

Minerality in wine: a geological perspective

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Tasting ‘minerality’ in wine is suddenly highly fashionable. And unusually for a wine-taste descriptor, the term is very often taken to imply a genesis: the sensation is the taste of minerals in the wine that were transported through the vine from the vineyard rocks and soils. However, there is an array of reasons why this cannot be. The minerals in wine are nutrient *elements* – typically metallic cations – and only distantly related to vineyard geological minerals, which are complex crystalline *compounds*. The mineral nutrients in wine normally have minuscule concentrations and they lack flavour anyway. Although attempts to explain the perception of minerality involve allusions to geological materials, these are irrelevant to its origin. Whatever minerality is, it cannot literally be the taste of minerals in the vineyard rocks and soils.

Keywords: minerality; mineral; vineyard; geology; flavour; taste

Introduction

Minerality is a word currently much used by populist wine writers to describe a perceived taste in wine. The growth in its usage has been phenomenal, from virtual non-existence just a decade or so ago to near ubiquity today. Yet there is much debate about what the term actually means: it lacks any agreed definition. Its scientific basis is at best conjectural; indeed flavour scientists remain sceptical even about its validity. A further remarkable aspect about minerality is that unusually among common tasting words it is often accompanied by at least an implication of its origin. And in one way or another, this is taken to involve the vineyard geology. It is these supposed geological aspects of minerality that are explored in this article.

Growth in usage

A glance at current writings on wine in newspapers, magazines, web blogs, company literature and the like shows frequent reference to things ‘mineral’ in wines. Thus a wine may have a mineral taste, a mineral edge, a mineral streak, and so on, or it possesses something called minerality. Although terms such as ‘lean’, ‘austere’ and ‘steely’ have long been in the wine lexicon, as have ‘flinty’ and ‘chalky’ for certain European white wines, the term minerality is a recent invention. It seems unclear exactly when and by whom. Certainly wine books before the turn of the millennium have no mention of it, including the standard books dealing with wine tasting (e.g. Peynaud, 1987; Vine, 1997; Waterhouse & Ebeler, 1998). Slachter found in 2012 a single

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mention of minerality in a book published in 2000 and only rather desultory remarks in books since then (<http://www.winenous.co.uk/wp/archives/3148>). Minerality is absent from the science-based tasting scheme of Jackson (2009), the aroma wheel of Noble et al. (1987) and the mouth-feel schemes of Gawel, Oberholster, and Leigh Francis (2000) and Pickering and Demiglio (2008). The updated edition (2011) of Jackson and Bakker's treatise on Wine Flavour Chemistry has no mention of minerals or minerality.

In striking contrast, modern popular writings are replete with mentions of minerality and the like. For example, a single article in the issue of *Decanter* magazine current at the time of writing employs the words mineral, minerally, and minerality 116 times in just a few pages (July 2012, pp. 76–83); 80 wines reviewed in the month of August 2012 on the Snooth web-pages mention mineral and minerality (<http://www.snooth.com/tag/mineral/>). Apparently, *Wine Spectator* magazine now uses minerality more frequently than the terms oaky, fruity and floral (<http://www.lavigne-mag.fr/actualites/vin-la-mineralite-un-concept-a-la-mode-52746.html>).

Clearly many wine commentators are finding this newly invented term very helpful. It seems that despite all the uncertainties, the term minerality is fulfilling a useful function. However, there is the conspicuous problem of its supposed geological origin.

Minerality as the flavour of minerals

It seems self-evident that the terms normally used to describe wine-tasting sensations are metaphorical, a way of attempting to put a flavour impression into words. No one thinks that a wine perceived as smelling of, say, tropical fruits or new-mown hay, or tasting of spice or leather has actually involved those materials in its production. But minerality is different. So often, reports of minerality in wine are accompanied by something to the effect that the sensation is the flavour of minerals actually present in the wine. Because people know that wine – like other foodstuffs – contains minerals it does seem a straightforward proposition. And even if it is not put explicitly, descriptions of wines being 'mineral-rich', 'mineral-loaded', 'packed with minerals' and so on, clearly signal that these wines are thought to contain unusually high amounts of tastable minerals (e.g. see Goode, 2012, pp. 64–65).

Moreover, most wine tasters probably know that essential to vine growth are the minerals derived from the rocks and soils of the vineyard. (In fact this dependence is so often emphasised that it almost seems that some still view vines as being largely made from minerals in the ground, a legacy from before the discovery of photosynthesis.) It would seem logical, therefore, to infer that minerality is the taste of the minerals that were originally taken up by the vine roots, transmitted through the vine to the berries and ultimately to the finished wine. Thus, a direct connection between the perceived minerality of the wine and the specific vineyard geology would seem entirely plausible (e.g. see http://www.chablisienne.com/files/pdf/minerality_presse.pdf; <http://quentinsadler.wordpress.com/2011/06/21/minerality-in-wine-flight-of-fantasy-fact-or-terroir/>).

The latest trend is to embellish the term with a reference to some specific mineral (as in a quartz, gypsum, or graphite minerality) or rock (as in a chalky, slaty or granite minerality), as though specific geological materials conferred particular kinds of minerality. (Entering into a computer search–engine the words mineral or minerality along with the name of a well-known mineral or rock returns plentiful examples.) The idea is simple, romantic, and manifestly a powerful marketing device in terms of giving a wine a specific provenance. In fact, this way of linking a wine with the much-revered 'sense of place' may be part of the reason for the explosive growth in the use of minerality.

The purpose of this article is to marshal the arguments why this idea, although attractive in its simplicity, has to be a misconception. Any connection between a sensation of minerality in a wine and vineyard geology cannot be literal and direct, but has to be complex and circuitous.

Confusion between nutrient minerals and geological minerals

Directly relating minerals in wine with those in the vineyard soils implies that they are the same things. However, although ultimately linked, they are not the same. When we talk about minerals in foodstuffs such as wine, we usually mean single elements, chiefly metallic elements such as magnesium, zinc, or iron. They are minerals *in the nutrient sense*. If they are in solution, as in vine sap, grape juice, and wine, these nutrient elements exist in ionic form, as cations, e.g. K^+ , Ca^{++} , and Mg^{++} . But minerals in the vineyard bedrock, stones, and the physical framework of the soils – minerals *in the geological sense* – are almost all compounds, and usually complex and insoluble ones at that. Of course, the nutrient minerals in vines and wine are very largely derived from the geological minerals (unless there is contamination of some kind) but by processes that are complex, protracted and constantly changing, being subject to a host of evolving variables. In other words, there is a major disconnect between the two kinds of minerals, even within the vineyard itself let alone through to the finished wine.

As an example, take the most common geological mineral in the outer part of the Earth, and presumably the most widespread in the world's vineyards: feldspar. This is actually a family of minerals with various permutations of calcium, potassium, sodium, aluminium, silicon and oxygen ionically and covalently bonded into a crystalline lattice that gives a grain of feldspar strength and rigidity. Not only that, but normally the feldspar particle will be bonded together with a host of other mineral grains to give the solid, rigid aggregate we call rock (or, if fragmented, a stone). To be accessible to vine roots, therefore, these elements have to somehow become detached and abstracted from the outer boundaries of this aggregate of crystal lattices. This may utilise mycorrhizae and other microbiota (e.g. Schreiner, 2005) but these function mainly in rich, shallow level soils that are usually not taken to produce wines with minerality. The other chief mechanism involves interchanging cations between either humus, also found mainly at shallow levels in the soil, or the surfaces of certain geological minerals and those in adjacent pore water.

Feldspar, and for that matter the other geological minerals common in vineyards such as calcite and quartz, has virtually no cation exchange capacity (CEC). Some clay minerals, however, with their large surface-volume ratios and electrostatically negative surface charges, are able on their extremities to loosely hold cations that can be interchanged with others in the adjacent pore water (e.g. Meunier, 2010). Weathering of feldspar to clays involves the water-driven rearrangement of the constituent elements into forms such as sericite or kaolinite, depending on circumstances. Both forms also have a relatively low CEC so an improvement in cation availability requires further reactions to produce higher CEC clays, such as illite or montmorillonite. The particular reaction routes taken by the degrading feldspar and the subsequent clays depend on a host of factors such as chemical environment, time, temperature, moisture content and pH. Additionally, the extent to which the CEC is actually utilised depends on the vine metabolism, allowing the expulsion of exchangeable protons and establishing appropriate gradients. Ionic transport from the clay surfaces to the vine roots, involving advection or diffusion through those pore-throats in the soil that are interconnected, also depends on variable chemical and hydrostatic gradients, as does the extent to which the transported ions actually pass into the vine roots.

The above is a terse outline of one example, but it hints at the complexities and the variables that are involved in making a constituent element of a geological mineral available as a nutrient mineral to the vine roots, and hence creating a detachment between the two different kinds of minerals.

Differing proportions of ions in geological minerals and wine

This disassociation in the vineyard between the geological and nutrient minerals increases within the vine (e.g. Keller, 2010). Various transporter proteins, lipid bilayers in membranes, hydrophobic deposits in cell walls, etc., determine how much of the nutrient ions absorbed by the roots are actually loaded into the vine xylem. The vascular system then apportions nutrients differentially around the various components of the vine. Even within the berries themselves, differing ratios of nutrients reach the skins, seeds and juice. Hence in normal circumstances the inorganic chemical profile of the grape juice bears only a distant and indirect relationship with the vineyard geochemistry (e.g. Bramley, Ouzman, & Boss, 2011).

This disconnect grows yet further during vinification. Fermentation removes from the must certain mineral nutrients, such as zinc, copper and barium, while adding others, such as aluminium, calcium and iron (e.g. Castiñera Gómez, Brandt, Jakubowski, & Anderson, 2004). Fining and/or filtering can remove yet more (and where geological materials such as bentonite are used, cations may be leached from them and actually added to the must). For example, Ruzic and Puskas (2001) found that anywhere between 20% and 50% of a wine's copper content was removed by filtration, whereas Tatár, Mihucz, Virág, Rácz, and Záray (2007) found that fining with bentonite could *increase* the rare earth element content by up to 830%. Ageing can increase copper, iron and manganese whereas calcium, aluminium and chromium are removed along with precipitates such as potassium tartrate (e.g. Pohl, 2007).

Consequently, the proportions of mineral nutrients in the finished wine bear only a complex, indirect and distant relationship with the geological minerals in the vineyard. This is why, incidentally, it has proved so difficult to find a reliable chemical way of using the inorganic constituents of a wine to detect adulteration or to fingerprint its provenance (e.g. Smaragdi & Kallithrakas-Kontos, 2006). Attempts have had to resort to trace elements, isotopes, sophisticated statistics and so forth, and although most conclude with some 'potentially promising' correlations, wines subject to counterfeit still rely in practice on diagnostic packaging devices. In summary, the complex relationships summarised above undermine the idea that minerality is simply the taste of vineyard minerals in the wine.

Minuscule concentrations of mineral nutrients in wine

The above discussion concerned the relative *proportions* of the mineral elements; the fact is that their *actual concentrations* in the finished wine are typically minuscule. Potassium, being the primary mineral nutrient of vines, is an exception but even this rarely exceeds around 1000 ppm,¹ i.e. roughly 0.1% of the wine (Jackisch, 1985), and in the wines analysed by Sauvage, Frank, Stearne, and Millikan (2002) it averaged only 577 ppm (0.06%). In fact the *total* inorganic content of wines typically ranges between only 0.15% and 0.4%, according to Coombe and Dry (2004).

The other main mineral nutrients present in wine are calcium and magnesium. Illustrative concentrations for calcium are 30–120 ppm (Sauvage et al., 2002), 50 ppm (Jackisch, 1985) and 10–15 ppm (Lara, Cerutti, Salonia, Olsina, & Martinez, 2005); Castiñera Gómez et al. (2004) reported magnesium concentrations between 60 and 80 ppm.

Eschnauer and Neeb (1988) detected a total of 50 different inorganic components in wine. However, about 25 of these were trace elements with concentrations 1–100 ppb (parts per *billion*) at most, and about 20 were ultra-trace elements at concentrations measured in parts per *trillion*. Such concentrations are so low that they barely exceed detection limits, even with modern analytical techniques. Cobalt, cadmium, nickel and selenium contents, for example, were for Cox, Eitenmiller, and Powers (1977) at the very levels of detectability (0.3, 0.05, 0.3 and 0.02 ppm, respectively).

These tiny concentrations conflict with the popular assertions that various wines are ‘mineral crammed’, ‘mineral laden’, ‘brimming with minerals’ and the like. However, minute though these numbers are, the real point is that these mineral elements practically have no flavour anyway. There is a whole range of organic metabolites in wine that we can sense in such low concentrations, but not so with inorganic cations. Some cations may be detectable on the palate above a certain threshold, but usually giving an unpleasant sensation. In other words, coupling these minuscule concentrations with the fact that almost all minerals are flavourless seems fatal to the idea of minerality in wine being simply the taste of minerals.

Inability to taste minerals

With very few exceptions, minerals – in both geological and nutrient senses – lack flavour. Regarding taste, our mouths’ gustatory organs can only deal with liquids. However, the geological minerals relevant to vineyards are solid and for all practical purposes are insoluble. Of the minerals common in vineyards, only calcite (the constituent of limestone) has a significant solubility but even here it is no more than about 47 ppm maximum in ordinary water; the values for feldspar and quartz are much less and for the clay minerals virtually zero (e.g. Arnórsson & Stefánsson, 1999; Gal, Bollinger, Tolosa, & Gache, 1996; Rimstidt, 1997). In other words, practically all geological minerals are tasteless. The only significant exception is the halide mineral called halite (sodium chloride, salt), which, of course, gives the sensation of saltiness on the tongue. Salinity, however, is to be avoided in vineyard soils, as is saltiness in wines (e.g. Walker et al., 2004). Licking a mineral or rock surface gives a tactile sensation but this is not a taste. Freshly polished surfaces of rocks (say limestone, granite, or slate) or of minerals (say quartz, calcite, or feldspar) cannot be distinguished by the tongue or by smell.

Aroma (= odour or smell, correctly olfaction), with taste the other component of flavour, is perceived in the olfactory bulb of the nose. In order to reach the organoleptic receptors located there, a substance has to volatilise (become vapour). Rocks and minerals cannot do this. The tendency for a substance to volatilise is indicated by its vapour pressure, and this is considerable for many of the metabolites such as esters, ketones, and higher alcohols found in wine (which is why they are collectively called aromatic molecules). Their vapour pressure is measured in tens of *kilopascals* and more (Perry & Green, 1997). In contrast, the vapour pressure of geological minerals and almost all nutrient elements is measured in a few tens of pascals at the most. A few metals show some tendency to sublime (change directly from solid to vapour) but they are so unstable as elements that they barely exist in nature. Moreover, they typically have unpleasant odours. Consequently, apart from the taste of saltiness, flavour is not a property listed in catalogues of metal or mineral properties. (The non-metallic element sulphur sublimates, and its smell is familiar in some vineyards in volcanic areas. However, it is widely used in viticulture and vinification anyway, and (though not as an element) is ubiquitous in wine.)

There have been attempts, mainly in the context of impurities in drinking water, to establish human ‘detection thresholds’ for some inorganic elements. Such values can only be very approximate as there are so many confounding factors, especially the variability between individual tasters and the nature of the accompanying ions and any other substances (e.g. Epke & Lawless, 2007). Even so, the numbers demonstrate several points that are very relevant here. Most importantly, in most cases even the lowest values for the detection thresholds are considerably higher than the concentrations normally found in wine.

For example, Companys, Naval-Sanchez, Marinez-Micaelo, Puy, and Galceran (2008) found zinc contents in red wines from Raimat, Spain, averaged 3 ppb and 4–5 ppb in white wines, yet

the World Health Organisation (2011) puts the taste detection threshold for zinc (in tap water) at 4 ppm, that is, a concentration a thousand times greater than that in the wines. Zacarías et al. (2001) determined a taste detection threshold for copper in water of 2.4–3.8 ppm and Epke and Lawless (2007) an odour threshold (in the presence of certain anions) of between 7.8 and 24.6 ppm; concentrations in Puglian red and white wines ranged only (despite copper applications in the vineyards) from 116 to 462 ppb (Provenzano et al., 2010) and the range of copper contents of some Croatian red wines peaks at 1.1 ppm (Banovic, Kirin, Curko, & Kovacevic Ganic, 2009). Sauvage et al. (2002) found calcium in south Australia wines at concentrations from 30 to 120 ppm; Lockhart, Tucker, and Merritt (1955) reported a taste detection threshold in tap water of 125 ppm.

Note that these values are the *minimum* concentrations for the presence of something to be sensed; moreover they are literally thresholds of detection and not identification (e.g. Lawless & Heymann, 2010, p. 127). That is, the presence of some flavour might be sensed but humans are not capable of recognising the kind of taint it is. In fact at values much greater than threshold levels, for many metals tasters report disagreeable sensations even if they cannot be identified (e.g. Bruce Goldstein, 2010, chapter 15). For instance, copper levels in water above about 4 ppm give a detectable bad taste (Cohen, Kamphake, Harris, & Woodward, 1960) and zinc ‘imparts an undesirable astringent taste to water’ (World Health Organization, 2011). These are hardly desirable attributes for a wine.

Furthermore, these are thresholds for tasting in water. Here, there are few competing flavour compounds (in tap water) and none in de-ionised water. Most bottled waters, incidentally, are drawn from a well or spring having resided in an aquifer for a long period, and hence can have high levels of directly dissolved solutes (Riemann & Birke, 2010). The detection thresholds must be vastly higher in wine, because of the presence of both sensory nonvolatile compounds (Sáenz-Navajos, Fernández-Zurbano, & Ferreira, 2012) and, especially, the hosts of aromatic vinous compounds that give wine its flavour. For example, although Sauvignon Blanc wines are often said to have marked minerality (e.g. see Green, Parr, Breitmeyer, Valentin, & Sherlock, 2011), the compounds particularly responsible for the characteristic flavour of this varietal are now known to be various mercaptans and methoxypyrazines (e.g. Benkwitz et al., 2012). And, in marked contrast with inorganic minerals, humans can detect and recognise these at extremely low concentrations (e.g. Pickering, Kartkik, Inglis, Sears, & Ker, 2007). For example, 2-methoxy-3-isobutyl pyrazine can be sensed ‘even at low parts per trillion levels’ and 4-mercapto-4-methyl-4-pentanone has an odour threshold of a mere 0.0001–0.005 ppb (Burdock, 2009). Moreover, because – unlike inorganic ions – such metabolites can offer both gustatory and olfactory sensations, we may be able to sense their flavours even at the subthreshold values for taste or smell when measured independently (Dalton, Doolittle, Nagata, & Breslin, 2000). Any semblance of flavour that the tiny amounts of inorganic elements might have in this environment will simply be swamped and lost.

There are wines that have anomalously high concentrations of mineral elements, almost always due to some form of contamination such as from agro-chemicals, traffic pollution, and winery plumbing (e.g. Tariba, 2011). These present problems for the winemaker. Not only do they taste disagreeable, some elements (such as copper, iron, and aluminium) present haze and colouration difficulties, and there may be a risk to public health (e.g. Ángeles Pozo-Bayón, Monagas, Bartolomé, & Victoria Moreno-Arribas, 2012; Tariba, 2011). In fact it is telling to point out that the obvious question regarding the detection thresholds of inorganic elements actually *in wine* seems unresearched. The reason may be the potential health issue: the concentrations needed to be added in order to bring the minerals up to detectable levels would almost certainly make the wine toxic (e.g. see Health Canada, 2011).

Minerality as a geological metaphor

Many wine commentators have attempted to explain what they think the word minerality is conveying. Not surprisingly – given the nature of the word – most efforts involve comparisons with geological materials, which might in itself be subliminally reinforcing the idea of a direct inter-relationship between vineyard geology and minerality. However, while these analogies might provide useful tasting cues or metaphors, they have no literal, direct bearing on the genesis of minerality in a wine.

Flinty taste/smell, or flintiness

Minerality is often related to a perceived flinty taste in a wine. Geologically, flint is rather loosely defined and sometimes used interchangeably with terms such as silica, quartz, and chert. However, all these are forms of silicon dioxide – silica. The silicon and oxygen atoms are locked in an efficient three-dimensional crystalline framework that makes all these materials unusually stable (non-vapourising), tough, insoluble and virtually inert. Consequently, they lack any taste or odour. Indeed, it is because of these properties that silica is used for glass, and hence the very bottles and glasses that contain wine. Consequently, the notion of a wine that was stored in a glass bottle (silica) and tasted in a drinking glass (silica) having the flavour or smell of flint (silica) somehow derived from the vineyard is something of an oxymoron.

However, another repercussion of the efficient crystalline framework of silica is its lack of cleavage planes, instead inducing conchoidal fracture, a tendency for the material to break with irregular, concave surfaces. Intersections of these fractures give sharp edges and points, leading to the well-known archaeological applications of flint and the like as cutting tools. Thus flint is also mentally associated with edges and sharpness, and hence, evidently, metaphorically with very dry, acid wines. It seems that instead of reporting a sharpness or tartness in wine, some writers like to refer instead to a flintiness. And for some, it is even more preferable to use instead the French equivalent of flint: *silix*. Curiously, although most geological and wine-tasting terms have their equivalents in the other European languages, of these the French word for flint virtually alone finds its way into tasting notes.

Vine roots cannot take up the inert, insoluble compound silica. So if sharpness or metaphorical flintiness is seen as at least some component of minerality, it cannot be derived from flint or related materials in the vineyard. This is illustrated, for example, by Chablis wines – to many the epitome of flintiness – coming from vineyards that are calcareous in composition and lacking flint or similar siliceous material.

Gun-flint aroma/struck flint and matches

Also frequently mentioned in attempts to elucidate what minerality means is an allusion to the aroma of gun-flint, or the smell of a struck flint or match. These odours arise from the property of pyrophoricity. Many solids might, if struck forcibly enough, expel some of the percussive energy as a spark and this may have some burning smell. However, certain substances in the presence of oxygen are capable of spontaneously bursting into flames – auto-igniting. That is, they are pyrophoric. Sodium, potassium and calcium, for example, are extremely pyrophoric and hence not found as uncombined elements in nature. The phosphorus used in match heads needs the addition of a little heat, such as from the friction of striking a match. A few metals, such as iron, aluminium and magnesium, can be pulverised such that the surface area of each tiny particle becomes exposed to sufficient oxygen for it to auto-ignite, making a spark (e.g. Angelo & Subramanian, 2008). A spark is a speck of burning material, usually producing an

associated smell as it vaporises. Tiny fragments of the geological mineral pyrite – iron sulphide – can be pyrophoric, giving a distinct sulphur-tinged smell.

People long ago discovered that fragments of iron could be induced to spark, especially by striking the metal sharply against a fine-grained, tough material such as flint. This later became the basis of the flintlock mechanism in early firearms – and the smell of gun-flint. The aroma comes not from the flint, which is acting purely as an anvil, but from the burning particles of pyrophoric iron. (Modern firearms and lighters, incidentally, employ ‘flints’ made of a synthetic alloy of cerium and iron.) These well-known smells associated with sparking and striking matches may be useful comparators for minerality but clearly their pyrophoric genesis has no connection with processes in vineyards or vines.

Earthy smell

An earthy smell, with which minerality is frequently compared, cannot be due to the inorganic components of rocks and soils, because they themselves are flavourless, as explained above. Rather, it appears to arise from organic compounds common on vines and in wineries, such as 2-methylisoborneol derived from algae, and a terpene known as geosmin (*trans*-1,10-dimethyl-*trans*-9-decalol) due to bacteria and moulds (e.g. Fugelsang & Edwards, 2007). Both these compounds have aromas that arise when the earth is being tilled. Moreover they have astonishingly low sensory thresholds, down to a few parts per trillion (Darriet, Pons, Lamy, & Dubourdiou, 2000). In fact levels higher than this in wine can lead to it being regarded as tainted (e.g. Canara et al., 2011).

Smell of warm/wet stones

Similarly, the well-known aroma of stone on a hot summer day or after a shower of rain is not due to the geological material itself but the release of the organic oils mentioned in the previous section together with what Bear and Thomas (1966) called petrichor. As mentioned earlier, a freshly fractured geological surface has no flavour but on natural exposure to air it rapidly becomes filmed with volatile compounds present in the atmosphere from the decomposition of animal and vegetable matter (Bear & Thomas, 1964). On warming, wetting, or when the relative humidity of the atmosphere approaches saturation, these volatile compounds are released to give the familiar petrichor smell. The substances include lipids, terpenes, carotenoids and, according to Bear and Kranz (1965), various fatty acids.

Seashells and fossilised shells

Some writers relate their perception of minerality to seashells. The link must really be with associated marine things because the shells themselves, being composed very largely of the (geological) minerals calcite and aragonite, have no taste or smell. More often though, the connection is made not with modern seashells but with their fossilised ancestors, which happen to be conspicuous in the bedrock of a number of the world’s vineyard regions (e.g. see Nesto, 2006). But equally, such fossilised shells have no flavour.

On dying, organisms in nature soon disappear, through scavenging and decay. Any hard parts, such as teeth, bones and shells, will survive longer and, if circumstances are right may become fossilised (irrespective of whether they are still intact or broken up). Normally this comes about either by internal rearrangements and replacements to give a durable crystalline structure, or by dissolution leaving an imprint in the host sediment, which eventually becomes rock. Either way, the fossil is a replica, normally with none of the original organism remaining, composed of

exactly the same geological minerals that make rocks and stones (most commonly calcite and quartz). Hence the materials are flavourless, for the reasons discussed earlier. Seeing fossil sea-shells in vineyard soils may prompt us to think of seafood and things maritime, but for the vines fossils are indistinguishable from any other piece of stone. Fossils in a vineyard bring nothing different to the nutrition of the vines or the composition of the resulting wine.

Metallic smell

Some people may recognise a ‘metallic’ smell, for example, the aroma we associate with handling coins and metal implements. However, as discussed above, metallic minerals lack flavour. The odour arises not from the metals themselves but through our having touched them, and the rapid reaction between the metal and skin chemicals to give highly volatile compounds. For example, Glindemann, Dietrich, Staerk, and Kuschik (2006) found that an odour described as metallic and mushroom-like in vapours next to skin touching iron was due to the ketone 1-octen-3-one, detectable by humans at very low concentrations.

In ways such as these, odours involving geological materials can be created and may make helpful comparators for explaining the sensation of minerality, but the processes are not relevant to the growth of vines. The rocks and minerals themselves remain flavourless.

Two instructive parallels: Priorat and Chablis

It is well documented that all but the most experienced tasters are vulnerable to external influences (e.g. Siegrist & Cousin, 2009), such as seeking and hence apparently detecting some sensation they think ought to be in the wine (e.g. Parr, White, & Heatherbell, 2003). Possibly this effect has made some contribution to the explosive use of minerality as a wine descriptor. The idea can be illustrated by two particular taste perceptions reported in wines from two different areas.

Priorat is a small region in NE Spain that has recently blossomed in popularity. At the same time, tasting notes on both red and white wines from Priorat have increasingly referred to a flavour of liquorice in the wine. Making a parallel with minerality is the very frequent assertion that this liquorice sensation comes directly from the vineyard rocks and soils.

The geology of Priorat is certainly striking, with a spectacularly rugged topography and exceptionally stony soils. The stones are fragments of the underlying bedrock, a dark grey Carboniferous slate, termed on the official geological map *Pizarras negras* (Instituto Geológico y Minero de España, 1972). This in itself does not explain the liquorice effect, which has not been noted in vineyard areas elsewhere in the world that are underlain by dark-coloured slates (e.g. Moselle, Germany and Cederberg, South Africa). Using a computer search-engine for, say, Priorat and liquorice will yield numerous statements giving the putative explanation: the soils at Priorat are special – they are *llicorella* soils. However it is put – either the liquorice flavour of the wine comes about because of these *llicorella* slaty soils, or it is the *llicorella* soils that are imbuing the wine with liquorice – it makes an attractive picture. But, rather like minerality, this superficially attractive idea fails to explain how the connection might work. Liquorice is an aromatic phenylpropene called anethole, of biological origin. It is not at all clear how any geology might generate this substance in wine.

It seems in the Priorat case that the whole connection might be based on a misunderstanding. *Llicorella* (sometimes *llecorella*) is an ancient, very localised, name in the local dialect of the Catalan language for these stony soils. It has no connection with what in English is called liquorice. The Catalan for liquorice is *regalèsia*; the Spanish *regaliza*, *orozuz*, or *alcazuz*. The pronunciation (l̪ak̪oɾe̞le̞) is also quite unlike liquorice. Perhaps some English-speaking wine commentator saw the word written down, made a connection with the English word liquorice

and, subconsciously or otherwise, made the extension to a flavour in the wine. Then having reported it, others followed the connection such that now wine drinkers may well be predisposed to sensing liquorice in Priorat wines. However, even if the sensation seems real, there appears to be no basis of an actual connection with the vineyard geology.

Wines from the Chablis area of northern France are often said to taste of things to do with the sea. (It is perhaps no coincidence that many wine enthusiasts are well aware that the Chablis region has a marine sedimentary bedrock with conspicuous fossils, the famous limestones and marls deposited on the seafloor during the Kimmeridgian and Portlandian (more properly Tithonian) ages of the Upper Jurassic epoch, roughly 150 million years ago.) In particular, Chablis wine is often said to be characterised by the iodine smell of the ocean, the iodine arising from the vineyard geology. Many of the references to iodine are allusional (though few people can be familiar with the smell of iodine, which textbooks list as pungent and irritating. Domestic medicinal iodine – ‘tincture of iodine’ – is dissolved in an organic solvent such as ethyl alcohol and so the aroma is quite different) though some are more explicit about elemental iodine and its source in the vineyard rocks and soils (e.g. http://www.billaud-simon.com/Billaud-Simon%20Text_Chablis_Vineyard.htm).

Thus, here again there are parallels with minerality but in this case with something tangible that can be quantified – the actual iodine content can be measured. Theoretical considerations suggest that the iodine contents should be very small (Fuge & Johnson, 1986). Geological minerals are generally unable to incorporate the large, monovalent iodine ion and it is the same with vegetation (unless it is a specially adapted form like seaweed). New analyses have shown that in practice this is the case at Chablis. The iodine content of vineyard soils at Chablis is not only minuscule, around 4 ppb, but is actually less than in nearby non-Chablis vineyards such as Corton (Tan, 2013). Similarly, low concentrations (around 5 ppb) are found in the leaf tissues. Most tellingly, the iodine content of Chablis wines also averages around only 4 ppb, less than Corton wines and less than half that of some New World Chardonnay wines (Tan, 2013) that attract no mention of iodine. In other words, as appears to be the case at Priorat, an edifice of anecdote has arisen which has no literal basis. The flavour perceptions are generated mentally.

Discussion and conclusion

The notion that minerality in wine is the taste of vineyard minerals leads to a contradiction about what kind of vineyard situation promotes it. Logically, those soils that are able to yield most nutrients to the vine would seem the most likely to imbue the wine with a high (nutrient) mineral content. That is, greater minerality would arise from the most fertile soils – the opposite of what is commonly believed. Most vine nutrition takes place just below the surface, where some combination of high CEC clays, humus, and mycorrhizae will be relatively plentiful. However, wine minerality is most frequently associated with infertile soils: those that are particularly stony, or where vine roots have to probe deeply into bedrock (e.g. Verheyden, Echensperger, & Morrison, 2011, p. 66). Here it is water that the roots are seeking, and at those depths (as well as with stony soils), organic material will be sparse and the transformations needed to convert rock into minerals with high CEC will have progressed little. The rock will have undergone only minor weathering: the water will have little solute.

This is not to say, however, that the anecdotal belief of minerality arising from unproductive soils is unfounded, but rather that any connection must be indirect. For example, it may be that the low nitrogen content of infertile soils leads to grape musts in which the yeast has to metabolise sulphur instead of nitrogen (Verheyden et al., 2011): there has been much speculation that minerality may involve sulphur-bearing compounds (Goode & Harrop, 2011). Furthermore, it is well established that very small amounts of metallic elements can influence the course and progress

of a host of metabolic reactions in the vine and in wine (e.g. Aceto, 2003; Pereira, 1988). These include acid buffering (Mackenzie & Christy, 2005), yeast activation (Birch, Ciani, & Walker, 2003), polyphenol oxidation (Danilewicz, 2012), co-factors in enzyme metabolism (Hänsch & Mendel, 2009) and wine stabilisation (Ribéreau-Gayon, Glories, Maujean, & Dubourdieu, 2006).

In fact, it may turn out with further research that the nutrient minerals of geological origin in vines and wines – minuscule in concentration and virtually flavourless though they may be themselves – are pivotal in determining wine character and flavour. However, this would have to take place in complex and circuitous ways. Thus perceiving minerality in wine would not involve tasting minerals but permutations of complex organic compounds whose production has been influenced by inorganic cations. Future research will no doubt evaluate this speculation. In any event, for all the reasons explained here, minerality in wine – whatever that perception is – cannot be in any literal, direct way, the flavour of minerals derived from vineyard rocks and soils.

Note

1. For ease of comparison, all concentrations are presented here in ppm (parts per million), ppb (billion) and ppt (trillion). Some of the cited references give values in units such as mg/l and millimoles and have been converted.

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