loess and marl are enriched in the silt and sand size fractions compared to the insoluble residue of limestone and dolomite.

5.2. Mineralogy

The bulk and clay mineral assemblage in the insoluble residue of limestones and dolomites also does not support development of terra rossa in Istria entirely by

Sample	Illitic material	Kl_D	Kl	Vermiculite	l.c. vermiculite	Chlorite	Mc	Boehmite
				<0.2 µm				
15	25		75	tr.			+	
22	45		55	tr.			+	
25	30		70	tr.			+	
47	23		63	tr.	14		+	
52	10		77	tr.	13		+	
60	32		60	8		tr.	+	+
100	15		81	4		tr.	+	+
131	22		78	tr.			+	
136	19		78	3			+	
				2 – 0.2 µm				
25	44	12	35	9			+	+
52	50	12	33	5		tr.	+	+

Table 4 Semiquantitative clay mineral composition of the <0.2 µm and 2–0.2 µm fractions of terra rossa after the removal of carbonates, humic materials and iron-oxides. Legend: Kl_D = Kaolinite which forms intercalation compounds with DMSO, Kl = Kaolinite which does not intercalate with DMSO, L.c. vermiculite = Low-charge vermiculite or high-charge smectite, Mc = Mixed-layer clay mineral, Ch/V = chlorite/vermiculite, Illitic material+Kl_D+Kl+Vermiculite+L.c. vermiculite+chlorite = 100 wt.% (taken from DURN et al., 1999).

Sample	Quartz	Plagioclase	K-feldspar	Goethite	Phyllos.+am.	Calcite	Dolomite
I.r. of limestone and dolomite							
56	6		6	4	84		
63	8		6	4	82		
75	14		2	6	78		
79	15			4	80		
85	8			4	88		
130	17		4	2	77		
Marl							
94	15	2			36	47	
Loess							
48	17	4	1	1	31	21	25

Table 5 Mineral composition of insoluble residues of limestone and dolomite and mineral composition of bulk samples of marl and loess (wt.%). Legend: Phyllos.+am. = Phyllosilicates and amorphous inorganic compound (taken from DURN et al., 1999).

Sample	Illitic material	Kl_D	Kl	Vermiculite	L.c. vermiculite	Chlorite	Smectite	Mc	Quartz
Limestone and dolomite									
56	+					+		Ch/V	+
63	+							+	+
75	+	+						+	+
79	+	+						+	+
85	+							+	+
130	+							+	+
Marl									
94	+					+	+	+	+
Loess									
48	+	+	+	+	x	+		Ch/V	+
<0.2 µm	29		36	tr.	35	tr.		+	
2–0.2 µm	53	10	12	9		16		Ch/V	

Table 6 Mineral composition of the < 2µm fraction of insoluble residues of limestone and dolomite, marl and loess after the removal of humic materials and iron oxides. Semiquantitative clay mineral composition of the <0.2 µm and 2–0.2 µm fractions of loess sample 48 are also presented. Legend: Kl_D = kaolinite which forms intercalation compounds with DMSO, Kl = kaolinite which does not intercalate with DMSO, L.c. vermiculite = Low-charge vermiculite or high-charge smectite, Mc = Mixed-layer clay mineral, Ch/V = chlorite/vermiculite, x = mineral present only in the <0.2 µm fraction, + = identified mineral. Illitic material+Kl_D+ Kl+Vermiculite+L.c. vermiculite+chlorite = 100 wt.% (taken from DURN et al., 1999).

the dissolution of carbonate rock. The dominant mineral phase in the insoluble residues is illitic material, and kaolinite which forms intercalation compounds with DMSO was detected only in three samples (17, 75 and 79). Plagioclase was only found in one sample (17) while all terra rossa samples contain this mineral (Table 2). The insoluble residues do not contain vermiculite which was observed in small amounts in the clay fraction of all terra rossa samples. Vermiculite is an unstable mineral in the pedogenic environment (BARNHISEL & BERTSCH, 1989; DOUGLAS, 1989). BOERO et al. (1992) suggest formation of hydroxy-interlayered vermiculite at the expense of 2:1 silicates in terra rossa of the moist environment of NE Italy. We postulate that the appearance of vermiculite in terra rossa from Istria can be related to some parent material other than the insoluble residue of limestone and dolomite. Low-charge vermiculite or high-charge smectite was detected in the <0.2 µm fraction of terra rossa samples which are situated below (47) or near (52) Upper Pleistocene loess (Table 4, Fig. 3). The presence of this mineral in those samples may indicate its aeolian origin because it was detected as one of the main mineral phases in the fine clay of the Upper Pleistocene loess in Savudrija (Table 6). The Upper Pleistocene loess post-dated terra rossa formation, but it indicates that during terra rossa formation, similar external materials might have contributed to terra rossa. This is especially important when we bear in mind that since the early Middle Pleistocene, loess deposition affected Istria

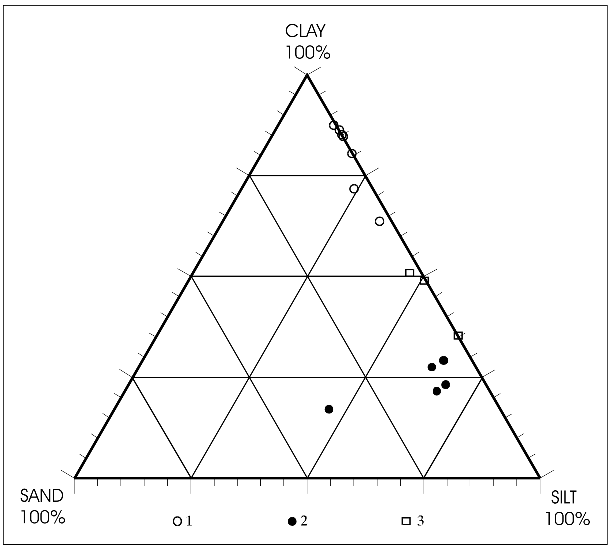

Fig. 10 Particle size analysis of: 1) the insoluble residues of the Jurassic and Cretaceous limestones and dolomites; 2) loess; 3) marl (taken from DURN et al., 1999).

and the Dalmatian Archipelago (CREMASCHI, 1990b). This is also supported by the characteristic heavy mineral assemblage in terra rossa, which in most terra rossa samples strongly resembles that of loess derived from the deflation of the Po plain sediments during the Middle and Late Pleistocene (DURN, 1996; DURN & ALJINOVIĆ, 1995). The heavy mineral fraction of these terra rossa samples is enriched in epidote–zoisite group minerals and amphiboles. The influence of the Po plain provenance heavy mineral assemblage is substantial even in terra rossa samples with evidently higher content of zircon, tourmaline and rutile.

5.3. Geochemistry

In order to chemically characterize insoluble residues of carbonate rocks and compare them with terra rossa, marl and loess, DURN et al. (1999) used elements with a high ionic potential which are considered relatively immobile in soil environments and suitable for geochemical "fingerprinting" (MUHS et al., 1987; MUHS et al., 1990), and elements with low ionic potential which are considered relatively mobile in soil environments. We chose the elements Ti, Nb and Zr from the first group and Na and K from the second group. The reason for taking the latter into consideration is the direct relationships of these elements to plagioclase (Na), and micaceous clay minerals (illitic material and mica) and K-feldspar (K).

(Na_2O/K_2O)x100 ratios in the insoluble residue of limestones and dolomites ranges from 2 to 4.3 and are much lower than ratios in terra rossa, loess and marl (Fig. 11). This, together with the results of bulk mineralogy (Tables 2 and 5) indicates that terra rossa, loess and marl are enriched in plagioclase compared to the insoluble residue of limestones and dolomites. Zr/Nb ratios in the insoluble residue of limestones and dolomites are also significantly lower than these ratios in loess, marl and the majority of terra rossa samples (Fig. 12). This is also partly valid for (Zr/Ti)x1000 ratios although there is obvious overlapping of the Mondolaco profile and the lower part of the Novigrad profile with the insoluble residue field (Fig. 13).

Geochemical ratios also support the influence of external material in the genesis of terra rossa (Figs. 11, 12 and 13). If we consider that Zr, Nb, and Ti are relatively immobile in soil, than parent materials other than the insoluble residue of limestones and dolomites may have influenced the composition of terra rossa.

Rare earth elements (REE) are often used as indicators of geological processes and for provenance determination in clastic sediments (CULLERS et al., 1988). REE patterns in the clay fraction of sediments are quite similar to those of their source rocks (CONDIE, 1991). REE in the sand-size fractions of soils derived from particular parent rocks may also vary significantly, reflecting the REE distribution of the parent rocks (CULLERS et al., 1988). However, the mobility and fractionation of REE during weathering

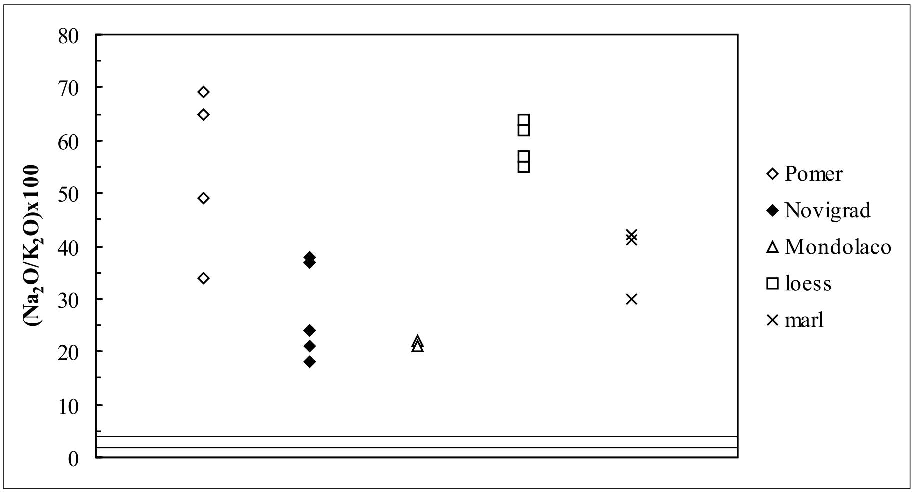

Fig. 11 Molar ratios of (Na_2O/K_2O) x100 in terra rossa, loess and marl (from flysch sediments). Two horizontal lines represent minimum and maximum values for this ratio in the insoluble residues of the Jurassic and Cretaceous limestones and dolomites (taken from DURN et al., 1999).

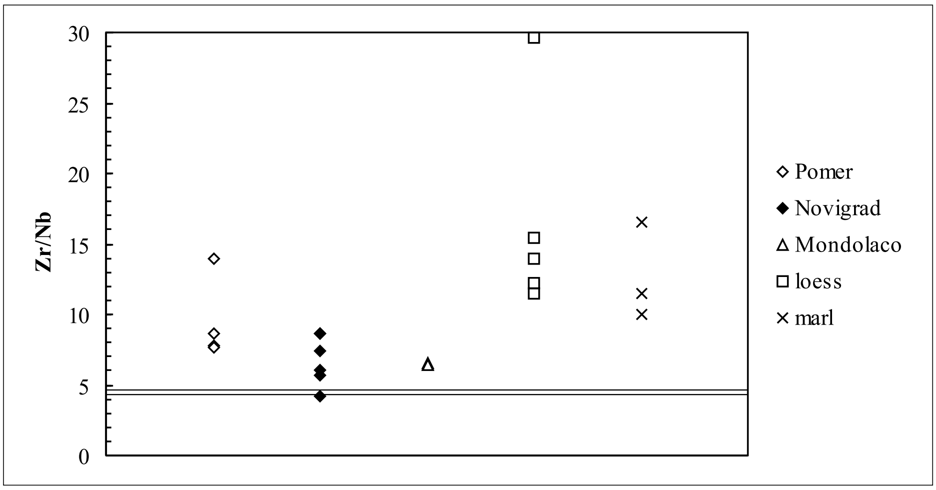

Fig. 12 Ratios of Zr/Nb in terra rossa, loess and marl (from flysch sediments). Two horizontal lines represent minimum and maximum values for this ratio in the insoluble residues of the Jurassic and Cretaceous limestones and dolomites (taken from DURN et al., 1999).

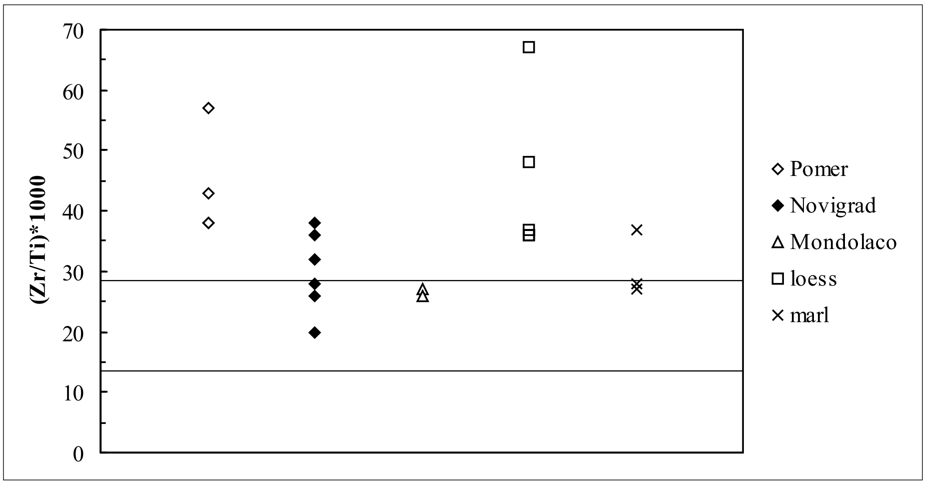

Fig. 13 Ratios of (Zr/Ti)x1000 in terra rossa, loess and marl (from flysch sediments). Two horizontal lines represent minimum and maximum values for this ratio in the insoluble residues of the Jurassic and Cretaceous limestones and dolomites (taken from DURN et al., 1999).

is also well documented (e.g. LAND et al., 1999). The total REE content of the <2 mm fraction of terra rossa samples from Istria is quite variable and ranges from 104.09 to 394.95 ppm (DURN et al., 2001b; Fig. 14). Chondrite-normalized REE patterns for all analysed samples (fraction <2 mm) show similar patterns to that of ES. Chondrite-normalized REE patterns of the <2 μm fraction of terra rossa are shown on Fig. 15 and of the <2 μm fraction of I.R. of loess, flysch and limestone on Fig. 16.

DURN et al. (2001b) concluded that the wide range of total REE contents in bulk samples, the difference in LREE/HREE ratios in different grain size fractions and the observed significant positive Ce-anomaly are in favour of a polygenetic origin of terra rossa in Istria. The difference in REE distribution can be attributed to the REE content of both parent carbonate rocks and different external materials which have contributed to the genesis of terra rossa (loess, flysch, bauxite), modified by weathering process which characterise specific pedoenvironments in which terra rossa is formed.

5.4. Micromorphology

The hierarchy of textural features in terra rossa from Istria is not yet fully investigated but micromorphological investigations performed so far clearly point to its polygenetic origin. A terra rossa profile near Medulin which represents a Stagni Chromic Luvisol (according to WRB, 1994) can be used as an example. Dissolution voids and cracks in limestone at the contact with terra rossa are infilled exclusively with clayey material (Fig. 17). This clayey material represents either the fine material of the groundmass (micromass) or clay coatings and/or infillings. The Bt horizon of the terra rossa has a vuggy–cracked microstructure (Fig. 18). The main coarse basic mineral component is subangular to angular quartz, the size and shape of which, in general does not match that of quartz in the insoluble residue of the underlying limestone. Mica and plagioclase are minor components while epidote and amphibole are very rare. Rounded bauxite and limestone fragments are also very rare and up to 5 mm in diameter (Figs. 19 and 20). In the Bt horizon sub-rounded to rounded fragments of pedorelics (soil clasts and fragments of clay coatings) up to 2 mm in diameter can be found (Fig. 21). Their distribution in

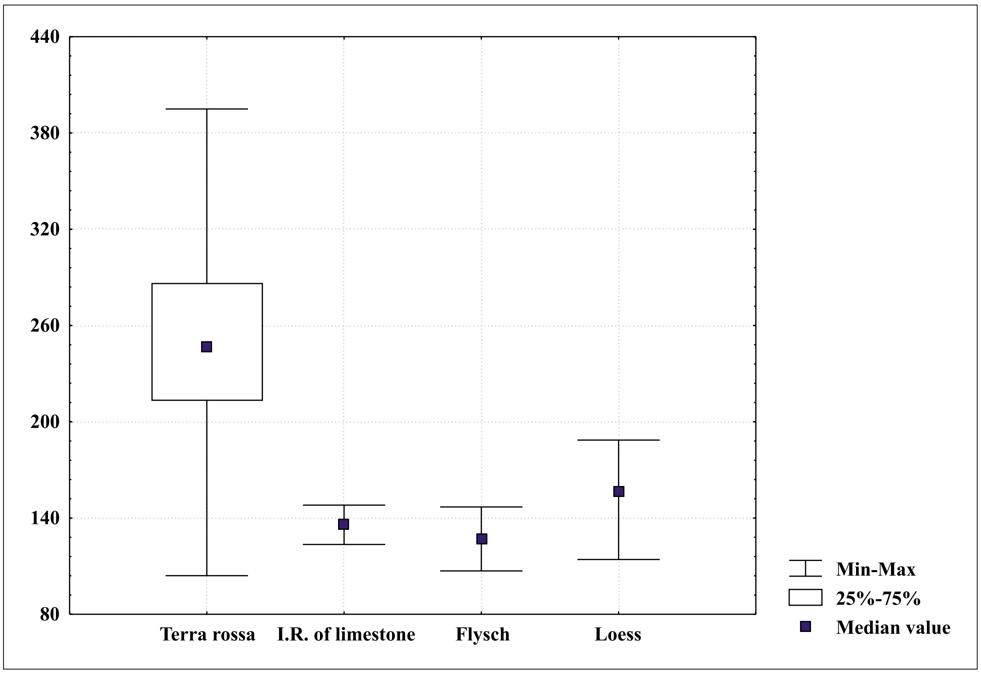

Fig. 14 Box & Whisker diagram for the total content of REE in terra rossa, flysch, loess and insoluble residues of the Jurassic and Cretaceous limestones.

the Bt horizon is partly clustered. However they are more abundant in the lower part than in the upper part of the Bt horizon. Some of them are structurally very similar to clay features observed in dissolution voids and cracks in the limestone. Although some of them can be regarded as papules (they are the result of repeated swelling and shrinking when broken clay coatings are incorporated into the groundmass) or a product of bioturbation, they can also be interpreted as a result of intense soil erosion. Textural pedofeatures present are microlaminated and laminated reddish and yellow clay coatings along planar voids, channels, vugs and vesicles and microlaminated clay and silt infillings of channels (Figs. 22 and 23).

The presence of pedorelics, epidote, amphibole, bauxite and limestone fragments as well as the size and shape of the quartz grains supports a polygenetic history of terra rossa soil. A pedo-sedimentary complex of terra rosa like material in Sjenokoša gives another good example of the complex history of this polygenetic soil (DURN et al., 2003).

6. DISCUSSION AND CONCLUSIONS

Terra rossa is a reddish clayey to silty–clayey soil especially widespread in the Mediterranean region, which covers limestone and dolomite. The bright red colour is a diagnostic feature of terra rossa and is a result of the preferential formation of haematite over goethite, i.e. rubification. Terra rossa has slightly alkaline to neutral pH and an almost completely satu-

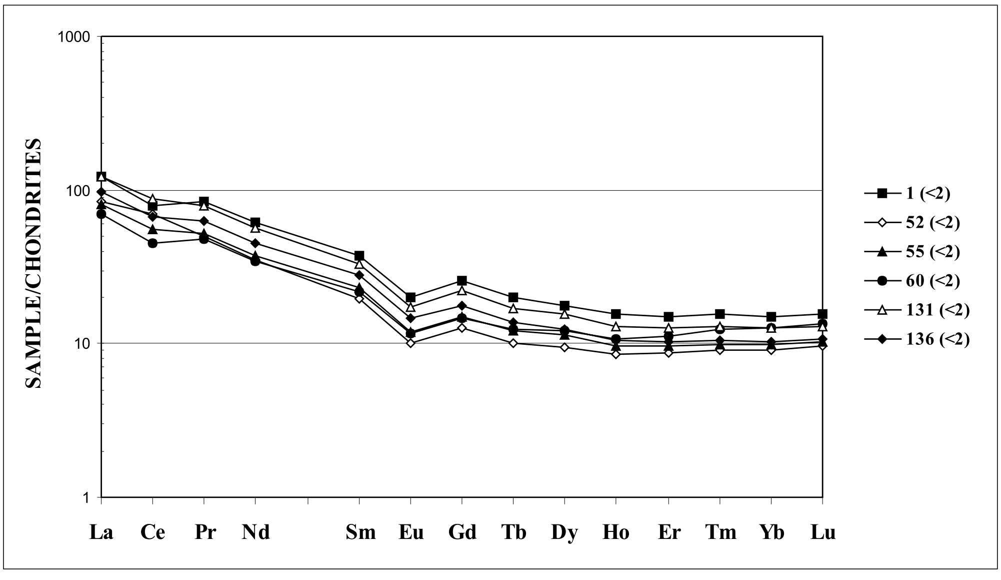

Fig. 15 Chondrite normalized REE patterns of the <2 μm fraction of terra rossa.

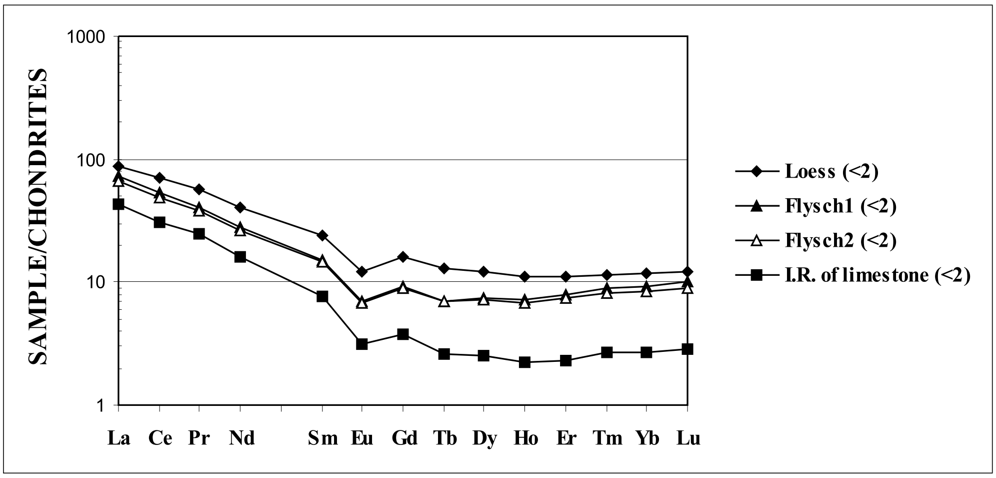

Fig. 16 Chondrite normalized REE patterns of the <2 μm fraction of insoluble residues of flysch, loess and the Cretaceous limestone.

rated base complex (dominated by calcium and/or magnesium). In some classification systems based on the Mediterranean climate as the major soil differentiating criterion, the term terra rossa is used as a name for the soil subclass "Modal Fersiallitic Red soil" when situated on limestones. (DUCHAUFOUR, 1982). Several national soil classifications (e.g. Croatian, Italian, Israeli) retained the term "terra rossa" for the hard limestone derived red soils. Terra rossa can be, among different authors, considered soil, vetusol, relict soil (non-buried-palaeosol), palaeosol or a pedosedimentary complex. Most authors today believe that terra rossa is a polygenetic relict soil formed during the Tertiary and/or hot and humid periods of the Quaternary (e.g. BRONGER & BRUHN-LOBIN, 1997; ALTAY, 1997; DURN et al., 1999). For example, BRONGER & BRUHN-LOBIN (1997) concluded that terra rossa situated on Quaternary calcarenites in NW Morocco is probably of Mid-Pleistocene age. Namely its formation extended over most parts of the Brunhes epoch, including those of the cool (glacial) stages. According to GVIRTZMAN & WIEDER (2001), Red Mediterranean soils situated in the coastal plain of Israel developed during the Last Glacial Stage, from 40 to 12.5 ka.

Some recent investigations in the Atlantic coastal region of Morocco (BRONGER & SEDOV, 2002) show that at least some terra rossa, previously referred to as polygenetic relict soils, should be regarded as Vetusols (soils which are marked by a continuity of pedogenetic processes in time), in accordance with the concept of CREMASCHI (1987). Namely, they concluded that soil formation processes were constant during terra rossa formation due to slight climatic fluctuations through the Brunhes epoch and the Holocene in the region.

In some isolated karst terrains terra rossa may have formed exclusively from the insoluble residue of limestone and dolomite, but it more frequently comprises a span of parent materials including, for example, aeolian dust, volcanic material or sedimentary clastic rocks which arrived on the carbonate terrain via different transport mechanisms. YAALON (1997)

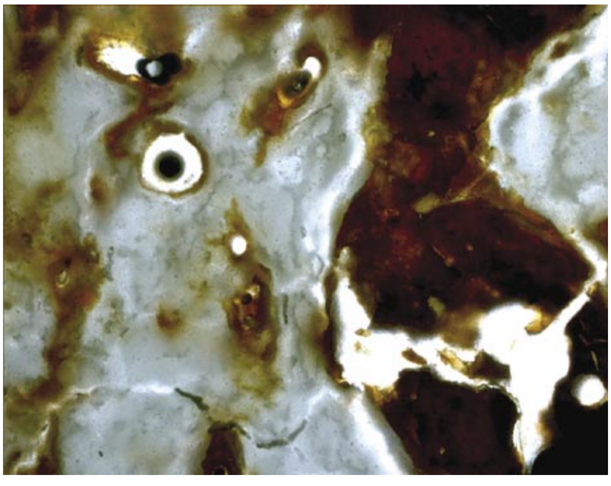

Fig. 17 Dissolution voids and cracks in limestone infilled with terra rossa. Medulin profile. Plain polarized light. Length of photo – 7.5 mm.

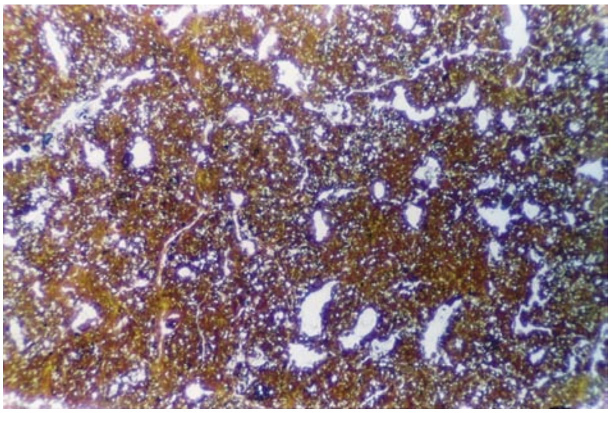

Fig. 18 Vuggy/cracked microstructure. Dominant voids are vugs and cracks. Vesicles and channels also occur. Most voids with Fe-oxide stained clay coatings. Iron depletion pedofeatures around open voids are also present (lower part of photo). Medulin profile. 35–43 cm, Bt horizon. Plain polarized light. Length of photo – 7.5 mm.

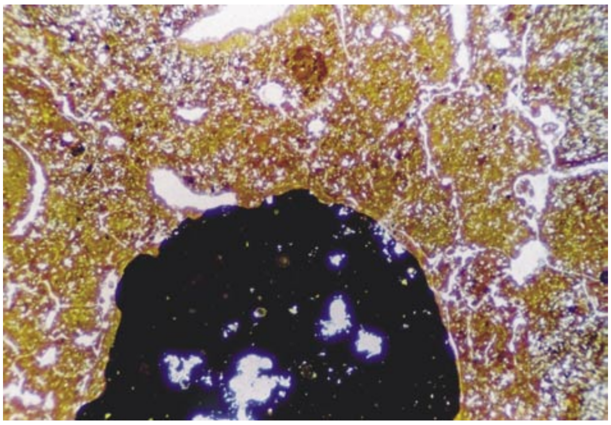

Fig. 19 Part of a bauxite fragment in terra rossa. Medulin profile. 60–68 cm, Bt horizon. Plain polarized light. Length of photo – 7.5 mm.

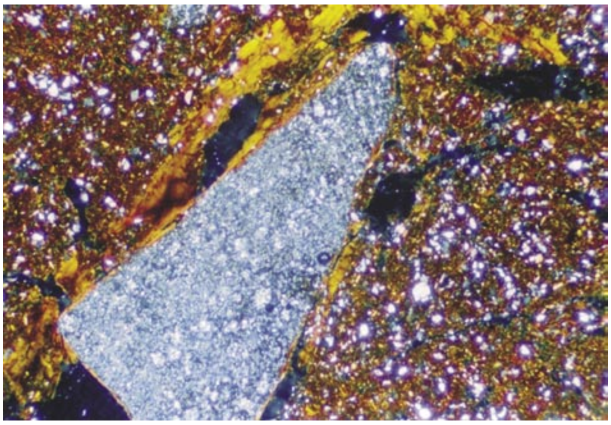

Fig. 20 Fragment of limestone in terra rossa and voluminous Fe-oxide stained clay coatings. Fragment of limestone is largely coated with clay. Medulin profile. 60–68 cm, Bt horizon. +N. Length of photo – 3.3 mm.

concluded that practically all terrestrial soils in the Mediterranean region might have been influenced by the addition of aeolian dust in the last 5 MY when the Sahara became a desert. He states that values of up to 50% of aeolian material in hard limestone derived soils are highly reasonable. Evidence of aeolian dust from the Sahara were found in in terra rossa in Morocco, Israel, Turkey, Spain, Greece, Portugal and Italy (e.g. BRONGER & BRUHN-LOBIN, 1997; YAALON & GANOR, 1973; DANIN et al., 1983; ALTAY, 1997; MACLEOD, 1980; RAPP, 1984; NIHLEN & OLSSON, 1995; JAHN et al., 1991; JACKSON et al., 1982). According to NIHLEN & OLSSON (1995) the mean annual deposition of dust from the Sahara in the southern Aegean area (Greece), varies from 11.2 to 36.5 g/m^2. He concluded that assuming constant deposition rates, the estimated thickness of a dust layer built up over a time span of 1000 years would be in the range of 7–21 mm. At this rate of accumulation the accreted dust manages to become completely assimilated by the prevailing pedoenvironment and is leached or bioturbated into the soil profile (YAALON, 1997).

This is why the addition of aeolian dust to a soil is usually difficult to identify. When the rate of accumulation increases to 40 μm/y, dust accumulates as surface loess (YAALON, 1997). This is especially important when we bear in mind that since the early Middle Pleistocene, loess deposition affected Istria and the Dalmatian Archipelago (CREMASCHI, 1990b). In Istria, the Upper Pleistocene loess post-dated terra rossa formation. (DURN et al., 1999) found that both loess older than that of the Upper Pleistocene age, and flysch may have contributed to the genesis of terra rossa in Istria. CHIESA et al. (1990) concluded that in the Marche region (Italy), aeolian deposits formed during the Pleistocene were affected by pyroclastic materials from the Tyrrenian area. This may imply that terra rossa soils in that region may also contain material of that parentage. LIPPI-BONCAMPI et al. (1955) and YAALON & GANOR (1973) mention the role of aeolian materials from volcanoes in the surrounding

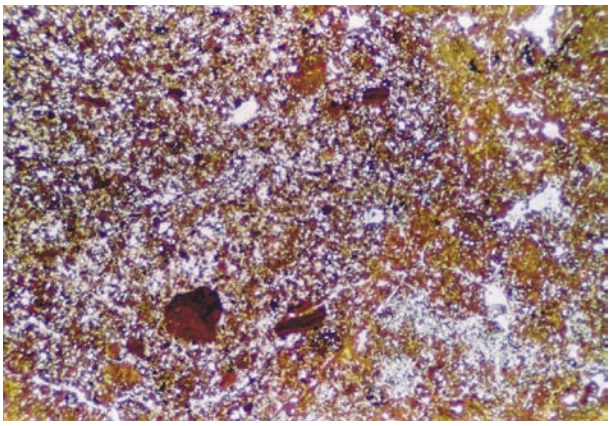

Fig. 21 Fragments of clay coatings and microlaminated clay coatings in terra rossa. Medulin profile. 60–68 cm, Bt horizon. Plain polarized light. Length of photo – 7.5 mm.

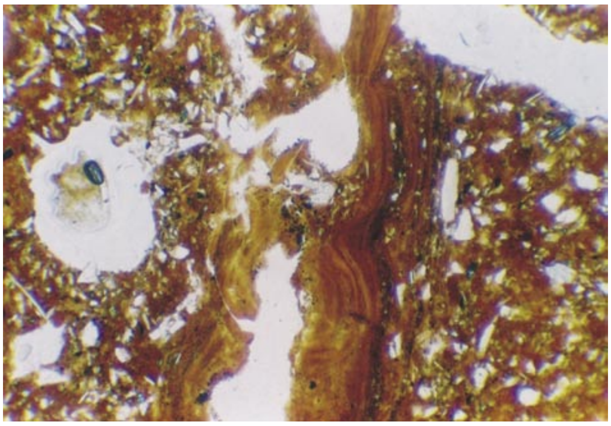

Fig. 22 Fe-oxide stained complex voluminous microlaminated clay coatings with sharp extinction zones. Medulin profile. 35–43 cm, Bt horizon. Plain polarized light. Length of photo – 1 mm.

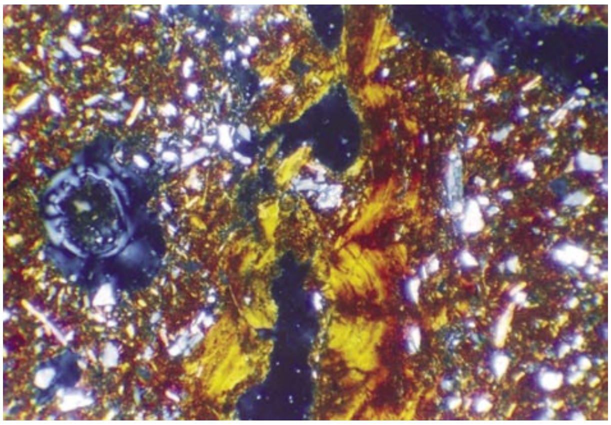

Fig. 23 Fe-oxide stained complex voluminous microlaminated clay coatings with sharp extinction zones. Medulin profile. 35–43 cm, Bt horizon. +N. Length of photo – 1 mm.

area, in the formation of terra rossa while ŠUŠNJARA et al. (1994) found vitric tuff interstratified within terra rossa near Gljev in the central part of Dalmatia (Croatia). Detailed research on two palaeosols, of Late Pleistocene (Pedomarker A) and Holocene (Pedomarker B) age, in the carbonate Apennine Range of central Italy, showed that they developed from air-fall pyroclastic material (FREZZOTTI & NARCISI, 1996). According to some ongoing studies, deposition of pyroclastic volcanic material, which was a recurrent process through the Quaternary in the Adriatic region, may have significantly affected soils in the region (B. LUGOVIĆ, personal communication).

BOERO & SCHWERTMANN (1989) concluded that it is of little relevance for the process of rubification whether the primary Fe sources are autochthonous or allochthonous as long as the general pedoenvironment remains essentially suitable for the formation of terra rossa. They suggested this pedoenvironment is characterised by an association of Mediterranean climate, high internal drainage due to the karstic nature of a hard limestone and neutral pH conditions. Terra rossa is well drained because it is well aggregated (high exchangeable Ca and Mg content) and situated on highly permeable carbonate rocks (TORRENT, 1995). It is formed as a result of: (1) decalcification, (2) rubification and (3) bisiallitization and/or monosiallitization. The bisiallitic type of weathering is not a specific characteristic of Red Mediterranean soils (FEDOROFF, 1997). Kaolinites were found as the main pedogenic clay mineral phases in terra rossa from Istria, Croatia (DURN, 1996; DURN et al., 1999) and NW Morocco (BRONGER & BRUHN-LOBIN, 1997; BRONGER & SEDOV, 2002). This may imply that the type of weathering in terra rossa, and the resulting authigenic clay mineral phases, depends on the time of formation, climate and parent materials. For example, BOERO et al. (1992) found that illite and kaolinite are the main clay mineral phases in terra rossa from xeric sites while Al-interlayered vermiculite occurred in cool, moist sites.

The concept of clay illuviation is not yet unanimously accepted as a leading soil forming process in Red Mediterranean soils (FEDOROFF, 1997). Illuviated clays usually coat and infill the dissolution voids in carbonate rocks at the contact with terra rossa. However, very often they are not clearly recognisable in the Bt horizon. VERHAYE & STOOPS (1973) consider that, as a result of repeated swelling and shrinking, clay coatings in terra rossa are broken and incorporated into the groundmass, first in the form of papules, and later as smaller, less differentiated units. Fe_d/clay ratios are relatively uniform in terra rossa from Istria and clearly indicate a predominance of co-illuviation of clay and Fe oxides, i.e. a connection between Fe-oxides and the clay fraction (DURN et al., 2001a). According to FEDOROFF (1997) rubification occurs in the upper horizons, then rubified soil material is translocated with the clays at depth. So, the translocation of clay particles is responsible for the distribution of the red colour throughout the whole profile. However, since they have been exposed to various climatic fluctuations terra rossa soils can be affected by eluviation, yellowing and secondary hydromorphy.

Erosion and deposition processes which were superimposed on karst terrains and induced by climatic changes, tectonic movements and/or deforestation might be responsible for both the patchy distribution of terra rossa and thick colluvial or alluvial terra rossa accumulations in uvala and dolina type of karst depressions (pedo-sedimentary complexes, soil-sediments). YAALON (1997) stressed that accumulated soil material served as a substrate for the development of new soils and fertile agriculture over several millennia in the Mediterranean area.

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