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**To cite this version:**

P. Courjault-Radé, M. Llubes, J. Darrozes, M. Munoz, Éric Maire, et al.. A 2D electrical resistivity tomography survey of a vineyard plot of the Gaillac appellation (France): interpretation with respect to possible implications on vine water supply. OENO One, 2010, 44 (2), pp.51-60. 10.20870/oeno-one.2010.44.2.1462 . hal-01587441

**HAL Id: hal-01587441**

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Submitted on 14 Sep 2017

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# A 2D ELECTRICAL RESISTIVITY TOMOGRAPHY SURVEY OF A VINEYARD PLOT OF THE GAILLAC APPELLATION (FRANCE): INTERPRETATION WITH RESPECT TO POSSIBLE IMPLICATIONS ON VINE WATER SUPPLY

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## Abstract

**Aims**: The aim of this 2D electrical resistivity tomography (ERT) survey performed on a vineyard plot of the Gaillac appellation was to investigate spatial and temporal variations in subsurface water supply in relation with pedo-geological and morphological features.

**Methods and results**: The ERT surveys were carried out under two contrasted - dry and humid - climatic conditions. All the resistivity profiles showed the superposition of two layers: a lower layer characterized by very low resistivity values (< 40 Ω.m) corresponding to a marly molassic subsoil overlaid by an upper layer characterized by moderate to high resistivity values (300 Ω.m to 1500 Ω.m) corresponding to a silty-sandy and gravely-pebbly soil sequence. The resistivity values of the molassic subsoil stayed very low independently of water supply conditions whereas those of the soil sequence decreased by a factor 2 (300/750 Ω.m versus 750/1500 Ω.m) when the plot was close to field capacity.

**Conclusion**: The ERT results coupled with pedological and morphological data strongly suggest that the water flow is preferentially restricted at the molassic subsoil/soil sequence interface, short-lived and of low amplitude.

**Significance and impact of the study**: Consequently, the water supply regime, which points out a potential risk of drought stress for vine crops, implies a minimization strategy when choosing vegetal material and viticultural management operations

**Keywords**: electrical resistivity tomography (ERT), Fer Servadou, Gaillac appellation, geology, pedology, gravesac, Syrah, vineyard, water supply

## Résumé

**Objectifs** : La campagne de mesures de résistivité électrique en deux dimensions entreprise sur une parcelle du vignoble de l'aire AOC de Gaillac, a été effectuée dans le but d'appréhender les relations spatiales et temporelles des apports hydriques de subsurface avec les caractéristiques pédo-géologiques et morphologiques de cette parcelle.

**Méthodes et résultats** : Les mesures de résistivité ont été menées sous des conditions climatiques contrastées, l'une en période sèche, la seconde en période humide. L'ensemble des profils de résistivité montrent la superposition de deux horizons. L'un, inférieur, présente des valeurs de résistivité faibles (< 40 Ω.m) et correspond au soubassement géologique de type molasses marneuses ; le second, situé au-dessus du précédent, montre des valeurs de résistivités modérées à élevées variant de 300 Ω.m à 1500 Ω.m. Cet horizon supérieur correspond à la séquence du sol constitué de galets à la base, surmontés par des horizons graveleux, puis silto-gréseux. Les valeurs de résistivité du soubassement molassique restent faibles indépendamment des variations des apports hydriques. Par contre, les valeurs de résistivité du sol varient d'un facteur 2 (300/750 Ω.m vs. 750/1500 Ω.m) quand la parcelle est proche de sa capacité aux champs.

**Signification et impact de l'étude** : Les résultats des mesures de résistivité couplés aux données pédologiques et morphologiques suggèrent nettement que les circulations d'eau se limitent préférentiellement à l'interface entre le soubassement molassique et le sol. En outre, ils indiquent que ces circulations sont de courte durée et de faible ampleur. Ainsi, le régime d'apports en eau met en évidence un fort risque de stress hydrique pour les plants de vigne. Cette situation implique de développer une stratégie de minimisation qui passe par le choix raisonné du matériel végétal et de méthodes viticulturales adaptées.

**Mot-clés** : appellation Gaillac, apport hydrique, Fer Servadou, géologie, Gravesac, pédologie, tomographie électrique, Syrah, vignoble

*manuscript received the 16 March 2009 - revised manuscript received the 20 January 2010*

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## INTRODUCTION

It is well-known that high-quality grapes grow only under certain optimum physical-chemical conditions related to the pedo-geological parameters of the soil and bedrock (Pomerol, 1990; Haynes, 1999; Morlat, 2001; van Leeuwen *et al*., 2004; Pellegrino *et al*., 2004 among others). More specifically, the soil water supply greatly affects vine water resources by regulating water supply to the roots. Therefore, it is one of the most important parameter controlling grape ripening and wine quality as shown in numerous studies (Morlat *et al*., 1992; Creasy and Lombard, 1993; Ojeda *et al*., 2002; Goulet *et al*., 2004; Bodin and Morlat, 2006; van Leeuwen and Seguin, 2006; Intrigliolo and Castel, 2009). The relationship between available water in the soil and bedrock and water supply conditions depends on soil permeability, which represents the ability to transmit fluids. Therefore, an accurate knowledge of the temporal and spatial evolution of the soil/bedrock water supply regime and water infiltration pathways is a main goal in precision viticulture (e.g. Morais *et al*., 2007; Tisseyre *et al*., 2007).

The non-destructive electrical resistivity method is commonly used to investigate the variations of water supply regime of the soil (Boutraud *et al*., 1984; Daily *et al*., 1992; Michot *et al*., 2003; Rein *et al*., 2004; Samouëlian *et al*., 2005). The purpose of electrical resistivity surveys is to determine the resistivity distribution of the bedrock/soil sequence volume. Artificially generated electric currents are supplied to the sedimentary sequence and the resulting potential differences are measured. Potential difference patterns provide information on the structure of subsurface to near surface heterogeneities and electrical characteristics (Kearey *et al*., 2002). The resistive characteristics of the subsurface depend on

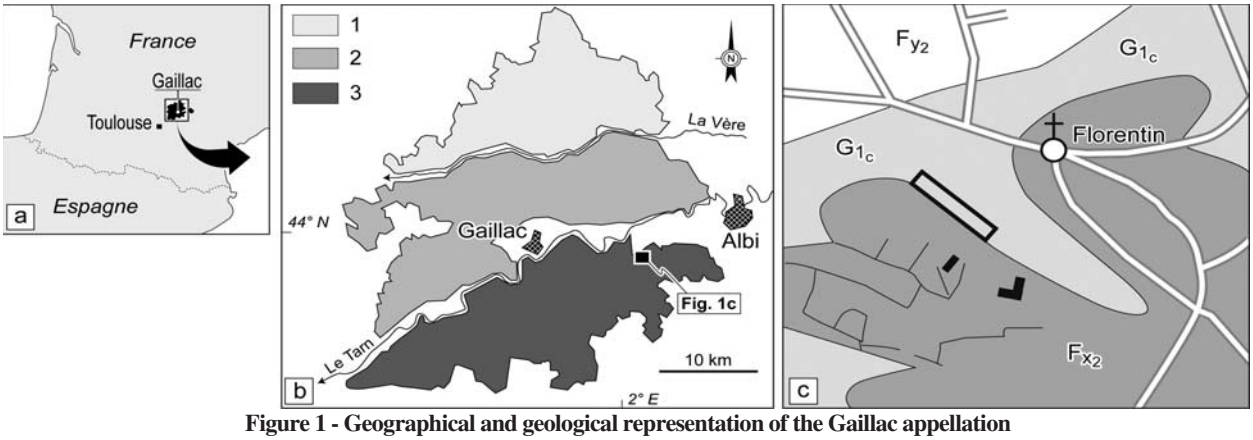


**Figure 1 - Geographical and geological representation of the Gaillac appellation**
**1a. Localization of the Gaillac appellation.**
**1b. The 3 main terroirs of the Gaillac appellation. The analysed plot is localized.**
**1, Cordes plateau; 2, Right bank "coteaux"; 3, Left bank terraces.**
**1c. Geological and morphological situation of the vineyard plot (arrow).**
(1), recent alluvial deposits (Fy2); (2), rissian alluvial deposits (Fz2); (3), Oligocene marly molassic basement (G1C).

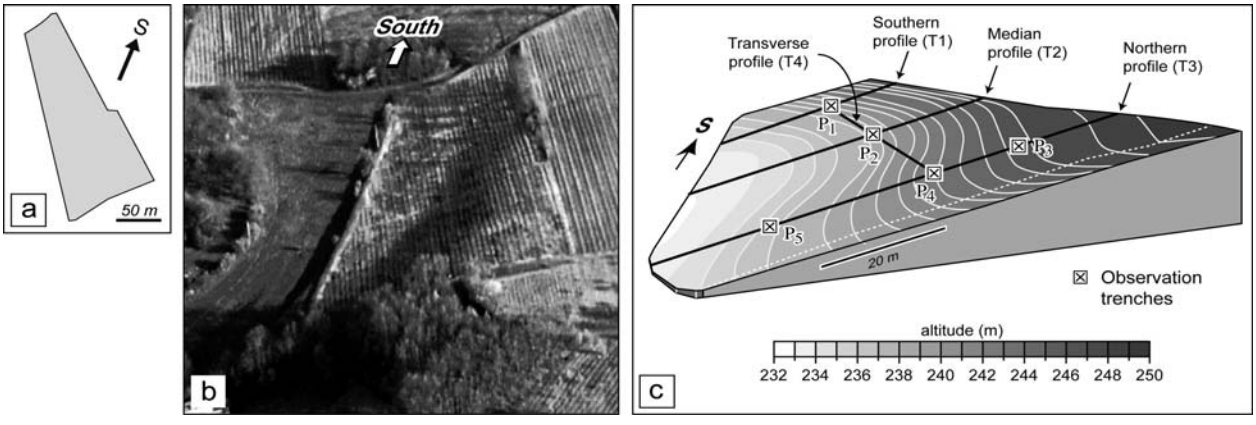


**Figure 2 - 2a - Sketch diagram of the analysed vineyard plot.**
**2b - View of the analysed vineyard plot in southern direction.**
**2c - Synthetic Digital Elevation Model of the plot with localization of the ERT profiles (T1 to T4) and observation trenches (P1 to P5).**


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different bedrock/soil properties such as the nature of the solid constituents (particle size distribution, mineralogy), the arrangement of voids (porosity, pore size distribution, connectivity), the degree of water saturation (water content), the electrical resistivity of the fluid (solute concentration) and the temperature (Campbell *et al*., 1948; Besson *et al*., 2004; Samouëlian *et al*., 2005). Electrical resistivity of the soil can vary on a wide scale of values, ranging from less than 10 Ω.m for clayey-saturated material or saline soils to about 10 000 Ω.m for dry sand or conglomerates (Samouëlian *et al*., 2005; Palacky 1987).

In recent years, the electrical resistivity method has been develop to assist precision viticulture (Lamb *et al*., 2004; Goulet and Barbeau, 2006; Tisseyre *et al*., 2007; Acevedo-Opazo *et al*., 2008; Morari *et al*., 2009). Here we present a comprehensive analysis of the main pedological and geological parameters of a vineyard plot of the Gaillac appellation using an electrical resistivity method. In the first part of the study, five selected observation trenches have been dug in order to determine the organization of the soil-bedrock sequence and the main pedological parameters (Courjault-Radé *et al*., 2005). In the second part, which is the aim of this paper, we have characterized the water supply regime of the plot by using the standard electrical resistivity subsurface geophysical investigation method (Benderitter and Schott, 1999; Panissod *et al*., 2001; Tabbagh *et al*., 2002 among others). Strategies for the minimization of drought-stress risks by selecting adapted grapevine cultivars, rootstocks and viticultural practices are discussed.

## MATERIALS AND METHODS

### 1. Description of the vineyard plot

a. Geological data and topography

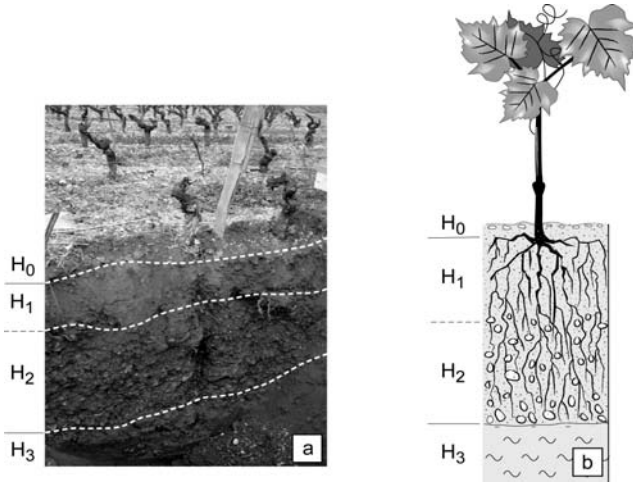


**Figure 3. 3a - A representative observation trench. 3b - The pedo-geologic organization of the bedrock/soil sequence.**
(H0) Anthropic horizon; (H1) silty -sandy horizon; (H2) grevely/pebbly horizon; (H3) marly molassic basement.

The plot analysed in this study is located in the Gaillac appellation, in the South-West of France. The plot has a trapezoid shape of approximately 1.7 hectares (Figures 2a, b). In order to integrate the role of topography in the location of preferential infiltration pathways, a topographical survey was carried out based on a detailed digital elevation model (DEM) of the plot built with the help of a high-performance global positioning system (Figure 2c). The results showed that the topography of the plot is mostly convex with an average slope of about 45% inducing strong draining conditions.

b. Bedrock - soil composition

The organization of the soil-bedrock sequence was further investigated with observation trenches (Figure 3). From top to bottom, the bedrock - soil sequence of the plot is composed as follows (Courjault-Radé *et al*., 2005): a thin (up to 0.20 m) superficial anthropic horizon enriched with quartz pebbles; an eluvial silty-sandy horizon (average thickness 0.40 m); a pebbly-sandy horizon (average thickness 0.60 m) deriving from alluvial material; and a molassic geological subsoil mainly composed of clays, patchily enriched in carbonates. In this paper, the geological subsoil is identified as the bedrock.

### 2. The ERT method

The ERT method (Griffths and Barker, 1993) consists of building a 3D electrical picture using the reconstruction of a two-dimensional network of parallel sections. The data are arranged in a 2D «pseudo section» plot that gives a simultaneous display of both horizontal and vertical variations in resistivity (Edwards, 1977; Zhou *et al*., 2001).

The 2-D resistivity tomography was obtained by using the ABEM Lund Imaging System and a multi-electrode Wenner configuration with an array of 64 steel electrodes. The electrodes A, M, N and B were positioned on a straight line with a constant distance « a » between the electrodes. A and B were the current electrodes and produced a bipolar field, M and N were the potential electrodes (Figure 4). The Wenner array is commonly used in profiling methods because it is more sensitive to vertical changes than to horizontal changes in subsurface resistivity and it is better adapted to subhorizontal

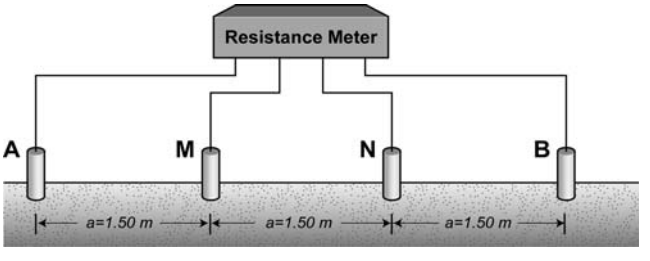


**Figure 4 - Wenner electrodes array configuration**


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geological structures (e.g. Loke, 2001). Moreover, the Wenner array has moderate depth of investigation compared to the other arrays and is better adapted for the analysis of near to subsurface bedrock/soil sequence (Griffiths and Barker, 1993).

The altitude survey was done in real time by a GPS working in a differential mode. Topographic profiles were built from the Digital Elevation Model (DEM) using ENVI software and then added to the resistivity data files treated with Res2Dinv software (Loke and Baker, 1996) (Figure 2c).

The inversion program Res2Dinv version 3.5 was used to calculate the resistivity sections (Loke and Barber, 1996). The apparent resistivity data from each 2-D survey line were inverted using a least-square method to obtain a pseudo-resistivity 2-D cross-section including the topographic variations (Loke, 1997).

### 3. The ERT surveys

The electrical resistivity tomography survey was performed as described by Binley *et al*. (2002). The four survey traverses were geolocalized using GPS positioning; they were set perpendicularly (3) and parallel (1) to the orientation of the plot. Hence, the survey traverses were oriented in two directions perpendicularly to one another (Figure 2c).These four survey traverses have been chosen to spatially fit with the different observation trenches in order to control the bedrock/soil sequence organization.

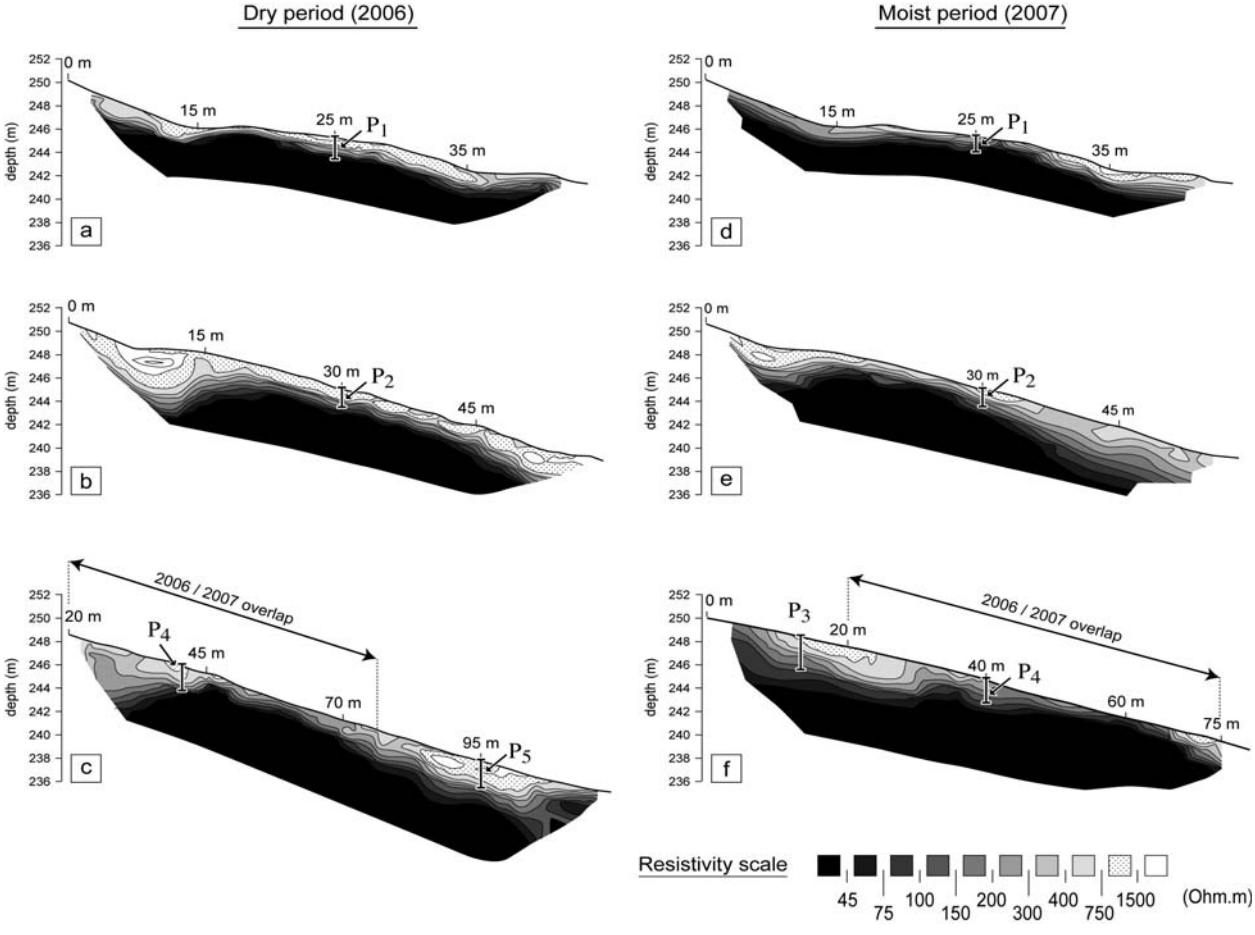
## RESULTS AND DISCUSSION

### 1. Electrical resistivity of the bedrock/soil sequence

In order to monitor water supply regime changes under different highly-contrasted precipitation conditions, ERT surveys were performed during the winter 2006 (after a dry season) and spring 2007 (very rainy, close to field capacity).

**Table 1. Comparison of ERT sections for dry (February 2006) and moist periods (June 2007).**

(T1 section : a and b profiles, T2 section: b and e profiles, T3 section section and f profiles)




The RMS estimate for inversion presented here is 8,9%. P1 to P5: localization of the observation trenches. T1 to T4: localization of electrical profiles. Note that altitudinal positions of the molasse bassement/soil sequence boundary are in agreement with those measured in the observation trenches (P1 to P5). Note the extent of high resistivity values (*i.e.* ≥ 750 Ω.m) of the medium profile both in dry and moist conditions (figs. b and e) in respect to the other profiles.


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Table 1 presents the results of the two data sets of apparent resistivity monitored on the plot. The calculated resistivity values ranged from 35 Ω.m to more than 1500 Ω.m. As for sequential organization, all the resistivity profiles showed a superposition of two highly contrasted resistivity layers: a first layer, at the bottom, characterized by very low resistivity values (up to 40 Ω.m) and a second upper layer with moderate to high resistivity values ranging from 300 Ωm to more than 1500 Ω.m at the very top. Its thickness varied from 1.5 m to 3.5 m (2 m in average). The transition between the two layers was systematically underlined by quick resistivity variations due to the inversion program Res2Dinv computation process when high gradient of resistivity values occurred (Loke, 2001).

A correspondence can be made between the resistivity values and the type of sediments identified in the observation trenches. The level of low resistivity values corresponds to the clay-dominated molassic subsoil whose upper limit is situated at an average of 2 m deep (Courjault-Radé *et al*., 2005). The high resistivity values of the upper level correspond to the silty-sandy and gravely-pebbly soil sequence whose depth varies from 1.50 m in average to more than 3.50 m at the very top of the plot (Courjault-Radé *et al*., 2005).

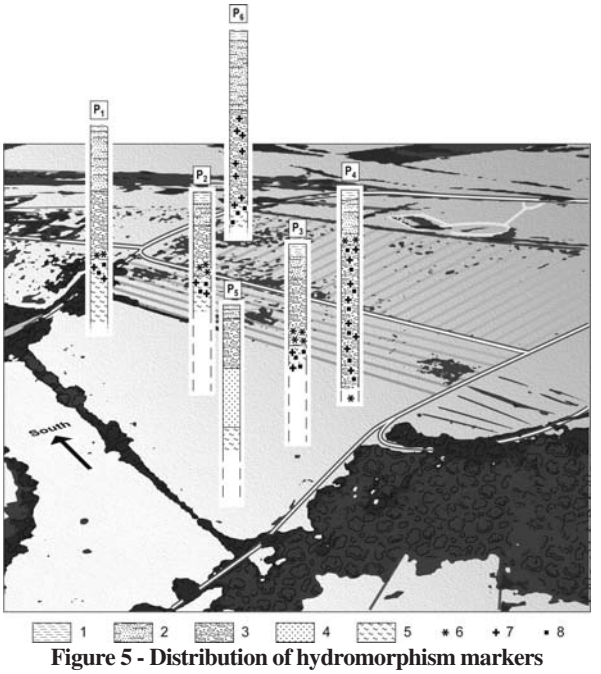


**Figure 5 - Distribution of hydromorphism markers in the sequences of the analysed plot (P1 to P5) and of the terrace tread (P6).**

Symbols: (1) anthropic horizon; (2) sand and silt; (3) pebble and gravel; (4) fine-grained sandstone; (5) molassic clayey basement; (6) spot of ferrous hydroxide; (7) spot of ferrous iron and ferrous hydroxide; (8) manganese oxide.

## 2. Comparison between the two ERT data sets

A preliminary remark has to be made about the possible influence of temperature. Indeed, comparisons of electrical resistivity measurements require the knowledge of the seasonal variation of temperature to avoid any misinterpretation of field measurements acquired on different dates because the electrical resistivity decreases when the temperature increases (Campbell *et al*., 1948; Samouëlian *et al*., 2005; Besson *et al*., 2004). The average surface temperature recorded was around 10 °C at the end of winter 2006 and around 18 °C at the end of spring 2007 (Infoclimat, 2009). Knowing that a 2% resistivity variation corresponds to a 1° C variation (Keller and Frischknecht, 1966), then electrical resistivity values have to be normalized (~15%) between the first and the second survey. Nevertheless, one must note that soil temperature variations decrease exponentially with depth, and only negligible fluctuations of soil temperature are observed at depths of about 1 meter (Bocock *et al*., 1982).

Comparison between the two ERT data sets gives evidences of resistivity variations in relation with dry or humid conditions (see Table 1). It allows delineating the infiltration pathways and the available water considering that variations of resistivity between the two surveys are due to significant variations in available water.

Apparent resistivity values of the marly molassic bedrock did not vary neither from one profile to another, nor from dry or humid periods: they were always lower than 40 Ω.m. As the proportion and the structure of clays did not vary between the two surveys, the stability of the resistivity results points out that the water contained in the marly subsoil has not changed because of its very weak permeability.

The resistivity values of the silty-sandy-pebbly upper soil sequence remained moderate to high whatever dry or humid conditions in agreement with its high draining potential coupled with the occurrence of a steep slope (Courjault-Radé *et al*., 2005). However, the resistivity values of the soil sequence varied by a factor 2 (even if 15% temperature reductions were taken into account) from 300 Ω.m to 750 Ω.m under moist conditions when the plot was close to field capacity and from 750 Ω.m to 1500 Ω.m under dry conditions.

The invariant localization of the soil sequence /bedrock boundary at 2 meters deep in average between the two surveys implies that the water flow at the bedrock/soil interface was short-lived and of low amplitude. It strongly suggests that no saturated horizon with very low resistivity values appeared at the soil/molasse interface but only very temporary water circulation when the plot was close to field capacity.

a. Pedological data

The lack of any saturated horizon (even temporary) at the soil/molasses interface agrees with the pedological


*J. Int. Sci. Vigne Vin*, 2010, **44**, n°2, 51-60
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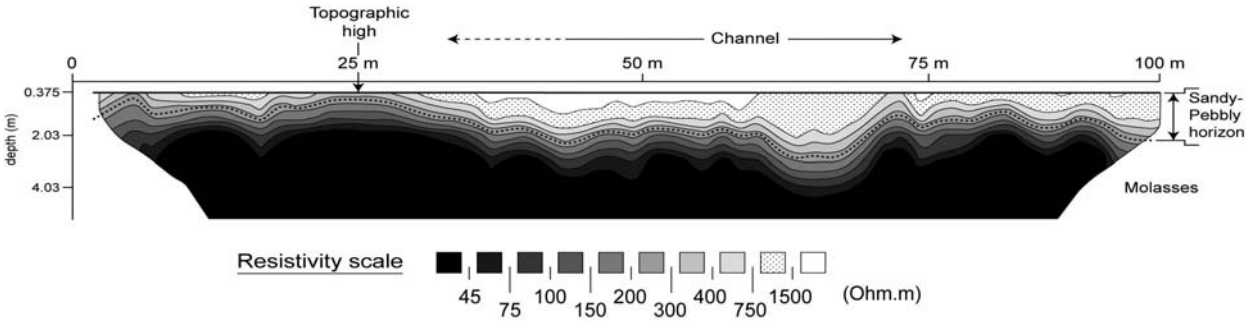


**Figure 6 - The NW-SE oriented electrical profile.**

The RMS estimate for inversion presented here is 7,4%. Note the topographic lows and highs characterizing the molassic basement roof.

data of the observation trenches (Figure 5). Patchily distributed red ferric oxides, indicative of temporary water circulations and prevalence of oxidative chemical conditions, were mostly observed near the soil/bedrock transition. Accumulations of manganese forming scattered nodules together with greyish patches of ferrous iron only occurred at the top of the clayey molasses sequence indicating that an incipient hydromorphism in reduced chemical conditions may occur at the top of the molassic subsoil. Some variations were observed depending on the topographic location of the analysed soil sequence (Figure 5). Reddish ferric oxides were patchily distributed in most part of the soil sequence of the upper third of the slope terrace. Scattered grey ferrous patches occurred only at the soil/molasses transition. These pedological markers indicate momentary water circulation in oxidative chemical conditions associated with local and temporary water saturation only at the soil/bedrock transition. The soil sequence of the middle part of the plot was characterized by very few reddish patches of ferric oxides which only accumulated in the vicinity of the soil/bedrock boundary. It indicates again momentary water circulation in oxidative conditions especially at the interface. Finally, the soil sequence of the lower part of the plot did not show any reddish patches of ferric oxides even at the soil/bedrock transition.

b. Topographical and morphological data

The morphology of the molassic bedrock surface can be roughly reconstructed on the basis of geological data, pedo-geological sequential organization, topographical and ERT experiment data. For this purpose, a fourth perpendicular NW-SE oriented profile was carried out (Figure 6). It was done along a same level line to avoid topographic adjustments and was situated on both sides of the central part of the plot in order to acquire data about the median profile (see figure 2c). Much as the NNE-SSW oriented profiles, this perpendicular profile displayed a similar succession highlighted by two high-contrast layers: the molassic marly subsoil characterized by a very low resistivity value sequence (up to 40 Ω.m) covered by a high to very high resistivity value layer corresponding to the pebbly and silty/sandy soil sequence ranging from 350 Ω.m at the bottom to more than 1500 Ω.m at the very top (Figure 6).

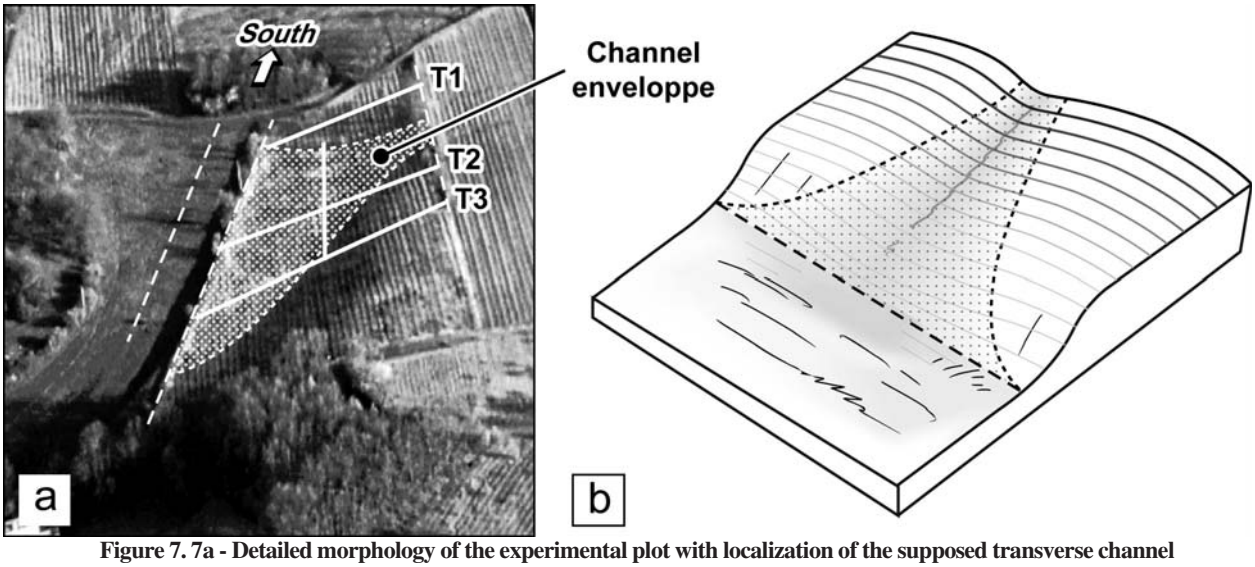


**Figure 7. 7a - Detailed morphology of the experimental plot with localization of the supposed transverse channel and the different electrical profiles (T1 to T4).**
**7b - Interpreted schematic morphology of the vineyard plot.**


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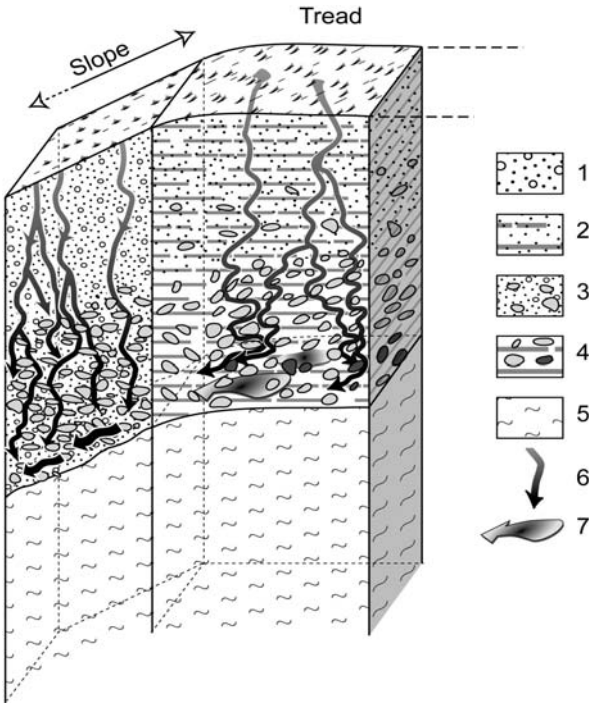


**Figure 8 - Synthesis of the preferential subsurface and near surface groundwater circulation pathways from the tread to the slope terrace according to topographical parameters, the sequential bedrock/soil organization and the scarcity of pedological markets giving evidence of hydromorphism process (not at scale).**

Symbols: (1) sands and gravels; (2) silts and clays; (3) pebbles, gravels and sands; (4) pebbles sealed by red and grey clays; (5) molassic clayey basement; (6) infiltration pathways; (7) temporary water flow.

The boundary between the silty-sandy-pebbly horizons and the molassic subsoil varied from near surface (< 0,4m) to 2.50/3.0 m deep, suggesting the occurrence of an antecedent morphology of the molassic bedrock surface highlighted by topographic lows and highs. This organization would explain that the medium profile is slightly more resistant either in dry or moist conditions (compare figures b and e, with figures a, d, c and f - Table 1). Furthermore, this organization agrees with the present-day morphology of the plot depicted by field data as the median profile appears to fit with the axis of a former channel (Figures 7a-b). It is worth noting that the occurrence of such a former channel agrees with the fluviatil origin of the early tertiary material characterized by a succession of channels and topographic highs (Cavaillé, 1973).

## 3. A water supply optimization strategy

The water supply regime pattern of the vineyard plot (Figure 8) has possible consequences on the risk of drought stress for vine crops, hence requiring a minimization strategy based on optimization of vegetal material and viticultural practices.

a. Choice of grapevine varieties

Two grapevine varieties have been selected, Syrah and Fer Servadou, taking into account the Gaillac appellation specifications and the macro to meso-climatic conditions characterized by oceanic-dominant influences together with momentary dry Mediterranean conditions (Anglade and Delaunois, 1991). The Syrah cultivar originates from the relatively humid climate of the Northern Rhone Valley in France (Vouillamoz and Grando, 2006). The drought response of Syrah is efficient when the water stress remains below a maximum threshold because of its limited anisohydric stomatal response (Shultz, 2003). Fer Servadou cultivar originates from the oceanic Spanish Basque area (Lavignac, 2001) and is also characterized by an anisohydric stomatal behaviour (Attia, 2007). Such a response to water stress appears to be distinctive of cultivars growing in areas where drought is rarely severe (Tardieu and Simonneau 1998; Timlin *et al*., 2008).

Hence, as the selected cultivars may be exposed to high water stress during drought period, optimization of the water supply strategy is required based on the choice of adapted rootstock and viticultural management practices.

b. Choice of an adapted rootstock

A way to reduce the risk of water stress is that roots (and/or rootlets) may reach (or penetrate) the soil/bedrock interface which is the site of preferential water circulation and of momentary accumulation of water at the very top of the molassic bedrock. In this scheme, the choice of an appropriate rootstock is a key parameter.

Different root systems of rootstocks determine their efficiency in taking up water from the soil. If their root system stays near the ground surface (tracing type), they require soils with adequate water supply. In contrast, a plunging pattern system helps roots to reach deep available water.

The Gravesac rootstock is adapted for an acidic sandy-gravel soil and has a relatively good resistance to drought conditions together with a moderate vigour (Shaffer *et al*., 2004). Furthermore, it can develop a semi-plunging root system which causes roots and rootlets to plunge deep into the soil. This allows the roots to reach available soil moisture at the bedrock/soil interface and therefore reduces the impact of drought.

c. Adapted soil management practices

Soil management practices may trigger roots to reach available water at the soil/bedrock interface.


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The high density planting (inter and intrarow) (up to 7500 vines per hectare) increases root density under the row and promotes deeper root penetration (Archer and Strauss, 1998; Jackson, 2008).

Competition between the grass cover and the vine root system greatly affects water supply conditions for grapevines (Morlat and Jacquet, 2003; Wheeler and Pickering, 2003). Consequently, the inter-row ploughing which avoids such competition would be better suited in the case of water stress. Furthermore, the intra-row ploughing which limits the development of superficial roots would also trigger the vine root system to plunge deeper in the soil to find the available water.

It is worth noting that a cover crop grapevine taking up water from deeper soil layers due to a vertical redistribution of the root system has been recently observed in Mediterranean climatic conditions (Celette *et al*., 2008).

## CONCLUSION

Reiteration of ERT surveys at two different periods with contrasting water recharge conditions, together with the knowledge of the geological and pedological organization of the soil/bedrock sequence and topography/morphology of the plot, leads to determine the main pattern of its water supply regime. The very low resistivity values (< 40 Ω.m) of the clayey-dominated molassic bedrock, whatever its water supply conditions, testify of its weak permeability. In contrast, the soil sequence stays moderatly to highly resistant (> 350 Ω.m), independantly of dry or moist conditions, even when the plot is close to its field capacity. This situation is in aggreement with the high permeability of the sandy-pebbly material and with the steep slope of the plot which triggers high drainage conditions. Furthermore, the ERT surveys point out that only temporary accumulation of water would occur at the bedrock/soil interface just after heavy rains, coming from direct vertical infiltrations.

The water supply regime pattern of the vineyard plot and the regional/local climatic conditions require a drought stress mitigation strategy for vine crops. This mitigation should be based on optimization of the choice of vegetal material and the viticultural management practices. As specifications of the Gaillac appellation impose selection of grapevine varieties which are adapted to a relatively humid climate, only suited rootstocks and viticultural practices can be used for such risk mitigation.

The next step of the study to be carried out on the experimental vineyard plot of the Gaillac appellation will focus on the relationships between vine physiology and bedrock/soil sequence hydrologic behaviour using infrared measurements (Alves *et al*., 2006; Tisseyre *et al*., 2007; Stoll and Jones, 2007 among others) and resistivity analysis at the vine crop scale. Furthermore, the implications of these infrared measurements coupled with the tomography results on vine water supply should be ideally validated by vine water potential measurements (preferable stem water potential) or $\delta^{13C}$ measurements as described by van Leeuwen *et al*. (2009). The forthcoming results will allow investigating physiologic behaviour of the vegetal material according to spatial and temporal water supply changes in the vineyard plot which derive from the main morphological/topographical, pedological and geological features of the vineyard which are now well established.

**Acknowledgements** : We are indebted to C. Cavaré for the quality of scheme which enhanced the manuscript.

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