THE GEOLOGICAL AND GEOMORPHOLOGICAL EVENTS THAT DETERMINE THE SOIL FUNCTIONAL CHARACTERS OF A TERROIR

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ABSTRACT
The geology of a region is deemed to be an important component of terroir, as it influences the shape of the landscape and the climate of vineyard. The nature of rock and the geomorphological history of a terroir affect soil physical and chemical composition through a dynamic interplay with the changes of climate, vegetation and other living organisms, as well as with man activities.
This work is aimed at demonstrating that the soil functional characters which differentiate the terroirs of a denomination of origin area are products and witnesses of the geological and geomorphological events, natural and human induced, which occurred in that trait of land. The final scope being enhancing the awareness of stakeholders about the possible environmental and economic losses that can derive from an irrational soil management, which can lead to the worsening or loss of irreproducible soil functional characters of the best terroirs.
The work makes reference to the denomination of origin "Vino Nobile di Montepulciano", where a four years research was conducted on the relationships between soil characteristics and the viticultural and oenological behaviour of Sangiovese vine. The soils of the Montepulciano vineyard range notably in fertility conditions and functional characters, also when formed on the same kind of sediments, in particular as for water and oxygen availability. The grape production at vintage, as well as the organoleptic characteristics of the wine, resulted strictly interactive with the different soils. The wines obtained on a first group of soils had a good structure and typicity, but the stability of wine sensorial profile during the years was low. A second group exhibited good structure, typicity, and a good stability of wine sensorial profile. A third group had low structure, low typicity, and high astringency all the years of trial.
The oldest soils of the Montepulciano vineyard started their formation during the Pleistocene. During the medium Holocene, man deeply influenced pedogenesis, but it is during the last 50 years that the intensity of the man action reached its maximum. Pre-plantation activities of the new specialized vineyards upset the land, leaving very different effects on soil functional characters. Where the soils before vine plantation were deep and rather homogeneous, soil functional characters remained the same, whereas they changed significantly where soils were shallower. Shallow soils on marine clays, in particular, resulted very vulnerable.
Best soils for the Nobile di Montepulciano wine production, that is, those belonging to the second group, were old soils, formed as a consequence of particular natural and human induced geomorphological events. Therefore they should be considered cultural heritages.

KEY WORDS
Climate change – cultural heritage – wine – quality – Sangiovese – Vino Nobile di Montepulciano

INTRODUCTION

Soil is considered a major component of terroir, although most evidences that relate wine with the specific soil conditions of the vineyard are empirical (Van Leeuwen et al., 2004). It has been largely demonstrated, for instance, that best terroirs for red wine production are often placed where some soil limiting factors reduce vine vigour and berry size (Van Leeuwen and Seguin 2006), so that grapes ripen completely but slowly. In these soils, high quality wines are obtained every year, in spite of climatic variations (Seguin, 1986).

In addition to empirical evidence, a few mechanisms have been understood. In particular, it has been proved that soil water availability influences the hormonal equilibrium of each vine variety, which in turn regulates the expression of the genotype (Van Leeuwen and Seguin, 1997). Similarly, nitrogen and water supply controls the biosynthesis of flavonols, through the activation of the enzyme Phenylalanine ammonia lyase, which diverts phenylalanine from the pathway that relate carbohydrates to the synthesis of proteins (Kao et al. 2002).

As a whole, nitrogen nutrition and water supply during certain phases of the vegetative cycle of the vine are considered essential factors of wine quality. Their role in determining the terroir effect has been experienced in many wine producing areas and with several varieties, among others, in France, with Cabernet Sauvignon (Choné et al. 2001), Merlot (Trégoat et al. 2002), and Sauvignon Blanc (Peyrot des Gachons et al., 2005), in Australia (White et al., 2007) with Sauvignon Blanc, in Hungary with Kékfrankos (Zsófi et al., 2009), in USA with Cabernet Sauvignon and Chardonnay (Chapman et al., 2005; Deluc et al., 2009).

Furthermore, there is an array of other empirical relationships that prove terroir dependence from soil characters. Among the most renown there is the effect of soil colour. Colour is one of the main soil characteristics. It can differ widely from bright white, as for some calcareous soils, to red, as in "terra rossa" soils, or black, in soils from slate. Soil colour affects the quality and quantity of light reflected into the bunch zone and grapevine canopy, thus influencing grapevine performance. The colour of light reflected from the soil surfaces appears to be used by the grapevine natural growth regulatory system to alter vegetative growth (Witbooi et al., 2008 a). In South Africa, with Cabernet sauvignon, grey soil surface resulted in higher grape colour at 520 nm, while the potassium content of the pulp was the highest on red soil surface treatments (Witbooi et al., 2008 b). Stony soils reflect heat if they are pale-coloured. Well known examples are the white cobbles of Chateauneuf-du-Pape, the pebbles at Sancerre (France), and at Monsant (Spain). In contrast, the metamorphic rocks and grey limestone of the Franconia (Germany) provide dark-coloured soils that warm relatively quickly and store heat, thus promoting ripening in this region (Maltman, 2008). Large thermal effects on soil surface temperature and on berry skin temperature were found in Geisenheim (Germany) for the vine Riesling and Pinot noir (Stoll et al., 2008). In the north Willamette Valley (Oregon, USA) basalt-derived surfaces enhance cytokinin synthesis through spreading the diurnal heat load (Nikolaou et al., 2000); similar effects arise further north in parts of the Walla Walla Valley, Washington, USA (Meinert and Busacca, 2000).

Another important soil quality is water drainage, which is considered a major terroir characteristic of the moraine deposits of Fanciacorta (Northern Italy) as well as of many other territories (Panont et al., 1997). A rapid soil water drainage has been found to affect significantly the precocity of bud breaking and the intensity of summer stress.

The results of a vine zoning in Emilia-Romagna (Italy) highlighted the relationship between lime content in soil and wine colour, structure and perfume intensity. As a matter of fact, in soils with absent or little lime, grape had lower sugar degree, wine colour intensity and structure. On the contrary, in soils with high active lime, grapes had a larger sugar and polyphenols content, and wines were full-bodied and with high colour intensity (Scotti, 2006). Also studies carried out in Alto-Adige (Northern Italy) with Schiava vine demonstrated that total polyphenols of grape increased with the increase of active lime in soil (Fregoni, 2005).

The potassium content of soil can have a strong effect on must acidity. In particular, the vine responds to an over potassium absorption synthesizing malic acid, to neutralize the surplus of K^+ ions. The reaction determines the decrease of acidity and the increase of pH (Hale, 1977; Calò et al., 2002). Berry potassium content has been also related to the pH value of must and some Authors have suggested that any factor that reduces the photosynthetic activity of leaves could increase potassium accumulation in berries (Freeman et al, 1982). Such factors can be water stress, wind exposure, and excessive shading of the canopy, like with Cabernet Sauvignon in South Africa (Carey et al., 2008).

High soil salinity strongly affects vine performance. Salt excess has both an osmotic and a toxic effect, causing reduction in yield, shoot growth and berry weight (Lanyon et al., 2004). However Costantini et al. (2009a) demonstrated a better performance of Sangiovese in the Chianti area when cultivated on very fertile but moderately saline soils, when the salinity was confined to the deep soil horizons.

The geology of a region is also deemed to be an important component of terroir (Vaudour, 2003; Maltman, 2008). Geology influences the shape of the landscape, conferring morphology, typical spaces and articulations that characterize a production district. Geology also influences the morphology of a territory and thus the climate of vineyard, through the altitude, the aspect of the slope, the vicinity to water bodies, the exposure to dominant winds. At Stellenbosch (South Africa) in particular, it has been demonstrated that site differences in wind exposure have stronger effect on Sauvignon blanc than seasonal climatic differences (Carey et al., 2008).

The nature of rock governs deep drainage, but also the quality of groundwater and irrigation water. A relevant characteristic of rock is the degree of its resistance to root penetration. This property derives from rock type, presence of planes of weakness, their spacing and orientation (Myburgh et al., 1996). For instance, some of the best grapes produced in the Upper Douro area of Portugal, as well as in Priorat in Catalunya (Spain), Languedoc Roussillon (South France) and in Chianti (Central Italy) are obtained from shallow soils on clay schist ("galestro" in Italian). The foliation of schist provides surfaces for roots penetration in an otherwise impenetrable material.

Furthermore, there is a common assumption that the kind of rock or sediment determines the soil physical and chemical composition of the vineyard (White, 2003). As a matter of fact, the linkage between rock and the overlying soil is in most cases weak, due to the frequent presence of allochthonous material, like aeolian dust, volcanic ash, colluvium, or human transported material and, above all, because of the transformations caused by pedogenesis. In fact, the geological and geomorphological history of a territory dynamically interacts with the changes of climate, vegetation and other living organisms, as well as with man activities, leading to soil formation. The soil of a vineyard is the metastable complex system coming out from a succession of rhexistasy and biostasy periods, during which rocks and sediments are weathered, transformed and translocated, leached and depleted, eroded and accumulated, mixed with organic particles, and organized in micro, meso, and macrostructures. The time scale of the biorhexistasy periods can range from millions of years, in very stable landscapes, to few years, in heavily anthropized territories. Aim of this work is to demonstrate that the soil functional characters which differentiate the terroirs of a denomination of origin area are at the same time products and witnesses of the geological and geomorphological events, natural as well as human induced, which occurred in that trait of land. Knowing the geological and geomorphological history of a terroir is relevant, because it can enhance the awareness of stakeholders about the possible environmental and economic losses that can derive from an irrational soil management, which can lead to the worsening or loss of the soil functional characters of the best terroirs.

MATERIALS AND METHODS

The work makes reference to the denomination of origin ”Vino Nobile di Montepulciano”. On 1st July 1980 the Vino Nobile di Montepulciano became the first Italian red wine to get the D.O.C.G. (guaranteed and controlled denomination of origin), which places it among the most prestigious wines in Italy and the world. “Prugnolo gentile”, a biotype of Sangiovese, is the basic vine-variety used for the production of the Vino Nobile and the most important winegrape in the classic wine territory. The Nobile is a wine of elevated structure and longevity, thanks to the rich supply of anthocyanins and polyphenols, capable of ensuring a positive evolution over a length of time. The considerable delicacy of the bouquet, distinguished by the pleasant scents of violet and woodland fruits, with elegant hints of spices, dried fruits and dried vegetable, completes the Nobile's profile of high quality and originality.
In the Montepulciano territory, a research was conducted on the relationships between soil characteristics and the viticultural and oenological behaviour of Sangiovese (Costantini et al., 1996; Campostrini et al., 1997). The study was carried out during four years. On the basis of a soil map of the Montepulciano hill at 1:25,000 scale, 54 experimental not irrigated plots, homogeneous in soil, were selected (9 soil types per 6 replications, tab. 1). Experimental soils were evaluated as for their physical, chemical, hydrological and biological properties. In addition, temperature and rainfall were monitored in 5 experimental sites, as well as soil temperature and moisture content. The mean rainfall of the studied years was lower than in the long term (1926- 1992: 685 vs. 728 mm). Also the year average temperature remained lower than the long term (1928-1992: 12.9 vs. 13.9°C; tab. 2). The value of Winkler's index fitted the requirements for Sangiovese (Fregoni, 2005). The number of days when the soil moisture control section is dry matched the requirements of the "ustic" soil moisture regime (USDA, 2010).

Table 1 - Topographic, physical, hydrological, and chemical characteristics of the experimental soils.

Parameters	Mean values and (standard deviation)
Elevation (m asl)	344(67)
Slope gradient (%)	6.6(3.6)
Aspect (°)	140(101)
Solar radiation (MJ cm2 yr-1)	0.917(0.047)
Rooting depth (cm)	106(28)
Stoniness (% v/v)	0
Rock fragments (% v/v)	0.9 (1.9)
Bulk density (g cm-3)	1.53 (0.08)
Clay (%)	35.1 (15.1)
Sand (%)	27.6 (20.9)
Available Water Capacity (mm m-1)	148 (44)
Organic C (%)	0.64 (0.20)
pH (H2O)	8.4 (0.18)
Electrical conductivity (dS m-1)	0.24 (0.19)
CEC (cmol(+) kg-1)	15.7 (4.8)
Total CaCO3 (%)	11.9 (7.0)

Table 2 - Mean climatic and pedoclimatic parameters of the experimental plots during the trial.

Parameter	Mean values and (standard deviation)
Annual rainfall (mm)	685 (114)
Mean air temperature (°C)	12.9 (0.7)
Mean soil temperature (°C)	15.3 (1.4)
Winkler's index	1815 (134)
Number of dry days of the soil moisture control section	83 (15)

Soil types had different functional characters. The characters were considered functional when they were statistically related to some viticultural parameters and when they actually discriminated between soil types at the reference scale (Costantini et al., 2008). For instance, the organic matter content did not resulted functional, since all the soils on trial were periodically cultivated during the growing season and were poor in organic matter (around 1%). Similarly, all experimental soils were base saturated and their cation exchange capacity was always between 10 and 20 cmol(+) kg-1. On the other hand, the soil characteristics which resulted statistically different between soil types (ANOVA), as well as statistically related to Sangiovese parameters (PCA), where those that could provide a physical or chemical limitation to vine growing.

Quanti-qualitative traits at vintage (yield per vine, cluster number, mean cluster weight) and sugar accumulation rate in berries were recorded. The grapes of each experimental plot were analysed at vintage for total soluble solids, titrable acidity, pH, malic and tartaric acid, and potassium. At ripeness 50-kg samples of grapes were collected and processed by the standard techniques for small-lot wine making. Descriptor terms were defined after several taste sessions, and the relevant terminology underwent normalisation. Through the application of the statistical analysis of PCA, the wines were grouped in groups.

The reconstruction of the geological events was based on the works of Costantini et al. (2009), Capezzuoli et al. (2009), Priori et al. (2008), Costantini and Lizio Bruno (1996), Ferrari and Magaldi (1978), and Losacco (1944). The statistical analysis of PCA and ANOVA were conducted with Statistica®. Geological sketches were created with a soil geodatabase and the software ArcGIS® and Surfer®.

RESULTS AND DISCUSSION

Soil functional characters

The soils of the Montepulciano vineyard range notably in fertility conditions and functional characters, also when formed on the same kind of sediments (tab. 3). On Pliocene marine sand, Cusona soils are very sandy and abundant in primary macroporosity, conferring them great air capacity and rapid drainage; they are poorly structured, have medium total and active lime content and show low salinity. Strada and San Gimignano soils instead are either coarse or fineloamy, their relatively high air capacity is the consequence of both particle size and aggregate formation. Their equilibrated texture and good structure confer a high available water holding capacity. Lime and salinity are reduced and do not cause any limitation to vine cultivation.

Monte, San Quirico and Quercia soils characterize vineyards placed on Pliocene marine clay. Monte soils are fine, poorly differentiated from the substrate, and show very low air capacity and prominent redoximorphic features. They have low available water capacity but are rich in lime and other salts, so that their electrical conductivity, averaged for the entire profile, is moderately high. San Quirico soils are fine-silty and show hydromorphy, although their air capacity is higher than Monte soils. Available water holding capacity is high and they are moderately rich in lime, but their averaged electrical conductivity is lower than Monte soils. Quercia soils are fine and show “vertic” properties (cracking soils), their air capacity is slightly lower and available water higher than San Quirico soils, the other properties being similar.

On the Pleistocene fluvial-lacustrine clay there are three main soil types, Valiano and Valiano aquic formed in the surroundings of the Valiano town, while Poggio Golo soils are close to Torrita. Both Valiano soils are similar, except for air capacity and internal drainage, which are worse in Valiano aquic. Available water capacity is also somewhat less in Valiano aquic than in Valiano, though reaching a rather high absolute mean value. The two Valiano soils have carbonates but do not show salinity. Poggio Golo soils are also fine and show hydromorphy, as a consequence of limited air capacity, but have rather high water holding capacity. Although very deep, they are “duplex” soils, that is, they show a marked change in propertied between the surface and the subsurface horizons, with a sharp increase in clay and firmness, and parallel decrease in air capacity and hydraulic conductivity, with depth. The “duplex” characteristic strongly limits root penetration. They have very low carbonates and other salts, so that the electrical conductivity is very low.

The hydrological monitoring permitted to group the experimental soils in terms of water or oxygen deficit as follow:

- soils without water and oxygen deficit during the whole vine growing season (San Gimignano and Strada soils),
- soils with reduced soil oxygen availability during early spring and moderate summer water deficit (San Quirico, Quercia and Poggio Golo soils).
- soils with pronounced summer water deficit (Cusona soils),
- soils with pronounced summer water deficit, and reduced soil oxygen availability during early spring (Monte soils).

Valiano and Valiano aquic soils were not monitored, but their behaviour was comparable to that of San Gimignano and San Quirico soils, respectively.

Table 3 - Classification and main functional characters of the experimental soils. Values are the average of all horizons of two soil profiles of each soil type, but O.M. is that of the plough layer.

Geology	Soils	Classification^	Air capacity [t] (%)	Oa[‡] (mm)	Total $CaCO_3$ $(\%ww^{-1})$	Active[¥] $CaCO_3$	Electrical conductivity (1:2.5) dS m-1
Pliocene marine sand	Cusona	Typic Ustipsamments	16.2	83	10.9	1.0	0.100
Pliocene marine sand	Strada	Typic Haplustepts, coarse-loamy	10.9	157	10.7	1.1	0.117
Pliocene marine sand	San Gimignano	Typic Haplustepts, fine-loamy	10.6	195	16.9	2.2	0.133
Pliocene marine clay	Monte	Aquic Ustorthents, fine	1.4	75	18.9	9.7	0.941
Pliocene marine clay	San Quirico	Aquic Haplustepts, fine-silty	3.8	146	16.1	6.8	0.541
Pliocene marine clay	Quercia	Vertic Haplustepts, fine	3.0	165	20.8	7.0	0.453
Pleistocene fluvial-lacustrine clay	Valiano aquic	Aquic Haplustepts, fine	5.5	142	9.7	2.9	0.287
Pleistocene fluvial-lacustrine clay	Valiano	Typic Haplustepts, fine	9.7	169	10.4	3.1	0.172
Pleistocene fluvial-lacustrine clay	Poggio Golo	Aquic Haplustalf, fine	2.3	139	1.7	0.6	0.166

^Classification= Soil Taxonomy (USDA, 2010).
[ǂ]Air capacity = difference between total porosity (from bulk density of undisturbed samples) and volumetric water content at field capacity.
[‡]Oa = available water holding capacity (difference between water content at field capacity and wilting point).
[¥]Active $CaCO_3$ is the lime soluble in ammonium oxalate.

Viticultural and oenological results

The grape production at vintage was strictly interactive with the different soils. In particular, the yield per vine, the mean cluster weight, the 100 berries' weight were deeply influenced by the soil type. The number of shoots in the various soils was significantly different, because of the adaptation of pruning to the different water capacity of soils. Also the sugar accumulation rate in berries underlined the importance of the soil for a minimum sugar level of grape, necessary to winemaking as Vino Nobile (tab. 4). In fact, vineyards on Cusona soils did not reach the minimum sugar content every year, but only in the more rainy ones. On the other hand, grapes on San Gimignano and Poggio Golo soils reached the minimum sugar content only at late time (tab. 5).

Table 4 - Mean values of viticultural parameters obtained from the experimental soils. Standard deviation in brackets.

Soils	Grape yield/vine kg	Cluster number n°	Mean cluster weight g	100 berries weight g	Sugar content °Brix	Sugar accumulation rate °Brix/day	Total acidity g/L
Cusona	2.26 (1.4)	12.5 (8.4)	185 (59.7)	167 (17.4)	21.5 (1.0)	0.31 (0.03)	7.64 (1.6)
Strada	4.57 (1.5)	15.2 (3.0)	322 (122.3)	196 (29.3)	20.8 (1.2)	0.31 (0.02)	7.28 (0.5)
San Gimignano	4.38 (1.5)	11.7 (3.4)	401 (153.2)	211 (26.8)	20.8 (0.9)	0.29 (0.02)	8.49 (1.0)
Monte	2.70 (0.4)	14.8 (0.7)	196 (36.8)	130 (0.5)	20.3 (0.8)	0.31 (0.02)	7.28 (0.1)
San Quirico	3.87 (1.3)	12.3 (4.5)	321 (154.8)	166 (29.8)	21.3 (1.4)	0.31 (0.02)	7.78 (0.6)
Quercia	3.45 (1.3)	12.7 (5.6)	312 (96.9)	160 (28.0)	20.9 (1.8)	0.31 (0.02)	7.73 (1.0)
Valiano aquic	5.07 (3.7)	18.6 (5.6)	245 (145.0)	178 (47.4)	21.7 (1.1)	0.30 (0.02)	7.77 (0.6)
Valiano	7.01 (0.8)	15.0 (1.0)	468 (23.1)	202 (16.7)	20.0 (0.6)	0.27 (0.01)	8.14 (1.0)
Poggio Golo	3.94 (0.9)	14.6 (5.4)	236 (41.0)	176 (18.8)	20.7 (0.9)	0.31 (0.02)	7.53 (0.9)

The wines obtained on a first group of soils (Valiano aquic, Cusona and Monte) had a good structure, a good typicity with high cherry and berry fruity. Unfortunately, the stability of wine sensorial profile during the years was low. A second group (Quercia, Poggio Golo and San Quirico soils) exhibited good structure, typicity, with medium level of cherry and berry fruit and a good stability of wine sensorial profile. The wine obtained on the Strada soils showed medium structure, medium astringency, low cherry and berry fruity with a good stability of the sensorial profile. Finally, the wine of San Gimignano and Valiano soils had a low structure, high astringency, low typicity, all the years of trial (tab. 5).

Table 5 - Nobile di Montepulciano grape production and wine quality according to soil and soil group. The number of stars reflects the quantity (grape) or quality of the organoleptic evaluation (other variables).

Group	Soils Name	Grape production	Harvest date	Wine structure	Wine harmony	Wine typicity	Year stability
1	Monte and Cusona	*	****	**	**	**	*
1	Valiano aquic	****	***	**	**	**	*
2	Quercia	**	***	**	**	**	**
2	Poggio Golo	**	**	**	**	**	**
2	San Quirico	**	****	**	**	**	**
3	Strada	***	**	*/**	*/**	*	**
3	San Gimignano	***	*	*	*	*	**
3	Valiano	*****	*	*	*	*	**

The interplay between geological and geomorphological events and the formation of soil functional characters

The territory of Montepulciano municipality was almost all completely covered by the sea during Early Pliocene. Only small islands, corresponding to the highest relives on Mesozoic rocks of the Chianti-Cetona mount ridge, were emerging from the sea. During Middle Pliocene, about four million years ago, the sea regressed and left a succession of deposits, some hundred meters thick, which were rather sandy at their top (Fig. 1). Pliocene was a time of intense pedogenesis, leading to the formation of very deep and red soils, similar to those currently widespread in the subtropics. There are no more remnants of these kind of soils at Montepulciano, since here, like in most part of Italy, they have been completely eroded, as a consequence of the successive uplift of the area and climate changes. However, a significant example of Pliocene soil, currently preserved and cultivated with vine, has been reported in the not far away DOCG of Montalcino (Costantini and Priori, 2007).

The Villafranchian (Late Pliocene and Early Pleistocene) saw the incision of the Pliocene deposits and the filling up with lacustrine sediments of the territory comprised between the

Apennines and the Chianti-Cetona mount ridge (Fig. 2). During Middle and Late Pleistocene the Villafranchian lacustrine sediments were eroded and filled up with new fluvial and lacustrine deposits (Fig. 3). Several fluvial terraces formed along the "Val di Chiana" paleo valley, which was crossed at that time by a southward streaming river, the "paleo Arno". The deposits on the terraces and hilly lands underwent a rather intense and prolonged pedogenesis, leading to the formation of deep and well developed soils, with contrasted horizons. Alternating biorhexistasy phases, in dependence of both tectonic movements and climate changes, caused the partial erosion of soils on slopes and the formation of deep colluvial soils on relatively more stable morphological positions.
During Early Holocene the morphology of the Montepulciano territory was very similar to the present (Fig. 4). The progressive filling up of the valley caused a further swamping of the lowlands, while tectonic movements led to the reversion of the drainage of the paleo Arno river. Poggio Golo soils dominated on the fluvial terraces formed in the previous geological era. The sharp contrast in texture between the surface and subsurface horizons of Poggio Golo soils was created as a result of the prolonged time of pedogenesis, during which carbonates and other bases were leached throughout the profile, clay particles deflocculated and were transported along the profile, where they progressively accumulated. Many macropores were therefore plugged by clay particles, so that firmness of the subsurface horizon increased, whereas air capacity and hydraulic conductivity decreased. Soil rooting depth and rootability (mass of soil that can be actually penetrated by roots, between and inside aggregates) were consequently constrained. The breakdown and weathering of rock fragments augmented the proportion of fine particles and released a great deal of elements, in particular metals. The elements were sequestrated by clays, accumulated, and iron painted the soils with characteristics reddish brown colours. Subsurface horizons with somewhat poor internal drainage caused the formation of perched temporary water tables during rainy seasons, thus the alternating reduction and oxidation of iron and manganese, their mobilization along fissures and root channels, and formation of characteristics bleached streaks, reddish and blackish mottles, and nodules of iron and manganese .
Neolithic/Early Bronze age was a time of rhexistasy and severe erosion affected soils on slopes (Fig. 5). Human settlements developed and forests were cleared. The reduced soil cover, combined with a climate deterioration, with dry spells and strong winds, led to a sharp increase of water and wind erosion. Colluvial sediments accumulated on the lower parts of slopes, leading to the formation of very thick soils, like some San Gimignano soils. Some aeolian sediments accumulated on soils placed on stable morphological positions. It was the case of Poggio Golo soils, where the aeolian contribution increased the difference in texture between the surface and subsurface horizons, but also somehow changed the chemistry of the soil, as the bases brought with the aeolian dusts saturated again the cation exchange complex and raised pH, halting or reducing notably clay lessivage. During the successive bronze ages and Etruscan and Roman civilizations, the climatic conditions improved, and so did the land management.
Pedogenesis of San Gimignano, Strada, San Quirico, Quercia, Valiano and Valiano aquic soils took place mainly during that time. A more or less developed structural subsurface horizon formed in all these soils, but with very different functional characteristics. San Gimignano and Strada soils formed on marine sands, rather permeable and quite easily weatherable, which promoted the leaching of marine salts and the genesis of a thick horizon with subangular blocky aggregates, lined by organic matter and iron oxides, with a good macroporosity. Below the combined action of vegetation and climate, sands could be easily broken down; hence the firm

sandy soil parent material easily transformed into friable soil, with excellent rootability. Weathering of primary minerals, aggregate dynamic, and mixing of marine layers of different particle size, operated by erosion and colluviation, favoured the accumulation of fine material and the genesis of the loamy texture. San Quirico and Quercia soils developed on marine clays and silts, almost impermeable and slowly weatherable. The formation of the structured horizon was restricted to the depth of about one, one and half meter. The aggregates were mainly cemented by clay particles and took an angular blocky or prismatic shape, as a consequence of the wetting and dry cycles. Shrinking and swelling of clay aggregates were particularly intense in Quercia soils, which acquired vertic properties (cracking soils). As a consequence, macroporosity remained low, consistence firm, and permeability very low. Soil resistance to root penetration was high and restricted root development. Rootability was further limited by salinity of the unleached, massive deep soil horizons.

Valiano and Valiano aquic soils formed both on Pleistocene fluvial-lacustrine clay. The continental instead of marine origin of sediments was the main cause of their much lower salt content. Low salinity and lack of sediment consolidation favoured drainage of soil parent material and pedogenesis. Valiano soils, in particular, although formed from clays, developed thick deep horizons with well structured angular blocky aggregates, which did not limited root penetration. On the other hand, Valiano aquic formed on more instable slopes, so that pedogenesis was continuously offset by water erosion. As a consequence, aggregates remained coarser and poorly developed. Microporosity dominated and internal drainage was constrained to the planes between macroaggregates.

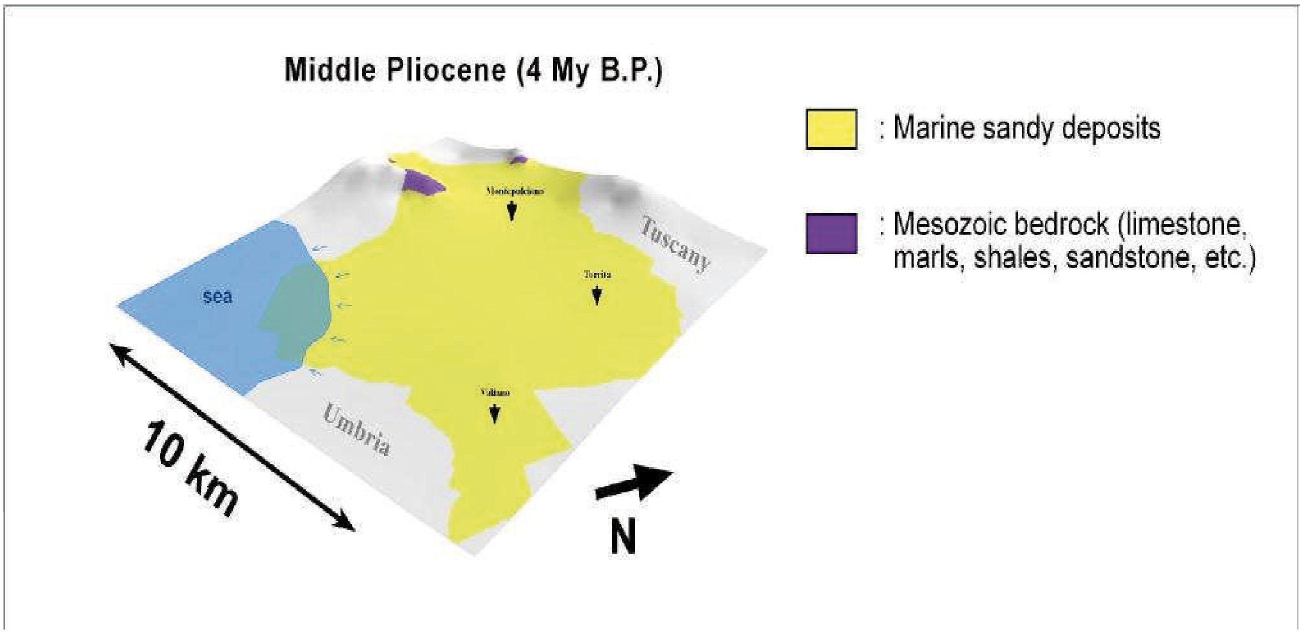
The last 40 years of the Holocene has been a period of strong but localized rhexistasy (Fig. 6). Huge land levelling and earth movements by bulldozing caused soil scalping and outcropping of almost unweathered sediments, which started a new cycle of pedogenesis, strongly ruled by man. This was particularly the case of many vineyard soils. Cusona and Monte are the most common examples of these kind of soils at Montepulciano, as well as in the province of Siena and in many other parts of Italy (Costantini and Barbetti, 2008). Below the plough layer, their characteristic are very likely to the substratum. Since both kind of soils lack of a subsurface structured horizon, available water holding capacity is always very low, leaving vine water uptake depending to a great extent on agricultural practices and on meteorology of the year. On the other hand, Cusona and Monte soils greatly differ as for air capacity and salinity, in dependence of the different nature of the substrate, so that Monte soils are the most limiting environments for vine at Montepulciano.

CONCLUSIONS

The soils of the Montepulciano terroirs formed during different geological eras. In some cases their development was a very long lasting process, which started during the Pleistocene, that is dozens of thousands of years ago. It is important to underline that best soils for the Nobile di Montepulciano wine production formed as a consequence of particular natural and human induced geomorphological events, which are no more reproducible. Therefore soil functional characters of best Montepulciano terroirs are precious and unique. Best terroirs not only fit the concept of “cru” (Seguin, 1986), but they can be also considered a soil heritage and a legacy (Costantini and L’Abate, 2009).

Man deeply influenced pedogenesis at Montepulciano since the medium Holocene, that is, since about 5,000 years BP. While also in the past the effect of man on the environment was dramatic, comparable to that of major geological events, it is during the last 50 years that the intensity of the man action has reached its maximum. With the advent of heavy mechanization and bulldozing, the pre-plantation activities of the new specialized vineyards upset the land, leaving very different effects on soil functional characters, in function of the original soil type. Where the soils before vine plantation were deep and rather homogeneous, like San Gimignano, Poggio Golo, Valiano and Valiano aquic, soil functional characters remained the same, whereas they changed significantly where soils were shallower. Soils on marine clays, in particular, due to the slow pedogenesis, were often shallow and vulnerable. Therefore San Quirico and Quercia soils could be easily converted into Monte soils, having worse functional characters for the Nobile di Montepulciano wine. Nevertheless, not always the consequences were negative. Cusona soils, for instance, which originated from Strada soils, had better functional qualities for Sangiovese wine.
As a final remark, it seems worthwhile to stress that the impact of land levelling and earth movements on soil functional characters should always be considered more carefully than currently done at Montepulciano, as well as in many other viticultural territories. On top of that, it is recommended that soils of the best terroirs, formed in an irreproducible past, will be treated as cultural heritage, and therefore protected from destruction.

Figure 1 – The sea left the Montepulciano territory during the Middle Pliocene, leaving a thick succession of sediments, mainly sandy at the top. The Mesozoic isolated reliefs are part of the Chianti – Centona mount ridge.



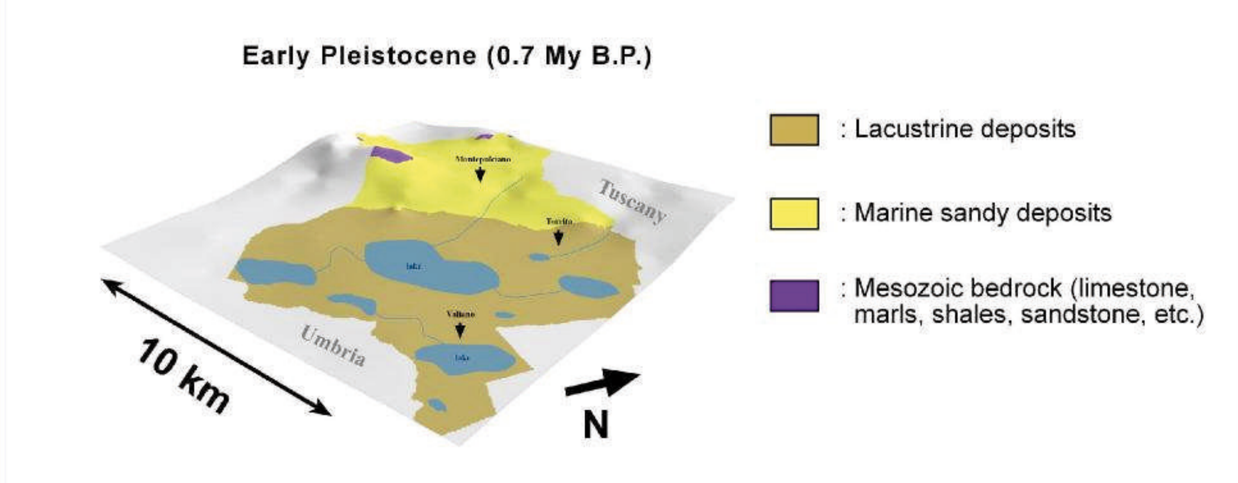


Figure 2 – During Late Pliocene and Early Pleistocene (Villafranchian) the Montepulciano territory was first incised and then filled up with lacustrine deposits.

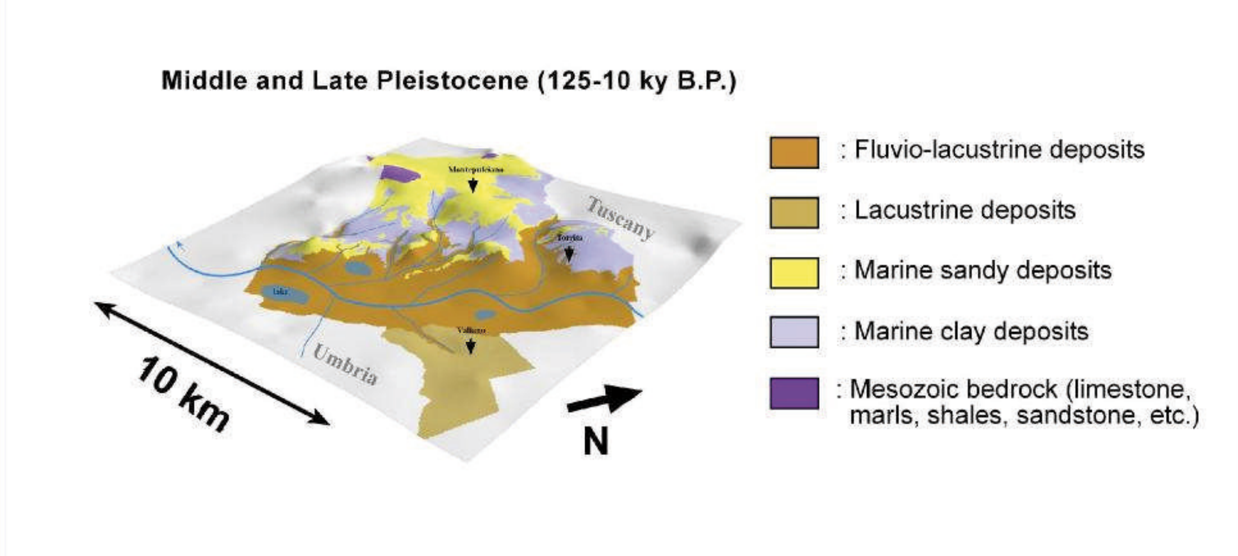


Figure 3 – During Middle and Late Pleistocene the Villafranchian lacustrine sediments were eroded and filled up with new fluvial and lacustrine deposits. Several fluvial terraces formed along the "Val di Chiana" paleo valley, which was at that time crossed by a southward streaming river, the "paleo Arno". The deposits on the terraces and hilly lands underwent a rather intense and prolonged pedogenesis, leading to the formation of well developed soils.

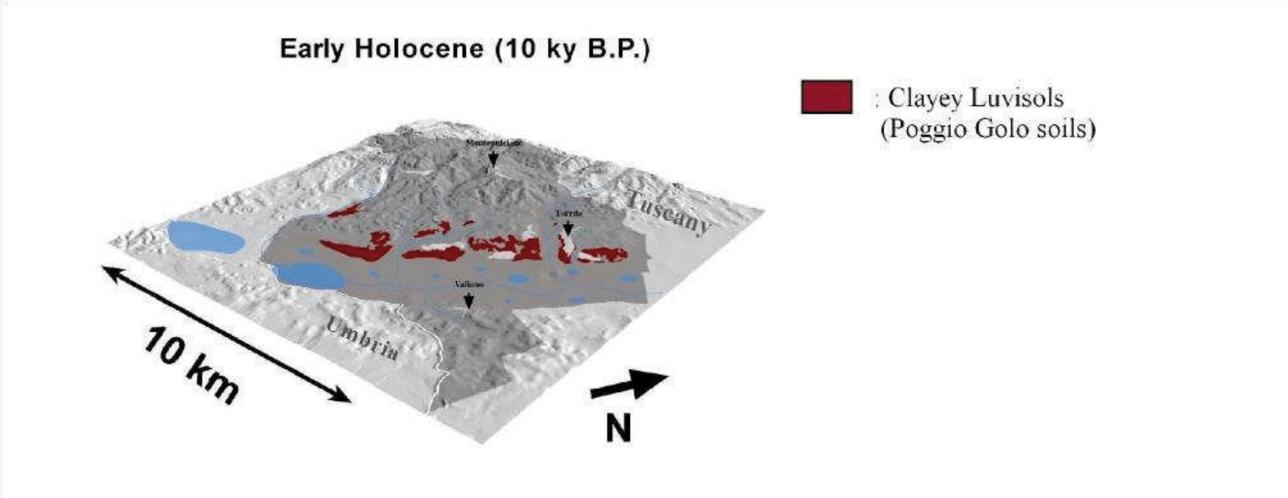


Figure 4 – During Early Holocene the morphology of the Montepulciano territory was very similar to the present. The progressive filling up of the valley caused a further swamping of the lowlands, while tectonic movements led to the reversion of the drainage of the paleo Arno river. Poggio Golo soils dominated on the fluvial terraces formed in the previous geological era.

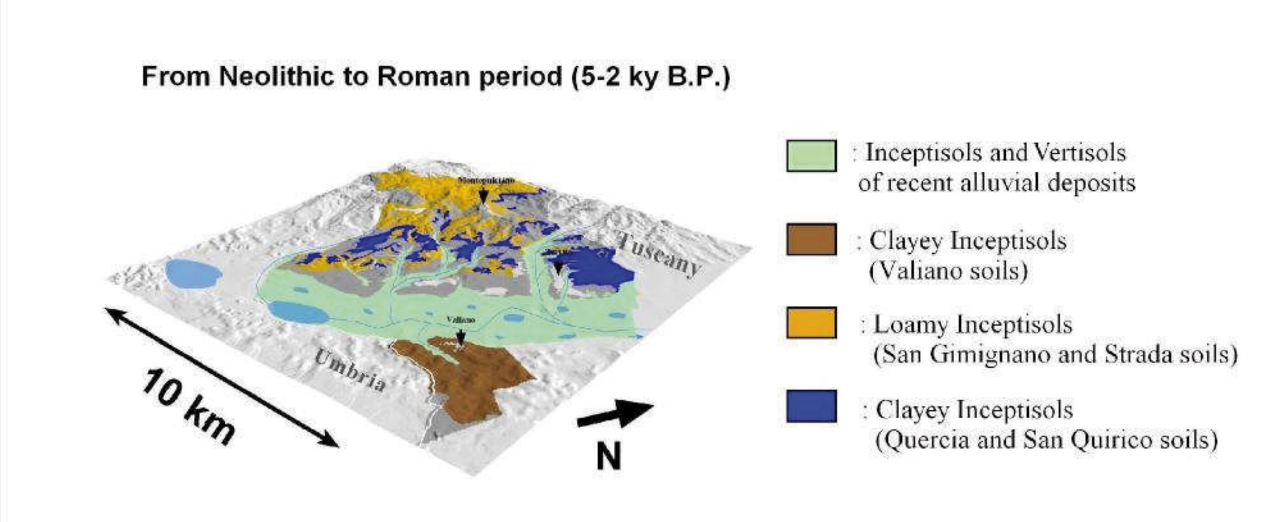


Figure 5 – Neolithic/Early Bronze age was a time of severe erosion of soils on slopes. Human settlements developed and forests were cleared. The reduced soil cover, combined with a climate deterioration, with dry spells and strong winds, led to a sharp increase of water and wind erosion. Colluvial sediments accumulated on the lower parts of slopes, leading to the formation of very thick soils, like some San Gimignano soils. Some aeolian sediments accumulated on soils placed on stable morphological positions. During the successive bronze ages and Etruscan and Roman civilizations, the climatic conditions improved, and so did the land management. Pedogenesis of Valiano, San Gimignano, Strada, San Quirico, and Quercia soils took place during that time.

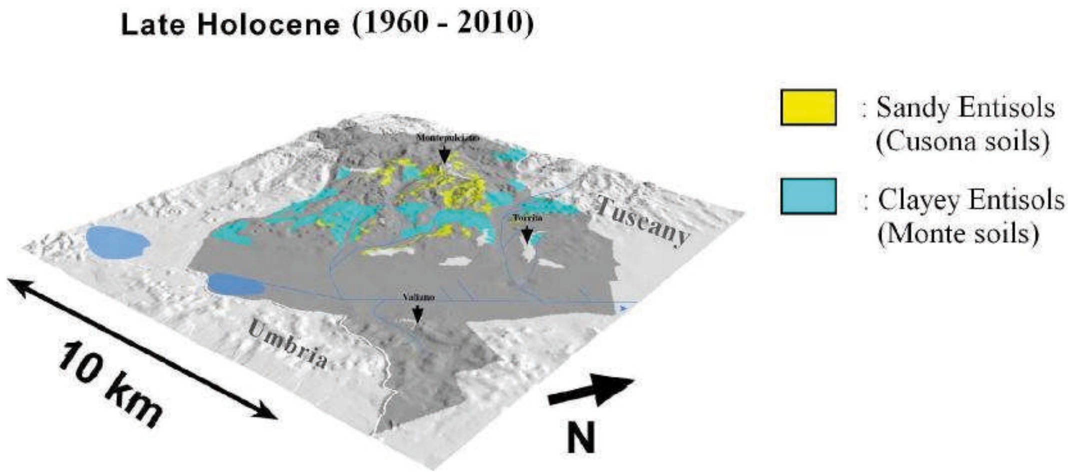


Figure 6 – The last 40 years of the Holocene has been a period of strong but localized rhexistasy. Huge land levelling and earth movements by bulldozing caused soil scalping and outcropping of almost unweathered sediments, which started a new pedogenesis. This was particularly the case of vineyard soils. Cusona and Monte are the most common example of these kind of soils.

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