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THE ROLE OF VINEYARD GEOLOGY IN WINE TYPICITY

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Abstract

Vineyard geology – bedrock and overlying soils – is widely supposed to help explain the typicity of wine from a particular area, though there has been little analysis of how this might come about. Such an evaluation is attempted here. Geology does underpin some of the physical parameters that affect vine performance, but in an indirect way and the factors are commonly manipulated artificially. A direct geochemical influence on wine flavour is widely inferred but remains undemonstrated. The popular model of nutrients being taken up by the vine and persisting to be tasted in the finished wine is untenable. The amounts that reach the fermenting must are minuscule, bear little relation to the substrate composition, and can be further complicated by contamination and fining. In the final wine these inorganic nutrients normally exist in concentrations far below human recognition thresholds and are "swamped" by the organic secondary metabolites that do dominate wine flavour. Hence any geochemical influence, like that of the physical factors, has to be highly complex and indirect. The notion of being able to taste the vineyard geology in the wine – a *goût de terroir* – is a romantic notion which makes good journalistic copy, and is manifestly a powerful marketing tactic, but it is wholly anecdotal and in any literal way is scientifically impossible. Thus critical evaluation leads to the conclusion that the role of geology tends to be exaggerated.

Introduction

Vineyard geology – the bedrock and soils derived from it – is commonly mentioned in the technical literature as an important influence on vine growth and wine character (e.g. White 2003, DPIW 2007). Some winemaking consultants believe it is responsible for the character of the wine from a particular area, e.g. “the soil gives a wine its typicity” (M. Rolland, in Joy 2007), as do some producers: “How else can you explain the iodized notes in Chablis if not by the composition of its soil?” (B. Billaud- Simon, in Joy 2007). Popular wine writers enthuse about the importance of vineyard geology in endowing wine typicity, as in “what really makes Alsace wines unique is the preponderance of fossilized seashells in the soil” (Wille 2001) and “the red soil is generally agreed to be of critical importance in making Coonawarra Australia’s greatest red wine region” (Halliday and Johnson 2006). Similarly, Champagne is commonly associated with chalk slopes, Chablis with Kimmeridgian limestone, Moselle wines with slate, Beaujolais with granite, etc. etc. (e.g. Jefford 2002).

Consequently, it has become *de rigueur* when describing a vineyard to specify its geology, even to detail the geological history and age of the materials involved. At the same time, tasting notes frequently employ geological words such as earthy, stony, and minerality, which tends to promote further an inferred direct link between the vineyard substrate and the resulting wine. Some writers make explicit a connection with wine taste: “drinking wine helps us taste geology” (Jefford 2000); “infused in the wine is a goût de terroir, a taste of the soil” (Kramer 2008). Such perceptions bolster a valuable tactic for the wine trade, as, being one of the few aspects of wine production that cannot be translocated or easily replicated elsewhere, a vineyard’s geology is something that can be invoked to promote a wine’s typicity, to give it a marketable uniqueness.

However, there has been remarkably little attempt to analyze how any connection between vineyard geology and wine might come about, and especially to evaluate critically the geological factors that might influence the finished wine. This is the purpose of the present article. The discussion begins by considering the physical factors that might influence vine performance and hence wine character, and then examines the possibility that vineyard geochemistry can affect wine taste. Finally, the idea that vineyard geology can be directly sensed in the finished wine – that the wine possesses a goût de terroir – is considered.

Role of physical geology

Geology and landform

Within the world's temperate climate belts, the interplay between crustal uplift, the spatial arrangement of surface rocks, their relative durabilities and geological processes of erosion fundamentally controls the distribution of sites suitable for grape growing. A summary of the resistance to weathering and erosion of common rock types, and how their 3-D arrangements affect landforms is given in Maltman (1998). In other words, bedrock geology determines the topographic relief of an area, at both regional and local scales, and this interacts with its hydrogeology and with a host of influential climatic factors. These include altitude (Mateus et al. 2001) and exposure (Mazza et al. 1999), together with slope aspect, convexity and inclination (Dumas et al. (1997). Solar warmth generally increases with greater slope inclinations (e.g. Robinson 2006), which is helpful during fruit ripening (Huggett 2006) though possibly damaging in high-altitude vineyards that rely on persistent snow cover to protect the vines during winter dormancy (Hamman et al. 1998). Slope character influences the exposure of the fruit to ultra-violet radiation (Smart 2002).

Landform governs air flow patterns and velocities, which can be important factors in vine performance. A modest flow helps reduce fungal problems but can hinder fruit set. Vortices can help combat ground frosts and hence lengthen the growing season, as, for example, at Niagara, Canada (Haynes 2000). However, excessive wind can not only damage vines (Kliewer and Gates, 1987) but through its cooling effect can reduce photosynthetic activity, though Mayberry (1987) reported that the mistral of the Rhone Valley helped concentrate solids in the grapes of Chateauneuf-du-Pape, France. Wind funneled along valleys eroded in weak rocks can have important local effects. In Franconia, Germany (Wahl 1988), the Main river has eroded weaker layers in a series of sandstones and clayey limestones, and here Freeman and Kliewer (1983) have argued that the channeled wind is more influential in grape ripening than either air temperature or sunshine hours. High wind speeds have been offered as an explanation for the high-acid grapes in parts of the Salinas Valley, California, eroded in a wide zone of complex faulting (Wahl 1988).

Airflow can also affect cloud cover, which influences photosynthesis (Kliewer et al. 1970). Spayd et al. (2002) showed that in the Yakima Valley of Washington, U.S.A. exposure to sunlight has a greater influence on grape flavonoid concentrations than temperature. The Willamette Valley, Oregon, achieves sufficient sunlight and avoids Pacific dampness through being in the rain shadow of the Coast Range to its west (Swinchatt 2006). The orientation of the mountain ranges in the high rainfall area of the Paarl region, South Africa, controls localised rain shadows; the Franschoek Valley benefits from its sheltered location in a zone preferentially eroded along faulted and hence fractured and weakened granite and conglomerates (Bargmann, 2003).

Vineyard soil and bedrock properties

Apart from vineyards sited on alluvial deposits, such as on valley floors or alluvial fans, virtually all vineyard soils are derived from the underlying or immediately upslope bedrock. The nature of this bedrock and its degree of weathering greatly influences the physical properties of the soil, an important influence on vine-root growth (e.g. Morlat and Jacquet 1993). In fact, Smart et al. (2006) have shown the substrate properties to be more influential on root growth than the genotype of the rootstock itself. The vineyard geology can also be important in vineyard management. For example, in sloping sites the mechanical strength of the soil determines its resistance to downslope creep and erosion (Meyer and MartõÂnez-Casasnovas 1999) and hence the need for terracing (e.g. Pla et al. 2006). Soil strength also affects the extent to which machines can work the vineyard soil (Ferrero et al. 2005).

The surface of the topsoil influences its heat transfer and storage properties (e.g. Maschmedt et al. 2002). For example, stony soils reflect heat if they are pale-coloured. The white cobbles or *galets* of Chateauneuf-du-Pape, the pebbly *caillottes* at Sancerre, France, and the *codols* (pebbles) at Monsant, Spain, are often mentioned in this respect, as are the pale *albariza* soils of Jerez, Spain. In contrast, the metamorphic rocks and grey limestones of the Franconia district of Bavaria, Germany, provide dark-coloured soils that warm relatively quickly and store heat, thus promoting ripening in this northerly region (Königer et al. 2001).

The thermal properties of surface stones also involves their ability to absorb impingent heat radiation as opposed to reflecting it, depending on the surface albedo (Evett 2002). For example, smoothly surfaced white stones provide a far greater albedo than rough, dark basalts, which will therefore warm more quickly but re-radiate the heat more quickly at night (Dvoracek and Hannabas 1990). The vineyards of the Ahr Valley in SW Germany, among the most northerly in Europe, are able to ripen red grapes probably because of the wealth of dark-coloured, low albedo, rocks that form the vineyard surfaces and in places comprise the embankments of the steep terraces as well as natural outcrops. The lower, western, part of the steep-sided valley is dominated by dark-grey slates and greywackes and the upper part by very dark basalt. Similarly, low-albedo basalt-derived surfaces in the north Willamette Valley, Oregon, U.S.A. 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, U.S.A. (Meinert and Busacca 2000).

Water availability in the vineyard substrate

The importance of water in vineyards has been much discussed (e.g. van Leeuwen et al. 2004; Van Leeuwen and Seguin 2006; Merouge et al. 1998), following the now classical work of Seguin (1986). Although the vineyard soil is commonly the predominant hydrogeological medium (White 2003), the ability of vines to exploit bedrock for water can be significant (Hancock, in Robinson 2006), especially in arid areas and where the overlying soils are thin. Ashenfelder and Storchman (2001) observed how the depth to the bedrock in the Mosel vineyards, Germany, becomes an important parameter where the overlying soils give poor storage. Hancock and Huggett (2004) argued that vines in the Coonawarra district of Australia excel not because of the much vaunted surficial terra rossa but because of the hydrogeological properties of an unusual breccia in the underlying limestone. In the belief that bedrock-penetrating roots are beneficial, some new vineyards in Bandol, France, have been excavated deeply and substantial quantities of soil removed, in order to prompt the vine roots to grow into bedrock (White 2003).

In addition to the hydrogeological properties of the rock, a relevant parameter is the degree of its resistance to root penetration. Myburgh et al. (1996) correlated diminished grape yields with restricted root development and documented how this depends on the root-resistance of the growing medium. This latter property is a function not only of rock type but whether or not the bedrock contains planes of weakness, together with their spacing and orientation. The Upper

Douro area of Portugal provides an illustration. That the best grapes are produced from areas with schistose bedrock rather than the associated granite is enshrined in the official system of ranking the vineyards of the region. The explanation may lie in the greater degree of root and rain penetration offered by the schist. Soils are exceedingly thin in this arid area and offer little water storage. The granite bedrock is massive (meaning, in geological terminology, that it lacks planar features) and root penetration is therefore low. In contrast, the foliation (schistosity) intrinsic to schists not only provides weak surfaces but generally in the Upper Douro they are steeply dipping or vertical, ideally oriented for roots to exploit.

The presence of clay in soil is well known to provide potentially vital water storage: the clay may have been sedimented in situ, as in the famous “mounds” of Bordeaux soils (Seguin 1986), derived from a clay-rich bedrock, as in the *galestro* soils overlying the argille scagliose of the Chianti region, Italy (Cita et al. 2004), or produced by weathering of a parent rock type that is not obviously clayey. For example, the feldspar minerals that are the dominant constituent of granite weather readily, especially in the presence of water, to the clay mineral kaolinite and thus increase the storage capacity of the weathered material. This applies, for example, to vineyard soils in NE Spain (Ubalde et al. 2005) and in South African vineyards based on granite, such as in the Stellenbosch region (Bargmann 2003).

Assessing the importance of vineyard physical geology

In ways such as those mentioned above, physical factors, underpinned by geology, help explain local variations in vine behaviour. Moreover, a range of microsensor technologies are now available (e.g. Hubbard and Rubin 2004) which are revealing unprecedented fine-scale physical differences between sites. Thus *in principle*, geology is playing a significant role in the vineyard and therefore potentially in helping define wine typicity.

However, there are a number of arguments that tend to lessen this apparent importance in practice (Maltman 2003). First, the connection as outlined above can be seen as rather academic. Most grape-growers are not interested in why their vineyard is sloping, the soil pale-coloured, etc. but how to deal with the result. And, of course, although such principles are enthusiastically dissected and debated in the literature on wine they apply to a greater or lesser extent to all plants and crops. In any case, from a physical viewpoint, it is not the lithology (*type* of rock) itself that matters - and certainly not its geological age and history - but specific physical properties that result. For example, limestone is often mentioned as being an ideal vineyard substrate (presumably because it happens to underlie several classic areas in France). In warmer parts of France, however, limestone soils are less esteemed and may even be of marginal suitability for viticulture (Hancock, in Robinson 2006). The only unusual property that limestone confers is soil alkalinity, and there is no evidence that this is particularly beneficial to vines (Bavaresco and Poni 2003). In fact, high pH reduces the availability of essential cations such as zinc and iron (Hellman 2004) and leaf chlorosis can result (Gruber and Kosegarten 2002). Limestone does, however, commonly provide good drainage (e.g. Huggett 2006) - as do a number of other rock types. In other words, although the ancient geological histories of vineyards are commonly elaborated by wine writers, together with discussions and maps of the actual lithologies, important in practice are the drainage, physiographic, thermal, and other physical parameters that the geology dictates.

A second argument does much to demote the role of geology in practice: most of the physical factors mentioned above are routinely manipulated artificially. Landform is the exception, but even here earth moving, land levelling, and terracing (e.g Pla et al. 2006), together with wind screening/wind machines, etc. (e.g. Fraser et al. 2006), are widely employed, diminishing the importance of the natural geology. Soil colour becomes less relevant as cover-cropping and mulching grow in popularity (e.g. Pinamonti 1998). Even the classic wine districts have a long history of intervention. According to White (2003) the famous chalk slopes of Champagne “have been augmented for centuries with lignite from local clays and silts” while the archives at Chateau Latour record three centuries of soil building and replacement. Of course the all-important factor of water availability is no longer dependent on the natural drainage and water retention properties of the vineyard but is dealt with artificially: the science of vine irrigation has lead to highly sophisticated vineyard technologies. (Even in France, recent legal changes now allow some irrigation.)

Third, the celebrated correspondence between the typicity of some classic wine districts and their geology is based on a fragile logic. A number of French appellation controlée sites were defined partly according to geological boundaries, but this was merely following historical dogma (e.g. Hanson 1982). Thus inferring now an importance for geology because of its correlation with vineyards of high status is based on cyclical reasoning. And because certain wine styles have become so firmly established in particular classic regions, it is unknown to what extent their vineyards could succeed with modern alternatives. As Johnson (1998) remarked, such questions “will never be answered because the pattern is set”.

Examples of the neat coincidence of bedrock strata with vineyard rank are usually presented on geological cross-sections, classically of the Côte-d’Or escarpments (e.g. Vigneaux et Leneuf 1980), but rarely with accompanying maps, where the coincidence starts to fail. Horizontal or very gently dipping strata – as in the Côte-d’Or - in map view must approximately follow topographic contours round a hill, but maps of the district show the vineyard classifications to be related to slope aspect, i.e. exposure to the sun. That is, the neat correspondence between bedrock geology and wine classification apparent in cross-section fails in map view. The official Chablis area was originally defined strictly according to geological boundaries, following historical dogma, but Huggett (2006) discusses how after much controversy this restriction was recently abandoned, tacitly recognizing the greater importance of slope properties and reducing bedrock geology to an indirect role.

Furthermore, in relating vineyard geology to a certain wine type there is a common tendency to overlook the numerous geological complications that arise in nature. Many rock formations are distinctly heterogeneous at a given site, and also can change laterally. For example, the celebrated Kimmeridgian Limestone of Burgundy has very variable amounts of marl and clay intercalated with it and smeared along joint planes (Hancock, in Robinson 2006); the much vaunted Chalk of the Champagne region in fact occupies only about a third of the surface area, with beds of clay and sand becoming more preponderant elsewhere (Jefford 2002). Even where the Chalk is outcropping - and hence depicted on a geological map - the vine roots may be tapping underlying formations of different lithology (e.g. Hancock, in Robinson 2006). Conversely, the outcropping bedrock may be overlain by such a substantial depth of broken and weathered regolith and soil that it is these horizons that are influencing vine growth, despite what is shown on the geological map. For example, the Beaujolais area is normally depicted as being dominated by granite, but in places there are several metres of material so decomposed that the vine roots are largely in a medium effectively behaving as sand (Hancock, in Robinson 2006).

Finally, the foregoing discussion largely concerns the influence of physical geological factors on vine growth and berry ripening: the extent to which this affects the resulting wine and its typicity is another matter. There are some difficulties with this notion. For example, vineyards in different regions but sited on similar bedrock and soils produce widely differing wine styles. Kimmeridgian Limestone is often claimed to account for the character of wines from Chablis and Sancerre but this same formation is widespread across France and well beyond, where it yields undistinguished wines and, in parts of the Champagne district, wines of quite different character. The granite at Dambach in Alsace, France is said to give wines that have “a beautiful elegance and very fine fruitiness” (http://vins-beck-hartweg.chez-alice.fr/granit_angl.htm), yet those produced on granite at Cornas attract words such as “impenetrable”, “meaty”, “powerful” and “brutal” (http://winetasters.ca/SemNotes/cornas.html). Conversely, the Côte Rotie, France, is classified and usually regarded as an entity, producing wines that are consistently different from nearby districts yet the hill has a diverse geology, including alluvial gravels, quartz-mica-schists, gneisses and granites – materials of highly differing physical properties. Examples abound of contrasting wine styles produced from bedrock and soils that are similar, and similar wines from areas with differing geology.

Even so, it is conceivable that physical geological factors do have some role in giving typicity, but in such an indirect and complex way that science is still some way from unraveling it. It is possible that interplay between soil temperature, slope, drainage etc. influences development of the flavour precursors in the ripening grapes that will ultimately have some effect on the taste of the eventual wine (e.g. see Goode (2005). The results of some recent studies are in line with this notion (e.g. Jackson and Lombard 1993; Gómez-Míguez et al. 2006; Andrés de Prado et al. 2007; Bauer, quoted in Werner 2008). Schlosser et al. (2005) detected some correlation between organic aspects of wines, such as ethanol and phenol content and titrateable acidity, and the physical setting of their parent vineyards on the Niagara Peninsula, Canada. Nevertheless, it is clear that the prevalent thinking about the role of vineyard geology in wine flavour is based on a very much simpler and more direct connection, involving inorganic vineyard geochemistry. As the fashionable image has it, a cocktail of nutrient minerals is taken up by the vine roots from the vineyard substrate and is transmitted through to the grape juice. These minerals then persist through vinification and are thus present into the wine-glass, where they can be tasted. To assess this popular picture, vineyard geochemistry has to be considered.

Role of geochemistry

Vine nutrients

Although 88% of the vegetative matter in a vine is derived through photosynthesis from CO_2 in the air (Bourgignon, quoted in Jefford 2002), the vineyard substrate has to provide most of the nineteen or so inorganic nutrients that are essential for normal vine growth. Bedrock commonly has a crucial role in this (e.g. Pool 2000). Although the normal weathering of most rocks will provide adequate nutrition for vines (e.g. Huggett 2006), Wooldridge (1990) has documented differing provisions of potassium from bedrocks such as granite, sandstone and shale, and Kruckeberg (1986) showed how soils derived from serpentinite – a widespread bedrock in Californian vine-growing areas – have serious problems of nutrient balances and deficiencies. Clays are particularly important in helping provide nutrient ions. In fact, Hopkins and Huner (2004) felt that the ability of clays "to retain and exchange cations on colloidal surfaces is the single most important property of soils". Their cation exchange capacity ranges from very high values for montmorillonitic soils, such as develop from impure sandstones or volcanic deposits, to relatively low values for kaolinitic soils, typically formed over granite. The degree of weathering of the parent rock influences the depth and amount of clay material, which has been argued by Bodin and Morlat (2006) and Morlat and Bodin (2006) to influence both vine behaviour and wine character.

However, the relations in chemical composition between the growing vine and its substrate are complex and indirect (e.g. Lanyon et al. 2004), with debatable correlation between soil nutritional analyses and vine performance (e.g. Gladstones 1992; Mackenzie and Christy 2005). Among a number of complicating factors, the different rootstocks onto which a cultivar can be grafted have differing uptake properties (Fisarakis 2004), there is close dependence on water availability (Keller, 2005), transpiration rates (Nikolau et al. 2000) and the pH of the soil (Bates et al. 2002). In fact, Green et al. (2004) showed that the inorganic content of grapes can depend more on irrigation waters than the substrate in which the vine is growing.

The nutrients taken up by the roots are differentially partitioned among the various components of the vine (Schreiner and Baham 2003) such that, for example, the aerial parts of the plant contain differing proportions from the roots (Brun et al. 2001). As a result – importantly – "there is startlingly little correlation between relative concentrations of the elements in the substrate and in the plants" (Epstein and Bloom 2004). And, of course, the levels of available nutrients are changed by applications of agrochemicals and can be affected by pollution. For example, anomalously high levels of copper in soils and vines due to repeated sprayings of fungicides are well known (e.g. Morgan and Taylor 2004, Pietrzak and McPhail 2004); high zinc concentrations in the Maribor region of Slovenia (Weingerl and Kerrin, 2000) were ascribed to the use of zinc-based fungicides. Vineyard posts made of treated timber can also contribute to the copper, chromium and arsenic content of the soil (Robinson et al. 2006).

As vinification proceeds, the inorganic chemical profile of the must becomes increasingly dissimilar from that of the vineyard soils. Only a small proportion of the inorganic nutrients absorbed from the substrate is passed to the growing berries, and some of these are taken up by the yeast during fermentation and eventually dropped out as lees. Filtering and fining of the must reduces further their concentrations, and using bentonite clay as a fining agent introduces yet additional chemical complications (e.g. Castineira Gomez et al. 2004). Additional changes in chemical proportions can arise from contamination in the winery, e.g. from fermentation vessels, spigots and pipes (Almeida and Vasconcelos 2003).

An illustration of the disconnect between the chemical composition of the vineyard and the finished wine is provided by the difficulties encountered in attempting wine "fingerprinting", that is, relating a wine to its place of origin so as to prevent fraud. Attempts have had to resort to using rare earth elements (Jacubowski et al. 1999), trace elements (Taylor et al. 2002), ultra-trace elements (e.g. Perez-Trujillo et al. 2002), Sr^{87}/Sr^{86} isotope ratios (e.g. Almeida and Vasconcelos 2001) and complex statistical manipulations (e.g. Fischer et al. 1999), but all with debatable results. Correlations that have been detected tend to relate to pesticide use and other sources of aerial contamination rather than with the vineyard substrate (Ettler et al. 2005). Analysis of the organic metabolites are showing somewhat more promise (e.g. Cliff et al. 2007) but even this is problematic because the compounds largely originate during vinification. In other words, there is no obvious way in which the inorganic chemical composition of a wine corresponds with where the grapes grew, a formidable difficulty for arguing that vineyard geochemistry directly helps determine wine typicity.

Nutrient concentrations

A further problem arises from the minuscule – and virtually untasteable – amounts of the inorganic nutrients in the finished wine. They make up only around 0.2 % of a wine in total. Individual elements are typically present in amounts ranging from some tens of milligrams/l for potassium, magnesium, calcium, and sodium (e.g. Almeida and Vasconcelos 2003), a few hundreds of micrograms/l for iron, and down to a few tens of micrograms/l and less for metals such as aluminium, copper, lead, zinc and chromium (Cerutti et al. 2005). The vapour pressures of these cations are virtually zero and consequently the concentrations are generally at levels far below human taste thresholds. For example, zinc and copper can only be sensed on the palate in amounts greater than around 3 milligrams/l, according to Zacarias et al. (2001), and, according to the work of Cohen et al. (1960), as much as 16 milligrams/l (and 62 milligrams/l for zinc) *in distilled water*. These thresholds are minimal amounts for detection; the levels at which the taste becomes recognizable is typically much higher. In contrast, some of the organic constituents occur at concentrations measured in grams/l yet, being volatile can be sensed at concentrations as low as parts per trillion. It is now well established that both the mouthfeel (e.g. Pickering and Robert 2006; Gawel et al. 2007) and organoleptic properties of wine are governed by these latter substances - a catalogue of polyphenols, volatile compounds, sugars, higher acids etc. - almost all synthesized during fermentation and maturation (e.g. Lund and Bohlmann 2006) and effectively “swamping” the inorganic nutrients.

A few inorganic cations, such as iron and magnesium, together with chloride and sulphate anions, have higher detection thresholds (Cohen et al. 1960) and can be present in wines at those concentrations and higher. But instead of this providing an instance of natural minerals subtly influencing flavour, such anomalous concentrations are commonly regarded as being problematic and to be avoided by winemakers. Metal ions give rise to bitter, insipid, “off” tastes (Pereira 1988), and their salts impart a range of undesirable sensations (Yang and Lawless 2005). Potassium, magnesium, calcium, and aluminium can all cause turbidity and precipitation problems, and higher than normal levels of copper and iron can induce haziness. Finally, it has to be pointed out that modern treatises on wine flavour (e.g. Waterhouse and Ebeler 1998; Clarke and Bakker 2004) make no mention of geology; most omit discussion of inorganic elements altogether. The conclusion has to be that vineyard geology does not - certainly in any direct and demonstrated way - imbue some unique flavour to its wine.

Nevertheless, in parallel with the speculation at the end of the section on physical factors, it is conceivable that the minute quantities of inorganic nutrients in the vine can somehow influence – wholly indirectly – some of the vast array of complex metabolic reactions involved in vine growth and wine making. In any of the various stages, from influencing mycorrhizal activity around vine roots through metabolism in the vine tissues (e.g. Jackson 2000) and eventually in the fermenting and maturing must, the inorganic elements ultimately derived from the vineyard substrate just might have crucial catalytic or retarding influences, even at minuscule concentrations. Metal ions are certainly known to act as cofactors in some enzyme activity (e.g. Keller 2005). Also, a wine’s organoleptic properties arise from the interplay on the palate of complex aromatic molecules, and it is just possible that tiny amounts of inorganic elements play some indirect but facilitating role in this interaction. There is little supporting data on these suggestions (but see Pereira 1988) but then detecting such effects has been beyond the reach of all but the most recent technology. Perhaps the new micro-analytical methods that are only now becoming available (e.g. Ebeler 2001), coupled with the powerful gene-based approaches now being pursued (e.g. Qiu 2002) may someday reveal that vineyard geochemistry does influence wine typicity and explain the battery of anecdotal evidence. However, at present this remains speculative and undemonstrated.

Geological tastes in wine: *goûts de terroir*

Even if some day a link is detected between geochemistry and wine flavour, this is not the same thing as claiming that the vineyard geology can actually be tasted. This extreme claim of a literal *goût de terroir* – for the vineyard geology to actually be discernible in the wine - pervades populist wine writings and so an examination is given below. However, this does lead to the conclusion is that in addition to all the difficulties discussed in the previous section, such a notion of actually tasting the geology is unsustainable for a number of reasons.

First, the claim is often based on an illusory precept arising from confusing three different meanings of the word “mineral”. The rocks and soils of vineyards are made of minerals in the *geological* sense - inorganic crystalline compounds, most commonly carbonate and silicate compounds. Unfortunately, soluble ions derived from them - the *nutrients* discussed in the previous sections - are also commonly referred to as minerals. In addition, it is fashionable to describe some wines as having a mineral *taste*. These are three different usages. Yet they are often merged and hence meaning is lost, such as in the widespread claim that a mineral taste in a wine is due to the vineyard minerals. All rocks and soils are made of geological minerals, not some more than others. Consequently, there is no basis for popular assertions that mineral tastes are marked in wines from vineyards with conspicuously stony soils, or from vines deeply rooting in bedrock. Similarly, despite claims such as “Alsace has the most complex soils, which means that mineral flavours are apparent in a number of Alsace wines” (Jefford 2000), an intricate geology does not lead to wines that have a more pronounced mineral taste.

Second, apart from sodium chloride and some rare, complex salts (Yang and Lawless 2005), earth materials are themselves literally flavourless. Consequently the mineral taste or “minerality” mentioned above can have no literal meaning (and according to Goode (2005) is almost certainly due to organic secondary metabolites produced during fermentation, possibly involving reduced sulphur compounds). Calcite, the mineral constituent of all limestones - including chalk - and the silicate “rock-forming” minerals have no taste or smell. Thus tasting descriptions such as “minerally, rocky flavours” http://www.thewinedoctor.com/tastingscellar/burgundy.shtml, “the pungency of fossiliferous pebbles makes Chablis stand out from other Chardonnays” (Jefford 2002); and a “mineral, more specifically quartz” taste (http://www.wineglas.com/winereviews_white_french.html) etc., can have no literal meaning. Obviously such phrases are, as with other tasting terms, often being used metaphorically, but if the vineyard comprises those same geological materials the scene is set for a direct causative link readily to be inferred. As an example, the wines of Priorat, Spain, are commonly reported to taste and even smell of graphite, even though this insoluble carbon polymorph has no taste or odour; it cannot be coincidence that most tasters are probably aware that Priorat is founded on unusual schists that are rich in graphite (e.g. Dawes 2003). Especially odd are the references in tasting notes to quartz. Besides being tasteless and odourless (and virtually insoluble at Earth’s surface temperatures), quartz - silicon dioxide -is the same inert compound as the bottles and wineglasses in which the wine is being tasted.

Third, misunderstandings can arise because rocks are classified fundamentally on their geological origin, as deduced from their texture or physical structure, rather than chemically.

One upshot of this is that bedrocks that are quite different in appearance can be remarkably alike chemically, with similar potential availability of nutrients. For example, patches of slaty soil around Andlau, in Alsace, France, are said to produce Riesling wines of different taste to those nearby on shale, schist, hornfels and granite (e.g. Price 2004). The Muscadet region has recently been officially divided into sub-areas claimed to produce differing wines, depending on differing proportions of gneiss, orthogneiss, paragneiss, mica-schist, granite, etc.(Ahmed 2007). These various lithologies may look strikingly different because of their differing geological origins -and they can give rise to soils of differing physical properties - but it is the bedrock chemistry that is usually invoked to explain taste differences and all these rock-types have roughly the same overall chemical composition.

Fourth, wines from areas known to be underlain by volcanic rocks are often ascribed a clear typicity (e.g. Óskarsson and Arnalds 2004), sometimes involving words such as “fiery”, “spicy” and “pungent” in tasting notes (e.g. http://www.hotelonlinehungary.com/hungary/wine_regions.htm). Presumably this is a purely psychological effect but some writers purport to be able to detect a “sense of volcanic ash in the tannin” (http://www.diamondcreekvineyards.com/diamond_creek-news12.htm) and a “a taste of volcanic ash” and “deep, smoky, mineral flavors” in Piedirosso wines from the flanks of Vesuvius, Italy (http://www.thewinenews.com/octnov03/cover.asp). Indeed, Jefford (2007) went so far as to claim that in wines from the volcanic island of Santorini “you can taste the fury of the earth”. Romantic though such notions are, volcanic rocks, being composed of silicates, are just as flavourless as other rocks. However, conspicuous in active volcanic regions is the smell and taste of sulphur and its compounds: perhaps this is what is being sensed in these wines? The difficulty here is that sulphur and sulphur compounds are extremely widely used chemicals in both viticulture and winemaking, as a fungicides, antiseptics, preservatives, etc, and have been for centuries (Johnson 1998). Consequently, the majority of wines, whether from volcanic regions or not, contain sulphites, not uncommonly detectable as sulphur dioxide, and poorly made ones may smell of hydrogen sulphide. Claims that wines from volcanic areas have exceptional typicity therefore seem unfounded.

Fifth, the idea that vineyard geology can be literally tasted in the wineglass is mechanistically impossible. On top of the difficulties regarding vine nutrients – charged ions - discussed in the previous section, this notion requires the uptake and transmission into a wine of solid aggregates of entire crystalline compounds (i.e. rocks). As an illustration of the problem, some of the vineyards in the Moselle, Germany, have strikingly slaty soils and the wines, especially Rieslings, are often said to taste of slate (e.g. http://wirtschaft.fh-trier.de/ri/fell/ortfell/weinort.php?nr=7&unr=2&eTyp=n&lan=en). Geologically, slate is an aggregate of several complex silicate minerals bonded to give a characteristic aptitude for cleaving into thin sheets. It is palpably absurd that somehow in the wine there exists a cleavable, complex solid, but such an implication is apparent in popular descriptions of Moselle wines. Clearly Moselle wines have a distinctive flavour, but unfortunately it is being expressed not by an abstract descriptor but by the name of the rock type in the vineyard, and this leads to the mistaken thought that the geology is directly responsible for this typicity.

Similar confusion follows from other geologically based tasting terms. For example, wines with an “earthy” taste are commonly related back to geology, but in the olfactory sense the term refers not to the flavourless substrate of a vineyard but to odours of organic matter such as humus, decaying compost, mushrooms, etc. “Acidity” is an important word in the wine lexicon, applied liberally to vineyard rocks and soils, and, of course, to wines. In the latter usage it refers to the complex mix of mainly organic acids in wine, normally expressed as pH, titrateable acidity, fixed/volatile acidity, etc. In soils it is usually expressed as pH; in rocks it reflects the silica content of the rock, a quite different matter. Thus acid rocks may or may not give rise to acid wines: there is no direct connection.

Conclusions

Vineyard geology is much mentioned as an important factor in giving a wine a particular character – helping endow a typicity – but critical evaluation of its role shows that there is misunderstanding about the possible connections, resulting in its significance commonly being exaggerated. The physical setting of a vineyard, ultimately due to bedrock geology, certainly affects parameters such as airflow patterns, slope character, thermal properties and water availability, and these demonstrably influence vine growth and berry ripening. However, in practice such factors can be somewhat academic, not least because they are commonly manipulated by artificial wind devices, earth moving, cover crops and, especially, irrigation. Nevertheless, it is conceivable that such physical factors ultimately influence the development of flavour precursors in the ripening berries, and hence in some indirect and as yet unknown way, the character of the eventual wine.

A geological role in wine typicity is most commonly ascribed to vineyard geochemistry affecting wine flavour but here any direct connection is particularly difficult to justify. Notwithstanding the blurring of the term "mineral" mentioned above, the popular model of nutrients being taken up by the vine from the soil and persisting to be tasted in the finished wine is untenable. The proportions that reach the fermenting must bear no apparent relation to the vineyard substrate, and they can then be further complicated by contamination and fining. Furthermore, in the final wine these inorganic nutrient ions normally exist in concentrations far below human recognition thresholds. They are "swamped" by the organic secondary metabolites that do dominate wine flavour. Hence the plethora of anecdotes on vineyard geochemistry giving wine typicity can only arise from some highly complex and indirect mechanisms, as yet undemonstrated scientifically. It is conceivable that the inorganic geochemistry, despite being represented in the finished wine in tiny and untasteable amounts, somehow influences the biochemical pathways followed during vine-gowth and vinification, but this remains speculative and unproven. Thus at our present state of understanding, the influence of vineyard geology in wine typicity is at best highly indirect, with a role much less major than its frequent mentions would suggest.

Finally, the notion of being able to actually taste the vineyard geology in the wine – a *goût de terroir* – arises partly through various misunderstandings of geological terminology and, presumably, through the sheer romance of the idea. Certainly the vision makes good journalistic copy, and is manifestly a powerful marketing tactic, geology being one of the few factors involved in wine production that cannot be translocated or easily replicated elsewhere. However, the proposition is wholly fanciful for a number of reasons and in any literal way is scientifically impossible.

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