Geology and wine: a review

Jennifer M. Huggett

HUGGETT, J.M. 2005. *Proceedings of the Geologists' Association*, **117**, 239–247. The geology of wine is important to the wine-maker, but of very little importance to the drinker. However, a geologist with an interest in wine is almost inevitably going to take more than a passing interest in what lies beneath vineyards. This may have resulted in the importance of the geology being over-rated. Many wine writers who are not geologists have dutifully described the geology associated with particular wine regions without actually stating *how* the geology is important. Jake Hancock was quick to realize that a lot of what is written about geology in wine books is at best misguided and at worst utterly wrong, and set about putting this to rights at every opportunity. Vines derive most of their nourishment from a depth extending down to 0.6 m, but will, most of the time, rely on water from down as far as 2 m for transpiration. Only during periods of drought will they draw significant water from >2 m. Clearly then, in areas where there is a deep cover of drift or a deep soil horizon, geological influence on vines will be minimal. Even where the soil is thin, geology will, in many areas where vines are grown, only control the quality of the grapes indirectly through influence on soil composition, geomorphology and water retention. These factors will be examined, together with examples of instances where geology does have a direct influence on wine quality.

Key words: viticulture, terroir, soil, slope

Department of Mineralogy, the Natural History Museum, Cromwell Road, London SW7 5BD, UK and Petroclays, 15 Gladstone Road, Ashtead, Surrey KT21 2NS, UK

1. INTRODUCTION

The role of the underlying rock in viticulture is at least four-fold. It influences the soil type (except where the soil is alluvial), it permits penetration of vine roots to varying degrees depending upon the nature of the rock, it controls geomorphology (slope) and it assists or hinders drainage of rainwater. This review will consider the importance of each of these to viticulture, but as they are all tied up in the French concept of terroir this will be examined first.

2. THE CONCEPT OF TERROIR

Terroir is a concept that originated in France. When lecturing on wine, Jake Hancock defined terroir as 'A delimited area with its own characteristic geology, climate and methods of viticulture'. However, Jake Hancock (1999) stated:

> It is difficult to think of another country where it could have started, since it has features so characteristic of second-class French thinkers, a combination of the obvious (e.g. the quality of a plant depends where you grow it) and the mystical.

Hancock has not been the only person to criticize terroir. The Australian wine expert Busby stated: 'Where there is a perceived marketing advantage in associating a wine with soil in a specific region the terroir concept is being exploited' (Busby, 1825). It was Jake's view (Hancock, 1999) that when Henri Coquand published a correlation of cognac quality with the chalkiness of the ground in which it is grown (Coquand, 1857) it was a deliberate hoax rather than poor science: the quality zonation is circular, the geology approximately linear (see also Selley, 2004, 2005). At the time it is probable that it was generally known to be a hoax, but subsequently became accepted as a serious explanation of cognac quality which no one bothered to check. Consequently, the hoax persisted for a remarkably long time, even being quoted and 'explained' in Wilson (1998). More recently, Australian soil scientist White wrote 'Most scientists admit they cannot express quantitatively the relationship between terroir and the characteristics of wine produced from that terroir' (White, 2003). It might also be said that the concept of terroir is essential to the *Appellation d'Origine Contrôlée* system

A version of this paper was presented orally at a joint meeting of the Geological Society of London, the Geologists' Association and the Palaeontological Association: *The life and work of Jake Hancock (1928–2004)* held at the Geological Society, Burlington House, London, 14 October 2004. The meeting was convened by Professor John C.W. Cope, who has also been Guest Editor for the manuscripts arising from the meeting, now published in the *Proceedings*.

0016-7878/06 $15.00

that effectively acts (often quite rightly) as agricultural protectionism in France.

The concept of terroir is also implicit in the tendency to associate wine flavours with aspects of the soil or bedrock. There are some instances where this may, indeed, be the case, as with the perceived slight saltiness of wines produced where there is a high salt content in the soil. The Manzanilla of southern Spain is often described as having a saltiness derived from its proximity to the sea (though I have not been able to locate any chemical analyses that might confirm this). While Peynaud (1996) described Cabernet Sauvignon grown in the Golf du Lyon sand flats as having seaweed flavours, that may in fact be due to the high concentration of sodium chloride found in the sand flats compared with that found further inland. This is conceivable because salt is highly soluble in water. Perhaps the most widely stated association of wine flavour with a mineral is the supposed 'flinty' character of Chablis wine. To a geologist it is difficult to imagine how a material as insoluble in normal groundwater as flint could contribute to the flavour of any wine, let alone what the flavour of anything so hard and insoluble could be. Equally fanciful is the suggestion that flint, shale and slate-bearing soils impart a 'gunflint' character to Riesling (Berry, 1989).

3. SOIL AND WINE QUALITY

Soil chemistry is influenced strongly by the underlying rock, except in alluvial soils. Vines require all the usual plant nutrients (mainly N, P, K, Mg, Fe) that are present in well-maintained soil on any rock, hence the parent rock type has little direct influence on wine quality. Of these components, N, Mg and Fe are principally required for leaf growth, while K and P are essential for flower and fruit production. Nitrogen deficiency is the most widespread problem in vineyards; however, this is a factor controlled almost entirely by artificial addition of nitrogen in the form of manure and artificial fertilizers, and by the actions of soil bacteria. Phosphorus is obtained as phosphate from fluorapatite, apatite and francolite, which may be in the soil or the underlying rock. A deficiency of apatite is rare in vines, despite its low solubility. This is because vines belong to the group of plants that have a symbiotic association with mycorrhizal fungi, which enables them to absorb sufficient phosphate. Geology is a major factor in the abundance of K^+ in soils – it is present chiefly in potassium feldspar, mica and illite, though the exchangeable K^+ found in smectite and vermiculite is the most accessible to plants. Smectite and vermiculite are found mostly in soils and in Mesozoic and Tertiary sediments, while mica and K-feldspar are present in a wide range of igneous, metamorphic and sedimentary rock-types. K^+ and PO_4^{3+} tend to be concentrated near the surface, especially in clay-rich soils, while Ca^{2+} and Mg^{2+} tend to be concentrated lower in the soil profile (Jackson, 1995). Potassium (essential for fruit development in all flowering plants) is most abundant in soils formed on volcanic rocks (e.g. Madeira, and the Kaiserstuhl in southern Germany), slate (e.g. Mosel and Porto) and shale (e.g. Porto). However, too much of the essential nutrients can also be bad for vines. In Burgundy in the 1950s over-zealous use of chemical fertilizers was responsible for loss of wine quality that was corrected only slowly by a return to more traditional methods of soil maintenance (Hanson, 1995). Exceptionally, particular soils may be depleted in essential elements due to a natural deficiency of them in the underlying rock. Soils formed on limestone generally contain less iron than soils on other rock types, hence they are more likely to be used for growing white grapes, which require less iron than do red grapes. In Bourgueil, in the central Loire region of France, most of the Cabernet Franc is grown on alluvial sands and conglomerates with a low iron content that can lead to chlorosis of the leaves. The better Bourgueil vineyards are on middle Turonian Tuffeau Blanc (a fine-grained limestone) which contains a small amount of glauconite (Voss, 1995). The vines may obtain the iron directly from the glauconite, though it is more probably that this mineral weathers in the soil profile to form kaolinite and iron oxyhydroxides, before it becomes available to the vines.

Vines derive most of their nourishment from a depth extending down to 0.6 m, but will, most of the time, rely on water from as far down as 2 m for transpiration. Only during periods of drought will they draw significant water from >2 m. At these times high porosity and low permeability (in both the soil and the underlying rock) will be an advantage. Soil thickness is an important factor in wine quality; in general, leaner wines are produced on thin soils and, on deep alluvial soils, wines can be 'flabby' if yields are not rigorously controlled. In Australia, because of the prevalence of summer drought in many wine-making regions, vineyards have been planted on thick alluvial soils with greater water retention than on many *in situ* soils. Soil texture varies with the proportions of clay, silt, sand and pebbles. The more sand and pebbles the more free-draining, the more clay the greater the water retention. Swelling clays (smectite and vermiculite) are able to expand and hold weakly bonded water layers in the interlayer sites. On a macroscopic scale, this means that pores can become blocked and the flow of water restricted, leading to water logging. In most vine cultivars this can lead to root damage; some cultivars are able to withstand some water logging, but high soil moisture invariably accentuates berry cracking and subsequent rotting (Jackson, 1995). Another property of clay-rich soils is that they lose heat faster than stony soils. Much of the heat (solar radiation) absorbed is transferred to water as it evaporates, thus cooling the soil.

In Bordeaux, ranking of *cru classé* estates has been correlated with the presence of deep, gravel- and sand-rich soils located on small rises close to rivulets or

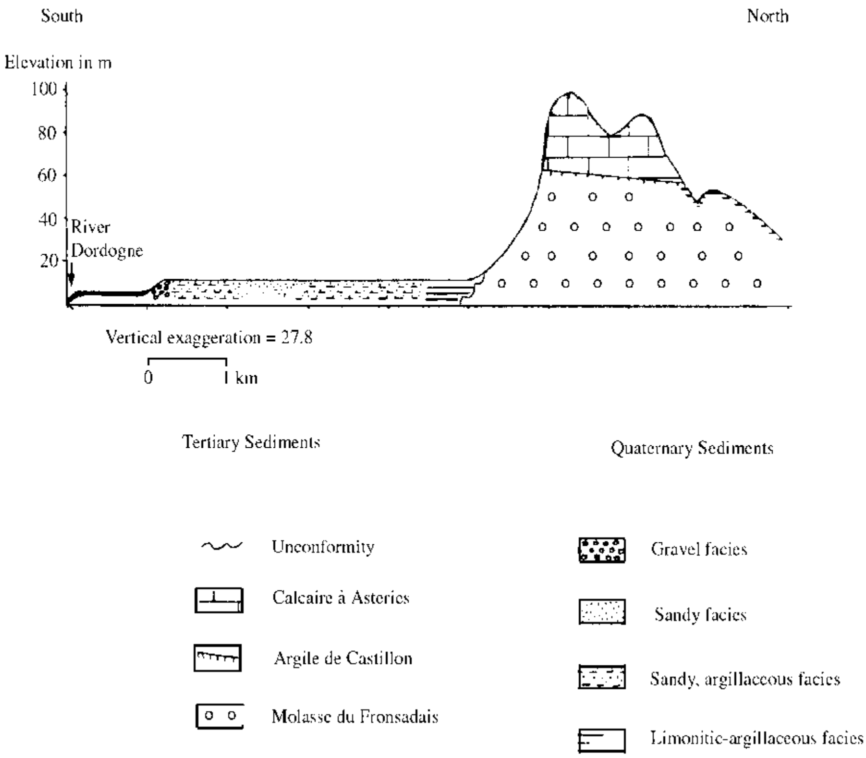

Fig. 1. Cross-section through Saint Emilion. Eight out of thirteen of the first growths are grown on the slope formed by the Molasse du Fronsadais (adapted from Van Leeuwen, 1989).

drainage channels (Seguin, 1986). These features promote rapid drainage and are thought to encourage deep root penetration. In these coarse-textured soils, water occasionally can percolate through soil to a depth of 20 m within 24 hours. Deep-rooted vines are, therefore, better able to survive damage from heavy rain or drought than are shallow-rooted vines. In Saint Emilion eight out of thirteen of the first growths are grown on the slope formed by the Molasse du Fronsadais, between the plateau alluvium and the limestone known as the Calcaire à Astéries (Fig. 1). These soils, which are thicker than those on the Calcaire à Astéries and thinner than the plateau alluvium, have been enriched with calcium-rich loess silt derived from Jurassic and Cretaceous limestones, and blown there during the late Pleistocene (Van Leeuwen, 1989; White, 2003). On the Calcaire à Astéries the soils are very thin and the water table very deep; to compensate, the vines have developed very deep roots, but are still prone to water shortage during periods of drought. Generally speaking though, the underlying geology of Tertiary marls and sandstones is of less significance to wine quality throughout Bordeaux than are soil depth, drainage and microclimate.

It has been concluded from a major study of the soils of Burgundy that vines produce the best wine where the soil contains both 'clay' (which in this context probably includes silt and some sand, as Gadille (1967) does not mention either size fraction) and pebbles. The explanation given for this is that pebbles improve drainage while clays do the reverse (or, more optimistically, clay improves water retention) and also add fertility in the form of exchangeable cations. Clearly, the presence of sand will also improve drainage, so that soils formed by weathering of clay-bearing sandstone would also provide a favourable physical environment for viticulture. An example of this is the three Montrachet vineyards in Burgundy. At Chevalier Montrachet (Fig. 2), at the top of the slope, the soil is 20% clay and 80% pebbles, of the three vineyards this is considered to make the most elegant wines. Batard Montrachet, at the base of the slope is described as rich and fat and has a soil with 50% clay and 50% pebbles. Le Montrachet, between the other two vineyards is considered to produce the finest wines, has a soil with 32–36% clay and 64–68% pebbles. While this might be inferred to indicate the ideal pebble and clay proportions for making fine wine, the position of the vineyards on the slope and soil thickness may also be important. The importance of slope is discussed below.

Re-radiation of heat from the ground can be an effective mechanism for minimizing the overnight drop in air temperature around vines. The diffuse

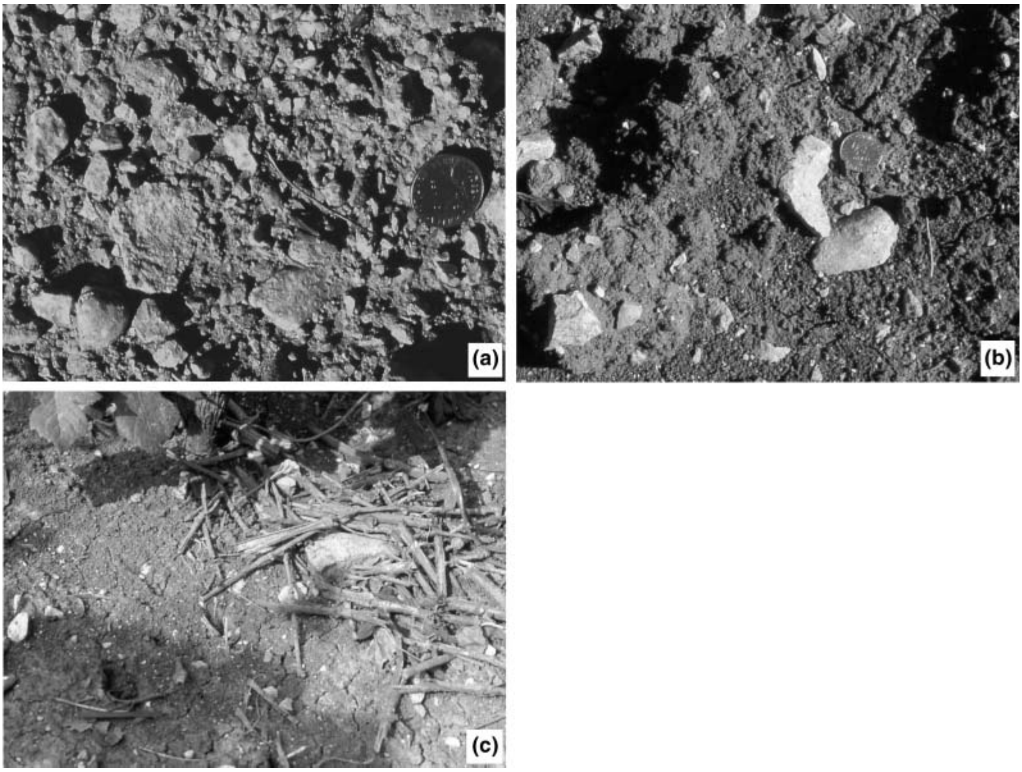

Fig. 2. The soils of the three Montrachet Crus: (**a**) Chevalier Montrachet, the top of the slope, with 20% clay and 80% pebbles; (**b**) Le Montrachet, the mid-slope, with 32–36% clay and 64–68% pebbles; (**c**) Batard Montrachet, with 50% clay and 50% pebbles.

reflectance, known as the albedos, of most rocks is in the range 0.1–0.3, i.e. 10–30% of radiation from the Sun is reflected (Hancock, 2005). Stony soils, and dark ones in particular, retain most of the heat absorbed by day and are able to radiate it back to the air around the vines by night. In climates marginal for viticulture, the presence of dark pebbles (such as the slate of the Mosel) is a highly advantageous soil property. In Australia it has been found that grapes ripen earlier on Red Brown Earths than on the paler Solonised Solonetz soils (Rankine *et al.*, 1971). However, it should be noted that the strength of re-radiation is inversely proportional to the square of height above ground – doubling the height of the grapes above the ground results in a four-fold reduction in energy reaching them (Jackson, 1995).

In Châteauneuf-du-Pape stream-rolled cobbles, derived from Alpine Molasse and known locally as *galets* are viewed as a sign of quality (Fig. 3). No explanation of how the cobbles affect quality has been found and there is no correlation between the presence of these stones and wine quality. Wilson (1998) suggested that it is, in fact, the red clay soil and ferruginous sands of the better vineyards that are important to wine quality.

4. SLOPE AND WINE QUALITY

Hanson (1995) quoted R. Gadille as saying that slope has a greater influence on the quality of wine than does bedrock. In the higher latitude wine regions of the world, this is probably true, as the amount of sunshine

Fig. 3. The soil of Châteauneuf-du-Pape, with Alpine molasse-derived cobbles known as *galets*.

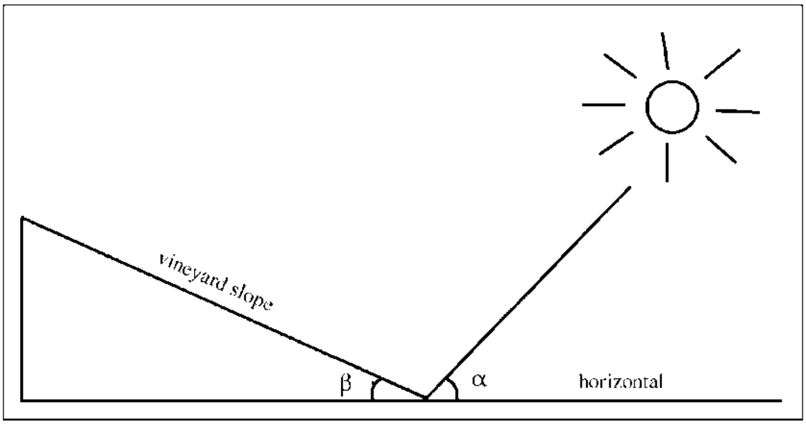

Fig. 4. Illustration of the relationship between slope and solar radiation (after Hancock, 1999).

reaching the vines and the drainage will be controlled largely by slope. Hancock (2005) expressed this mathematically as $I=K\sin(a+\beta)$, where I is the intensity of radiation received on the slope, K is a constant, a is the angular elevation of the Sun and β is the angle of inclination of the slope to the horizontal along a meridian (to the south in the Northern Hemisphere, to the north in the Southern Hemisphere). This is illustrated in Figure 4.

It follows from this relationship that slope will be of greatest importance early and late in the growing season when the Sun is lower in the sky than it is in summer. Hence, slope is particularly important for avoiding frost in spring and assisting with ripening in autumn. Thermal belts on slopes comprise a layer of cold air at the bottom of a valley and another near the ground over the plateau above the slope (Hancock, 2005). As a result of this, the temperature difference between sites no more than 3 km apart horizontally, may be as much as 8° C over height differences of <100 m (Hancock, 2005). Germany, the most northerly wine growing region in mainland Europe, is renowned for its steeply sloped, south-facing vineyards in the fault-controlled valleys of the Mosel and the Rhine. However, in wine regions with regular summer drought the enhanced amount of sunshine reaching slopes facing the Sun (south-facing in the Northern Hemisphere, north-facing in the Southern Hemisphere) and the enhanced drainage on slopes will be a disadvantage rather than an advantage.

The importance of geology has been argued most vociferously in Chablis (northern Burgundy, France), but has now been officially abandoned. It is generally acknowledged that chardonnay, the grape of Chablis, produces the finest wines on alkaline soils formed on limestone and carbonate-rich mudrocks (marls). Chablis, as a defined region, was recognized by the wine tribunals in 1923 as being grown on a sub-soil of Kimmeridgian limestone (actually a carbonate-rich mudrock in this region), while Petit Chablis could be grown anywhere else within the 20 communes of Chablis. This was opposed strongly by some growers who argued, probably correctly, that orientation, slope and altitude are as important as sub-soil and, moreover, some quality Chablis had always been grown on Portlandian limestone. Figure 5 shows that, in Chablis, the mid-slope favoured for quality vineyards throughout Europe, coincides with the Kimmeridgian outcrop. The relatively soft Kimmeridgian carbonate-rich mudrock is capped by Portlandian Barrois limestone and underlain by the Calcaires à Astartes (both true limestone). The Serrein River has cut down through the Barrois, which forms the caps of hills, and the softer Kimmeridgian carbonate-rich mudrock, which now forms the slopes. The south-facing slopes naturally receive the most Sun, which in such a northerly wine region as Chablis is important. It is on these slopes that the Grand Cru Chablis is grown. In 1976 the reference to Kimmeridgian limestone was dropped from the definition of Chablis and it was acknowledged tacitly that slope and orientation are of greater importance to wine quality in Chablis.

Subsequently, the geological misunderstanding has crossed the Channel, with English wine growers making much of planting on the Kimmeridgian, while not realizing that in this country the Kimmeridgian is clay, not limestone as in France.

In Burgundy the best vineyards are frequently on the mid-slope. This is not just because this is where the soil composition is ideal, but because the mid-slope is where the greatest amount of sunshine is received on the SE–SW-facing slopes. In Champagne the mid-slope is also the preferred site for vineyards (Fig. 6). It was formerly erroneously thought that this was due to a special property of the Chalk in this part of the slope. According to Chappaz (1955): 'The winegrowers of old, although ignorant of the geology, always stopped their vineyards right at the contact of the two Chalk formations' – the Belemnite (Campanian) and Micraster (Santonian) biozones. This was repeated in

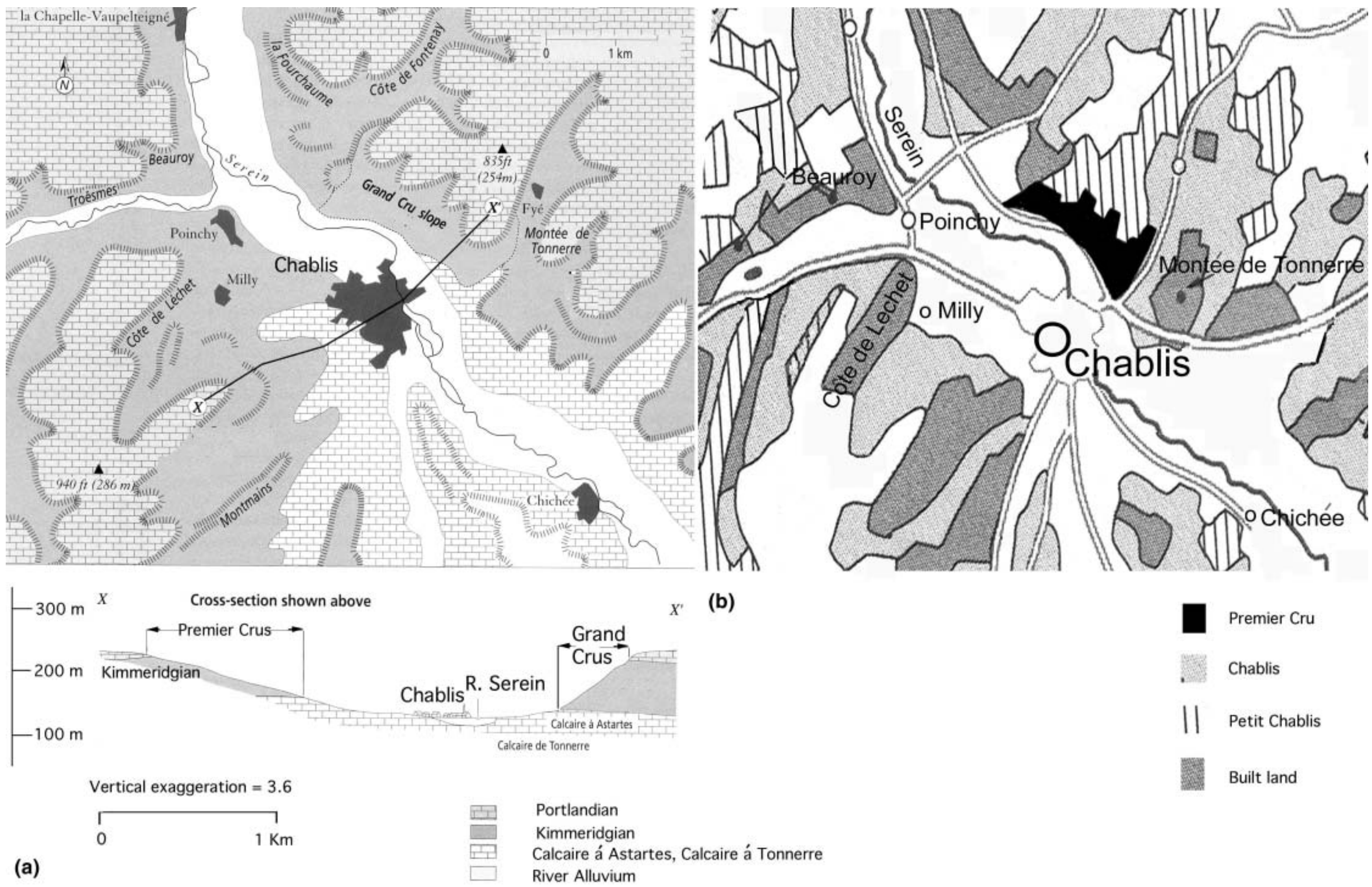

Fig. 5. (**a**) Geology of the area around Chablis, with cross section X–X' (adapted from Wilson, 1998). (**b**) Map of the Premier Cru, Chablis and Petit Chablis vineyards (adapted from the French Geological Survey map and drawn to the same scale as the geological map in (a)).

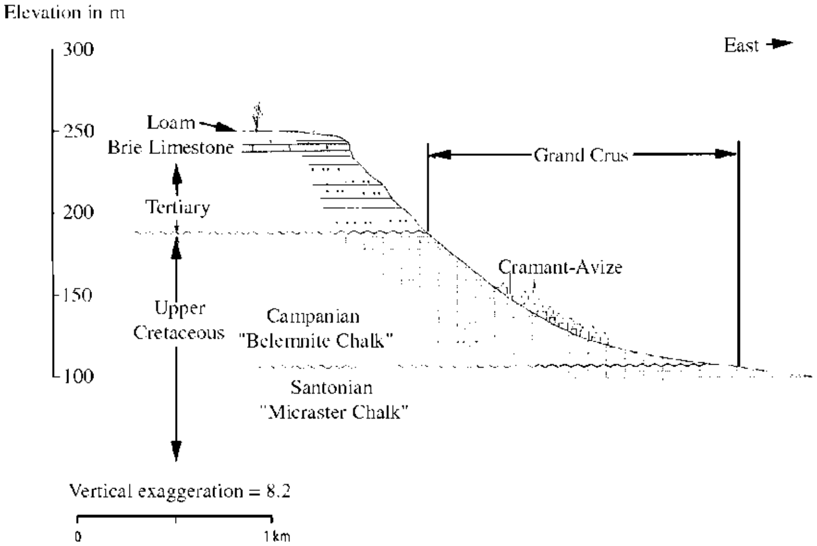

Fig. 6. Cross-section through Cramant-Avizee, Champagne (adapted from Wilson, 1998).

Table 1. Approximate porosity, matrix permeability and mass permeability ranges for the rock types on which most vines are grown.

Rock type	Porosity (%)	Matrix permeability (mD)	Mass permeability (mD)
Sandstone & conglomerate	<40	30–400	50–3000
Shale	8–20	<0.3	10–10 000
Limestone (other than chalk)	<25	very variable	very variable
Chalk	30–45	2–3	30–3000
Granite & schist	<0.1	<0.01	variable, often high

subsequent literature (e.g. Forbes, 1967) and became an accepted 'fact', without any questioning as to why to vines should perform so differently in adjacent chalk zones of similar mineralogy. The real reason for the difference is the soil. The Chalk hills in Champagne are capped by soft, Paleocene sands and muds, which are locally lignitic. These sediments have been washed down the chalk slope, as far as the base of the Belemnite zone (Wilson, 1998). Wilson (1998) argued that it is the lignite that is critical to the soil quality because it contains inclusions of pyrite and thus provides iron and sulphur, elements in short supply in chalk. However, it is as likely that the soil is enriched by the clay minerals and pyrite (probably weathered to other ferric iron minerals and sulphate by the time it reaches the Belemnite zone) not derived from the lignite.

5. BEDROCK CONTROLS ON WINE QUALITY

The ideal water balance for vines is provided by a bedrock with medium to high porosity (*c.* 15–45%), high fracture permeability (>100 mD) and low matrix permeability range (*c.* 1–100 mD). The porosity and permeability characteristics of the range of rock types on which vines are grown most commonly are shown in Table 1. This shows that chalk most consistently provides the ideal porosity and permeability for viticulture. However, moderately cemented, fractured limestones other than chalk, sandstone and conglomerate will also frequently fulfil the criteria for the ideal water balance, as can deeply weathered and fractured schist or granite. Where the slope bedrock is impervious, e.g. shale, drainage through the rock is extremely slow and most water will move down slope as surface runoff, taking soil with it.

Geology is only one of many factors in wine quality and, in most cases, the influence of the bedrock is only indirect. There are wine regions where only one rock type is present, yet the quality of the wine produced varies enormously due to other factors. Examples are Champagne (chalk) and Mosel (schist), where the viticultural methods are probably the most important control. There are equally famous wine regions where the soils are derived from a variety of rock types without any associated variation in quality, examples

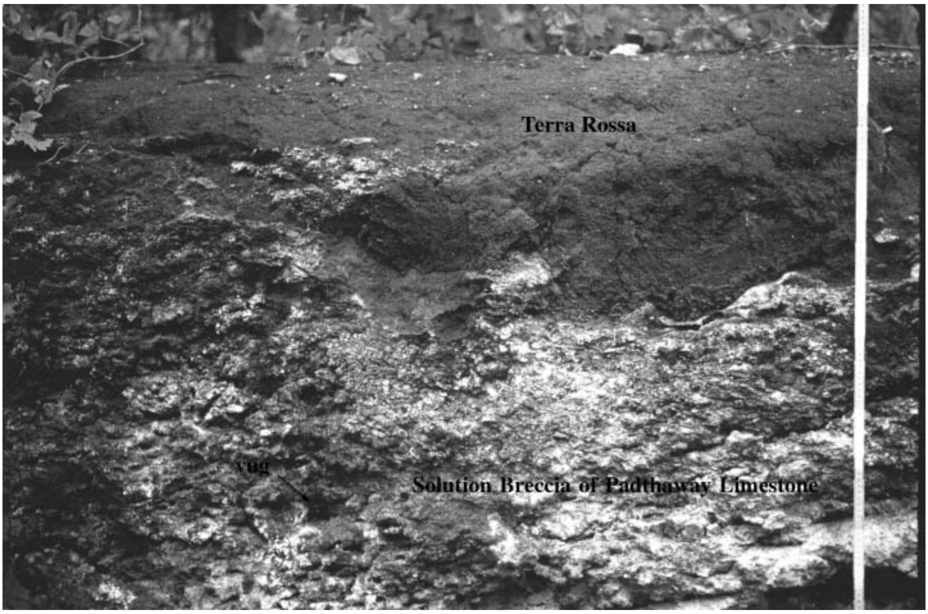

Fig. 7. Terra Rossa laterite on limestone solution-breccia profile at Rouge Homme, Coonawarra. The measuring pole is 1 m.

are Bordeaux, Rheingau and Beaujolais (Wallace, 1972; Seguin, 1986). However, there are a few wine-making areas of the world where the underlying rock has a real influence on wine quality and a selection of these is discussed below. The Coonawarra district is discussed in most detail, because this is the region that the author was working on with Jake Hancock at the time of his death.

In the Douro, a bedrock of schist (rich in K) is preferred over granite (also rich in K) because the schist rock is much more fractured than the granite, permitting greater penetration of rainfall and of the vine roots. In contrast, the great vineyards of Beaujolais are on both granite (Chiroubles, Fleurie, Moulin-à-Vent, Chenas) and schist (Morgon, Brouilly, Julienas, Saint Amour). This is because in Beaujolais the granite is intensely fractured and deeply weathered (Pomerol, 1984). Professor Leneuf and Dr Lautel of Dijon University believe that the particular character and robustness of Moulin-a-Vent wines may be due to the presence in the granite of a seam rich in manganese minerals (Wilson, 1998).

Coonawarra is an area where there is, indeed, a geological explanation for the success of vineyards in that area (Hancock & Huggett, 2004). The principal feature to which the quality of the best Coonawarra wines has been widely attributed (e.g. Mayo, 1991; White, 2003) is a narrow strip of Terra Rossa laterite soil. This soil overlies the Upper Pleistocene Padthaway Formation. This formation is composed of lacustrine and lagoonal dolomites, limestone, claystone and sandstone. The Padthaway Limestone beneath the Terra Rossa has undergone extensive solution so that what remains now is a collapsed limestone solution-breccia (Fig. 7). Hancock & Huggett (2004) estimated from visual observation that the overall porosity is high, perhaps $\geqq 30\%$. This is a much higher porosity than should be encountered in the unaltered limestone. The matrix permeability is inferred to be highly variable. Some of the pebbles and boulders of unaltered limestone with limited solution porosity will have very low matrix permeability, probably no more than 5 mD, while the patches of limestone–sand will have high matrix permeabilities, possibly >100 mD. However, this contrast is minor compared with the anticipated permeability of major vertical joints and sub-horizontal bedding planes, all enlarged by solution. Gaps of several centimetres are common, and permeabilities of >1 D are anticipated. Thus, the drainage conditions at Coonawarra are ideal for vines and are remarkably similar to those in true chalks, as described by Hancock & Price (1990). The Terra Rossa has a high mass-permeability and will allow any excess rainfall to penetrate the underlying, also highly permeable, limestone. Hence, after even very heavy rainfall, excess water will drain away. It follows from this that the limestone solution-breccia will hold moisture for the vines, during even months of no rainfall. The annual rainfall in Coonawarra is around 650–660 mm. It falls between April and December, particularly during the winter months, while the harvest coincides with a dry period (Kidd, 1983; John, 1990). Although some growers do irrigate, it is clear from the above that irrigation should only be necessary in Coonawarra for the establishment of new vines and possibly to ensure the take-up of nitrogenous manure.

6. SUMMARY

In hot climates, prone to summer drought, soil may be the most important factor after viticulture, while in cooler climates, slope and slope aspect are probably the second most important factors. Slope and slope aspect are controlled by a combination of geomorphological and geological factors. Only rarely, as in the Coonawarra and the Douro, is the bedrock an important factor in wine quality.

ACKNOWLEDGEMENTS

Being asked to write this paper and to give the talk that preceded it meant pay-back time for the author. Payback for the many bottles of excellent wine that Jake shared with the author at his kitchen table – usually preceded by consultation as to which would be the best variety of potato to serve with the chosen wine. The author would also like to thank Andy Gale and Dick Selley, whose comments on an earlier draft much improved the manuscript.

REFERENCES

Berry, E. 1989. *The Wines of Alsace.* The Bodley Head, London.

Busby, J. 1825. *A treatise on the culture of the vine and the art of making wine.* R. Howe, Government Printer, Australia.

Chappaz, G. 1955. *Le Vignoble et le Vin de Champagne.* Louis Lamat, Paris.

Coquand, H. 1857. Réunion extrordinaire a Angoulême du 6 au 14 septembre 1857. *Bulletin de la Societeé Géologique de la France,* **14**, 841–903.

Forbes, P. 1967. *Champagne the Wine, the Land and the People.* William Morrow and Co, New York.

Gadille, R. 1967. *Le Vignoble de la Côte bourguignonne.* Les Belles Lettres. Publications de l'Université de Dijon, Paris.

Hancock, J.M. 1999. Feature Review – "Terroir; The role of Geology, Climate and Culture in the making of French Wines" by James E. Wilson 1998. *Journal of Wine Research,* **10**, 43–49.

Hancock, J.M. & Price, M. 1990. Real chalk balances the water supply. *Journal of Wine Research,* **1**, 45–60.

Hancock, J.M. 2005. Geology of wine. In (Selley, R.C., Cocks, L.R.M. & Plimer, I.R.; eds) *The Encyclopaedia of Geology Volume III.* Elsevier, Amsterdam, 85–90.

Hancock, J.M. & Huggett, J.M. 2004. The geological controls in Coonawarra. *Journal of Wine Research,* **15**, 115–122.

Hanson, A. 1995. *Burgundy.* Faber and Faber, London.

Jackson, R.S. 1995. *Wine Science principles and applications.* Academic Press, London.

John, P.G. 1990. Wine making expectations for premium Coonawarra dry red styles. *Proceedings of the 7th Australian Wine Industry Technical Conference.* Publisher?, Place?, 11–15.

Kidd, C.H. 1983. General description of Coonawarra. In (Lester, D.C. & Lee, T.H.; eds) *Coonawarra Viticulture.* Proceedings of a seminar by the Australian Society of Viticulture and Oenology, Coonawarra, June. Publisher?, Place?, 5–6.

Mayo, O. 1991. *The wines of Australia.* Faber & Faber, London.

Peynaud, E. 1996. *The Taste of Wine.* John Wiley and Sons, Inc, New York.

Pomerol, C. 1989. *Terroirs & vins de France.* Bureau de Recherches géologiques et minieres, Orleans (English translation printed by R. McCarta).

Rankine, B.C., Farnachon, J.C.M., Boehm, E.W. & Cellar, K.M. 1971. Influence of grape variety, climate and soil on grape composition and quality of table wines. *Vitis,* **10**, 33–50.

Seguin, G. 1986. "Terroirs" and pedology of wine growing. *Experientia,* **42**, 861–873.

Selley, R.C. 2004. *The winelands of Britain; past, present and prospective.* Petravin, Dorking.

Van Leeuwen, C. 1989. *Carte des sols du vignoble de Saint-Emilion.* Syndicat Viticole Saint-Emilion, Saint-Emilion.

Voss, R. 1995. *Wines of the Loire.* Faber and Faber, London.

Wallace, P. 1972. Geology of wine. *24th International Geological Congress (IGC).* Publisher?, Place?, Section 6, 359–365.

White, R.E. 2003. *Soils for fine Wines.* Oxford University Press, Oxford.

Wilson, J.E. 1998. *Terroir, the role of Geology, Climate and Culture in the Making of French Wines.* Mitchell Beazley, London.

Manuscript received 4 March 2005; revised typescript accepted 11 June 2005