Terroir: Science Related to Grape and Wine Quality

LAWRENCE D. MEINERT, Guest Editor

Science of Terroir: Overview
Soil-Related Factors
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Terroir: Science Related to Grape and Wine Quality

Guest Editor: Lawrence D. Meinert

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Lawrence D. Meinert

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The Mineralogical Society of Great Britain and Ireland is an international society for all those working in the mineral sciences. The society aims to advance the knowledge of the sciences of mineralogy, crystallography, petrology, and geochemistry, and to apply its application to other subjects, including the environmental sciences. The society furthers its aims through conferences and the publication of scientific journals, books, and monographs. The society publishes Mineralogical Magazine and Clay Minerals. Students receive the first year of membership free of charge. All members receive Element.

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The Clay Minerals Society (CMS) began as the Clay Minerals Committee of the US National Academy of Sciences in 1955. The society, which incorporated with the primary purpose of stimulating research and disseminating information related to all aspects of clay science and technology. The CMS holds annual meetings, workshops, and field trips and publishes Clay and Clay Minerals and the CMS Workshop Lectures. Membership benefits include reduced registration fees to the annual meeting, discounts on the CMS Workshop Lectures, and Elements.

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The Geochemical Society (TSG) is an international organization founded in 1955 for students and scientists involved in the practice, study, and teaching of geochemistry. Geochemical Society programs include hosting the annual Goldschmidt Conference (GCA), supporting geochemical symposia through the Meeting Assistance Grant Program, and supporting student development through our Student Travel Grant Program. GCA annually recognizes excellence in geochemistry through its medals, lectures, and awards. Members receive reduced registration fees to Elements, special member rates for GCA and GSC, and publication and confer­ence discounts.

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The Deutsche Mineralogische Gesellschaft (DMG; German Mineralogical Society) was founded in 1908 to “promote mineralogy and all the sciences in which the knowledge of mineralogy is reflected in the list of honorary fellows, which include M. V. Lomonosov, P. Esquel, C. W. Correns, P. Ramdohr, and H. Strunz, to name a few. Today, the subdisci­plines in the DMG are also bridging the gap with other communities such as materials science, solid state chemistry-physics, and environmental sciences. The society espe­cially tries to support young researchers, e.g. by attending conferences and symposia. Membership benefits include the European Journal of Mineralogy, Mineralogy, and Elements, and a once­yearly registration fee for the annual meeting.

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The Polskie Towarzystwo Mineralogiczne (Polish Society of Mineralogy, Crystallography, and Geochemistry) was founded in 1924 by professors from academia and industry and was established to promote knowl­edge in the fields of miner­alogy, crystallography, petrology, and geochemistry internationally. The society coorganizes the 23rd Polish Mineralogy Congress and publishes the Polish Journal of Geochemistry.

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Meteoritical Society
Society membership is an international organization founded in 1933 for professionals and academics interested in meteorites and the inter­stellar processes that produced them. The society promotes the professional interests of its members involved in the study of meteorological, paleontological societies.

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THE MAKING OF GREAT WINE

DOI: 10.2138/gselements.14.3.147

As we set up the publication schedule for each year, the principal editors of Elements try to ensure that the journal maintains enough diversity to hold the interest of you, our readers. In this context, we sometimes accept proposals for issues on very well-known mainstream subjects (such as layered intrusions) which we think can usefully be updated and summarised at a good level. We also try, however, to bring you subjects which are outside the mainstream yet still can be grouped loosely within the areas of geochemistry, mineralogy and petrology. That is how we categorise the current issue dealing with the environmental aspects of making high-quality wine.

In the current issue, Larry Meinert has, at our request, undertaken to guest-edit an issue on terroir, the loosely defined role of environmental conditions, especially soil and climate, in which grapes are grown and that are generally believed to give a wine its flavour and aroma. The principle of terroir and its importance in the production of high-quality wine is fundamental to the wine industry in many European countries. Wine laws are made to reflect the specific, narrowly defined, regions from which wines are produced (termed “appellations”) which officially sanction the idea that combinations of certain vineyard sites and grape varieties create unique wines which accurately reflect their geographical origins. France, for example, has over 300 such appelation d’origine contrôlée (AOC) regions, each with clearly defined grape varieties that may be grown and, frequently, the required proportion of each variety. There are restrictions on irrigation and on the volume of wine which may be produced per hectare of land area. All of these rules serve to emphasize the uniqueness of each tightly defined area. By contrast, in Australia, and to some extent the US, there was traditionally quite a bit of scepticism about the importance of terroir, with a feeling that European winemakers were emphasizing its importance as a means of protecting their prices and business. Until recently, many Australian winemakers made little attempt to correlate specific soils with particular grape varieties and, apart from some very broad parameters, made almost no attempt to link soil type and wine quality. Nevertheless, in Australia we learn that Clare Valley is best for Riesling wines, Hunter Valley for Semillon, and Barossa Valley for Shiraz. So, terroir influences are clear in the New World as well as the Old. And, as the approach to winemaking has become more scientific, the empirically derived rules of the French AOC and its equivalents in Spain (the DOC), Italy (the DOCG) and others, have been taken apart on a more quantitative basis so that the different parameters may be adjusted to enhance the quality of wine from almost any region without completely covering the influence of terroir. Read this issue and you will find how such adjustments are made and the importance of pruning, irrigation and temperature, for example, at different times of the growing season.

My years of experience indicate that Earth scientists tend to be enthusiastic, if rather uncritical, wine drinkers. But even the most uncritical of us will have wondered sometimes why red wines from warm climates often taste of blackberries or why some Pinot Noirs have a distinct cherry flavour. Similarly, the acidity and asparagus odour of those famous Sauvignon Blancs from New Zealand and the pineapple and melon flavours of Chardonnays from warmer regions imply strong climatic effects on flavour. But what about the influences of soil and geology? We English have been led to believe that, because the Jurassic and Cretaceous sediments of the Champagne region reappear on the English side of the sea, England is able to produce sparkling wines which should compare well with those of the famous French area. The climate is also very similar and, indeed, slightly warmer in England during the winter. So, is there anything truly unique about the Champagne terroir? By the time you have finished reading this issue you will probably be disappointed by the conclusion that the distinct terroir has much less to do with soil geology and more to do with climate, hillslope and timing of water supply to the vines.

Probably the biggest blow to the mystique of terroir was the “Judgment of Paris”, a competition that took place in 1976 and in which 11 judges, predominantly French, blind-tasted red Bordeaux and white Burgundy wines against, respectively, Cabernet Sauvignon and Chardonnay from California’s Napa Valley. In both cases, the California wines won overall. This demonstrated three things. First, that winemakers in Napa had made substantial strides in deconstructing the process scientifically in order to understand how great wines are made. Second, that the influence of terroir on wine quality was possibly overstated. Finally, because the competition was organised by a Briton (Steven Spurrier) it tended to confirm the French view of la perfide Albion.

Reading the articles in this issue have, for me, been an enlightening and educational experience. How about another enjoyable but peripheral subject? Anyone for an issue on groundwater and beer?

Bernard J. Wood
Principal Editor
ABOUT THIS ISSUE

Geologists love their beer and wine. There is abundant proof of this statement if you have ever attended an international geoscience conference. Typically, included with an attendee’s registration packet received upon arrival at the conference are beer/wine tickets. Scientists may disperse through the day to attend talks, workshops, and poster sessions, but, late in the afternoons, kegs of beer and bottles of wine are rolled out and the scientists will quickly converge on the beer/wine stations. Organizers of the meetings strategically place these stations throughout the exhibition halls to encourage scientists to gather with one another, visit poster sessions, or wander amongst the exhibit booths. The lines at the stations can be very long and the beer and wine will flow nonstop during these gathering times. This culture of beer and wine extends far beyond international conferences to departmental functions and to local pubs after a long day doing field work or research.

As the topic of this thematic issue of *Elements* is on wine, the question begs to be asked, where does all that wine originate? According to the Organisation Internationale de la Vigne et du Vin (http://www.oiv.int), the top five wine producing countries are Italy, France, Spain, USA, and Australia. Together, these 5 countries produced 148.3 Mhl (million hectoliters; 1 hl = 100 liters) of wine in 2017, which is ~60% of the world’s total wine production (250 Mhl). Who are the top consumers for wine? The USA, with consumption estimated at 32.6 Mhl in 2017. That result may strike many wine connoisseurs as odd because wine consumption is typically associated with European culture. Perhaps a more useful statistic would be to report consumption statistics as liter per capita. Here we can clearly see our European friends topping the charts, with 20 of the top 29 wine consuming countries being located in Europe. Portugal, France, Italy, Switzerland, and Austrian residents consume, on average, 38 to 58 bottles of wine a year. These 29 wine consuming countries are also home to 13,558 of our 15,565 *Elements* members. Hence, the topic of *terroir* is quite appropriate for coverage in *Elements*.

Whether you choose to imbibe on the fermented fruits of the Earth or prefer to abstain, we hope that you enjoy reading this thematic issue on terroir.

DID YOU SEE IT?

To add to your reading enjoyment, the guest editors of the April 2018 issue on comets strategically hid an image of the TARDIS (from the popular BBC TV series *Dr. Who*) on the cover of the magazine. Did you see it?

Although they restricted themselves to one drink at lunchtime, Friedhelm and Bernie still found they were not at their most productive in the afternoon.

FAREWELL & THANK YOU

With this issue, Bernard (Bernie) Wood (University of Oxford, UK) completes his term as a Principal Editor of *Elements*. Bernie attended his first *Elements* editorial meeting in June 2014 and has been a vital part of the editorial team since 2015. During his tenure, he oversaw the following issues: “Supergene Metal Deposits” (v11n5), “Enigmatic Relationship Between Silicic and Volcanic and Plutonic Rocks” (v12n2), “Studying the Earth with LA–ICP–MS” (v12n5), “Sulfides” (v13n2), “Mineral Resources and Sustainability” (v13n5) and “Terroir: Science Related to Grape and Wine Quality” (v14n3). In addition to working closely with our guest editors and handling manuscripts, he has been very active in soliciting and encouraging scientists to submit proposals for possible inclusion in *Elements*. As mentioned in his editorial (see page 147), the topic you are reading in this issue of *Elements* was solicited by Bernie. He has also championed the idea of field-based thematic issues that feature iconic geologic regions, the first of which will be published in August 2018 on the Central Andes and a second to be published in 2019 on the South Aegean Volcanic Arc. Thank you, Bernie, for all your hard work and dedication to keeping *Elements* relevant and interesting to our readers.

Friedhelm von Blanckenburg, Nancy Ross, Jon Blundy, and Jodi Rosso
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Andrew Hall is a physical geographer with expertise in emerging technologies and techniques for the analysis of large environmental datasets, particularly datasets derived from remote sensing and climatology. As a researcher at the National Wine and Grape Industry Centre at Charles Sturt University (Australia) from 2000 to 2012, Andrew led spatial science and climatology projects, including internationally influential research on modelling climate-change effects on grapevine phenology and remote sensing applications for viticulture. Andrew is now Acting Director of the Institute for Land, Water and Society (Charles Sturt University) with current research projects in wetland monitoring, climate refugia, and habitat occupancy.

David G. Howell received his PhD from the University of California Santa Barbara (USA) in 1974. He is a fellow in the American Association for the Advancement of Science and the Geological Society of America. For 30 years, he was a research geologist with the US Geological Survey. He teaches with Doug Posson in Stanford Continuing Studies (an institutional extension of Stanford University, California, USA), “Exploring the geology and wines of California and France”. Howell and Posson also lead wine and geology tours in California and France. Howell currently lives on a farm in New Hampshire (USA) and continues to consult with vintners in Napa Valley (California).

Gregory V. Jones is the Director of the Grace and Ken Evenstad Chair for Wine Education, he holds the Evenstad Chair in Wine Studies, and he is a professor and research climatologist in the Department of Environmental Studies at Linfield College (Oregon, USA). Jones specializes in the study of climate structure and suitability for viticulture, and how climate variability and change influences grapevine growth, wine production, and wine quality. He conducts applied research for the grape and wine industry in Oregon and many regions worldwide, has given hundreds of international, national, and regional presentations, and has published extensively on climate and wine-related research.

Stefanos Koundouras is Associate Professor in the School of Agriculture of the Aristotle University of Thessaloniki (Greece). He holds a PhD in viticulture from the University “Victor Segalen” Bordeaux II (France), where he studied the impact of terroir parameters on vine–water relations and on grape and wine attributes. His current research focuses on vine ecophysiology, vineyard management techniques and their impact on grape metabolites, climate change, and precision viticulture.

Sarah L. MacDonald has over 14 years of experience in geographic information systems (GIS) and remote sensing. Her passion for all things geospatial began at the University of California Los Angeles (USA) where she received her bachelors in geography in 2006. After graduation, Sarah worked as...
a GIS Specialist for URS Corporation in Oakland, California. In 2013, Sarah received her doctorate from the University of California Berkeley (USA) in the Environmental Science, Policy and Management Department in the Kelly Research & Outreach Lab. She now owns and manages Envision Geo LLC (California, USA), a geospatial technology firm focused on providing high-quality GIS and remote sensing services and advanced data visualization and cartographic design.

Lawrence D. Meinert obtained his geology PhD from Stanford University (USA), became a university professor for 30 years, and then led the Energy and Mineral Resources branch of the US Geological Survey. He has operated a small home winery for 35 years, specializing in a barrel-fermented Bordeaux blend of Cabernet Sauvignon, Merlot, Carménère, and Malbec. His teaching and research covers a wide range of fields, from exploring for gold mines to that liquid gold in bottled form: fine wine. Meinert has published research on vineyard siting and performance in Argentina, Chile, Italy, New Zealand, South Africa, and several appellations of the US.

Laure de Rességuier is a researcher in the Viticulture and Enology Department at Bordeaux Sciences Agro (part of Bordeaux University’s Institut des Sciences de la Vigne et du Vin in France). De Rességuier researches the effect of climate on terroir, as well as spatial and scale-related effects. She is currently managing a project on spatial temperature variability at the local scale and its consequences on vine development and grape ripening. De Rességuier also teaches geomatics (geographic information systems) and new technologies applied to viticulture in several Master’s programs.

Jonathan P. Swinchatt has worked as a geologist in the oil industry, taught at two universities, produced educational videos on Earth and Earth processes, and written (together with David Howell) *The Winemaker’s Dance: Exploring Terroir in the Napa Valley*, (2004, UCB Press). Until recently, he conducted geologic studies of vineyards for winegrowers in California and Europe. He has also written a series of 12 articles on North American wine regions, published in the award-winning magazine *World of Fine Wine*.

Cornelis (Kees) van Leeuwen is Professor of Viticulture and head of the Viticulture and Enology Department at Bordeaux Sciences Agro (part of Bordeaux University’s Institut des Sciences de la Vigne et du Vin in France). He conducts research on terroir in viticulture, including the effect of climate, soil, plant material, and water. In recent years, his focus has been on the impact of climate change on viticulture. Van Leeuwen has mapped the soils of numerous wine estates and appellations and has been responsible for research and development of Château Cheval Blanc in Saint-Emilion for 25 years. He is the editor-in-chief of the open access journal *OENO One* (http://oeno-one.eu/indexub).
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The Science of Terroir

Lawrence D. Meinert

Terroir involves the complex interplay of climate, soil, geology, and viticulture, all of which influence the character and quality of a wine from a given grape variety, rootstock, and viticultural practice. Contrary to the assertions of some wine writers, the minerals and character of the soil cannot be tasted in the wine. Rather, it is their effect on the grape ripening process that gives certain wines a “sense of place”. Most important is water availability, which is a function of climate (rainfall and humidity) and soil water-holding capacity. The soil structure reflects the geologic history of a region and may have evolved over millions of years as influenced by faulting, weathering, and bedrock mineralogy. Far-field effects such as glaciation and resultant sea-level change can affect landscapes that are thousands of kilometers apart.

Keywords: terroir, wine, grapes, climate, enology, viticulture

INTRODUCTION

Human interest in wine predates all written records. This can be seen from archeological finds in China, Georgia, Greece, Iran, and Turkey that date back some 9,000 years and by the discovery of what was a fully functioning winery established in Armenia more than 6,000 years ago (McGovern 2003). Because ripe grapes and other sugar-containing fruits will naturally ferment with indigenous yeasts, it could be argued that a rudimentary form of wine actually predates humanity. Regardless of that chicken and egg conundrum, there is abundant historical evidence that wine and winemaking go back many millennia and that people have long appreciated the mystery and magic of good wine. It is a long-established observation that some places seem to produce much better wine than others, even when broad characteristics of geography and climate are similar. This interest in “place” has been referred to as “terroir” (from the French, meaning “land”, itself from the medieval Latin terratorium) and this broad concept includes many different aspects of the physical environment. The use of the word “terroir” has increased dramatically in the past few decades (Fig. 1); yet, terroir remains mysterious to many people, with confusion and more than a bit of mythology about what it is, how it is documented, and even how it is pronounced (tehr-wahr vs. tehr-wah). Matthews (2015), in his comprehensive book Myths of Winegrowing, even goes so far as to suggest that the term “terroir” be abandoned altogether in favor of the more generic “environment”.

TERROIR

This introductory article sets the stage by attempting to clarify that elusive concept we call “terroir”.

Keywords: terroir, wine, grapes, climate, enology, viticulture

Figure 1: Usage* of the word “terroir” in English-language books between 1900 and 2010 as tracked by Google ngram analytics (https://books.google.com/ngrams), accessed 1 January 2018. The * symbol added to “usage” of “terroir” means the number of times the word “terroir” was used as a percentage (multiplied by 10^7) of all words tracked by Google ngram analytics.

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This issue of Elements is entitled “Terroir”, and it concerns the physical environment in which grapes are grown and from which wine is made. In this context, the focus is on how scientific studies help us to understand the interaction between the physical environment and the grape, and, ultimately, the wine. The authors of the individual articles come from different scientific backgrounds and address different aspects of terroir: climate, geology, geography, plant physiology, soils, and remote sensing. All are useful to elucidate the mysteries of the grape and the complex journey from vineyard to finished wine.
Terroir is the integration of individual factors that contribute to wine quality. To make matters even more complicated, there is the variable of time. What may be “good terroir” in one year may be less so in another. For example, in years that are relatively warm and dry, vineyard X having a particular slope, elevation, sun angle, and soil type, may produce better wine than vineyard Y, ... whereas the reverse may be true in years that are cooler and wetter. Finally, there are the human-controlled variables. These include grape variety, rootstock, canopy management, fertilization, and irrigation, not to mention the role of culture and personal preference in deciding what constitutes good wine in the first place.

Thus, it is necessary to attempt to separate cause and effect, ideally while holding other variables relatively constant, so that factual documentation of temperature, solar radiation, water availability, soil texture and composition, and other physical factors can be distinguished from romantic imagination, i.e. a “taste of place” that may be sensed by an individual but cannot be scientifically documented.

Some wine myths include the demonstratably false notion that minerals in the soil make their way through the plant to the grapes and, subsequently, into the wine. This is reflected in some winemaker terminology such as “mineral-ality”, which implies that there is something in the soil that can be tasted in the wine. The soil-wine connection seems to have some support in the fact that many wines possess “chemical fingerprints” that can be used to trace their origin. However, most of the measurable trace elements have no sensory effect, and it is plant physiology, not geochemical composition of soils, that controls the ripening and sensory characteristics of the grape (Taylor et al. 2002; Greenough et al. 2005; Koundouras 2018 this issue). Thus, if soil mineralogy and geochemical composition do not show up directly in the grape, and, ultimately, in the wine, what is the terroir effect and how do we explain the repeatedly observed difference between wines from nearby vineyards X and Y?

**Water Availability**

A first step in clarifying the terroir effect is to consider differences in water availability to the grapevine during the growing season. This may be the single most important variable in terms of ultimate wine quality (van Leeuwen et al. 2009; Matthews 2015). The first-order control on water availability is climate and, more specifically, rainfall and humidity (Gladstones 1992; Jones 2018 this issue). Too much water, as in many tropical climates, is incompatible with quality wine. Zero rainfall, such as in the Atacama Desert (Chile), would also be incompatible with producing quality wine, certainly in the absence of irrigation. In general, it is desirable for grapevines to have only limited access to water in order to avoid excess vine vigor, i.e. growing more leaves relative to fully ripened fruit (Smart and Robinson 1991; Koundours 2018 this issue). The timing of water availability during the growing season is also important. For example, the benefit of moderate water deficits for red wine grapes has been demonstrated by numerous workers in terms of higher anthocyanins and tannins (Table 1 provides definitions of some terms used in this and other articles in this issue, that may not be familiar to all readers), features characteristic of high-quality red wines (Roby and Matthews 2004; Keller 2008; van Leeuwen 2018 this issue). In a location with too much rainfall (or at the wrong time), a soil that is free draining would be a positive feature, whereas a soil with clay, which can hold water, could be negative. In contrast, a location with too little rainfall (or not at the right time) might benefit from deeply weathered soils with a high clay content and a pore structure that can retain water. Thus, it is not that clay-rich or free-draining soils are inherently good or bad: it is in a particular context that they might be essential. This concept is examined in more detail by van Leeuwen (2018 this issue), and the spatial variability of vineyard soils is illustrated by Hall (2018 this issue). Documenting measurable physical characteristics is a goal of terroir studies so as to understand how these characteristics affect grapevine physiology and wine grape properties. The fact that soil mineralogy and chemical composition cannot be directly tasted in finished wine does not mean that they have no effect. More importantly, documenting what is actually occurring is an essential first step in the understanding of terroir.

**Geological Variables**

We need to take a large step back to consider what controls physical variables. For example, the geological history of a region can include thousands (or millions) of years of weathering to form a given soil horizon, including its clay content. Even further back in the geologic and tectonic history, faults, or other geologic boundaries, may have influenced the variable water-holding capacity of soils near the surface in a vineyard or district. For example, one of the most famous correlations between subsurface geology and wine quality is the occurrence of repeated offsets along certain step faults in the basement rocks in Burgundy (France) (Figs. 2A, B). The subsurface faults, only identified in the past century, show a simple correlation with appellation boundaries that date back several centuries, if not millennia, in terms of perceived vineyard differences and wine quality. It is not that the faults created magical terroir, but rather that they strongly influenced the location and amount of weathering of the subsurface rock types, and this led to differing amounts of clay, and so to differing water-holding capacities of the weathered rocks. This, in turn, can affect grape ripening and sensory characteristics. Thus, the bedrock is not reflected directly in the taste of the wine but, rather, the faulting caused variable degrees of weathering and soil formation. This then led to differences in the content of water-holding clays that in turn influenced differences in grapevine physiology and grape composition, that then created demonstrable differences in wine quality. Thus, the “terroir effect” is directly related to the geologic history, but not in the sense that anyone can taste the rocks in the wine.

Most terroir study is focused on individual vineyards or districts (Swinchatt and Howell 2018 this issue). However, some correlations can be made at regional to global scales, such as the worldwide lowering of sea level during the glacial maximum about 15,000 years ago and the locally abundant sediments produced by glaciers in many disparate parts of the world. For example, more than 90% of Washington State (USA) vineyards are located in areas affected by glacial outburst floods (Meinert and Busacca 2000) that formed coarse gravels and well-drained, nutrient-poor soils (Fig. 2E). Many other wine-producing areas of the world (such as parts of France and New Zealand) also have links to this glaciation and sea-level change event, thereby having some common terroir links even though they are thousands of kilometers apart.
A prime example of the indirect effects of glaciation can be seen in the Graves-Médoc region of Bordeaux (France) (Wilson 1998). Outwash gravels from glaciations in the Pyrenees Mountain Range (along the French–Spanish border) and in the Massif Central (central France) overloaded the Garonne and Dordogne Rivers with coarse gravels, which in turn led to the formation of the Gironde Estuary, which itself had been enlarged and deepened by the lowering of sea levels during the glacial periods. Each period of glaciation produced its own series of gravel outwash floodplains along the rivers. The best (“First Growth”) vineyards are mostly on the same type of gravel. Names such as Château Lafite Rothschild, Château Haut-Brion, Château Latour, and Château Mouton Rothschild are well known to wine-lovers throughout the world, and it may be no coincidence that each of these prestigious estate vineyards is located on gravel terraces (Figs. 2C, 2D). The most famous gravel, oenologically speaking, is the Günz Gravel in Bordeaux (France), home of many First Growth wines. Recent work has distinguished at least six subdivisions of these gravels that can be correlated with different vineyards (Becheler and Tastet 2010).

Less well known are the gravel outwash plains of the South Island of New Zealand. These plains were fed by the extensive alpine glaciation of the Southern Alps, which transect the South Island. The outwash gravels form the substrate for many of the vineyards in the Marlborough area of New Zealand, and some of the wineries of this region focus on the coarse gravels for their best vineyards (http://www.stoneleigh.co.nz/). Another gravelly area in New Zealand, the Gimblett Gravels, is perhaps the first viticultural region in the world to specifically define itself on the basis of a gravel unit (Fig. 2F). Legally, wines from this appellation have to consist of at least 95% grapes grown on the Gimblett Gravels (http://www.gimblettgravels.com/index.htm). Again, it is not that the gravel directly affects the taste of the wine but that the drainage characteristics of the gravelly soil are an important part of proper ripening of the grapes that then form the basis of great wine.
Having considered some of the physical variations that are part of terroir, it is also appropriate to discuss some aspects of climate, vineyard management, and winemaking that affect the ultimate quality of wine. At the risk of being repetitious, it needs to be stated again that none of these effects individually are the determining factor, other than in a negative sense when they are outside a window of temperature, rainfall, permeability, and so on, that is permissive to the making of quality wine.

On the climatic front, temperature is the most important variable and can be measured in a number of ways, such as growing degree days (a heat index used to predict when a crop will reach maturity), the Huglin index (a specific bioclimatic heat index for vineyards), or the biologically effective degree-day index. These terms are explained in more detail by Jones (2018 this issue). The simplest measure of temperature is average growing season temperature (April through October in the Northern Hemisphere; October through April in the Southern Hemisphere), which is functionally equivalent to the other forms of temperature measurement but is more widely available and is easier to use.
Grape Variety
Predominant over all of the above variables, which may be regarded as permissive rather than determinative, is the choice of grape variety (genotype) and, to a lesser extent, rootstock (the underground part of the vine). As documented by numerous studies over the years (e.g. Amerine and Winkler 1944; Gladstones 1992; Jones 2018 this issue), some grape varieties are suited to grow under particular climatic conditions. An underlying theme of this “Terroir” issue is that the physical conditions of terroir modify, enable, and ameliorate the overall climate setting to allow particular grape varieties to develop to their full potential. To produce quality wine, the chosen grape variety must reach full ripeness. Therefore, early ripening varieties (Riesling, Pinot Noir) are best for cooler, shorter growing seasons, whereas later-ripening varities (Zinfandel, Nebbiolo) are only practical in warmer, longer growing seasons. For a given region or climatic zone, one can then look at physical terroir factors such as slope, elevation, soil structure, and solar radiation to select prefered sites for the desired grape variety. Further modification can be achieved by vineyard management practices, such as drainage tiles, row spacing and orientation, cover crops, canopy pruning, and crop load (yield), fertilization, and irrigation. Other factors include the microbiological content of soils (e.g. yeasts and bacteria), which can imprint sensory characteristics on top of all the physical and cultural practices described above. The two best known results of soil microbiology are the production of the “earthy, musty” flavors that are imparted by *Brettanomyces* and *Streptomyces*. It is ironic that some of the “earthy” flavors that some winewriters passionately ascribe to terroir are actually biological in origin (and could be described as poor sanitation practice) rather than being a function of the soil or a “sense of place”.

Winemaking Process
In the end, there is the winemaking process itself. This can modify the initial starting material (the grapes) in a variety of ways and is part of the human creative process. Like chefs who could prepare a particular dish such as chicken in many different ways, ranging from mild and delicate to hot and spicy, the winemaker, through the choice of yeasts, malolactic fermentation, oak barrel treatment, and fining and aging practices, can produce distinctly different wines from a given batch of grapes. Conversely, a winemaker can aim for a similar wine style from grapes grown in different regions and under markedly different conditions. For example, it is relatively easy to control the acid content of grapes and wine by careful selection of harvest maturity and fermentation/acidification choices, such that the resulting wine has some of the crisp, tart characteristics of a cool climate region, such as Sancerre (France) or Marlborough (New Zealand).
CONCLUSIONS
This introduction concludes close to where it started. Namely, that there are many physical and cultural factors that affect the quality and characteristics of grapes and the wine made from them. These factors can be identified and studied to better understand the characteristics of wine from a particular region, a particular producer, or a particular vintage. Where viticultural and enological practices are prescribed either by cultural tradition or by rules (legislation or appellation), this leads to a wine style that can be identified as characteristic of a region. However, it should be recognized that other wine styles could be made from those grapes and that region. Like the previously described lack of direct sensory effect of soil mineralogy, this could be interpreted to mean that there is no such thing as terroir, or even a “sense of place”, only variables of grape selection and viticultural and enological practice, all subject to human choice and manipulation. This may be true enough but it misses the opportunity to use objective science to document, interpret, and better understand the variables involved in the journey from vineyard to bottled wine.

REFERENCES
van Leeuwen C, de Rességuier I (2018) Major soil-related factors in terroir expression and vineyard siting, Elements 14: 159-165
van Leeuwen C and 5 coauthors (2009) Vine water status is a key factor in grape ripening and vintage quality for red Bordeaux wine. How can it be assessed for vineyard management purposes? Journal International des Sciences de la Vigne et du Vin 43: 121-134

The natural environment, or terroir, in all of its detail is what the five papers of this issue of Elements explore, and they specifically explore the factors of climate, geology, plant physiology, remote sensing, and soil. Collectively, these five papers give a broad picture of terroir that should allow individual readers to better understand the many variables that go into making the very enjoyable beverage that is fine wine.

ACKNOWLEDGMENTS
Guiding highly technical subjects to a smooth landing that can be understood by interested but nonspecialist readers requires not only exceptional writing skills but also dedicated reviewers who can tackle multidisciplinary papers. All of the papers in this special issue were reviewed by multiple specialists, as well as generalists, including: Alan Busaca, Andrew Hall, Jeff Hedenquist, Markus Keller, John Livingston, Roger MacQueen, David Reidmiller, Andy Reynolds, Dejan Tescic, and Cornelis van Leeuwen. In addition, Principal Editor Bernie Wood is thanked for initiating the idea of this special issue (with help from Barb Dutrow) and being the final reviewer for the collected papers. 
Major Soil-Related Factors in Terroir Expression and Vineyard Siting

Cornelis van Leeuwen¹ and Laure de Rességuier¹

1811-5209/18/0014-0159$2.50 DOI: 10.2138/gselements.14.3.159

A “terroir” is a cultivated ecosystem in which the vine interacts with the soil and the climate. The soil influences vine phenology and grape ripening through soil temperature, water supply and mineral supply. Limited water supply to the vines is critical for reaching a suitable grape composition in order to produce high quality red wines. Soil nitrogen availability also plays a key role in terroir expression. Ideally, vineyards should be established in areas where soil temperature (relative to air temperature), soil water-holding capacity (relative to rainfall and potential evapotranspiration) and soil nitrogen availability are optimum for the type of wine to be produced. Terroir expression can also be optimized by choosing appropriate plant material and via vineyard floor management techniques.

**THE SPECIFIC ROLE OF THE SOIL IN TERROIR EXPRESSION**

**Vineyard Soils are Diverse and Soil Type Impacts Wine Quality**

The soil in which vines grow influences both the quality and the style of a wine. The impact of the soil, when combined with climate, topography and grapevine variety, is referred to as the terroir effect. But great wines are not restricted to one soil type or terroir. Fine wine can be produced from the gravelly soils developed on Quaternary alluvium, such as in Pauillac (Bordeaux, France) (Table 1A, Fig. 1A); from the clayey lime-rich soils developed on Jurassic limestone, such as in Mazis-Chambertin (Burgundy, France) (Table 1B and Fig. 1B); or from Paleogene heavy clay soils, as at Saint-Emilion (Bordeaux) (Table 1C and Fig. 1C).

High quality potential vineyard soils may be coarse (Table 1A) or fine textured (Table 1B and 1C), have high pH (Table 1B) or low pH (Table 1A), and may be rich in organic matter content (Table 1A) or be poor in it (Table 1C). There is no straightforward relationship between soil composition and wine quality, and an in-depth analysis of how the vine reacts to specific soil types is necessary to obtain a better understanding of the soil effect in terroir expression. Vineyard soils are also often modified by human intervention. The high copper content in soils from the Bordeaux area (Table 1C), for example, is the result of copper sprayings to protect the vines against mildew.

**Different Approaches to Studying Soil**

Experts from different scientific backgrounds study vineyard soils, resulting in a range of ways in which soils can be viewed. Geologists study the parent material and geomorphologists the topography. Soil scientists map vineyard soils and agronomists study soil physical and chemical compositions. Soil microbiologists analyze the microbial community of vineyard soils. All these approaches provide useful information but, generally, remain highly descriptive.

Yet, there are many factors involved in terroir expression, which implies that terroir studies have to be multi-disciplinary. If the soil has an impact on grape composition and wine quality, it is necessarily mediated through the vine. In order to explain the effect of terroir on wine composition, interactions between the soil and the vine (and possibly the climate) need to be taken into account. The soil provides minerals, water, anchorage to the vine, and a specific temperature regime in the root zone. Hence, the

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**Figure 1** The soils of three famous vineyards. (A) Gravelly soil developed on Quaternary alluvium in Pauillac (Bordeaux, France). PHOTO: OLIVIER TREGOAT. (B) Clayey lime-rich soil developed on Jurassic limestone in Mazis-Chambertin (Burgundy, France). PHOTO: ADAMA (F-21160 FLAVIGNYOT). (C) Heavy clay soil on Paleogene substratum in Saint-Emilion, Bordeaux. PHOTO: CORNELIS VAN LEEUWEN.
understanding of its effect in terroir needs to be focused on the effect of soil temperature, soil water supply, and soil mineral supply on vine development, phenology and grape ripening dynamics. Moreover, contrary to geological outcrops or soil types, these variables can be quantified.

**MAJOR SOIL-RELATED PARAMETERS IN TERROIR EXPRESSION**

**Soil Temperature in the Root Zone**

The timing of ripeness in a particular terroir is critical in the production of a good wine. If grapes ripen too early in the season in warm conditions, those grapes become high in sugar and low in organic acids. Wines produced from such grapes are unbalanced and lack freshness. Moreover, aromatic complexity is reduced in warm ripening conditions. If grapes ripen too late in the season, they may not reach full ripeness, resulting in acidic wines and those with an excess of “green flavours”. The ideal window for reaching ripeness is roughly situated between the 10th of September and the 15th of October in the Northern Hemisphere, or March in the Southern Hemisphere (van Leeuwen and Seguin 2006), although it obviously also depends on the style of wine the grower aims to produce. The timing of phenology (budburst, flowering, and the onset of ripening) is mainly driven by air temperature and the specific temperature requirements of the grape variety. To remain within the ideal ripening window, growers who are looking for optimal terroir expression adapt their choice of the grapevine variety to local climatic conditions so as to plant early ripening varieties in cool climates and late ripening varieties in warm climates (van Leeuwen and Seguin 2006). Soil temperature in the root zone also impacts phenology. Soil temperature depends on energy balance, which is related to soil colour and albedo (proportion of sunlight reflected on the soil), slope steepness and direction, and it is highly affected by water content, because water has a high specific caloric capacity: wet soils warm up more slowly compared to dry soils. Soil structure also affects soil temperature.

In vineyards where the combination of local climatic conditions and the precocity of the major grapevine variety results in ripening late in the ideal calendar window, a warm soil in the root zone generally results in better wines. This is clearly the case with Cabernet Franc in the Loire Valley (France), Cabernet-Sauvignon in Bordeaux (France) and Cabernet-Sauvignon in Hawke’s Bay (New Zealand). For varieties ripening in the middle of the ideal ripening window – Merlot in Bordeaux, or Cabernet-Sauvignon in the Napa Valley (California, USA) – soil temperature has little impact on quality performance. Cool soils may be an advantage in warm climates because they can slightly delay ripeness, although this aspect is poorly documented.

<table>
<thead>
<tr>
<th>Layer 1</th>
<th>Layer 2</th>
<th>Layer 1</th>
<th>Layer 2</th>
<th>Layer 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>DEPTH (cm)</td>
<td>0–50</td>
<td>50–100</td>
<td>0–55</td>
<td>40–80</td>
</tr>
<tr>
<td>COARSE ELEMENTS (%)</td>
<td>35%</td>
<td>70%</td>
<td>10%</td>
<td>2%</td>
</tr>
<tr>
<td>FINE EARTH (%)</td>
<td>65%</td>
<td>30%</td>
<td>90%</td>
<td>98%</td>
</tr>
<tr>
<td>Coarse sand</td>
<td>55%</td>
<td>85%</td>
<td>3%</td>
<td>55%</td>
</tr>
<tr>
<td>Fine sand</td>
<td>16%</td>
<td>8%</td>
<td>4%</td>
<td>13%</td>
</tr>
<tr>
<td>Coarse silt</td>
<td>7%</td>
<td>1%</td>
<td>21%</td>
<td>11%</td>
</tr>
<tr>
<td>Fine silt</td>
<td>10%</td>
<td>2%</td>
<td>28%</td>
<td>11%</td>
</tr>
<tr>
<td>Clay</td>
<td>12%</td>
<td>4%</td>
<td>45%</td>
<td>9%</td>
</tr>
<tr>
<td>TEXTURE (fine earth)</td>
<td>Sandy</td>
<td>Sandy</td>
<td>Clay</td>
<td>Sandy clay</td>
</tr>
<tr>
<td>ORGANIC MATTER (%)</td>
<td>4.2</td>
<td>0.24</td>
<td>1.79</td>
<td>0.86</td>
</tr>
<tr>
<td>ORGANIC CARBON (%)</td>
<td>2.44</td>
<td>0.14</td>
<td>1.04</td>
<td>0.50</td>
</tr>
<tr>
<td>TOTAL NITROGEN (%)</td>
<td>0.24</td>
<td>—</td>
<td>0.13</td>
<td>0.037</td>
</tr>
<tr>
<td>C/N ratio</td>
<td>10.2</td>
<td>—</td>
<td>8.0</td>
<td>13.4</td>
</tr>
<tr>
<td>pH (water)</td>
<td>6.2</td>
<td>6.2</td>
<td>8.2</td>
<td>7.6</td>
</tr>
<tr>
<td>CATION EXCHANGE COMPLEX</td>
<td>K+ cmol+/kg</td>
<td>0.25</td>
<td>0.09</td>
<td>0.48</td>
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<td>Mg2+ cmol+/kg</td>
<td>0.78</td>
<td>1.65</td>
<td>0.67</td>
<td>1.28</td>
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<tr>
<td>Ca2+ cmol+/kg</td>
<td>7.57</td>
<td>0.68</td>
<td>++</td>
<td>5.32</td>
</tr>
<tr>
<td>S (SUM OF CATIONS)</td>
<td>8.6</td>
<td>++</td>
<td>++</td>
<td>++</td>
</tr>
<tr>
<td>% BASE SATURATION</td>
<td>95%</td>
<td>Sat.</td>
<td>Sat.</td>
<td>Sat.</td>
</tr>
<tr>
<td>CATION EXCHANGE CAPACITY (cmol+/kg)</td>
<td>9.1</td>
<td>1.8</td>
<td>23.1</td>
<td>6.7</td>
</tr>
<tr>
<td>TOTAL LIME (%)</td>
<td>0</td>
<td>0</td>
<td>3</td>
<td>0</td>
</tr>
<tr>
<td>TRACE ELEMENTS</td>
<td>Cu mg/kg</td>
<td>4.8</td>
<td>—</td>
<td>—</td>
</tr>
</tbody>
</table>

**Table 1**  
SOIL COMPOSITION IN THREE FAMOUS VINEYARDS. (A) Gravelly soil developed on Quaternary alluvium in Pauillac, Bordeaux. (B) Clayey lime-rich soil developed on Jurassic limestone in Mazis-Chambertin, Burgundy. (C) Heavy clay soil on Paleogene substratum in Saint-Emilion, Bordeaux.


**Effect of Soil Mineral Supply (Except Nitrogen) on Terroir Expression**

Soils supply vines with minerals (i.e., essential elements), including the major elements (N, P, K, Mg, Ca) and minor elements (Fe, B, Mn, Zn, among others). Except for nitrogen, which will be addressed in the next section, there is little evidence that soil minerals are major drivers of terroir expression. In popular wine books, terroir expression is repeatedly attributed to “deep roots picking up trace elements” but no demonstration is provided on how these elements could possibly be transformed into aroma compounds or other sensory attributes of wines. Seguin (1986) found no close relation between soil minerals and wine quality.

**Effect of Soil Nitrogen Supply on Terroir Expression**

Nitrogen is a highly important nutrient in all agricultural crops, including grapevines. The level of nitrogen supply influences vine vigour, crop level, berry size, and affects both major metabolites of the grape (sugar, organic acids) and the secondary metabolites (phenolic compounds, aromatic compounds and aroma precursors). The soil availability of nitrogen to the vine is not easy to estimate, because the vast majority of nitrogen in the soil is in organic form, which is not directly accessible to the vines. The organic matter first has to be turned into mineral nitrogen by soil microorganisms before it can be absorbed by the vines, predominantly as NO₃⁻. This is a complex and dynamic process, which depends on many factors: soil aeration, soil temperature, soil humidity, soil pH, and the type of organic matter (in particular its C/N ratio). The amount of available mineral nitrogen is clearly linked to soil type and, thus, makes it part of the terroir effect, although it can obviously also be manipulated through fertilization practices and vineyard cover crop management.

In the production of red table wines, moderate nitrogen supply is an important quality-enhancing factor. Vine vigour is related to nitrogen supply (Fig. 2). Low nitrogen limits berry size and berry malic acid content, and it increases sugar content and phenolic content (Chne et al. 2001). In white wine production, the desired level of nitrogen supply is higher in comparison with red wine production. In Sauvignon Blanc, nitrogen stimulates the synthesis of volatile thiol precursors (volatile thiols are major aroma compounds in many grapevine varieties, including Sauvignon Blanc, positively associated with wine quality). Because nitrogen also stimulates the synthesis of glutathione (a compound that preserves aroma compounds in musts and wines) and limits the production of tannins (that are involved in volatile thiol degradation), moderately high nitrogen supply to the vines is desired in white wine production, at least for those varieties dependent on volatile thiols for their aromatic signature (Choné et al. 2006). Excessive nitrogen supply is not desired because it increases susceptibility of grapes to grey rot (Botrytis cinerea) (Mundy 2008). It is important to note that optimum nitrogen supply is different in red and white wine production. This observation explains, at least partially, why some soils are better for the production of high-quality white wines and others for the production of high-quality red wines. Soil availability of nitrogen, however, can also be managed by the grower (see section “management of terroir”).

Some authors have attributed a major role to soil microorganisms in terroir expression, although these authors remain relatively vague about the mechanisms involved in this potentially beneficial effect (Bourguignon 1995). It is true that a healthy soil should have at least some minimum level of microbiological activity, because soil microorganisms play a major role in the transformation of organic nitrogen into mineral nitrogen. Without microbiological activity, vines would suffer severe nitrogen deficiency and not survive. However, microbial rules and interactions in vineyard soils are highly complex and we cannot yet say for certain that higher microbiological activity systematically induces higher quality and enhanced terroir expression. Very high microbiological activity in the soil would simply result in excessive nitrogen release, which is detrimental to wine quality, in particular in red wine production (Choné et al. 2001). Soil microbiology has recently received increased attention because the soil microbiome is site-specific (Bokulich et al. 2014). However, the relationship between vine health and healthy biomes needs further investigation.

**Effect of Soil Water Supply on Terroir Expression**

Vine water status depends on climatic parameters (rainfall and reference evapotranspiration), the capacity of the soil to store water, the transpiration rate of the vines, and, when applied, irrigation practices. The impact on vine
water status by soil and climate is similar in magnitude (van Leeuwen et al. 2004). Soil water is stored in soil porosity. Except for water-logged soils, water is drained out of the large soil pores (>10 µm in diameter). Water in extremely small pores (<0.2 µm in diameter) cannot be extracted by vine roots. Pores within the 0.2 µm to 10 µm range can store water against deep drainage and yet progressively release it to the vines. The percentage of total soil volume within this range of pore size varies with soil texture: approximately 5% in a very sandy soil, 10% is a very clayey soil, and 20% in a very silty soil (Saxton et al. 1986). Hence, soil texture has a major impact on vegetative and soil-water movements. Soil water holding capacity can be considered infinite because water consumed by the vines will be replaced through lateral soil-water movements.

Vine water status has a major impact on vegetative and reproductive growth, fruit composition and wine quality. Evidence that regular, but limited, water supply to the vines is a major factor explaining the terroir effect was first published in the 1960s (Seguin 1969) and confirmed many times since (Duteau 1987; van Leeuwen et al. 1994; Trégoat et al. 2002; Koundouras et al. 2006; van Leeuwen et al. 2009). Limited water supply leads to shoot growth cessation and restrains berry growth, in particular when water deficits occur pre-véraison (Table 2). Water deficit also reduces berry malic acid content (Table 2). The impact of water deficit on berry sugar content is non-linear: grape sugar is increased under mild water deficit because of reduced carbon allocation to shoots, but sugar is reduced under severe water deficit because of restrained photosynthesis (van Leeuwen et al. 2009). Water deficit increases skin phenolics, in particular anthocyanins (Table 2; Duteau et al. 1981; Trégoat et al. 2002; Ollé et al. 2011), which is a major asset in the production of high-quality red wines. Limited water supply to the vines increases precursors of many aromas in red grapes (Koundouras et al. 2006) and improves the aging bouquet of fine red wines (Picard et al. 2017) and their global quality (Table 2; Koundouras et al. 2006). Severe water stress, however, can impair red wine quality.

Vine water deficit is not a major driver of white wine quality because their aromas may be negatively impacted. Strong water deficit negatively impacts aromas from the volatile

### Table 2

<table>
<thead>
<tr>
<th>Location</th>
<th>Saint-Emilion (Bordeaux)</th>
<th>Saint-Emilion (Bordeaux)</th>
<th>Nemea (Greece)</th>
<th>Bordeaux</th>
<th>Saint-Emilion (Bordeaux)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cultivars</td>
<td>Cabernet Franc</td>
<td>Merlot, Cabernet Franc, and Cabernet-Sauvignon</td>
<td>Agiorgitiko</td>
<td>Merlot</td>
<td>Merlot</td>
</tr>
<tr>
<td>Number of observations</td>
<td>8</td>
<td>72</td>
<td>6</td>
<td>10</td>
<td>48</td>
</tr>
<tr>
<td>Reference</td>
<td>(1)</td>
<td>(2)</td>
<td>(3)</td>
<td>(4)</td>
<td>(5)</td>
</tr>
<tr>
<td>Indicator of water deficit</td>
<td>average pre-dawn leaf water potential – harvest</td>
<td>minimum pre-dawn leaf water potential – harvest</td>
<td>average pre-dawn leaf water potential – harvest</td>
<td>pre-dawn leaf water potential at ripeness</td>
<td>minimum stem water potential over the season</td>
</tr>
<tr>
<td>Shoot growth cessation (day of the year)</td>
<td>0.95***</td>
<td>0.66***</td>
<td>0.94**</td>
<td>0.71***</td>
<td></td>
</tr>
<tr>
<td>Total shoot length (cm)</td>
<td>0.63**</td>
<td>0.83*</td>
<td>0.94**</td>
<td>0.71***</td>
<td></td>
</tr>
<tr>
<td>Véraison (day of the year)</td>
<td>−0.04NS</td>
<td>0.54NS</td>
<td>0.79**</td>
<td>0.77***</td>
<td></td>
</tr>
<tr>
<td>Berry weight (g)</td>
<td>0.71*</td>
<td>0.44***</td>
<td>0.54NS</td>
<td>0.79**</td>
<td></td>
</tr>
<tr>
<td>Yield (kg/vine)</td>
<td>0.45NS</td>
<td>0.69*</td>
<td>0.45NS</td>
<td>0.69*</td>
<td></td>
</tr>
<tr>
<td>Grape sugar (g/L)</td>
<td>−0.68NS</td>
<td>−0.25*</td>
<td>−0.93**</td>
<td>−0.16NS</td>
<td></td>
</tr>
<tr>
<td>Total acidity (g tartrate/L)</td>
<td>0.58NS</td>
<td>0.53***</td>
<td>0.74NS</td>
<td>0.77***</td>
<td></td>
</tr>
<tr>
<td>pH</td>
<td>−0.58***</td>
<td>−0.58***</td>
<td>−0.94**</td>
<td>−0.94**</td>
<td></td>
</tr>
<tr>
<td>Malic acid (g/L)</td>
<td>0.85**</td>
<td>0.51***</td>
<td>0.87*</td>
<td>0.55NS</td>
<td></td>
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<tr>
<td>Tartaric acid (g/L)</td>
<td>0.04NS</td>
<td>0.04NS</td>
<td>−0.94</td>
<td>0.83***</td>
<td></td>
</tr>
<tr>
<td>Grape anthocyanins (mg/L)</td>
<td>−0.78*</td>
<td>−0.67NS</td>
<td>−0.92***</td>
<td>−0.51***</td>
<td></td>
</tr>
<tr>
<td>Wine anthocyanins (mg/L)</td>
<td>−0.84**</td>
<td>−0.64NS</td>
<td>−0.90***</td>
<td>−0.51***</td>
<td></td>
</tr>
<tr>
<td>Total phenolics (index)</td>
<td>−0.54NS</td>
<td>−0.48***</td>
<td>−0.98***</td>
<td>−0.99***</td>
<td></td>
</tr>
<tr>
<td>Ripening speed</td>
<td>−0.54NS</td>
<td>−0.48***</td>
<td>−0.98***</td>
<td>−0.99***</td>
<td></td>
</tr>
<tr>
<td>Global wine quality (rating)</td>
<td>−0.54NS</td>
<td>−0.48***</td>
<td>−0.98***</td>
<td>−0.99***</td>
<td></td>
</tr>
</tbody>
</table>

**Significance**: *, **, *** represents significance at p < 0.05, 0.01, and 0.001, respectively; NS: not significant

**References**: (1) van Leeuwen et al. (1994); (2) van Leeuwen et al. (2004); (3) Koundouras et al. (2006); (4) Trégoat et al. (2002); (5) van Leeuwen et al. (2009).
thiol family and, thus, reduces the quality of white wines produced from Sauvignon Blanc (Peyrot des Gachons et al. 2005).

As regards terroir expression and irrigation, it may be noted that full irrigation would not (as deduced from the above) be good for red wine production. Irrigation tends to be used sparingly in the Old World but is a factor in some wines produced in the New World.

INTEGRATIVE INDICATORS IN TERROIR STUDIES

Soil Depth

Soil depth has a slightly different meaning for soil scientists and viticulturists. For soil scientists, soil depth represents the weathered layer above the parent rock. When vines are established, this layer is generally explored by the root system. For viticulturists, however, soil depth corresponds to rooting depth, which can extend beyond the weathered soil layer when parent material is either soft or contains cracks.

The role of soil in terroir expression is often erroneously attributed to deep-rooting vines. The first vineyard soils to be studied on a scientific basis were from the Médoc area of Bordeaux (Seguin 1969). These Médoc sandy soils had a high gravel content, and their capacity to store water was so low that deep rooting was necessary to prevent vines from facing excessive water stress during dry summers. Later, a very popular wine atlas was published by Hugh Johnson (1977) in which he reproduced a soil profile from Seguin’s study but, unfortunately, from which many wine writers subsequently concluded that deep rooting is always a critical factor for terroir expression. In most situations, the relationship between rooting depth and wine quality is rather the opposite. When soils are not extremely poor, deep rooting provides access to unlimited water and possibly nitrogen, which increases vine vigour and yield. This then decreases the quality attributes of the grapes, such as the anthocyanins and tannins that go to make a good red wine. The effect of soil depth on grape quality was investigated by Morlat and Bodin (2006) and by Bodin and Morlat (2006) in the Loire Valley (France). These authors compared phenology, yield parameters and grape composition for three groups of vineyard soils under increasing depths applied to weakly weathered rock, moderately weathered rock and strongly weathered rock. The highest grape quality potential was obtained from soils derived from weakly weathered rock and with limited depth and soil-water availability. These conditions tended to make the soil temperature in the root zone higher, thereby enhancing the precociousness of subsequent phenological stages and grape ripening curves.

For sites on hillsides, erosion is a key driver of soil depth (Brenot et al. 2008), shallow soils being located upslope and deeper colluvial soils distributed closer to and at the bottom. This is the case in Burgundy where the highest quality wines are produced at the middle and top parts of the slopes (Wilson 1998). On the richer soils at the bottom of the slopes, lower quality wines are produced. Because vine performance is often closely related to soil depth, soil depth can be used as an integrative parameter in terroir studies.

It is not desirable, however, to have roots located in the top 20 cm of the soil because this zone is generally too rich in nitrogen. Roots close to the soil surface may also pick up water from rainfall events close to harvest time, with possible dilution of grape components. Managing the vineyard floor with the use of cover crops or mechanical weed destruction (tilage) tends to prevent roots from colonizing the layer close to the soil surface. Weed control with herbicides, on the other hand, can promote shallow root growth.

Vine Vigour

Vine vigour is driven by plant material (in particular the rootstock) and soil fertility. When plant material is homogeneous over a given area, vigour can be used as an indicator of the effect of environmental factors on the vine (for an example see Fig. 2B). Vigour can be easily mapped by means of remote sensing and used as a zoning tool, as described by Hall (2018 this issue).

MANAGEMENT OF TERROIR

Human Factors in Terroir Expression

Because a vineyard is a cultivated ecosystem, the grape grower plays a major role in terroir expression. He or she can orientate terroir expression through the choice of plant material and management practices. In this way, it is possible to manage terroir in order to maximize terroir expression in each location.

Indicators of Major Terroir Parameters

Water and nitrogen supply to the vines, as well as soil temperature, are major soil-related terroir parameters. Many indicators of vine water and nitrogen status have been developed over the past decades. Among these indicators, δ13C measured in grape juice is a convenient tool for assessing vine water status (van Leeuwen et al. 2009). The δ13C method is based on the observation that grape sugar is enriched in 13C (compared to 12C) when vines are grown under water deficits. Yeast available nitrogen (YAN) is a practical indicator for assessing vine nitrogen status at high throughput (van Leeuwen 2010). By means of these tools, vine water status (Fig. 3) and vine nitrogen status (Fig. 4) can be mapped at high resolution. In this example (from Château Pape Clément, appellation Pessac–Léognan), the soils are gravelly and are rich in organic matter in the western part of the vineyard, explaining greater water deficit and higher vine nitrogen status compared to the eastern part where soils are more clayey and lower in organic matter. Soil temperature can be measured, but because it is variable both spatially and temporally it is not easy to compute a relevant indicator. Warm and cool soils can be identified by experience: warm soils tend to be coarse textured and high in coarse elements. Because the relevant factor for soil temperature is the temperature in the root zone, shallow rooting soils can also be considered as warm soils.

Management of Vine Water Status

The production of high-quality red wines requires moderate water deficits. Frequently, red wine grapes are negatively affected by too much soil water. There are no clear vine symptoms for this, so it can be overlooked by growers. In situations of excess vine water, the selection of soils with low soil water holding capacity and the implementation of training systems that increase transpiration (e.g. high planting density, high leaf area per hectare) may help to reach water deficit levels that promote wine quality. White varieties generally perform better in soils with high soil water holding capacity than red varieties. Installation of drainage tiles is only a partial solution, because they only allow the evacuation of water stored in macro pores. In soils with high soil water holding capacity, large amounts of water are stored in micro pores and drainage tiles have little effect. In dry climates, where excessive water stress may negatively impact yields and jeopardize wine quality, vineyard soils should have at least a medium
soil water holding capacity. The choice of plant material is a powerful tool to protect vineyards against drought through the combination of drought-resistant rootstocks and drought-resistant cultivars. Another possible adaptation to dry conditions is the use of the Mediterranean bush vine training system (called the "gobelet"). When such adaptations still do not result in high-quality wines with economically sustainable yields, irrigation can be considered if there are adequate water resources available. Only deficit irrigation, however, is compatible with terroir expression.

**Management of Vine Nitrogen Status**

Vine nitrogen status is a terroir parameter easy to manage. When vine nitrogen status is very low, yield and vine vigour may be overly impacted. Red wine quality potential can be negatively impacted by low nitrogen availability, but important white wine aromas can be jeopardized. Vine nitrogen status can then be adjusted by organic or mineral fertilizers. If the vine nitrogen status is too high, it may provoke excessive vigour, thereby negatively impacting red wine quality potential and increasing susceptibility to grey rot (*Botrytis cinerea*). Cover crops can be an easy-to-implement solution to decrease vine vigour by acting as competition for available nitrogen.

**Management of Soil Temperature**

Optimal terroir expression is closely related to the timing of ripeness of the grapes at the end of the season, avoiding high temperatures if too early and cool temperatures if too late. The timing of ripeness is mainly driven by air temperature, but is also impacted by soil temperature, slope and aspect. When, in a given region, grapes tend to ripen too early, ripeness can be delayed by using later-ripening varieties or by setting plants on north-facing slopes (south-facing slopes in the Southern Hemisphere). When grapes tend to ripen too late, the use of early ripening varieties may help to achieve a more regular full ripeness of the grapes. And when an important variety for a given region reaches ripeness at the end of the ripening window, planting in warm soils or on south-facing slopes (north-facing in the Southern Hemisphere) should be preferred to reach full ripeness more easily.
CONCLUSION
The relationship between the sensory attributes of a wine and its origin is referred to as the “terroir” effect. Soil is a major factor in terroir expression, with its effect being mediated through the vine. Hence, soil–vine interactions have to be taken into account when studying the effect of soil on terroir expression. The soil effect has to be broken down into quantifiable components so as to measure its impact on grape composition and wine quality. Soil mainly influences grapevine phenology, vegetative and reproductive development, and grape composition through its effect on temperature in the root zone, as well as through its impact on vine water and nitrogen status. Tools have been developed to quantify these effects, both temporally and spatially. Once the major terroir parameters are quantified, growers can adapt their plant material and management practices accordingly, and so optimize terroir expression in their particular vineyard site.

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The Climate Component of Terroir

Gregory V. Jones

Climate's Role in the Expression of Terroir in Wine Characteristics.

<table>
<thead>
<tr>
<th>Wine Characteristic</th>
<th>Cool Climate</th>
<th>Intermediate to Warm Climate</th>
<th>Warm to Hot Climate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fruit Style</td>
<td>Lean, Tart</td>
<td>Ripe, Juicy</td>
<td>Overripe, Lush</td>
</tr>
<tr>
<td>White Flavors</td>
<td>Apple, Pear</td>
<td>Peach, Melon</td>
<td>Mango, Pineapple</td>
</tr>
<tr>
<td>Red Flavors</td>
<td>Cranberry, Cherry</td>
<td>Berry, Plum</td>
<td>Fig, Prune</td>
</tr>
<tr>
<td>Body</td>
<td>Light</td>
<td>Medium</td>
<td>Full</td>
</tr>
<tr>
<td>Acidity</td>
<td>Crisp, Tangy</td>
<td>Integrated</td>
<td>Soft, Smooth</td>
</tr>
<tr>
<td>Alcohol</td>
<td>Low to Moderate</td>
<td>Moderate to High</td>
<td>High to Very High</td>
</tr>
<tr>
<td>Overall Style</td>
<td>Subtle, Elegant</td>
<td>Medium Intensity</td>
<td>Bold</td>
</tr>
</tbody>
</table>

Keywords: terroir, grapevines, wine, viticulture, enology, climate

INTRODUCTION

All crops have environmental controls which influence productivity and quality. Geology, soil, landscape variations, weather, and climate each play prominent roles in agriculture with the relative importance varying by scale and crop. What aspect of these factors is most important for a given crop? For the majority of agricultural enterprises climate plays the most fundamental role by influencing whether a crop is suitable for a given region, controlling crop productivity and quality, and, ultimately, driving economic sustainability (van Leeuwen et al. 2004; Jones et al. 2012). The role that climate plays in agriculture can be broadly divided into its influence on the quality and productivity of broadacre crops and specialty crops. While broadacre crops such as wheat, corn, rice, and soybeans are grown across relatively wide geographic and, therefore, climatic ranges, specialty crops, which include coffee, avocados, cacao, pineapples, and winegrapes, are suited only to very narrow geographic ranges that experience quite specific climates.

As a component of terroir, the overall climatic influence on wine can be discussed from two interrelated perspectives: ripening potential, and wine style. In terms of ripening potential, winegrapes can be grouped into early, intermediate, and late maturing varieties (Jones et al. 2012). Early maturing varieties (e.g. Müller Thurgau, Gewürztraminer, Chardonnay, Pinot Noir) do best in cool climates that have relatively short growing seasons; later maturing varieties (e.g. Cabernet Sauvignon, Mourvèdre, Grenache) require warmer and longer growing seasons. The interaction between varieties and climate also produces variations in wine styles that are the most easily identifiable for consumers: the general characteristics of wines from a cool climate versus those from a warm-to-hot climate. Varieties that are best suited to a cool climate tend to produce wines having a lower alcohol content, crisp acidity, a lighter body, and typically bright fruit flavors. In contrast, those from hot climates tend to have a higher alcohol content, soft acidity, a fuller body, and more dark or lush fruit flavors (Table 1).

However, while climate is the dominant factor that controls ripening potential and wine style characteristics, geology and soil produce the subtle differences and/or the expression of fruit characteristics and wine styles within the same climate or region.
When assessing climate’s role in terroir and growing wine grapes for wine production one must consider a multitude of factors that operate over various time periods and over many spatial scales. In this article, general climatic influences important for wine grapes are discussed at the macroscale (hemispheric to global climates), the mesoscale (regional climates), the toposcale (site climates), and the microscale (vine row and canopy climate).

**GLOBAL TO REGIONAL CLIMATE COMPARISONS**

Globally, grapevines are grown in regions where temperatures during the growing season average 13–21 °C (Jones 2006). These temperature limits are found mostly in the mid-latitude regions of the continents in both hemispheres (e.g., Europe, North and South America, Australia, New Zealand, and South Africa). However, using latitude as a comparison for climate suitability for viticulture and wine production is often misunderstood. A common statement made by growers/producers in many regions in both the northern and southern hemispheres is that “we are on the same latitude as Bordeaux; therefore, we can grow the same varieties and make the same quality and style of wine as Bordeaux.” But unless one has been to Bordeaux, it is hard to imagine that the climate there is substantially more humid with much greater rainfall during the growing season than the commonly compared wine region, Napa Valley (Nemani et al. 2001). While both are known for their Cabernet Sauvignon wines, they do it in quite different climates. Bordeaux has relatively low daytime temperatures and high nighttime temperatures due to higher humidity, whereas the Napa Valley has much higher daytime temperatures and much lower nighttime temperatures due to lower humidity. This has mostly to do with the ocean temperatures offshore and the orientation of the coastlines.

The historical classification of climates has allowed for broad comparisons of wine region climates, with the most common being the Köppen climate classification system. As originally developed, it was broadly based on the expression of climate in the native vegetation and combines average annual, seasonal, and monthly, temperatures and precipitation to define homogeneous regions. The modified version of the system in use today divides all climates into six broad groups: tropical climates, dry climates, mild mid-latitude climates, severe mid-latitude climates, polar climates, and highland climates (Peel et al. 2007). Each of these six groups are further subdivided according to various temperature and precipitation characteristics. Due to the geography of the Old World wine regions of Europe and the use of the Köppen system, wine production has become synonymous with Mediterranean (i.e., mid-latitude) climates. However, Mediterranean climate types only make up roughly 15 percent of the surface area of wine regions globally (Jones et al. 2012). Other important mid-latitude climate types include humid subtropical (e.g., eastern US, eastern Australia, Uruguay), maritime temperate (e.g., Bordeaux), and maritime Subarctic (e.g., British Columbia). Other prominent Köppen climate types that wine regions fall within include mid-latitude dry-cold (e.g., Colorado (USA), Iran), subtropical dry climates (e.g., Priorat (Spain) and Mendoza (Argentina)), and humid continental severe mid-latitude climates (e.g., Finger Lakes Region (New York, USA) and Niagara (Canada)).

**INDIVIDUAL WEATHER/CLIMATE FACTORS IN TERROIR**

Individual weather/climate factors affecting grape growth, production, and wine quality include solar radiation, average temperatures, temperature extremes (including winter freezes, spring and fall frosts, and summer heat stress), heat accumulation, ripening period temperatures, wind, precipitation, humidity, and soil water balance characteristics (Fig. 1). At scales from a region to a site, these factors can be strongly controlled by landscape and soil variations, thereby creating numerous interactions within these factors.

**Solar Radiation**

Throughout the growth stages of the grapevine, the amount of insolation (i.e. sunlight reaching the Earth’s surface) is critical in maintaining the proper levels of photosynthesis (Mullins et al. 1992). The most critical stages come during the development of the berries (yes, grapes are called berries!) starting at bloom and continuing through the harvest. During bloom, high amounts of insolation result in effective plant tissue differentiation into flowers. Low absolute insolation during the bloom stage can influence “coulure” (the failure of grapes to develop after flowering) and can also impact the differentiation of inflorescence primordia in the buds, ultimately reducing fertility for the next season. The relationship between low amounts of insolation and coulure is not linear, nor predictable, but is seemingly tied to varietal characteristics. During the ripening of the berries, insolation acts to control anthocyanin (color) development, and the amount of sugar in the grapes, and, therefore, the wine’s potential alcohol content. Controls on the amount of insolation include: 1) those...
that are inherent with Earth/Sun relationships, such as overall amount received by any point on the surface of the Earth, seasonal variations in the angle of incidence of the sun's rays, and the day length; 2) those that are controlled by variations at or near the Earth's surface, such as cloud cover, the reflective nature of the surface of the soil, and the role topographic variations (slope, aspect, and obstruction) have on the relative amount of insolation received. Growers also have some measure of control on insolation through row orientation and canopy management practices that can reduce impacts on leaves and berries.

**Average Temperatures, Heat Accumulation, and Bioclimatic Indices**

Growing season duration and temperatures are a critical aspect of viticulture because of their major influence on grape ripening and fruit quality, and, therefore, variety adaptation to specific regions or sites (Gladstones 1992). It is in its ideal climate that a given grape variety can achieve optimum ripening profiles of sugar and acid that can be naturally timed with flavor component development to maximize a given style of wine and the vintage quality. The growing season necessary for the cultivation of winegrapes varies across early to late ripening varieties and from region to region, but averages approximately 170–190 days (Mullins et al. 1992). The general thermal environment for grapevines has numerous influences, which can be positive or detrimental depending on the timing with plant growth. Negative influences typically come from extremes but can also come from prolonged periods of average temperatures that are below normal during growth events such as bloom. Positive influences include how prolonged temperatures above 10°C can initiate plant growth in the spring and how temperatures influence overall heat accumulation, which in turn drive ripening potential.

In addition to the air temperature, both within and outside the canopy, the temperature of the soil can have a strong influence on vine growth and fruitfulness (Vaudour et al. 2015). This is especially important during the spring where warmer soils initiate root growth sooner and, when combined with warm air temperatures, accelerates sap flow and budbreak. During later growth stages, warm soil surfaces, enhanced by heat retention from rocky surface or subsurface material, aid in ripening by warming the vine canopy during the day and into the night. Furthermore, during the winter (from after leaf fall through budbreak the next year), an average temperature minimum or effective chilling unit (hours below a certain temperature) is generally needed to effectively set the latent primary buds for the following year (Keller 2010).

A simple measure of temperature’s role in terroir is maturity groupings based upon average growing season temperatures (Fig. 2). Average growing season temperatures (April through October in the Northern Hemisphere; October through April in the Southern Hemisphere) are statistically identical to growing degree days and similar to other bioclimatic indices (Jones et al. 2012) but they use more readily available data; they are generally easier to calculate, use and understand; and they have been related to the potential of varieties to mature in climates worldwide. Data from average growing season temperatures show that quality wine production is limited to 13–21 °C worldwide. Many of the varieties shown in Figure 2 are grown and produce wines outside of their individual bounds depicted, but these are more bulk wine (high yielding) for the lower end market and do not typically attain the typicity (the characteristic of a wine that makes it typical for the region or grape of origin) or quality for those same varieties in their ideal climate. Furthermore, growing season average temperatures below 13°C are typically limited to hybrids or very early ripening varieties that do not necessarily have large-scale commercial appeal. At the upper limits of climate, some production can also be found with growing season average temperatures greater than 21 °C, although it is mostly limited to bulk wines, fortified wines, table grapes, and raisins.

Good examples of how average growing season temperatures define suitability are found with three common varieties: Pinot Noir, Chardonnay, and Cabernet Sauvignon. Pinot Noir is typically grown in regions that span cool to lower intermediate climates with average growing season temperatures that range from roughly 14.0–16.0°C [e.g. Burgundy (France) or the Willamette Valley (Oregon, USA)]. One of the coolest of these is the Tamar Valley of Tasmania (Australia), while one of the warmest is the Russian River Valley of California. Across this 2°C climate niche, Pinot Noir produces the broad style for which it is known, the cooler zones producing lighter, elegant wines, and the warmer zones producing more full-bodied, fruit-driven wines (Table 1). While Pinot Noir can be grown outside the 14.0–16.0°C growing season average temperature bounds it is typically unripe or overripe and readily loses its typicity and quality. Compared to Pinot Noir, Chardonnay has been found to be one of the most flexible and forgiving varieties, producing a range of wine styles across a wider range of temperatures. Chardonnay can be grown in relatively cool climates (~14–16°C average growing season temperature) creating an elegant, crisp style that is characterized more by apple and pear, whereas in warmer climates (~16–18°C) it produces a bolder style with more peach to honey notes that is often enhanced via the use of oak barrel ageing. On the other hand, Cabernet Sauvignon is an intermediate to warm-to-hot climate variety with growing seasons that

![Figure 2](image-url)
range from roughly −16−20°C (e.g. Bordeaux or Napa). An example of a region near the lower climate limit for Cabernet Sauvignon suitability is Hawke’s Bay (New Zealand), while one of the warmest at the upper climate limit is in Robertson (South Africa).

In addition to average growing season temperatures, ripening period temperatures are important for quality wine production (Gladstones 1992). The ripening period is broadly defined as the growth stage that starts with véraison (the initiation of sugar accumulation and the change in berry color) to harvest. This period averages 40–60 days for most varieties and wine regions, with research pointing to the importance of the last 30 days, which is when the majority of the polyphenols, color, flavor, and aroma compounds develop (Keller 2010). During this period, the diurnal temperature range has a strong influence on the quality potential of the fruit and the resulting wine. For example, the majority of the cooler climate varieties achieve greater typicality in ripening periods with higher diurnal temperature ranges whereby daytime temperatures are high enough to facilitate ripening and nighttime temperatures can slow respiration and metabolism. These conditions bring about the more delicate aromas and wine styles associated with cool to intermediate climate varieties. Many warmer climate varieties, on the other hand, typically require warmer nighttime temperatures to more fully ripen and to metabolize compounds that are considered detrimental to quality. For example, Cabernet Sauvignon contains a high concentration of methoxypyrazines, which are responsible for the characteristic “green, herbaceous, or vegetative” aromas from under-ripe fruit. One of the implications from a warming climate is that the sensitive ripening period has shifted from cooler autumn conditions to the hotter conditions of late summer in many regions worldwide.

**Temperature Extremes**

In contrast to average temperature influences on potential vine growth, ripening, and wine style, some of the most important individual temperature aspects include the potential of mid-winter low-temperature injury, late spring frosts, and the influence of excessive summer heat on grape quality. In regions that have a more continental climate (e.g. eastern Washington, or Niagara), low temperatures during the winter can lead to icewine harvests but, depending on the severity, also lead to vine injury and a severe limit on production viability. Research has also shown that there is a minimum winter temperature that the grapevines can withstand. This minimum ranges from −5°C to −20°C, with some varieties and hybrids more cold hardy than others (Keller 2010), and is chiefly influenced by microscale climate variations controlled by location and topography. Temperatures below these thresholds will damage plant tissue by the rupturing of cells, enzyme reductions by dehydration, and a disruption of membrane function that could eventually kill the vines (Mullins et al. 1992).

In the spring, prolonged temperatures above 5–10°C initiate vegetative growth (Winkler et al. 1974; Jones et al. 2012). However, during the spring growth stage, temperatures below 0°C can damage vegetative parts of the plant, and hard freezes (−2−2.2°C) can reduce the yield significantly by injuring leaf and fruiting tissue. Nearing maturation in the fall, early frost or freezes can lead to the rupture of the grapes, which in turn influences disease development and can result in a significant loss of weight in the fruit. Frost and/or freeze occurrence during the spring and fall generally comes in two forms: 1) advection frosts and 2) radiation frosts. An advection frost occurs as cold air masses are brought into a region with the passage of a cold front. Frosts and freezes associated with cold air masses can occur sporadically during the spring and fall and can cause problems over the majority of a region. Radiation frosts, on the other hand, occur throughout most of the fall, winter, and spring; are strongly influenced by local topographic features; and are a much more common problem in wine regions. Radiation (or ground) frosts occur as the ground and the air in the lower layers of the atmosphere (within and just above a grapevine canopy) give off heat, warming the air in successive layers upward while the colder air sinks into the lower lying areas (i.e. an inversion). If the dew point temperature is low enough, the result is that the air near the ground is cooled to the frost point. On nights when inversions form, a warmer thermal zone or belt develops upslope that provides a measure of protection from the coolest valley bottom sites (Gladstones 1992). The thermal zone varies from region to region but is generally found from 30 to 300 meters off the valley floor (in narrow valleys, vineyards need to be situated higher up in elevation than in broad valleys). Inversions are common in many grape-growing regions globally and occur most frequently on long, calm, cloud-free nights (Jones et al. 2012).

At the other end of the spectrum of temperature influences, extreme heat (temperatures greater than 35°C) in either the growing season or ripening period, negatively impacts winegrape production through the inhibition of photosynthesis (Gladstones 1992). High temperatures can even delay maturity and reduce color development and anthocyanin production. While a few days of temperatures greater than 30°C can be beneficial to ripening potential, prolonged periods >35°C can induce heat stress in the plant and lead to premature véraison (color change and start of ripening), a possible abscising of the berries, and (partial or total failure of flavor ripening (Mullins et al. 1992).

**Wind**

The role that the wind—both speed and direction—plays in the growth of the grapevine and the production of fruit is mainly through the effects on vine health and yield. But wind can also play a role on the heat budget of a vineyard. This is exhibited in both a physical nature, through direct contact with the vines and through physiological effects of photosynthesis disruption (stomata closure) and reduced disease infestations (Mullins et al. 1992). During the early stages of vegetative growth, high winds can break off the new shoots, delaying and even reducing the amount of flowering. As the berries proceed through véraison and into the maturation stage, high winds can be very effective at desiccating the fruit and can result in lower volume and quality. However, drying winds that occur at night and early morning can help reduce the occurrence of fungusborne diseases through limiting the formation of dew on the leaves and berries (Jones et al. 2012). Nighttime winds can also be beneficial in that they can help limit the occurrence of radiation frosts in some regions.

Local winds, generated from a region’s topography, are very common in viticulture areas worldwide. The most common local winds are the general land–sea breeze (affecting coastal regions or regions near large bodies of water) and the mountain-valley breeze (affecting inland areas with substantial topographical relief), which provides the dry-summer viticulture regions with some relief through late afternoon advection from the coast or down the mountains. Although the overall occurrence of winds can have both positive and negative effects on the growth and maturation of grapevines, they can be mitigated somewhat by location, topography, and the use of natural and human-made windbreaks. However, windbreaks in a region might also serve as an obstruction for cold air drainage and could enhance frost or freeze conditions.
Precipitation, Humidity, and Water Balance Characteristics

Given its importance to the growth and productive balance in grapevines, fruit quality, fruit yield, and disease pressure, understanding water relationships in any wine region is critically important (Jones et al. 2012). Factors such as ambient atmospheric moisture or humidity, local rainfall rate, duration, frequency and timing, soil water holding capacity, and evapotranspiration rates are all important aspects. In addition, each of these aspects of water availability can be evaluated in terms of a water balance, or water budget.

Atmospheric humidity is very important in regulating the evaporative demands put on the grapevines and the occurrence of fungal diseases. During the growth stages of the grapevine, some of the climatic conditions that can most severely afflict the vines and berries are associated with moisture. Atmospheric moisture is commonly measured as relative humidity (i.e. a measure of the amount of moisture in the air at a given temperature), and, as such, displays a distinct diurnal and seasonal cycle. Relative humidity is normally highest early in the morning, when temperature is lowest, and at a minimum during the maximum heating of the day. The contrasts between morning and afternoon relative humidity are the least along coastal regions and the greatest inland. Because lower temperatures give higher relative humidity, and because cold air can pool in valleys and in obstructed areas on slopes, humidity levels and the associated fungal problems can be enhanced in these zones (Gladstones 1992). Over the course of the season, relative humidity is lowest during the summer and highest during the winter with the contrast between the seasons being the greatest for the afternoon values. However, in extreme cases, water stress resulting from low relative humidity can be seen in leaf loss, severe reductions in vine metabolism, and fruit damage or loss (Mullins et al. 1992). Even moderate periods of moisture stress can substantially reduce the relative level of photosynthesis, resulting in lower fruit yields and quality. However, controlled moisture stress through irrigation, applied at the right times during growth and ripening, can enhance quality and control yields (Keller 2010).

While high levels of atmospheric moisture allow certain fungal problems to develop, the occurrence of rain during critical growth stages can lead to devastating effects. Ample precipitation during the early vegetative stage is beneficial to initial growth, but during bloom it can reduce or retard flowering; during berry growth it can enhance the likelihood of fungal diseases; and during maturation it can increase fungus occurrence and growth, dilute the berries (which reduces the sugar and flavor levels) and severely limit the yield and quality (Mullins et al. 1992). Annual rainfall varies tremendously in wine regions worldwide, from 200 mm to 1,800 mm, with some regions experiencing rain all year while others have wet winters and dry summers. In hot climates, grapevine viability seems to be limited if annual rainfall is less than 500 mm, although this problem can be overcome by regular irrigation, if available and allowed. Extreme meteorological events, such as thunderstorms and hail, while generally rare in most viticultural regions, are extremely detrimental to the crop. Both events can severely damage the leaves, tendrils, and berries during growth and if they occur during maturation can split the grapes, causing oxidation, premature fermentation, and a severe reduction in volume and quality of the yield (Keller 2010).

As an integration of many climate parameters, a soil–water balance takes into account seasonal variations in temperature, precipitation, and available soil moisture to give an estimation of water requirements (either natural or via irrigation). A water balance essentially defines the “water need” by plants and the atmosphere in any region. In most grape-growing regions there is a period of soil–water surplus from late fall through late spring, followed by a period of draw-down of soil moisture through evaporation (by the atmosphere) and transpiration (by plants) during the summer through the early fall, when precipitation begins replenishing the soil. Adequate soil moisture recharge during the spring can drive vine growth and result in more effective bloom and berry set. While water deficits during the summer growth period tend to positively affect wine quality (van Leeuwen et al. 2009), some soil moisture during this period can also reduce heat stress. However, high levels of soil moisture can drive too much vegetative growth and lead to inadequate ripening along with delayed leaf fall, putting the vines at risk of late fall frost/freeze events (Keller 2010).

IS THERE AN IDEAL CLIMATE FOR WINE PRODUCTION?

Given the discussion above regarding the complex climate influences on growing grapes for wine production, is there such thing as an ideal climate? First, it is clearly best to match the grape variety to its climate requirements. In its optimum zone, a given variety will more consistently produce higher quality fruit and wine because the optimum climate provides a more equitable growth period and tends to balance the four ripeness clocks that are running simultaneously but at different rates – sugar accumulation, acid respiration, phenolic ripeness, and fruit character (Jones et al. 2012). However, even if a variety is planted in its optimum zone, vintage variations in weather and climate can drive large differences in fruit production, wine quality, and wine styles. Furthermore, any given variety has thresholds associated with climate (see Fig. 2) where if it is being grown in too cool a region, or the growing season is too cool, then lower sugar levels, unripe flavors, and unbalanced wines will result (Jones 2006). Alternatively, if a given variety is being grown in too warm a region, or the vintage is too warm, then lower acid retention, overripe flavor, and unbalanced wines will result.

Even though the influences are complex and science has not yet come up with a simple, single measure to define and compare climate’s role in wine production universally, growers and producers would be very happy with the following conditions from harvest to harvest (Jones et al. 2012). After harvest and heading into winter, a grower would like to see a slow decline in temperatures that lead to a slow hardening of the vines. Rapid temperature drops during this time could damage the plants before they are ready for winter (hardened off). The over-winter period would ideally provide more moderate temperature impacts, but enough chilling for the vines to break buds evenly and initiate growth in the spring (Keller 2010). In the spring slow changes in day length combined with moist, but warming, soil profiles and frost-free conditions would allow for optimal and risk-free budbreak and initial plant growth. Around flowering, moderate daytime temperatures with high insolation, low cloud cover, and no rainfall would allow for an ideal bloom and fruit set. From fruit set to the start of ripening a summer filled with optimum heat accumulation for a given variety, with low day-to-day temperature variability, moderate water deficits, and low heat stress would lead to a greater chance of a timely and even véraison. From véraison to harvest, ideal conditions would see little to no rainfall with the vines ripening into the early fall where shortening day lengths bring about changes in diurnal temperature ranges and a balance of the four ripeness clocks (Jones et al. 2012).
CLIMATE CHANGE
In addition to the discussion above on climate structure and suitability, it is important to consider long-term changes in climate and their role in the sustainability of the industry. What is clear is that viticultural regions worldwide are located in relatively narrow geographical and climatic ranges (Jones 2006). In addition, winegrapes have relatively large varietal differences in climate suitability (Fig. 2), further limiting some winegrapes to even smaller areas that are appropriate for their cultivation (Moriondo et al. 2013). These narrow ‘niches’ for optimum quality and production put the cultivation of winegrapes at greater risk from both short-term climate variability and long-term climate changes than other broadacre crops. In general, the overall wine style that a region produces is a result of the region’s baseline climate, while climate variability determines vintage yield and quality differences. Both natural and human-induced climatic changes, which influence both variability and average conditions, therefore have the potential to bring about changes in wine production and wine styles. Our understanding of climate change and the potential impacts on viticulture and wine production have become increasingly important as changing levels of greenhouse gases and alterations in Earth surface characteristics bring about changes in the Earth’s radiation budget, atmospheric circulation, and hydrologic cycle (IPCC 2013).

Globally averaged surface temperatures have increased by ~0.9°C since the end of the 19th century (IPCC 2013). While both daily minimum and maximum temperatures have increased since 1950, many wine regions have seen variable day/night warming that has altered diurnal temperature ranges (Jones 2015). These observed temperature trends affect agricultural production viability by impacting winter hardening potential, frost occurrence, and growing season lengths (Jones 2015). One result of a warming climate is that, today, vineyards are found as far as 50°–57° N in Canada and Scandinavia and 44°–46° S in New Zealand, Chile, and Argentina (Jones and Schultz 2016). While opportunities exist for new wine-producing regions, existing regions with acclimated varieties and long-produced wine styles (i.e. terroir) face increased risks such as the intense European heatwaves in 2003, 2007, and 2015.

As a result of warmer climates, changes in grapevine growth events have been documented with earlier budbreak, bloom, véraison, and harvest dates seen in wine regions worldwide (Jones et al. 2012). Averaged over numerous locations and varieties, grapevine growth stages have shown an average 5 to 10 days earlier response per 1°C of warming over the past 30 to 70 years, with the intervals between phenological events 5–15 days shorter on average. One result is that many regions are seeing ripening that is occurring in a hotter period of the summer, with a greater disconnect between the four ripeness clocks (Webb et al. 2007). Trends to higher sugar levels and lower acidity in the fruit and higher alcohol levels in wines have been observed (Jones 2006) and appear to be partially tied to earlier plant growth driven by higher temperatures (Jones 2015) and a greater concentration of CO2 in the atmosphere (Kilmister et al. 2016).

CONCLUSIONS
Terroir is complex. There are numerous influences derived from the complex interactions between climate, geology, landscapes, and soils, along with how growers manage the plant system and producers manage the winemaking process, that ultimately produce the joy that is wine. While we know that climate is the baseline factor in the continuum of terroir influences—controlling what can be grown where and how—the complexity of the interactions means that simple descriptions of a wine’s geographic origin are hard to come by. Although one could specify a close-to-ideal climate for wine production, it is seldom experienced due to numerous factors, such as untimely rain, cold periods, heat stress, which make each vintage unique. Adding to the puzzle of climate’s role in wine production is the fact that one must also remember that geology, landscape, and soil are very important factors that mediate the interaction between climate and the wine, especially soil water supply and nutrition. These more local-scale influences produce the subtle style differences that give rise to much of the lexicon of terroir and wine. Moreover, we are now experiencing—and will continue to experience—changes in our climate that necessitate a more complex understanding of what wines are produced where and when.

REFERENCES
van Leeuwen C and 5 coauthors (2009) Vine water status is a key factor in grape ripening and vintage quality for red Bordeaux wine. How can it be assessed for vineyard management purposes? Journal International des Sciences de la Vigne et du Vin 43: 121-134
The most important characteristics upon which wines are evaluated are the intensity and complexity of their flavors. Flavor describes the combined impression created by both the volatile compounds, which are responsible for wine aroma, and the nonvolatile components, which determine the taste sensation. Environmental factors (topography, soil, climate), termed terroir, influence the levels of grape metabolites related to wine organoleptic properties, i.e., properties that can be detected by the sense organs, such as taste, color, odor, and feel. However, modern vineyard management practices have the potential to modify a vine’s response to natural site influences and so modify the flavor of the resultant wine.

INTRODUCTION
The berry of the grapevine (Vitis vinifera L.) has a complex chemical composition, containing hundreds of different compounds. Anatomically, berries have three major tissue compartments, each one differing in chemical composition and internal structure: the skin, the pulp (containing the juice), and the seeds (Fig. 1). The growth pattern of grape berries follows a double sigmoid curve with three distinct phases: first, an initial growth period starting after flowering (late May to mid-June in the Northern Hemisphere) characterized by rapid cell division and expansion in green berries; second, a short lag phase, which ends with véraison (change of color); third, a period in which cell expansion is resumed by active solute accumulation, corresponding to grape ripening (Fig. 2).

Among grape components, sugars provide the carbon skeletons for the synthesis of organic acids and nitrogenous compounds and constitute the primary metabolites imported into the berry from the leaves. Sugar and acid contents are important determinants of wine quality because they define the basic aspects of a wine’s chemical composition, such as alcohol content and acidity. The grape berry is also the site of biosynthesis of a diverse group of compounds, called “secondary metabolites”, which play an important physiological role in plant adaptation to abiotic constraints and pests, but which are also crucial in the determination of the quality of grape and wine attributes (color, taste, and aroma). The most important secondary metabolites, from a winemaking perspective, are the phenolic compounds, which give the principal sources of wine color and mouthfeel properties, and the volatile compounds, which are the major determinants of wine aroma.

Phenolic Compounds
Phenolic compounds comprise a miscellaneous group of over 4,000 natural plant products. Grape phenolics are classified into nonflavonoid (benzoic and cinnamic acids, plus stilbenes) and flavonoid (flavonols, anthocyanins, and proanthocyanidins). Among the latter, anthocyanins are the pigments located in the skins of grape berries (Fig. 1), and they determine the red color of the produced wines. Anthocyanins themselves are tasteless, or indistinctly flavored (Table 1). Accumulation of anthocyanins commences at véraison (Fig. 2) and reaches its maximum around harvest period.

Proanthocyanidins (or condensed tannins) are polymers composed of subunits of flavan-3-ols and derive from both the skins and seeds of the berries (Fig. 1). Tannins are responsible for the astringent and bitter sensation of red wines (“astringency” refers to the drying mouthfeel sensation that results from the interaction of wine tannins with salivary proteins). The intensity of astringency sensation is positively related to tannin concentration, but it is also determined by proanthocyanidin molecule size: the larger proanthocyanidins are more astringent, the smaller ones more bitter. Tannins from skins and seeds vary in their relative amount and size; therefore, their impact on wine sensory properties is different. Seeds are richer in short-chained tannins, giving a relatively bitter taste, whereas the more polymerized tannins from the grape’s skin contribute to the astringency sensation of the wines.

Tannin biosynthesis occurs after flowering, during the first period of berry growth, and reaches a maximum at véraison (Fig. 2). After véraison, seed tannins follow a continuous decrease while skin tannins change little. As a result of the changes in the amount of skin and seed tannins during berry development, the composition of the extracted tannins into a wine changes considerably at the final stages of ripening. This final stage is characterized by a proportional reduction in the more bitter tannin components of the seeds. Winemakers generally consider skin tannins to be more appropriate for the production of premium wines, compared to seed tannins. A potential explanation for this is that extracted skin tannins in ripe berries bind with anthocyanins and polysaccharides present in skin cell walls, which reduces their protein-interaction capacity and also contributes to the stabilization of wine color.

Phenolic compounds are particularly important for the quality of red wines produced from the processing of whole grapes. Thus, phenolic compounds are important indicators...
wine aroma intensity and complexity, but also form the nature, levels, and combination of volatiles determine low concentrations (on the order of $10^{-4}$ – $10^{-12}$ g/L). The aroma compounds, many of which we can detect at very low concentrations, form the sensory properties of phenolic compounds and is a concept related to a vast spectrum of changes, comprising flavonoid accumulation or degradation pattern, changes in flavonoid structural composition (e.g. polymerization), flavonoid interactions with other berry components and, finally, flavonoid extractability from skin and seed tissues during the winemaking process.

**Aroma Compounds**

The aroma of wine is caused by several hundred volatile aroma compounds, many of which we can detect at very low concentrations (on the order of $10^{-4}$ – $10^{-12}$ g/L). The nature, levels, and combination of volatiles determine wine aroma intensity and complexity, but also form the varietal character of wine, so differentiating one wine from another. The volatile components of grapes responsible for the varietal aromas are mainly localized in the internal cell layers of the skin of the berries and to a lesser extent, in the pulp and juice (Fig. 1). Pre- and postharvest grape handling can significantly affect the concentrations of the aroma molecules, simply because the amounts present in berries are inherently low.

Volatile compounds that contribute to wine aroma exist in grapes, in part, as free volatile forms but mainly as nonvolatile aroma precursors that release the aromatic molecules during wine fermentation or ageing. Among the volatile substances existing in free form in grapes, the methoxypyrazines are the principal aroma components responsible for the vegetative flavors (bell pepper). Methoxypyrazines accumulate early in berry formation and decrease during the later stages of grape maturation. On the other hand, aroma precursors include thiols (volatile sulfur compounds derived from cysteine or glutathione) and glycosides called y infamous compounds have a variety of olfactory nuances ranging from vegetative aromas to grapefruit and pineapple notes. Fruity and floral aromas are also associated with the family of aliphatic compounds (higher alcohols, esters, and aldehydes), except the C5 aldehydes (hexanal, and (E)-2-hexenal) which are related to the grassy aromas of unripe fruit (Table 1).

**Factors Affecting the Levels of Phenolic and Aroma Compounds**

The type and levels of secondary metabolites found in grapes vary greatly among the different cultivars. A “cultivar” refers to an assemblage of plants selected for desirable characteristics that are maintained during propagation: “Chardonnay” or “Syrah” are examples of grape cultivars. Of course, external conditions also exert a measurable effect on the levels of grape compounds that relate to wine color, taste, and aroma. The importance of the physical aspects (topography, soil, climate) of grapevine habitat on the quality and typicity of wine sensory attributes is commonly described by the collective French term terroir. The spatial variability of climate (i.e. within a wine-growing region as a result of variations in altitude, aspect, or slope, often described as “mesoclimate”) is reported to be the most important factor among the terroir components to affect the unique sensory properties of a wine (Jones 2006). The impact of soil on grape and wine parameters is mostly associated with its ability to induce different levels of vine vigor and vine yield, the soil’s physical properties being key (van Leeuwen et al. 2004). The impact of soil chemical properties and crop nutrition with respect to fruit and wine quality should not be overlooked, although the effect of most soil inorganic elements has not, so far, been linked to significant changes in vine development and grape quality (van Leeuwen et al. 2004).

In conjunction to site characteristics, vineyard design and seasonal operations (e.g. pruning, canopy manipulation, irrigation, fertilization, floor management) also affect the levels of important secondary metabolites by modifying a vine’s response to environmental factors. Vineyard management interferes with the effects of local climate, by adapting vine “microclimate” (which mainly refers to the thermal, light and humidity conditions in the canopy), and

![Figure 1](image1.png) Structure of a ripe grape berry (seed, pulp, skin) and the localization (and molecular structure) of the major secondary metabolites that are the tannins, anthocyanins, and aroma compounds.

![Figure 2](image2.png) Evolution of berry size and color, from flowering to harvest (90–120 days after flowering), with indications of the period of accumulation of the major secondary metabolites of proanthocyanidins (greens), anthocyanins (added pinks) and aroma compounds (added greys). Véraison is the onset of berry ripening as manifested by a change in color in red grapes. Adapted from Coombe (2001).
the effects of soil, by controlling vine balance (a viticultural term referring to a state of equilibrium between crop level and vegetative growth of the vine). In this article, we examine the effects of environmental and viticultural conditions on the flavor compounds in grapes and wines.

**TERROIR AND THE PHENOLS**

Among climatic factors, light and temperature exert a direct role on the biochemistry of phenolic compounds. Anthocyanin accumulation is promoted by high light incidence on grapes (Jeong et al. 2004) and by daytime temperatures of 25°C coupled with cool (15–20°C) nights (Downey et al. 2006). Significant reductions in anthocyanin content have been observed in grapes exposed to temperatures of 35°C (Mori et al. 2007). Grapes exposed to sunlight were also reported to contain increased skin tannins (Cortell et al. 2006).

Interestingly, the microclimate surrounding the grapes can be easily and effectively manipulated by selective fruit-zone defoliation. In a trial conducted in Greece (Kotsiridis et al. 2012), leaf removal increased skin anthocyanins in Merlot and Cabernet Sauvignon grapes and significantly reduced seed tannins (Fig. 3). This produced grapes with a more desirable phenolic profile for the winemaker. However, the effects on grape composition are not always consistent and depend on the interaction between light intensity and temperature, especially in a warm climate, because the concomitant increase in exposed berry temperature may cause lower pigmentation (Spayd et al. 2002).

With respect to soils, low to medium potential sites, generating moderate vine vigor, are generally preferable for the maximization of phenolic metabolites because they allow greater light penetration in the fruit zone due to increased canopy porosity and preferential allocation of photosynthetic products to the ripening berries due to reduced competition from vegetative organs. A study conducted in a Greek vineyard with the red grape cultivar ‘Agiorgitiko’ showed that grapes situated on the upper slopes (Fig. 4) had berries with the highest phenolic content and were the ones best suited for the production of premium red wines. Grapes from the shallower soils and the lowest water reserves were associated with low vine vigor (estimated as winter pruning wood weight) and yield (Tagarakis 2014).

Water and nutrient supply to the vines can be also manipulated by grape growing practices such as irrigation, fertilization, and vineyard floor management. Among soil nutrients, nitrogen has been connected with changes in grape phenolic concentration, with excessive levels generally shown to have a negative impact, mostly due to increases in vine vigor. Similarly, moderate potassium applications enhance sugar translocation into the berry, which is important for polyphenol synthesis, but excessive potassium may decrease wine acidity. Cover crops grown alongside the vines to act as competition for resources can be used advantageously to promote grape and wine anthocyanin and tannin levels, as a result of restricted vine vigor (Nazrala 2008).

However, the direct manipulation of water availability through irrigation is generally accepted as the single most important management factor in determining berry and wine phenolic composition, especially in warm viticultural regions. A moderate water restriction has a positive impact on the accumulation of anthocyanins in grapes, commonly attributed either to suppressed vegetative growth or to smaller berry size which is itself possibly associated with a higher ratio between skin surface area to juice volume and, hence, to a lower dilution of skin-located metabolites in the final wine. However, the dependence of skin proportion on berry size is challenged by other works suggesting that bigger berries have also thicker skins (Roby and Matthews 2004).

Molecular genetic studies have shown that anthocyanin formation in the grapes of vines subjected to water deficit is stimulated by an earlier expression of genes of the flavonoid biosynthetic pathway (Castellarin et al. 2007). Skin

**TABLE 1  CHEMICAL CLASSES OF FLAVOR-RELATED COMPOUNDS FOUND IN GRAPES**

<table>
<thead>
<tr>
<th>Chemical class</th>
<th>Localization in grape berries</th>
<th>Flavor contribution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Monoterpenes</td>
<td>Skin (mostly) and pulp</td>
<td>Floral and citrus aromas (mostly in white cultivars)</td>
</tr>
<tr>
<td>C13-norisoprenoids</td>
<td>Skin (mostly) and pulp</td>
<td>Fruity (peach, tropical fruit), also floral (violet) aromas</td>
</tr>
<tr>
<td>Volatile phenols and sesquiterpenes (rotundone)</td>
<td>Mostly skin</td>
<td>Smoky and spicy aromas</td>
</tr>
<tr>
<td>Higher alcohols and esters</td>
<td>Skin and pulp</td>
<td>Generally fruity, also floral (rose) aromas</td>
</tr>
<tr>
<td>Sulfur-containing compounds (thiols)</td>
<td>Skin and pulp</td>
<td>Fruity (grapefruit, pineapple), also vegetative (box tree) aromas</td>
</tr>
<tr>
<td>Methoxypyrazines</td>
<td>Skin and seeds</td>
<td>Vegetative aromas (bell pepper, green peas)</td>
</tr>
<tr>
<td>C6 aliphatic compounds</td>
<td>Skin (mostly) and pulp</td>
<td>Vegetative aromas (green leaf, cut grass)</td>
</tr>
<tr>
<td>Anthocyanins</td>
<td>Skin</td>
<td>Color (in red cultivars)</td>
</tr>
<tr>
<td>Tannins</td>
<td>Skin and seeds</td>
<td>Astringency and bitterness</td>
</tr>
</tbody>
</table>
tannins also show a similar increasing tendency with water deficits (Casassa et al. 2015), whereas seed tannins are more often observed to follow an opposite trend, with higher levels at higher water availability (Kyraleou et al. 2017). Regarding the effects of water conditions on the compositional properties of skin and seed proanthocyanidins, such as polymerization, the amount of research is limited. Water deficit can increase proanthocyanidin polymerization, especially of skin-located tannins (Kyraleou et al. 2017). Thus, water deficits would be expected to lead to more astringent wines by increasing both the amount and the size of skin tannins.

Comprehensive investigations on the relation between the amount and composition of grape proanthocyanidin with grape and wine sensory properties are, currently, rather fragmentary. In order to give a more realistic insight on the effect of irrigation on grape in-mouth attributes, Kyraleou et al. (2016) performed an experiment. The same amount (15 g/L) of skin or seed tissue powder were collected at harvest from different irrigation treatments and were dissolved into model wine and tasted by experienced wine assessors who had been trained to evaluate astringency (ISO 8586-1). According to the results, skin and (mainly) seed extracts from irrigated vines were perceived as more astringent whereas extracts from nonirrigated vines were attributed a lower astringency note (Fig. 5) (Kyraleou et al. 2016). Thus, the unexpected lower astringency of the skin samples from the non irrigated vines must be related to factors other than tannin concentration. The explanation would most likely lie in the associations formed between skin tannins and other cellular components such as cell wall polysaccharides, lignins, and proteins that reduce tannin capacity to interact with salivary proteins. These complexes are more frequently formed under advanced berry maturity, commonly associated with vines submitted to moderate water deficits.

**TERROIR AND AROMA COMPounds**

Wine quality is mostly evaluated on the basis of its aromatic profile. Terroir is thought to play a key role in wine aromatic identity; furthermore, it is a widespread opinion among wine enthusiasts and marketers that the pivotal role of terroir on the aroma of wines is primarily the result of geology and soil composition, together with topographical features such as slope orientation and altitude. Climate receives much less credit.

The link between geology and wine quality is very popular in wine culture. The example most often cited of a direct connection between the geological origin on wine aroma is “minerality” (earthy smell, or smell of wet stones), seemingly connected to the presence of certain minerals in the soil or underlying rock. Although some nutrient mineral elements can participate in a salty taste (Na or K), they lack aroma. Yet, geological minerals are insoluble, so they cannot be absorbed by vine roots (Maltman 2013). Instead, it appears that certain volatile compounds, such as benzenemethanethiol, can contribute to the “mineral” aromatic character of certain wines (Tominaga et al. 2003). Nevertheless, geology might affect wine aromatic character indirectly, acting (together with topography) on the development of soil type.

Different soils give grapes and wines different concentrations and types of aroma compounds. This can result from different soil textures and structure, the presence of calcium carbonate, or the nutrient content, among many soil factors. However, soil composition does not seem to have an independent effect on grape aroma quality: mostly, it is an indirect one, related to soil water and nutrient availability. As a general rule, fruity wine aromas are usually enhanced under conditions of moderate soil fertility and water (stony or sandy soils with good drainage, water deficit to no irrigation) while the more vegetative and spicy aromas are more expressed in wines from soils that are deep, clay-rich and that have higher nitrogen and water reserves. Conditions of limited-to-moderate water and nutrient supply (dry farmed vineyards, dry areas or light-textured soils) might be better for the aromatic ripening of red grapes, whereas for white cultivars (especially early ripening ones), best aroma expression is obtained when water and nitrogen are less limiting (Peyrot des Gachons et al. 2005).

Similarly, for phenolic compounds, the soil effect on the levels of aroma precursors in grapes is mostly mediated through water supply to the vines. In an experiment conducted in nonirrigated vineyards in Nemea (Southern Greece) with the red cultivar ‘Agioritiko’ (Koundouras et al. 2006), the levels of precursors of the main aromatic

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**Figure 4** (main photograph) Part of a 1 ha Agioritiko vineyard in 2010 in central Greece. (inset) Six maps of the spatial variability of the phenolic composition of grapes, as related to topography, soil, water status and biomass production. Abbreviations: $\Psi$, midday stem water potential (a measurement of plant water condition with lower/ more negative values denoting increased water stress); PW = winter pruning weight; Anth = total anthocyanins in the juice; TPI = total grape phenolics index. Pearson correlation coefficients for the inter relationships of soil and vine parameters with grape phenolic potential correspond to the mean values per 10×20 m cell. Adapted from Tagarakis (2014).
components were increased on soils that induced a limited water availability and moderate vine vigor. Moreover, in wine tasting trials of the wines produced from each site (Fig. 6), wines from plot H (a shallow soil developed on a soft limestone bedrock) consistently scored higher, followed, in increasing water availability order, by the wines from plot P (uniform, calcareous silty loam situated on a flood plain), and by wines from plot A (clay loam, with a hardpan of nearly 70% clay at 140 cm of depth, leading to permanent water logging due to poor drainage). In white cultivars, water deficit activates the carotenoid and isoprenoid metabolic pathways in Chardonnay grapes, resulting in increased concentrations of terpenols and C_{13}-norisoprenoids (Deluc et al. 2009), these latter compounds contributing positively to the floral and fruity aroma of the wines. However, for white grapes producing “green” aromas (like Sauvignon blanc), a sustained water deficit seems to limit aroma potential (Peyrot des Gachons et al. 2005). Water deficit is also reported to decrease the concentration of aroma precursors and aroma retention or breakdown. Both daytime and nighttime temperature (especially during the last month before harvest) are associated with wine aroma typicity. Higher daytime temperatures (but not exceeding 30 °C) allow for greater primary metabolism, whereas low nighttime temperatures slow down night respiration and ripening speed, thereby preserving the more delicate grape aromas; among aroma compounds, monoterpenes are increasingly volatilized as the temperature increases over the ripening period (Loreto and Schnitzler 2010). However, different volatile chemical groups have different temperature requirements. For example, norisoprenoids appear to be relatively insensitive to temperature (Keller 2015). Cooler regions and years tend to increase the expression of vegetative odors linked to the presence of methoxyypyrazines (Allen et al. 1991). Syrah grapes grown in warmer climates with higher bunch zone temperatures also tend to have less pheophytin (related to rotundone levels) and more fruity aromas (related to C_{13}-norisoprenoids) (Zhang et al. 2015).

Sunlight exposure also appears to be crucial for the determination of potential wine quality, mostly by promoting the formation of glycosylated aroma compounds in grapes (e.g. monoterpenes and C_{13}-norisoprenoids). Among monoterpenes, linalool is the most stimulated by sunlight and is associated with high expression levels of the corresponding genes. But the biosynthesis of geraniol and nerol can be inhibited by excessive sunlight exposure (Zhang et al. 2017). To increase levels of monoterpenes, leaf removal would be an effective strategy when applied around véraison, which is when the expression of the terpene synthase genes reaches its maximum (but mostly under cool climate conditions where the risk of sunburn damage due to the concomitant increase in exposed berry temperature is lower).

A cultivation system that can also enhance grape aroma potential (especially on high potential sites or in regions with high precipitation) is cover cropping. This works by controlling soil nutrient and water supply. White clover, alfalfa, and tall fescue in a Cabernet Sauvignon vineyard increased the levels of volatile alcohols, esters, terpenols and C_{13}-norisoprenoids in the wines when compared to wines from tillage applications (Xi et al. 2011). High soil fertility, mainly nitrogen content, is related to poor ripening due to vigor stimulation. However, soil nitrogen content has a direct effect on certain aromatic grape compounds by enhancing the synthesis of cysteinylated aroma precursors of volatile thiols, which are responsible for the varietal aroma of Sauvignon blanc wines (Peyrot des Gachons et al. 2005).

Although climatic factors are less often associated by wine connoisseurs with wine aromatic quality and authenticity, berry aroma compound biosynthesis is very susceptible to meso- and microclimatic changes in local atmospheric conditions, such as solar radiation and temperature, as determined by the general climate of the area and modified by local topography (mesoclimate) or by the grape grower (microclimate).

Temperature determines both the activity of enzymes of the corresponding metabolic pathways for the formation of aroma precursors and aroma retention or breakdown. Both daytime and nighttime temperature (especially during the last month before harvest) are associated with wine aroma typicity. Higher daytime temperatures (but not exceeding 30 °C) allow for greater primary metabolism, whereas low nighttime temperatures slow down night respiration and ripening speed, thereby preserving the more delicate grape aromas; among aroma compounds, monoterpenes are increasingly volatilized as the temperature increases over the ripening period (Loreto and Schnitzler 2010). However, different volatile chemical groups have different temperature requirements. For example, norisoprenoids appear to be relatively insensitive to temperature (Keller 2015). Cooler regions and years tend to increase the expression of vegetative odors linked to the presence of methoxyypyrazines (Allen et al. 1991). Syrah grapes grown in warmer climates with higher bunch zone temperatures also tend to have less pheophytin (related to rotundone levels) and more fruity aromas (related to C_{13}-norisoprenoids) (Zhang et al. 2015).
light incidence increases the levels of carotenoids during the green berry phase, but after véraison, it accelerates carotenoid breakdown to C_{13}-norisoprenoids (Bureau et al. 2000). Conversely, light has a negative impact on vegetative or spicy aroma compounds, like the methoxypyrazines (Marais et al. 1994).

**CONCLUSIONS**

A good site for the production of richly flavored wines is commonly considered one that enhances complete ripening of the appropriately chosen grape cultivar, either by creating favorable meso- or microclimates and/or by adjusting nutrient and water availability in the soil to moderate levels. On the side of viticultural practices, irrigation and microclimate manipulation are the most important tools in controlling grape phenolic and aroma potential in relation to grape cultivar and the desired wine style. However, the role of soil on terroir has received significantly less attention by the scientific community than climate. Moreover, the ability to detect and monitor volatile compounds by current analytical means remains a laborious, time-consuming, and expensive task. Lastly, there is a lack of knowledge on the relationship between secondary metabolites (types, concentrations, etc.) in grapes and their actual sensory impact on wine flavor.

An expanded database for each chemical substance and for relevant site/vineyard factors across a wide range of cultivars will greatly assist grape growers in improving site selection and adjusting vine management to achieve optimum phenolic and aroma expression in their wines.

**ACKNOWLEDGMENTS**

The author wishes to thank Larry Meinert, Bernard Wood and the Elements editorial staff for their superb efforts in putting this issue together. Reviewer comments significantly improved the present article.

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The Scale Dependence of Wine and Terroir: Examples from Coastal California and the Napa Valley (USA)

Jonathan P. Swinchatt, David G. Howell, and Sarah L. MacDonald

INTRODUCTION

Randall Grahm is a currently active Californian winemaker who is the proprietor of the Bonny Doon Vineyard. He famously once said “... without terroir, winemaking is a hollow game, a hall of mirrors.” But what exactly is “terroir”? Cistercian monks are credited with organizing the vineyards of Burgundy, delineating where the Earth produces great wine. The monks did this without the knowledge of geology, which had not yet been developed. Furthermore, they believed the Earth was flat and less than 10,000 years old. So clearly, great wines can be made without science. But we are in the 21st century with science at our disposal, and presumably with the ability to unravel at least some of the mysteries of terroir.

Terroir, as applied to wine, is a systems word that indicates the interaction of a group of components—climate, soil, geology, and topography—that, together, create the environments within which grapes are grown. The system is so complex that it is difficult to grasp as an integrated whole, even though we casually make statements such as “This wine reflects its terroir,” though the meaning of such statements is often obscure. It is likely that the true meaning of terroir will remain a bit mysterious to most of us. Still, we can examine the effects of terroir’s individual components on wine and achieve some understanding of how they interact. When we do this, it quickly becomes clear that where our attention comes to lie—on climate, geology, topography, or soil; and on grape variety, grape quality and character, or wine flavor and aroma profile—depends on the scale at which we are looking.

At the smaller scale, soil character and local climatic variation shape grape flavor and aroma. These notions are discussed in relation to four California wine regions: Sonoma County, Paso Robles, Santa Barbara County, and Napa Valley.

SONOMA COUNTY TERROIRS

Sonoma presents us with a geographically anarchic, if also charming, tangle of mountains, valleys, coastal ridges, plains, and rivers, difficult to understand and confusing to navigate. The county, much of which is devoted to the growing of grapes for fine wine, is also geologically complex, underlain in various parts by the Franciscan Formation (itself a mélangé of rock types), the marine sandstone and siltstone of the Wilson Grove Formation, the diverse lithologies of the Sonoma Volcanics, and a variety of alluvial and fluval sediments. Given this physical diversity, one might expect the presence of multiple terroirs. And, indeed, there are, represented by 17 recognized (and in part overlapping) American Viticultural Areas (AVAs), each of which exhibits its own geographic and geologic diversity. To unravel the intricacies of terroir and wine in even one of these AVAs is a task well beyond the scope of this article.

Regionally, however, there is a clear and overriding pattern conditioned by climate and reflecting, in particular, the control of temperature on the grape varieties favored in any particular location. Western winds carrying moist air blow over the cool California current that flows south along the Sonoma coast, forming a fog that bastes the coastal ridges and penetrates inland, cooling the western part of the county and flowing up the Russian River Valley. In these areas, the cool climate varieties of grape (Pinot Noir and Chardonnay) are favored, along with the temperature-adaptable Syrah. In the eastern valleys (Sonoma, Alexander, Knights) and along the mountain slopes in the eastern portion of the county (Sonoma Mountain, the Mayacamas Mountains), warmer temperatures and less fog favor

At the smaller scale, soil character and local climatic variation shape grape flavor and aroma. These notions are discussed in relation to four California wine regions: Sonoma County, Paso Robles, Santa Barbara County, and Napa Valley. The physical parameters of terroir are scale dependent. At the regional scale, climate is paramount and relates to the grape varietals most suited to the setting. Intermediate factors include geologic setting, sun exposure, and topography, all of which influence grape quality and character. At the smaller scale, soil character and local climatic variation shape grape flavor and aroma. These notions are discussed in relation to four California wine regions: Sonoma County, Paso Robles, Santa Barbara County, and Napa Valley. The physical parameters of terroir are scale dependent. At the regional scale, climate is paramount and relates to the grape varietals most suited to the setting. Intermediate factors include geologic setting, sun exposure, and topography, all of which influence grape quality and character. At the smaller scale, soil character and local climatic variation shape grape flavor and aroma. These notions are discussed in relation to four California wine regions: Sonoma County, Paso Robles, Santa Barbara County, and Napa Valley.
between San Francisco and Los Angeles (sits astride the headwaters of the Salinas River, midway
The Paso Robles AVA, one of the largest in California,
PASO ROBLES TERROIRS
the intricacies of the local terroirs, this geographic distinc-
chagrin of Paso Robles’s winemakers, who are well aware of
moderately dissected rolling plain to the east. Much to the
area, however, what might impress you most is
to the area, what might impress you most is
the contrast between the hills west of the river and the
and clone chosen to work best with the details of its terroir,
i.e. position relative to fog and sun, soil character, and
drainage. Hirsch’s signature wine, named after the San
Andreas Fault that runs adjacent to his land, is crafted by
blending wines from all 25 blocks. Hirsch feels that this
wine best represents his piece of land.

PASO ROBLES TERROIRS
The Paso Robles AVA, one of the largest in California,
sits astride the headwaters of the Salinas River, midway
between San Francisco and Los Angeles (Fig. 1). Recently,
the original AVA has been subdivided into 11 sub-AVAs,
to reflect the geographic and geologic complexity of the
region. Were you to drive into the town as a tourist new
to the area, however, what might impress you most is
the contrast between the hills west of the river and the
and warm.
That being said, it is difficult to avoid making this regional
distinction. The hills are the southernmost extension of
the coastal Santa Lucia Mountains, and their climate
is conditioned by proximity to the ocean. Cool, moist air
from the Pacific climbs their western side, drops much of
its moisture in the mountains, leaving little for the dry
plains to the east. The hills also protect the plains from
the cooling effect of the westerly winds. Though it gets
hot in the hills (90–100°F are common) it is even hotter
on the plains, though both environments cool drastically
at night. The result of these climatic differences is a focus
on Rhône grapes in the hills (especially Syrah, Mourvèdre,
and Grenache) and on Bordeaux varietals on the plains
(particularly Cabernet Sauvignon and Merlot).

This regional overview emphasizes the control of climate
and topography on the choice of varietals grown in
any particular area. At the same time, it hides the true
complexity of the Paso Robles AVA. The mountains are
underlain by the Monterey Formation, a complex of
siliceous (from diatoms) and calcareous (from foraminifera)
mudstone and siltstone, in some places grading into what
is almost, but not quite, limestone. The AVA is bordered
on the east by the San Andreas Fault and is cut through
by subsidiary faults that juxtapose contrasting lithologies.
During uplift of the Santa Lucia Range, erosion shed debris
that covered the eastern plains with alluvial and fluvial
sediments. Later, the plains were tilted to the west and
dissected by rivers and streams. The result, in the east,
is a complex mix of alluvial fans and river terraces punctu-
ated by outcrops of Monterey Formation on topographic
highs. Combined with the effects of local topography on
rainfall and temperature, the result is an intricate array of
local terroirs throughout the Paso Robles AVA.

One winery of particular note is Tablas Creek, in the hills
west of Paso Robles. In the 1970s, wine importer Robert
Haas and his friends the Perrin family of Châteauneuf-
du-Pape in the Rhône Valley (France), became convinced
that California’s Mediterranean climate would support the
grape varieties grown in the Rhône but not then common
in California, varieties such as Mourvèdre, Syrah, Grenache,
Roussanne, Marsanne, and Viognier. In 1985, Haas and the
Perrins began looking for land and finally found it four
years later on Tablas Creek, 12 miles from the ocean in the
steep western Paso Robles hills. Lacking confidence in the
rootstocks and clones then available in California, they
imported material from the Perrin property of Château
Beaucastel (France), going through the lengthy and arduous
process of quarantine and indexing required to prove that
the vine cuttings were free of disease. They finally planted
their first vineyard in 1997, producing their first wine in
2000. The effort proved a great success—in the years since,
Tablas Creek has made their vine materials available to all.
SANTA BARBARA COUNTY TERROIRS

Wine in Santa Barbara County is concentrated on a unique piece of land that lies about half way between the Paso Robles AVA and Los Angeles. Coastal mountains throughout the west lie parallel to the coast, trending north–south, except here, in the Transverse Ranges, which trend east–west, perpendicular to the coast. How they got this way is a complex story but suffice it to say that they were caught up in movement along the San Andreas Fault system and rotated, over several million years, into their present orientation. The mountains frame three major valleys—Santa Maria, Los Alamos, and Santa Ynez (north to south)—each of which provides a corridor for cool coastal air to penetrate inland. In Santa Barbara County, AVAs are associated with two of these valleys: Santa Maria Valley and the Santa Ynez Valley (Fig. 1). Los Alamos Valley does not have AVA status but is an active wine producing region.

In the Santa Maria Valley AVA, vineyards occupy the wide Santa Maria Mesa, a dissected bench above the Sisquoc River. In this coolest of Santa Barbara AVAs, Pinot Noir and Chardonnay are the primary focus. The same is true of Los Alamos, a producer of Pinot Noir and Chardonnay, mainly from extensive vineyards owned by large commercial producers. Los Alamos is warmer than Santa Maria, but cooler than the Santa Ynez Valley to its south.

In the western part of the Santa Ynez Valley, Pinot Noir and Chardonnay thrive in the Sta. Rita Hills AVA. Eastward in Santa Ynez, temperatures rise, as reflected by dominant grape varieties in the three eastern sub-AVAs. Of these, the westernmost and coolest, Ballard Canyon AVA, specializes in Syrah and other Rhône varietals, Los Olivos District AVA to the east supports both Rhône and Bordeaux varietals (particularly Cabernet Sauvignon and Merlot), and the warm Happy Canyon AVA in the east produces wine mainly from red Bordeaux grapes.

This overview perhaps emphasizes similarities among these three valleys that physically are quite distinct. The Santa Maria Valley is trumpet shaped, open to the west, with large vineyards (up to several hundred acres) occupying gentle alluvial slopes on benches above the Sisquoc River. The valley narrows to the east, where the land becomes more irregular and the vineyards are progressively smaller. Los Alamos is a narrow (less than a mile wide) linear valley with large vineyards covering its alluvial floor and climbing the south facing slopes of the bordering hills. The Santa Ynez Valley is more diverse than either of the above. In its westernmost portion, tight meanders of the Santa Ynez River outline benches with vineyards growing in alluvial sediments or landslide debris. Vineyards north of the river occupy small niches in the Santa Rita Hills or the rolling plateau at their summit where vines grow in marine and estuarine sandstones and siltstone. Farther east, the valley becomes more linear, though vineyards occupy small niches in low bordering hills. Farther to the east, north–south valleys ("canyons") house the three sub-AVAs mentioned above.

Pinot Noir was first introduced to Santa Barbara County by Richard Sanford who had returned from Vietnam in 1967 with the memory of transcendent Burgundy from Volnay, tasted while he was overseas. He returned determined to try to produce such a wine in America. After studying climate records of regions throughout California and traversing Santa Barbara County in his ancient Mercedes with a thermometer by his side, he settled on a piece of land on a landslide deposit on the south bank of the Santa Ynez River. Together with his friend Michael Benedict, he raised the capital needed to buy the land and plant it with Pinot Noir in 1971. They produced their first wine in 1976, of a quality that attracted a number of people to settle in Santa Barbara County to grow and make Pinot Noir. After a series of unfortunate incidents, Sanford lost the vineyard, his winery, and even the use of his name on a wine bottle label. He now makes wine under the brand Alma Rosa.

THE NAPA VALLEY AVA

At first glance, Napa Valley (Fig. 1) appears to be a relatively simple and straightforward place—a narrow, linear, north–west–southeast trending valley bounded by mountain ranges on east and west. Appearances can be deceptive, however, hiding in this case a complex mix of climate, topography, sun exposure, geology and soils that provides an unusual diversity of microenvironments or, in today’s winespeak, terroirs. In some places, within a few tens of feet, one might encounter several quite distinct sets of growing conditions. Napa’s prominence in the wine industry has made it the subject of considerable attention: more is known about winemaking in Napa than in any other winegrowing region in North America, allowing us to take a more detailed look at what we have called here the scale dependence of wine and terroir.

Most of the production in the Napa Valley AVA (Fig. 2) takes place within the Napa Valley per se and in the adjacent mountains, the Vacas to the east and the Mayacamas to the west. The Vaca Mountains and the northern third of the Mayacamas are underlain by diverse lithologies of the Sonoma Volcanics (lava flows, ash fall and welded tuffs, ignimbrites), while the middle and southern parts of the Mayacamas are underlain, respectively, by rocks of the Franciscan Formation and the Great Valley Sequence. These varied lithologies not only provide diverse vineyard substrates in the mountains but have also provided sediments for a series of larger and smaller alluvial fans that...
line the west side of the valley. Only a few small fans are present on the valley’s eastern edge, a dichotomy perhaps explained by the post-glacial history of the region (see Swinchatt and Howell 2004). Fluvial sediments line the Napa River, which pursues an erratic course southward down the valley. In general terms, vines grow in thin residual deposits in the hills, in alluvial sediments along the edges of the valley and in fluvial sediments along the river. Napa has a Mediterranean climate, with hot, dry, summers and cool, wet, winters. Rainfall, mostly in the winter, is greater in the hills than on the valley floor; fog shrouds the valley during the summer until mid-morning. Temperatures are coolest in the south (adjacent to San Pablo Bay) and increase northward up the valley. Temperature decreases with elevation in the hills, though the tops of the mountain ridges lie beyond the reach of the daily summer fog, exposing mountain grapes to longer hours of sunlight.

As with other wine regions discussed here, climate appears to be the primary control on the dominant grape varieties in Napa. The regional climate has proven ideal for Cabernet Sauvignon, which is grown throughout the valley, accounting for 40% of Napa’s grape production. It includes some of the most expensive and sought-after wines in the world, a financial factor that surely adds to the dominance of this grape. Still, in the cooler southernmost part of the valley, the Carneros District, Pinot Noir and Chardonnay dominate, supporting the notion that on a regional basis, climate holds sway.

Looking a bit more closely, however, the complexities of terroir begin to arise. Cabernet Sauvignon from mountain vineyards, for example, grown for the most part on thin, well-drained, residual soils, tend to be more structured, more powerful, with harder tannins than those that characterize wines from the valley edge. The cause is unclear. Is it a reflection of climate, topography and sun exposure, or vineyard substrate, both, or something else? In earlier decades, (1970s to 1990s), these wines often required years, even decades, of bottle aging to soften and become enjoyable drinking. Modern viticulture, however, has allowed growers to produce grapes with more mature (and softer) tannins, while winemakers have evolved approaches in the winery (softer pressing, for example to avoid breaking seeds) that lead to wines that are more approachable when young.

Character differences are also present in wines from the western and eastern sides of the valley. West-side wines (Cabernet Sauvignon) are said to show more fruit than those on the east, which are often said to be somewhat more tannic. In the past, this has been attributed to different sun exposure—west-side grapes are exposed to the cooler morning sun when it peeks through the summer fog around 10 AM, while east side grapes are exposed to the heat of the afternoon sun. The story, however, might well be more complex than this because valley floor AVAs, affected in their design as much by politics as by geography or geology, stretch from one side of the valley to the other and incorporate a diversity of growing conditions. In addition to experiencing distinctly different temperature and sun exposure regimes, grapes in any one of these AVAs grow in a diversity of substrates. On the lower slopes of the mountains, vines are rooted in thin residual materials, developed on sedimentary or volcanic rocks on the west, volcanic rocks on the east. On the west, well-developed alluvial fans line the edge of the valley, providing a diversity of substrate types, from coarse, rocky sediments at the valley edge and along distributary channels, to finer deposits in interchannel areas. On the east, fans are small and scattered and grade rapidly into fluvial sediments of the Napa River. With each closer look, the relationship of terroir to wine becomes more complex.

**THE OAKVILLE AVA**

Before we bore down into the Oakville AVA (Fig. 2) to examine the distribution of various soil types, let us first look at the distribution of alluvial fans in the central part of the valley, the area that encompasses the Rutherford, Oakville, and Yountville sub AVAs (Fig. 3). The contrast between the east and west sides of Napa Valley is pronounced. The Vaca Mountains are older than the Mayacama Mountains; the Vacas are approximately 2–3 million years old and the Mayacamas are approximately 1 million years old (see Swinchatt and Howell 2004). The five alluvial fans on the west of the valley, the historically famous bench lands of Napa, display fan sizes roughly comparable to their respective watersheds. Alluvial fans grow as a consequence of major gully-washing storms, larger than any storms experienced in the last 100 years. Supposing low-probability high-impact 1,000-year storms are needed, in the million years since the Mayacamas began rising, as many as 1,000 such storms built these fans.

Across the valley to the east we see two huge watershed areas but only three small alluvial fans (Fig. 3). We infer that during the early stages of growth of the Vacas, two very large alluvial fans spread westward across the ancestral Napa region. These fans have been removed by erosion during low-stands of sea level during the Pleistocene Epoch.

![Map of the Oakville American Viticultural Area (AVA) of central Napa Valley](image)

**FIGURE 3** Map of the Oakville American Viticultural Area (AVA) of central Napa Valley (see the dark grey area outlined in Fig. 2) and the surrounding region. This map shows the locations of the region’s alluvial fans and watersheds. Watersheds are letter and numerically labelled after their primary name, e.g. Rutherford Watershed 1, R2, R3. The number “29” in a circle refers to Highway 29 which bisects the area. **Map by S.L. MacDonald of Envision Geo LLC**
Some evidence of this is along Conn Creek, the drainage for Lake Hennessy, where we find pebble to cobble size fragments of red radiolarian chert in the provenance of Childs Valley along the east edge of the Hennessy drainage basin (Swinchatt and Howell 2004). The three fans (Rudd, Tench, and Rector) (Fig. 3) are much younger and reflect more recent fan development roughly contemporaneous to the fans on the west.

Each of these fans shows a pattern of sediment differentiation, generally with coarser-grained material near the hills and progressively finer-grained material towards the axis of the valley. This simple fining outward pattern is disrupted in some locations by longitudinal stringers of gravel that reflect deposition in stream channels that run down across a fan.

With this characterization of alluvial fans in the central part of Napa, we can look more specifically at the soil distribution across the Oakville sub AVA (Fig. 4). This AVA extends to an elevation of 500 feet (152 m) in the Mayacamas and as high as 1,066 feet in the Vaca. Vineyards in both these ranges are characterized by soils developed in the decayed bedrock. In the Vaca, volcanic andesite produces mostly red soils with core stones. This decayed bedrock is evident in a number of vineyards, such as Mount Eden, Garguli, Backus, Dalle Valle, and Oakville Ranch, to name a few. On the west, in the foothills of the Mayacamas, the volcanic rock is more varied with tuff and volcanoclastic strata as evinced by the Harlan Estate vineyard. The West Napa Fault runs through the foothills and juxtaposes Great Valley sequence clastic strata (the underpinnings for the Futo vineyard) with the volcanics. Thus, in Oakville, there are three distinct types of residual soils (numbers in white, 1, 8, and 9 on Fig. 4), each with their own chemistry, with their own grain-size distribution, and each with contrasting slopes and solar aspects. Their terroirs are different, and we suspect so too are their wines.

Towards the valley, away from the foothills, lies the domain of alluvial fans (numbers in white, 2, 5, 6, and 7 shown in Fig. 4). The Oakville sub AVA has a number of small fans, each with their own distinct watersheds contributing unique assemblages of rock fragments. Soils developing on these fans will vary as a consequence of differing grain size and different rock types that in turn create contrasting drainage patterns; these attributes of terroir may affect the character of the wines.

This east to west symmetry of residual–alluvial–residual is further expressed with a fluvial axial zone, unit 4 on Figure 4. This zone seems to be the most uniform and reflects flood-stage deposition of clay, silt, and sand. The only disruption to this symmetry is Unit 3 on Figure 4. This poorly defined area corresponds to relic material from the once extensive Lake Hennessy fan. The Groth “Sweet Spot” vineyards produce Groth’s Reserve wine from this domain that garnered the first 100 point rating in Napa from Robert Parker (one of the world’s most influential wine critics). Further research on the distribution of Unit 3 will perhaps identify other vineyards reflecting this particular terroir.

Oakville AVA is well known for its Bordeaux-styles wines, arguably some of the best in the world. The Oakville Winegrowers Association, boasting more than 70 growers and wineries, is a close-knit group that staunchly protects their identity of the Oakville sub AVA. Laws controlled by the ATF (US Bureau of Alcohol, Tobacco, and Firearms) preclude further subdividing Oakville or any other sub AVA. Yet it is clear from the discussion of the soil domains in Oakville, that differentiation among and within vineyards may be significant. As the winemakers learn more about their land and their terroir, they will find ways to convey their uniqueness in the market place.

**Figure 4** Soil types in the Oakville American Viticultural Area (AVA) of central Napa Valley. The soils of the Oakville district are broadly categorized into three types. In the hills (Fig. 4, 1, 8, 9), residual soils are created from the breakdown of the various volcanic and clastic bedrock units. Along the margins of the valley (Fig. 4, 2–7) just below the hills, distinct alluvial soils form on the fans composed of material washed down from the adjoining hills during torrential rain events. Along the axial part of the valley where the Napa River flows are fluvial soils (Fig. 4), finer grained loam coming from upstream locations and deposited from flood waters. Unit #3 represents alluvial material from an older large fan exiting from the Lake Hennessy drainage basin. Most of this material has been removed from the valley floor during sea level low stands. Map by S.L. MacDonald of Envision Geo LLC

**TERRITORIAL VARIATION WITHIN SINGLE VINEYARDS**

Grapes and wine from a single vineyard of even modest size reflect the effects of all these levels of wine and terroir. The varietals grown reflect the regional climate. The overall quality and character are conditioned by topographic considerations and sun exposure. Wine character is further influenced by the mix of soil conditions and drainage that occur in any particular vineyard. And variation even within a single vineyard block can be reflected in grape flavor and aroma.

During a study of vineyard conditions at Stag’s Leap Wine Cellars (located in the Stags Leap District AVA) (Fig. 2), winemaker Michael Silacci (then, and now, at Opus One Winery) described how they would pick grapes in block 8, a rectangular plot about 8 acres in area. He said that he had identified a “sweet spot” in the block, one in which grape flavors were subtly but distinctly different, and more desirable, than elsewhere, and that this sweet spot had the mapped shape of the candy known as the Hershey Kiss, i.e., a squat, sharp-tipped cone. The geologist conducting the study drew an outline, based on geologic characteristics revealed in 38 backhoe pits covering the 8 acres, on a block map. The outline, shaped like a Hershey Kiss, encompassed an area in which the rocky sediments of a mudflow were within 12 inches (30 cm) of the surface.
Outside the indicated area, the mudflow debris became finer grained and was found at progressively deeper depth away from the “Kiss”. When shown to Silacci, he affirmed that the area outlined matched his sweet spot, though he added that the area would expand and contract from year to year. Something in the geology was being reflected by grape flavors as measured by the winemaker’s taste buds.

In another study, at Rudd Oakville Estate two parts of the vineyard, one north of the winery, one south, were designated, on the Napa soils map, as being underlain by the same soil type. Geological analysis indicated that the northern segment is part of a small alluvial fan, the southern part includes a portion of this fan along with landslide deposits and several blocks of residual soils on andesitic Sonoma volcanics, the red soils that typified the vineyards on the Vacas just up hill and to the east. The winemaker reported that grapes and wine from the two areas were notably different in character.

And in a third study, at Eisele Vineyard (located in the Calistoga AVA) (Fig. 2), a correlation was found between geological conditions and vineyard management difficulties. In one part of the vineyard, vines are planted in material derived from three different sources—two small alluvial fans and one hillside. This particular mixed-source area coincided with an area that had presented chronic problems of vineyard management. Apparently, the local variation created by the mixing of these sources proved challenging to address through standard viticultural approaches.

In these three cases, geology is probably not the primary cause. More likely that something reflected in the geology is also reflected in the grapes and/or the vines, possibly related to water drainage or how water is made available to plant roots, e.g. through the intermediary of clay minerals.

**A NOTE ON FIRE DAMAGE IN NAPA AND SONOMA, 2017**

Assessing the impact of the Napa/Sonoma fires of 2017 (Fig. 5) involves two metrics. The first is based on data: acreage burned, structures destroyed, lives lost and value of insurance exposure. These numbers are roughly 300,000 acres, 8,000 structures, 30 lives, and (to date) 3 billion dollars.

When it comes to impact on the wine industry, metrics become more muddled for several reasons. First, there is reluctance on the part of the industry to expose their damage. Second, the fires occurred after most of the grapes had been picked: due to hotter and drier than average conditions, roughly 85% of the harvest had already taken place. Third, the vineyards acted as fire barriers due to the absence of dry brush around the vines and moist conditions created by irrigation. In place after place, fires would burn right to the edge of a vineyard and then stop. And fourth, most of the wine caves (subterranean structures for the storage and aging of wine) and wine storage facilities were sealed from smoke and were spared fire damage. Any reasonably accurate assessment of the damage to the industry will await the release of the 2017 vintage.

**SUMMARY**

Climate and geology are both important to terroir. Climate provides opportunity and influences the choice of grape varieties. Geology in the broadest sense (notably topography and soil texture) becomes significant at the more local level. And climate and geology affect different aspects of grapes and wine. Climate affects ripeness more than it does flavor, while geologic attributes perhaps have greater impact on flavor and character. Geology per se is probably not the driver. Rather, something reflected by the geology, such as the associated microbiology, or the soil clay content and type which could influence water availability, is being reflected in the grapes and wine. In any case, the notion that different environmental aspects are impactful at different scales perhaps opens up our ability to think about and discuss the complex notion of terroir. Too often we call upon this useful concept to explain things that we otherwise do not understand.

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Remote Sensing Applications for Viticultural Terroir Analysis

Andrew Hall

With the rise of remotely piloted aircraft systems, increasing computing power and advances in image processing software, the opportunities for vineyard observations through remote sensing are increasing. Remote sensing and image analysis techniques that are becoming more available include object-based image analysis, spatiotemporal analysis, hyperspectral analysis, and topoclimatology. Each of these techniques are described and discussed as potential for development within a viticulture and terroir context. While remote sensing applications are well established at the smaller precision viticulture scale, the larger spatial scale of terroir analysis requires adaptation and new models of analysis.

INTRODUCTION

Viticultural terroir can be defined as the interaction between environment and cultural practices that produce wine characteristics typical of a region. Cultural practices are highly influential on the characteristics of wine, but these are themselves ultimately dependent upon the local environment (van Leeuwen and Seguin 2006). Climate, soil characteristics and topography are the environmental determinants of terroir, and many characteristics of their physical properties can be quantified and mapped (Bonfante et al. 2011). By characterizing the environmental determinants of high-quality wine, suitable viticultural techniques may be identified based on the practices of regions with similar characteristics. A key step in identifying the factors that influence terroir is making a link between wine attributes and the environment (e.g. Ubalde et al. 2010; Zsöfi et al. 2011). There is, therefore, a requirement for high-quality contiguous spatial data of the physical elements of the environment for terroir analysis. Remote sensing is the primary tool for the acquisition of such data.

Spatial metrics describing climate, soil and topography that contribute to a description of terroir have been employed in recent viticultural suitability studies (e.g. Jones et al. 2004). The principle tool for quantifying environmental terroir components is remote sensing. With the increasing accessibility of remotely piloted aircraft systems as platforms for remote sensing devices (Fig. 1), remote-sensing image data of vineyards are becoming both more accessible and significantly lower in cost. This paper focusses on the remote sensing products that can quantify the spatial differences in environmental factors (notably, soil and climate) that influence terroir.

LINKING GRAPEVINE CANOPY TO GRAPE COMPOSITION AND YIELD

An important element of viticulture is the relationship between fruit quality and the characteristics of the grapevine vegetative canopy. It is the microclimate within the canopy that affects grape development and the consequent composition and yield of the fruit at harvest (Smart 1985). These relationships have been shown to exist at a high spatial precision from remote sensing images derived at the single grapevine scale (Hall and Wilson 2013). Two commonly measured compositional elements of wine grapes are titratable acidity and total soluble solids, which are used by vineyard managers to objectively assess crop ripeness. During the phenological stage of véraison (when berries colour and soften), titratable acidity decreases and total soluble solids, indicative of berry sugar content, increases. Phenolic compounds, such as flavanols and anthocyanins, also develop in grapes...
during véraison. These compositional elements of wine grapes play an important role in the quality and value of finished wines (Harbertson and Spayd 2006). Studies on the microclimate of the fruiting zone have shown that anthocyanin concentration is dependent upon the temperature of the fruit during ripening (Bergqvist et al. 2001). Because berry temperature increases linearly with sunlight exposure (Bergqvist et al. 2001), it is the grapevine canopy density and extent that likely affect the accumulation of phenolic compounds and, hence, the flavour profile of the finished wine.

Numerous physical, biological and chemical factors, including spatial variations in topography, physical and chemical characteristics of soils and the incidence of pests and diseases, influence vine health and productivity. High-quality wine production results from informed management of vineyard variability with the goal of producing grapes with high-quality attributes at economically profitable yields. Such management decisions rely upon the availability of accurate and reliable data to describe the variability exhibited by the vines. Mapping vineyard variables on the ground requires a considerable amount of data, and traditional methods of generating such data are time consuming and expensive. By using remote-sensing technologies, the vegetative characteristics of large areas of vineyard can now be assessed rapidly.

**REMOTE SENSING DEVICES AND VEGETATION INDICES**

There are many options for the acquisition of remotely sensed image data that could provide useful information for viticulturists. Remote sensing technologies applicable to viticulture include optical, thermal, light distancing and ranging (LiDAR), microwave, and fluorescence remote sensing (Jones and Grant 2015). For optical remote sensing, analogies can be made with hand-held cameras used for general photography. Thermal remote sensing is particularly useful for measuring spatial variability in transpiration (Jones et al. 2002; Bellvert et al. 2014), and, by inference, general metabolic rates and water stress. LiDAR is an active remote sensing system that emits laser pulses that, after interacting with the surface, are detected by the device, precisely recording the travel time. Accurate elevation maps of the surface can be built up through such a system to produce high-spatial-resolution terrain maps. Canopy morphology maps can also be produced using LiDAR (e.g. Wei et al. 2012). Microwave remote sensing has limited utility for direct sensing of vegetation condition but is commonly used to measure soil moisture at large spatial scales, which may be applicable within large terroir studies. Fluorescence remote sensing uses the fluorescence properties of some materials to determine their presence. Elements of grapevine biomass have fluorescent properties that can provide useful vineyard management data and can be mapped with specialised remote sensing devices (Baluja et al. 2012; Zarco-Tejada et al. 2012).

Optical remote sensing is the most common remote sensing method, producing a 2-D image of the ground. Solar radiation reflected from many small areas of the surface is collected by an imaging device and converted to digital data. A multispectral remote sensing system will collect approximately 3–30 wavebands. The most familiar set of wavebands are the three that roughly correspond with the primary colours of human vision (the visible bands): red, green, and blue (RGB). The actual range of wavelengths detected for each visible band is within the wavelength range of 400–700 nm, with blue centred at about 450 nm, green at 550 nm, and red at 650 nm. Wavelengths outside the visible part of the electromagnetic spectrum are especially useful for vegetation remote sensing. Near-infrared radiation, incorporating a range of wavelengths approximately 750–900 nm, is strongly reflected and transmitted by the spongy mesophyll cells within leaves, whereas visible wavelengths tend to be absorbed in leaves by chloroplasts. The transmission of near-infrared radiation by leaves enables a large proportion of the near-infrared radiation to interact with leaf layers below the initial top layer to provide information on vegetation density. Near-infrared images are, therefore, very useful for estimating spatial variability in leaf density and is a highly used waveband in vegetation remote sensing.

Vegetation indices that combine spectral bands sensitive to vegetation density are generally derived from multispectral imagery to enable analysis of vineyard canopy. Many remote sensing vegetation indices can be derived to describe the photosynthetic capacity of the vegetation, commonly referred to as the photosynthetically active biomass. The normalised difference vegetation index (NDVI) is very commonly used, calculated as the normalised difference between visible light (usually a visible red band) and a near-infrared band. Two example vineyard NDVI maps are presented in **Figure 2**. The NDVI is effectively a unitless ratio, ranging from −1 to 1, where higher values indicate greater vegetation density. Values below zero are rare in nature.

**REMOTE SENSING OF VINEYARDS**

Clear differences in grapevine canopy can be identified within the remotely sensed NDVI images. Those differences can be evaluated both quantitatively and qualitatively. For example, consider the two vineyard management blocks shown in **Figure 2**. The lighter coloured parallel lines are the grapevine rows, with variation in their width and brightness indicating on-ground differences in canopy size and density, respectively. Towards the top of the image in **Figure 2A**, generally brighter areas indicate larger, more dense, vegetative canopies, with specific areas of even brighter pixels that relate to the topography, sub-surface drainage and soil water availability differences within this vineyard. In the lower part of the vineyard block in...
A distinct change in the canopy size is apparent, which is the result of a vineyard management error made during winter pruning. Identification of generally larger canopies to the left side and top few rows (Fig. 2B) led to managed changes in the irrigation system to even out vineyard variability. Measures of canopy size and density (see following paragraph for discussion of methodology) for individual grapevines can be derived from the remotely sensed vegetation index images. These measurements can then correlate with fruit yield and quality measures, but with differences in correlation strength dependent upon vineyard characteristics. For example, the machine-pruned larger canopy vineyard shown in Figure 2B exhibited strong positive correlations between the canopy metrics and yield, and negative correlations between the canopy metrics and quality-indicating fruit descriptors. In the hand-pruned smaller canopy vineyard (Fig. 2A), however, these relationships were significantly weaker and less consistent. A possible contributory reason for this was the difference in relative canopy density between the two vineyard study sites. Greater canopy density in the machine-pruned vineyard enabled a more accurate average measure for each canopy unit.

The minimally processed imagery shown in Figure 2 is useful for qualitative visualisation of differences in vegetative canopy within vineyards. Quantitative analyses, on the other hand, require image data from discrete vineyard areas. High spatial resolution imagery, individual grapevine plants are a convenient spatial unit. Figures 3 illustrates image processing steps to derive canopy metrics for each grapevine in a small vineyard. Pixel values below a threshold NDVI are first removed to produce an image that has clear white space between the vineyard rows (Fig. 3B). The centre line of the vineyard rows is then derived (Fig. 3C), and each point in the centre line is associated with information about the one-pixel cross-section of the vineyard row. This information includes average pixel values (i.e. vegetation density), number of pixels (i.e. vineyard row width) and other metrics that describe shape (e.g. Hall 2003). Using a software mapping function (interpolation), images that clearly show differences in canopy characteristics can be produced from the centre line canopy data (Fig. 3D, compare the NDVI map in Fig. 3B). In addition, using the regular grapevine plant spacing of most vineyards, aggregated adjacent centre line data can be averaged to produce canopy metrics for each grapevine. Canopy size split into five categories is shown as an example map product in Figure 3E, where each grapevine plant is represented by a single dot, the colour of which relates to a size category. An example application of the canopy size map produced in Figure 3E is shown in Figure 3F, which is a targeted sampling scheme to ensure an equal number of canopy size categories are sampled. Sampling is an important process close to fruit maturity to assess ripeness and to schedule harvest.

The NDVI is a commonly applied index in remote sensing, but it can be less suited to the analysis of dense vegetation (Huete et al. 2002). In high spatial resolution vineyard images, vineyard canopy pixels can saturate the NDVI, resulting in limited information about canopy density variation. Hall and Wilson (2013) investigated various multispectral-derived vegetation indices for their ability to most accurately describe canopy characteristics in terms of enabling predictive mapping of wine grape yield and composition data. Imagery was processed to produce canopy descriptors for each individual grapevine unit (the process for a single vineyard at one point in time is shown in Fig. 3) in two study vineyards multiple times over three years. Of the indices investigated, canopy metrics derived using the triangular vegetation index (Broge and Leblanc 2000) were superior at predicting spatial patterns of fruit quality and yield. In comparison to the commonly used NDVI, the triangular vegetation index is more sensitive to overall chlorophyll density and more able to differentiate levels of photosynthetically active biomass (PAB) in dense vegetation. Vegetation indices sensitive to differences in dense vegetation, including the enhanced vegetation index (Huete et al. 1997), were stronger predictors than the traditionally used NDVI.

More specific metrics that target particular grapevine properties, such as leaf pigment concentration (chlorophyll and carotenoids) and plant water status, can be produced using hyperspectral remote sensing. Hyperspectral remote sensing devices, which collect many more bands of the spectrum using narrow contiguous wavebands, are required for this more detailed spectral analysis. A spectral response curve (Fig. 4) can generally be produced for a range of wavelengths when using hyperspectral devices. Hyperspectral remote sensing potentially offers much greater accuracy in terms of vineyard diagnostics; strong correlations have been demonstrated between biochemical vineyard metrics and indices derived from hyperspectral data (Zarco-Tejada et al. 2005).
Spatial resolution is an important element of remote sensing systems. In comparing systems on remotely piloted aircraft (0.05 m resolution), manned aircraft (0.5 m resolution), and satellites (5 m resolution) for the characterisation of intra-vineyard canopy variability, Mateřik et al. (2015) reported that for vineyards with small vegetative gradients (i.e. low spatial variability in canopy variability), only the higher resolution images were able to characterise intra-vineyard variability. There is, therefore, a trade-off between resolution and area covered. The balance between spatial resolution and area covered is a common remote sensing consideration, with higher spatial resolution imagery offering more accurate metrics but tending towards smaller areas being covered.

Further to spectral and spatial resolution, temporal resolution can be an important consideration in remote sensing. Temporal resolution is essentially the time between imaging missions. By collecting remotely sensed imagery at times spaced throughout the growing season, the strength of the relationship between remotely sensed canopy metrics and fruit composition and yield have been shown to vary with time (Hall et al. 2011; Hall and Wilson 2013). Figure 5 illustrates an explanation of the cause of the changing relationships between remotely sensed canopy metrics and fruit composition and yield. Smaller vines experienced budbreak earlier, so early in the growing season they have relatively high photosynthetically active biomass in comparison to the larger vines. As the growing season progresses, the larger vines develop a larger canopy, so that by véraison, when canopy growth ceases, the larger vines have relatively high photosynthetically active biomass in comparison to the smaller vines. At a mid-time point during canopy development there is a period when all vines, regardless of size, have similar photosynthetically active biomass, making it difficult to determine spatial patterns using remote sensing vegetation indices.

**SOIL AND SOIL MOISTURE**

Vineyard soils influence wine production. Strong correlations between soil characteristics, vine nutrition, and sensory properties of finished wines have been demonstrated within different zones identified from a combination of spatial data describing environmental conditions (Bramley et al. 2011). The spatial variability in canopy can be linked back to the soil characteristics and topographical features that vary at spatial scales within the vineyard. A region of soil within a vineyard that tends to promote slightly more grapevine growth will produce grapevines of a larger size over time, entrenching a stable pattern of spatial variability. Year-to-year temporal variability in climate and weather interacts with the spatial variability to produce spatiotemporal variability, i.e. the strength of correlations between canopy descriptors and fruit composition and yield can vary from year to year (Hall and Wilson 2013).

A key soil property in determining plant growth is plant available water-holding capacity. The dynamic response of plants is influenced by this plant available water-holding capacity. In a study where climate and management factors were held constant, crop phenology metrics derived from MODIS (Moderate Resolution Imaging System) satellite imagery could be linked to soil water conditions (Araya et al. 2016). Grapevine response to water stress can be further inferred from thermal infrared remote sensing. Remote sensing systems that utilise energy emitted from the Earth (terrestrial radiation) can be used to estimate surface temperature. When used in a vegetation monitoring context, foliage temperature can be related to the level of transpiration. Relatively warm regions of vegetative canopy in a vineyard are indicative of water stress. Jones et al. (2002) demonstrated the use of infrared thermography specifically to detect stomatal closure in grapevine canopies and the associated level of heat stress.
CLIMATE

Temperature is the key determinant of grapevine varietal suitability to a region, and heat indexes are regularly used to compare regions (e.g. Hall and Jones 2010; Jones et al. 2010). In addition, grapevine phenological development (predicting budbreak, harvest date and ripening period temperatures) can be estimated using air temperature records (e.g. Hall et al. 2016). Work characterising the temperature climates of winegrape growing regions often emphasises within-region spatial variability, mainly as a result of topographic variability (e.g. Jones et al. 2010). Weather station data may be spatially irregular, requiring interpolation of climate point data with the aid of digital terrain models (e.g. Webb et al. 2016).

Topoclimes are local climates influenced by topography. Topoclimatic data can be produced at a relatively fine spatial scale using satellite digital elevation data. In addition, topography-specific remote sensing devices (light distancing and ranging, LiDAR) can produce finer scale products for smaller areas through the use of aircraft mounted systems. Progress in structure-from-motion, in which 3-D models are derived from multiple overlapping images of a scene taken from slightly differing vantage points and angles, provides finer scale topographic information and may even be used to describe grapevine canopy structure (Mathews and Jensen 2013). Descriptors of topoclimatic data derived from digital terrain models include elevation, exposure, solar radiation load, aspect, and cold-air hollows. Viticulture-related metrics, such as growing-degree days, modelling phenology, and cold and heat indices to model specific weather events, can then be derived to inform spatial variability in a terroir-scale context.

REMOTE SENSING IMAGE ANALYSIS

With knowledge of the important aspects of climate and phenological response in the form of high spatial resolution maps, the base data required for zoning areas at a terroir scale are available. A relatively new technique for vineyard zoning is based on image analysis (OBIA), which is appropriate as a classification technique for high spatial resolution imagery (Fig. 6) or spatially extensive image data at the terroir scale. The starting point for OBIA classification is seed generation, whereby points in an image are identified that have similar levels of total variability in the spatial data surrounding them. Polygons derived from the seed points produces the initial set of objects; the pixels in each object have similar reflectance characteristics. Classification through OBIA can be applied in various ways in a viticultural context. At the precision viticulture scale, classification can be performed based on physical environmental properties, such as soil electrical conductivity, topography and remotely sensed imagery, to identify management zones that can then be used to inform vineyard sampling protocols or segmented harvests. At the terroir scale, topoclimatic and phenological metrics are likely to be more informative, but significant work to validate the bases for such an analysis is required. Links at the terroir scale between spatial data products and on-ground measures of yield and fruit quality metrics are key.

While progress in remote sensing applications in precision agriculture has been strong since the late 1990s, the gains made at the precision viticulture scale using remote sensing techniques do not necessarily cross over to the spatial scale of analysis for terroir applications. Precision viticulture tends toward within-vineyard block analysis with a level of detail that can distinguish vineyard variability down to the single grapevine scale. Viticultural terroir, on the other hand, tends toward regional scale variability and is concerned with attributes that determine wine typicality across areas that potentially encompass many wine regions. Because of the differences in spatial scale, terroir analysis requires different approaches to those used at the precision viticulture scale. Some precision viticulture research techniques can be adapted to a larger scale of analysis, and remote sensing products suitable to larger scales of analysis are available (e.g. Vaudour et al. 2002).

CONCLUSIONS

Remote sensing is a fundamental tool for the acquisition of spatial data required for the analysis of environmental aspects of viticultural terroir. Recent research in precision viticulture using remote sensing has shown that spatial variability in environmental conditions drives significant spatial variability in grapevine phenology and grape composition. This knowledge of the level and effects of spatial variability within vineyards is transferable to the larger terroir scale. Various remote sensing products

**Figure 6** Classification in an object-based image analysis framework for an ultrahigh spatial resolution (0.02 m) red–green–blue image of an area of variable vegetation. (A) Yellow dots represent “seed” points that provide the basis for the classification. (B) The areal classification result is produced based on the colour of the image pixels surrounding the dots. Vegetation (or features) now imaged are trees, shrubs, grass/annuals, no vegetation, and shadows. Image: A. Hall
are valuable for viticultural terroir analysis, by mapping variation in vineyard canopy, monitoring water stress and mapping fine scale climate variation. Remote sensing-derived phenological metrics, coupled with temporal remote sensing analyses are likely the key to successful studies linking physical characteristics of the environment with descriptors of wine grape quality and yield components at a regional scale.

ACKNOWLEDGMENTS

This work is supported by a grant from the Australian Grape and Wine Authority and incorporates data collected using the resources of the National Wine and Grape Industry Centre, Charles Sturt University (New South Wales, Australia). The author appreciates ongoing support provided by the university’s Spatial Data Analysis Network.

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The Clay Minerals Society

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THE PRESIDENT’S CORNER

As this is my last column, I must thank all the members of The Clay Minerals Society for giving me the opportunity to serve as president. This is a great honor, which I do not take for granted. This year has been a humbling and educational experience. I extend thanks to all the people who have served CMS as committee chairs, committee members, councilors, officers, and office staff: you are the heart of the society. To close out my term, I would like to further make a case for the value of clay science research from natural environments.

In my first President’s Corner (Elements, v13n4, p 282), I discussed the increasing number of published materials science clay studies and the decreasing natural science publications. In my last column (Elements, April 2018, v14n2, p 127), I included an excerpt from a 1989 CMS Newsletter interview with the late Professor Robert C. Reynolds Jr., where in discussing the trends in our (natural science) field he said, “there is a renaissance in materials science”, which is driven by the economics of metal films such as semiconductors that are intercalated compounds analogous to mixed-layered clay minerals. In 1967, Reynolds published the first calculation of a full X-ray diffraction profile from a mixed-layered clay, illite-smectite. At the same time, Professor Victor A. Drits, Head of the Laboratory of Physical Methods for Investigating Rock Forming Minerals at the Geological Institute of the Russian Academy of Science in Moscow, developed a sophisticated computer program to calculate diffraction patterns from mixed-layered clay systems and from a wide variety of intercalated lamellar compounds. Reynolds was a geologist whose work evolved into materials science, and Drits is a physicist whose enormous body of work made significant contributions to the structure, composition, origin, and evolution of clay minerals in natural systems.

Professor Drits was interviewed by CMS for the February 1992 CMS Newsletter. The following is an abbreviated excerpt from his response, which I think provides insight into the relationship between the natural and materials science fields.

CMS: [H]ow did your personal research interests develop over the years?
Drits: [B]eing a part of the Geological Institute, we were always collaborating with geologists. My interests were in two directions. The first is developing methodological approaches to interpreting diffraction and spectroscopy data obtained from fine-disperse minerals. The second is solving crystal structures, the more exotic and complicated the more challenging, both clay and non-clay.
CMS: You’ve mentioned your cooperation with the geologists at your institution. In which directions did this cooperation develop?
Drits: For the thirty years that I’ve been working at the institute, I’ve been constantly participating in studying diverse geological objects and processes. The main problems in our cooperation were associated with revealing interrelationships between fine structural peculiarities, composition, and formation conditions of minerals in various geological environments; in elucidating mechanisms for structural transformations of minerals; in searching for regularities in the distribution of clay minerals in continents, transition continental–marine zones, in marine sediments and basalts, and so on.

We described, in terms of the solid-phase transformation, illitization, and development of ordered mixed-layer illite/smectite in the course of diagenesis from bentonites of Karaganda basin (Republic of Kazakhstan). Using the density-gradient technique, we could quantitatively evaluate the degree of heterogeneity in glauconites differing in age and rock type in order to solve the problem of their formation conditions.

In the early sixties, we studied the transformation history of biotite and muscovite at different decomposition stages and in different geological environments. We believed that the existence of these main micas of crystal rocks in the sedimentary cycle would clarify the genesis of sedimentary clay minerals. We showed that in humid diagenesis–epigenesis, illitization of detrital flakes of biotite accompanies chloritization. A study of muscovite flakes differing in density, found in weathering crusts, indicated that kaolinitization proceeds without any appreciable intermediate phases, through dissolution–precipitation. Studying the crystalchemical features of clay minerals formed under different facies and climatic conditions, we concluded that both under low pH typical for coal-bearing complexes and under high pH and high mineralization of solutions typical for evaporite basins, authigenic clay formation often proceeds through synthesis and is hardly affected by the initial composition of the detrital mud. Some of these results were summarized in English in the special volume of Sedimentology published in 1970.

When we got samples from the first two expeditions of Glomar Challenger, we studied smectite from the Atlantic sediments and found them to be relatively Fe-rich in composition and layered. We concluded that they were authigenic products of basalt alteration. Comparing dioctahedral smectites derived from basalts and ultrabasic rocks of continental versus marine origin, we found a pronounced, though still puzzling, difference in the exchange cations: Ca = Na on land and K in the sea. Remarkably, the paragenesis of authigenic smectite was found to be characteristic only of pelagic clays.

The interview with Professor Drits continued in his precise and charming style, describing in detail many other discoveries about clay minerals and their origin and evolution in natural environments. The body of work by Professor Drits and his colleagues stands alone in both rigorous structural analysis and the relationship to geological environment. While clay studies related to materials science seems to have a stable future, the decreasing interest and support for clay studies in the natural world is a concern. Without the high quality of research in natural systems by scientists like Drits, Reynolds and others, clay work in material science research in natural systems would be less productive where physical properties are controlled by structure and composition.

Quality clay science research in natural systems deserves academic support, which I am sure would make positive feedback in the practical problems of fine disperse materials.

CITED REFERENCE


Douglas K. McCarty (mccardog@gmail.com), President, The Clay Minerals Society

CMS MEMBERSHIP RENEWAL

Don’t forget to renew your membership for 2018!
GS BOARD OF DIRECTORS OPEN POSITIONS

The Nominations Committee of the Geochemical Society (GS) is seeking nominees for open board seats with terms beginning in January 2019. The potential nominees should have established reputations of leadership in geochemistry and be willing to devote considerable time and effort to the work of the society. Suggestions should be communicated by 15 July 2018 to any member of the Nominations Committee or to the GS business office at gsoffice@geochemsoc.org. More information regarding the duties and responsibilities of board positions can be found on the society’s website.

HIGHLIGHTS FROM THE ANNUAL REPORT

The GS publishes an annual report to its members that concisely describes the society’s activities in the previous year. The most recent report shows that in 2017 the society had 4,500 members from 74 countries; students made up 24% of this total. There were 77 members who volunteered their time on a board or committee and another 89 members who served as associate editors of Geochimica et Cosmochimica Acta. Nearly 150 members made donations to support the society’s programs, including the three new special lectures and awards that were started since 2016. Find the entire report at www.geochemsoc.org/news.

GOLDSCHMIDT2018: BOSTON

https://goldschmidt.info/2018

The Geochemical Society and the European Association of Geochemistry are looking forward to welcoming delegates from around the world to Boston (Massachusetts, USA) in August for the 28th Goldschmidt Conference. Here are a few of the highlights planned for the meeting:

Plenaries

MONDAY
Sara Seager, planetary scientist and astrophysicist at the Massachusetts Institute of Technology (USA): “Mapping the Nearest Stars for Habitable Worlds.”

TUESDAY
Caroline Slomp, Professor of Marine Biogeochemistry at the Department of Earth Sciences, Utrecht University (Netherlands): “Oxygen Loss in Coastal Waters: Impact on Geochemical Cycles.”

WEDNESDAY
Tuba Özkan-Haller, professor and Associate Dean for Research and Faculty Advancement at the College of Earth, Ocean, and Atmospheric Sciences at Oregon State University (USA): “Transforming Academia: Advancing Diversity, Inclusion, and Social Justice in the Geosciences.”

THURSDAY
Fumio Inagaki, deputy director of the Research and Development Center for Ocean Drilling Science and the Kochi Institute for Core Sample Research, both at the Japan Agency for Marine-Earth Science and Technology: “Exploring Deep Microbial Life in the Planetary Interior: What Are the Limits of Habitability.”

FRIDAY
Bernard Marty, Professor of Geochemistry at the École Nationale Supérieure de Géologie, Université de Lorraine and researcher at the Centre de Recherches Pétrographiques et Géochimiques (CRPG) (France): “Origin and Early Evolution of Terrestrial Volatiles.”

Early Career Events

These events are open to all students and early career professionals. Some events have limited capacity, so be sure to register early.

- Sunday
  Oral Presentation Skills for Students; Succeeding in Academia/ Finding and Succeeding Outside of Academia

- Monday
  Dual Careers in Academia; Publishing and Reviewing

- Tuesday
  Flipping a Geochemistry Classroom Using Team-based Learning; Learn about Funding Opportunities

- Wednesday
  Pop-up talks

- Thursday
  Communicating Science; How to Be a Successful Post-doc

Child Care

The conference has appointed Kiddie Corp to provide on-site, subsidized childcare and a full program of activities for the children of delegates. They have provided high-quality childcare at many large conferences and can accommodate children ages 6 months to 12 years old. Advance registration is required by 16 July 2018. For more information, select “Family Friendly” on the homepage of the conference website, goldschmidt.info/2018
AWARDS TO BE PRESENTED AT GOLDSCHMIDT2018

The Geochemical Society and the European Association of Geochemistry look forward to welcoming you to Boston (Massachusetts, USA) for the 28th Goldschmidt Conference®. During the conference, the societies will honor the distinguished scientists shown on this page. Learn more about Goldschmidt and register at: goldschmidt.info/2018/

GEOCHEMICAL SOCIETY

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CLARKE MEDAL: Noah Planavsky (Yale University, Connecticut, USA)
ENDOWED BIOGEOCHEMISTRY LECTURE: Adina Paytan (University of California, Santa Cruz, USA)
F. EARL INGERSON LECTURE: Yuichiro Ueno (Tokyo Institute of Technology, Japan)

EUROPEAN ASSOCIATION OF GEOCHEMISTRY

UREY MEDAL: Susan L. Brantley (Pennsylvania State University, USA)
SCIENCE INNOVATION AWARD: Jess Adkins (California Institute of Technology, USA)*
HOUTERMANS MEDAL: Morgan Schaller (Rensselaer Polytechnic Institute, New York, USA)

GS/EAG

PAUL W. GAST LECTURE: Caroline Slomp (Utrecht University, Netherlands)
ROBERT BERNER LECTURE: Simon Poulton (University of Leeds, UK)

GEOCHEMICAL SOCIETY OF JAPAN

SHEN-SU SUN FOUNDATION

2018 GEOCHEMICAL JOURNAL AWARD: Shigeyuki Wakaki (Kochi Institute for Core Sample Research, JAMSTEC)
2018 SHEN-SU SUN AWARD: Qiuli Li (Institute of Geology and Geophysics, Chinese Academy of Sciences)

2018 GS/EAG GEOCHEMICAL FELLOWS

Miryam Bar-Matthews (Geological Survey of Israel)
Robert J. Bodnar (Virginia Tech, USA)
Daniel Frost (University of Bayreuth, Germany)
Jérôme Gaillardet (Institut de Physique du Globe de Paris, France)
George Helz (University of Maryland, USA)
Janet G. Hering (Swiss Federal Institute of Aquatic Science and Technology, ETH Zurich, EPFL, Switzerland)
Catherine Jeandel (Laboratoire d’Études en Géophysique et Océanographie Spatiales, France)
Craig Manning (University of California, Los Angeles, USA)
William S. Reeburgh (University of California, Irvine, USA)
Niels Revsbech (Aarhus University, Denmark)
Zachary Sharp (University of New Mexico, USA)
Susan Trumbore (Max Planck Institute for Biogeochemistry, Germany)
Fu-Yuan Wu (Chinese Academy of Sciences)

NOMINATIONS OPEN FOR 2019 SOCIETY HONORS

Do you know an outstanding scientist who should be recognized on this page next year? EAG and GS strive to honor the accomplishments of a diverse group of award recipients each year, but this depends on a strong pool of nominations from the geochemical community.

The deadline for GS awards and the Geochemical Fellows program is 31 October 2018. The deadline of EAG awards is 15 November 2018. Learn more at: www.eag.eu.com/awards and www.geochemsoc.org/awards

* Medallists also named Geochemical Fellows by virtue of their medal.
Meteoritical Society

http://meteoriticalsociety.org

2018 REPORT OF THE METEORITE NOMENCLATURE COMMITTEE (NOMCOM)

The purpose of the Meteorological Society’s Meteorite Nomenclature Committee (NomCom) is to approve new meteorite names, to establish guidelines, and to make decisions regarding the naming of meteorites. The committee also keeps the community appraised of new meteorites through the Meteoritical Bulletin and the Meteoritical Bulletin Database (https://www.lpi.usra.edu/ meteor/). Although the yearly publication of the Meteoritical Bulletin lags behind the database entries, new meteorites are automatically added to the next issue of the bulletin by the database editor. The contents of the bulletin are accessible using the “Publication” dropdown window to the next issue of the bulletin by the database editor. The contents for accepting the Editor position. Current membership is as follows:

I would like to thank Audrey Bouvier for her service as Editor of the Meteoritical Bulletin from 2014 to 2018 – this is a particularly time-consuming position. Also, I would like to thank Jérôme Gattacceca for accepting the Editor position. Current membership is as follows:

<table>
<thead>
<tr>
<th>NomCom Committee</th>
<th>Term Ending</th>
</tr>
</thead>
<tbody>
<tr>
<td>Laurence Garvie (Chair)</td>
<td>2018</td>
</tr>
<tr>
<td>Mutsumi Komatsu (1st term)</td>
<td>2019</td>
</tr>
<tr>
<td>Knut Metzler (2nd term)</td>
<td>2018</td>
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<tr>
<td>Tasha Dunn (2nd term)</td>
<td>2019</td>
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<tr>
<td>Emma Bullock (2nd term)</td>
<td>2019</td>
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<tr>
<td>Vinciane Debaille (2nd term)</td>
<td>2020</td>
</tr>
<tr>
<td>Hasnna Chennoufi (2nd term)</td>
<td>2020</td>
</tr>
<tr>
<td>Francis McCubbin (1st term)</td>
<td>2018</td>
</tr>
</tbody>
</table>

Three ex-officio NomCom members

| Jéréme Gattacceca (1st term) | 2019 | (Meteoritical Bulletin Editor) |
| Jeff Grossman (4th term)     | 2020 | (Database Editor)             |
| Meenakshi Wadhwa (Chair)     | 2020 | (Meteoritical Society Vice President) |

Meteoritical Bulletin Database (MBDB)

**Meteorites.** First and foremost, the database is a record of all recognized and classified meteorites as accepted by the Meteorite Nomenclature Committee (NomCom) of the Meteoritical Society. In addition, the database lists all approved dense collection areas (DCAs), including their keyhole markup language (KML) coordinates for direct viewing in GoogleEarth. The NomCom also keeps a list of all collections and repositories.

The Meteoritical Bulletin database (MBDB) continues to see significant growth, with around 1,923 meteorites added over the last calendar year for a total of 57,763 classified meteorites (as of 2 April 2018). Notable entries include twelve confirmed and probable falls (Table 1), four of which are not ordinary chondrites. Though a purely subjective list, other notable entries include Sericho (pallasite from Kenya with total mass well over 10 t), Los Vientos 200 (a fresh CH3), five new irons from Mars (Aeolis Mons 001 and 002 and Aeolis Palus 001 to 003), Los Vientos 189 (an anomalous IID iron), Northwest Africa 11610 (CO3 stone with a mass of over 28 kg!), and Northwest Africa 11575 (ungrouped achondrite). There continues to be strong numbers for new Lunars (45 for total mass over 50 kg) and Martians (13 for total mass near 4 kg).

Most submitters understand the importance of the database as a worldwide source for meteoritical information, and the depth of their submissions reflect this understanding. I continue to encourage submitters to see these submissions as mini-refereed publications - they are reviewed by the NomCom, which consists of 12 of your fellow scientists. Often, the submission will be the only time the meteorite is studied in detail, and, as such, sufficient petrographic and geochemical information should be included so as to be useful for future scientists.

**Dense Collection Areas.** There are currently 370 named dense collection areas (DCAs) – a list of all DCAs can be found at https://www.lpi.usra.edu/meteor/DenseAreas.php. Two of the DCAs are on Mars, viz. Aeolis Mons and Aeolis Palus. These DCAs are warranted given the numbers of meteorites observed by the Mars rover Curiosity. The names of a DCA derive from the International Astronomical Union–defined geomorphological units. Currently, the Aeolis Mons DCA contains two meteorites; the Aeolis Palus DCA contains three.

**Type-Specimen Repositories.** The NomCom voted on and approved the following type-specimen repositories: SIGM – the V. S. Sobolev Institute of Geology and Mineralogy (SI) (Russia); FMMR – the Fersman Mineralogical Museum RAS, (Russia); MLP – the Museo de La Plata (Argentina); PRL – the Physical Research Laboratory, Ahmedabad (India); UBonn – the University of Bonn Mineral Museum (Germany); ETH – the Eidgenössische Technische Hochschule Zürich (Switzerland); IUEM – the Université de Bretagne Occidentale (France). In accordance with §7.1f of the Guidelines for Meteorite Nomenclature, type specimens of all new meteorites “must be deposited in institutions that have well-curated meteorite collections and long-standing commitments to such curation.” For more on repository information, see https://www.lpi.usra.edu/meteor/MetBullAddresses.php?grp=country.

Essential information on meteorite nomenclature, instructions, the template for reporting new meteorites, and NomCom membership can all be found at http://meteoriticalsociety.org/page_id=106. The template that should be filled out for new submission can be found at http://meteoriticalsociety.org/page_id=63. This template is in Excel format with instructions both on page one of this file and header for each column (just let your mouse hover over the column header name).
Here is where I would like to make a special plea—please take the time to follow these instructions, especially for special characters such as micron, degrees, etc.

Finally, do not hesitate to contact us with questions or concerns about the NomCom, especially with suggestions for improvement.

Laurence Garvie
Chair of the Nomenclature Committee

2018 J. LAWRENCE SMITH MEDAL AWARDED TO KEVIN McKEEGAN

The 2018 J. Lawrence Smith Medal of the US National Academy of Sciences was awarded to Kevin D. McKeegan (University of California, Los Angeles). “The medal is awarded every three years for investigations of meteoric bodies and includes a $50,000 prize. The award was established as a gift from Sarah Julia Smith in memory of her husband and has been presented since 1888.” Kevin received the 2018 medal “for contributions to understanding of the processes and chronology of the early solar system as recorded by primitive meteorites, for innovation in analytical instrumentation, and for showing that the oxygen isotopic compositions of the Earth and rocky planets and meteorites are distinctly different from that of the Sun.” Past recipients of the medal include Hiroko Nagahara (2015), Harry Y. (Hap) McSween (2012), Robert (Bob) Clayton (2009), Klaus Keil (2006), and John Wasson (2003).

GIFTS AND GRANTS GUIDELINES CHANGED

The stated mission of the Meteoritical Society is “to promote research and education in planetary science with emphasis on studies of meteorites and other extraterrestrial materials that further our understanding of the origin and history of the solar system.” Besides the society’s publications, the annual scientific meetings, establishing official names for newly found meteorites, and the awards sponsored by the society, there are other ways by which we work toward furthering our mission. This includes supporting student travel to conferences and workshops, supporting student research, assisting scientists from economically disadvantaged countries, supporting classes or field schools (especially those that bring meteoritics and planetary science to developing countries), compiling oral histories from prominent members of the society, and supporting outreach to the broader public community on meteoritics and planetary science.

To support these activities, the society has created an endowment fund. The majority of the endowment consists of the General Fund which can support one-time activities that are not part of normal society business. The endowment fund also has the named funds within it: the Nier Fund, the McKay Fund, and the Travel for International Members (TIM) Fund. Details about activities supported by all of these funds are given under the Activities Supported section on the society’s website.

For those who wish to assist in this mission, donations can be made to the General Fund or to any of the specific funds (see Ways to Contribute on the society’s website).

CALL FOR NEW MEETING LOCATION PROPOSALS

The society is currently accepting proposals for future annual meeting locations. The next meeting location to be chosen will be for the year 2022. Please submit questions and/or proposals to metsocsec@gmail.com.

ANNUAL MEETING SCHEDULE

<table>
<thead>
<tr>
<th>Year</th>
<th>Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>2018</td>
<td>Moscow (Russia) 22–27 July</td>
</tr>
<tr>
<td>2019</td>
<td>Sapporo (Japan) 8–12 July</td>
</tr>
<tr>
<td>2020</td>
<td>Glasgow (Scotland, UK) 9–14 August</td>
</tr>
<tr>
<td>2021</td>
<td>Chicago (Illinois, USA) dates TBD</td>
</tr>
</tbody>
</table>

RENEW YOUR MEMBERSHIP NOW!

Please don’t forget to renew your membership for 2018. Students, this is particularly important if you are interested in applying for one of our student presentation awards, as you must be a member to be eligible. You can renew online at http://metsoc.meteoriticalsociety.net.
UNITED WE STAND

Inauguration of the DVGeo Office in Berlin

A reception celebrating the establishment of the new Berlin office of the Dachverband der Geowissenschaften (DVGeo), the umbrella organization for the Earth sciences in Germany, took place 1 February 2018. The new office is shared with the Berufsverband Deutscher Geowissenschaftler (BDG), the German professional organization of geologists, geophysicists, and mineralogists, which has members employed in industry, government, and academia. Moving in together allows both organizations to act in concert and to represent the Earth sciences in unity to the outside world – true to the slogan “united we stand!”

Over 140 participants from academia, industry, politics, government agencies, and stakeholder organizations attended the reception, which was held in the central, dinosaur-boasting, atrium of the Museum für Naturkunde Berlin (MfN). The diversity of the Earth sciences was illustrated in several keynote talks given by the presidents of the four founding members of the DVGeo: the German Geological Society (DGGV), the German Geophysical Society (DGG), the German Paleontological Society (PalGes), and the German Mineralogical Society (DMG), as well as by representatives of BDG and MfN. Reiner Klemd, in his role as DMG President, discussed the importance of mineralogy in the raw-material needs of modern industrial nations, and stressed the need for a resource-focused university education in mineralogy to train students in how to face potential future raw materials scarcity.

DMG President Reiner Klemd illustrates what mineralogists can contribute to future challenges regarding modern industrial nations’ demand for high-technology raw materials. Photo: H.-R. Knöfler, Museum für Naturkunde Berlin

This, and other topics, were discussed by the participants long into the night. The relevance and importance of the Earth sciences for society in general, and for future geopolitical challenges in particular, crystallized during the evening. The Berlin reception went down well and encouraged the DVGeo and the BDG to pursue their joint efforts to increase Earth science literacy among the public and to represent a unified front for the Earth sciences to the outside world.

Christopher Hamann (Berlin)

GOOD meeting attendees at the GeoZentrum Nordbayern. Photo: Patrick Bobek

3rd GEOLOGY OF ORE DEPOSITS (GOOD) MEETING

28 February–3 March 2018; FAU Erlangen Nuremberg, GeoZentrum Nordbayern

Following the success of the first two Geology of Ore Deposits (GOOD) meetings in Freiberg and Hannover (both Germany), the 2018 meeting at the GeoZentrum Nordbayern featured an impressive array of talks and poster presentations that covered all aspects of mineral-deposit research, from hyperspectral remote sensing to detailed fluid-inclusion studies. Masters and PhD students, as well as early career researchers, presented their cutting-edge research. The quality of the presentations was exceptional throughout. DMG President Reiner Klemd gave the welcoming address; keynote talks were given by Andreas Audetat (University of Bayreuth) and Thomas Angerer (University of Innsbruck, Austria), Anne Papenfuß won the prize for the best student speaker, and Stefan Schaefer won for his poster presentation. Both winners received book prizes sponsored by Schweizerbart Borntraeger. The meeting’s field trip was to the historic mines at Kupferberg and Gleissinger Fels, and both were well attended. We thank Stefan Hoehn for giving an insightful presentation on the complex formation history of the Cu-mineralization at Kupferberg.

GOOD participants visit the historic underground mine at Gleissinger Fels. Photo: Patrick Nadoll

The meeting was organized by Patrick Nadoll (FAU GeoZentrum Nordbayern) and his team of student helpers: Patrick Bobek, Adrian von Heydebrand, Uli Fliehr, Matti Kern, Felix Mackowiak and Lukas Tremel. The organizers would like to thank the Deutsche Mineralogische Gesellschaft (DMG) and publisher Schweizerbart Borntraeger for their support. The fourth GOOD meeting will be held at the Jacobs University in Bremen in 2019. We look forward to seeing you all there.

Patrick Nadoll (Erlangen)

SECTION MEETING

CPKM/AMITU workshop 2018, 28 February–2 March 2018

As in previous years, the annual joint workshop of two DMG sections – the Chemistry, Physics and Crystallography (CPKM) section and the Applied Mineralogy in Technology and the Environment (AMiTU) section – was held in Bad Windsheim (Northern Bavaria) at the end of February.

Altogether, 20 presentations covered a wide range of themes in applied mineralogy and crystallography, including archaeological studies that used X-ray diffraction, in situ and real-time hyperspectral Raman imaging of phase transformations during thermal annealing of ceramic materials, and studies on early stages of corrosion in hot, aggressive
environments to name a few. The plenary lecture was by Dr. Melanie Keuper (3D Flow Industry GmbH & Co. KG) with the title, “New Ways for a Mineralogist – High-Tech Ceramics and 3D Printing.” Young scientists, in particular, took the opportunity to present their graduate or undergraduate research and to discuss scientific questions with senior researchers in their field.

Our thanks go to Christoph Berthold (University of Tübingen) and Helmut Klein (University of Göttingen) for a pleasant and perfectly organized workshop. Reservations for the next meeting, which will be in Bad Windsheim again (27 February–1 March 2019), can be sent to C. Berthold.

Hieronymus Hölzig (Leipzig)

DMG SHORT COURSES 2018

Fall courses open for enrollment

Three DMG short courses (all are based in Germany; see list below) that will run during autumn 2018 are now open for enrollment. All courses are aimed primarily at advanced-level undergraduate and graduate students but are always open to more senior researchers as well. Non-local student members of DMG are eligible for travel support to the amount of €50. Further information about the courses can be obtained at www.dmghome.de/aktuelles/doktorandenkurse.

K5 Application of Diffusion Studies to the Determination of Timescales in Geochemistry and Petrology. Joint MSA–DMG short course, Prof. Sumit Chakraborty, Dr. Ralf Dohmen, 1–5 October 2018 (sumit.chakraborty@rub.de).

K6 In situ Analysis of Isotopes and Trace Elements by Femtosecond Laser-Ablation ICP-MS [In situ-Analyse von Isotopen und Spurenelementen mit (MC-) ICP-MS gekoppelt mit Femtosekunden-Laserablation]. Institute for Mineralogy, Leibniz University Hannover, organized by Prof. Dr. Stefan Weyer and others, 8–12 October 2018 (s.weyer@mineralogie.uni-hannover.de).

K7 Introduction to Secondary Ion Mass Spectrometry in the Earth Sciences. Helmholtz Centre Potsdam – GFZ German Research Centre for Geosciences, Dr. Michael Wiedenbeck, 3–7 December 2018 (michael.wiedenbeck@gfz-potsdam.de).

SHORT COURSE REPORTS

High-Pressure Experimental Techniques and Applications to the Earth’s Interior

Bayerisches Geoinstitut, Universität Bayreuth, 19–23 February 2018

The Bayerisches Geoinstitut invited interested students, doctoral candidates, and scientists to the high-pressure short course in Bayreuth. The 5-day course took place 19–23 February 2018 and was attended by 29 participants from 6 different countries and a total of 16 different institutes. The purpose was to get an insight into various experimental methods of mineralogy, geochemistry, and geophysics to understand better the composition, structure, and dynamics of the Earth’s interior. For those participants who wanted to receive two ECTS credits for the course, a one-hour written exam was offered afterwards.

Each of the five days day was divided into a morning of theory, concerning the various high-pressure techniques and analytical methods (e.g. spectroscopy or electron microscopy), and an afternoon of practical exercises. Participants not only examined the results of previous experiments, they also carried out small experiments or analysed materials on their own. For example, thermocouples or capsules were independently produced in the laboratory course for the multi-anvil press. Participants also received insight into how to evaluate an experiment. The results of LA–ICP–MS analysis, for example, were examined directly afterwards.

A constructive exchange among the course participants and the institute members was promoted and was initiated by the organizers throughout the course. Additionally, all participants were invited to a guided tour of the Bayreuth Catacombs, followed by a dinner in a traditional Franconian restaurant.

After a very informative week, the director of the Bayerisches Geoinstitut, Dan Frost, said goodbye to all participants. The course was a success. So, we say a warm “Thank you very much” to organizers D. Frost, F. Heidelbach, L. Kison-Herzing, and to all the associated helpers.

Jennifer Primocerio (Bochum) and Anastasia Zemlitskaya (Mainz)

Exploration Geology: Ore Deposit Geology, Alteration Geochemistry and Ore Interpretation

Albert-Ludwigs-Universität Freiburg, 19–22 March 2018

The short course on exploration geology was organized by the Mineralogy and Petrology group at the University of Freiburg (Germany) and was attended by 27 participants from 18 institutes and six countries. The short course offered both theoretical background and practical training in exploration geology, whole-rock and alteration geochemistry, and ore interpretation. Practical training included ore microscopy and geochemical data processing, the latter having a special focus on visualization and modelling software iogAS and GCDKit. Case studies from exploration projects in Scandinavia and Greenland showed that diverse geological situations demand a range of geochemical tools to be employed. A poster session gave the opportunity for participants to present and discuss their own projects. The short course was concluded by a one-day field trip to mine sites in the Schwarzwald and Kaiserstuhl.

Participants and lecturers at the DMG’s 2018 high-pressure experimental techniques short course at BGI.

Course instructors were Professor David Dolejš, Dr. Kateřina Schlöglová, Dr. Malte Junge and Dr. Denis Schlatter. In addition, a plenary lecture by Professor Hartwig Frimmel (University of Würzburg) entitled “How Gold Became Concentrated to Ore Grade in the Earth’s Crust” was sponsored by the SGA (Society for Geology Applied to Mineral Deposits). We appreciate partial support from the DMG and SGA.
President’s Letter

Indispensability

Maybe no one is truly indispensable, but sometimes it surely seems like it. As many of you know, Alex Speer, Executive Director of the Mineralogical Society of America (MSA), will retire at the end of 2019 after 25 years at the helm, and with 50 years as an MSA member. When Alex joined MSA as, what was then termed, a “Scientific Administrator,” things were very different than today. How different? Although the digital revolution and the information age had both started much earlier, in 1995, MSA was not connected to the Internet and computers barely impacted the lives of the staff. The MSA Business Office was located in Washington DC, the Editorial Office in Ann Arbor (Michigan) and limited off-site storage was rented in Gaithersburg (Maryland). Now the MSA Business and Editorial Offices are both located in Chantilly (Virginia) in space that is 50% larger, together with more than enough available storage (although with the change to digitally printing just the number we need means that we will no longer store hard copies of the American Mineralogist and the Reviews in Mineralogy and Geochemistry volumes for 20 years).

Compared to 1995, membership is up only slightly. But submissions to the American Mineralogist are one-third higher and the number of published pages has doubled; one-third of these pages now use color, whereas color was not realistically available to authors in 1995. Importantly, the number of subscribers to the American Mineralogist is nearly 25% higher. In 2005, MSA entered into a nonexclusive publishing agreement with GeoScienceWorld, a positive development for the society that was initiated by Alex Speer. On the financial side, our turnover today is twice that in 1995 and our Fund balance is three times greater. From the beginning of the century, MSA has awarded the Dana Medal (in addition to the Roebling and Public Service Medals, the MSA Award, and the MSA Undergraduate Prize), has increased from two to three the number of Distinguished Lecturers, and has increased from one to three the number of research grants awarded annually. Finally, our Internet services, which did not exist in 1995, have become important for members and for outreach. Now, all past and current MSA publications are posted on the MSA website and are searchable by anyone using Google; MSA-talk has around 3,000 subscribers; and Mineralogy4Kids had 3.26 million page views in 2017. Today, MSA offers a wider range of enhanced services to its members, the staff is larger to deal with the increased workload, and the workplace is largely electronic.

This is the background to my major task as the 2018 MSA President. We have begun the process of searching for an Executive Director to join MSA in January 2019, which will allow the appointee to overlap with Alex during his final year. After the spring meeting of the MSA Council, I will establish a search committee of past presidents whose charge it will be to recommend a shortlist of candidates for interview to the Executive Committee. We plan to advertise in the early summer, complete the review of applicants by the late summer, and conduct interviews in October.

What can you do to help? Two things. First, you can pass on information about the position to potential candidates. Second, you can nominate candidates: simply email me a name with a brief paragraph of support, and I will pass on your suggestions to the search committee.

Changes of this magnitude are made only rarely by “Learned Societies,” but getting the right outcome is hugely important to the future and longevity of the MSA.

For sure, things will be very different after 2019!

Michael Brown, 2018 MSA President

Notes from Chantilly

Balloting for the 2018 election of MSA officers and councilors is underway. The slate of candidates now follow. President: Mickey E. Gunter, University of Idaho (USA); Vice President (one to be selected): Carol D. Frost, University of Wyoming (USA), and Kimberly T. Tait, Royal Ontario Museum (Canada). Treasurer: Thomas S. Duffy, Princeton University (USA). Councilors (two to be selected): Aaron Celestian, Los Angeles County Natural History Museum (USA); Vincent van Hinsberg, McGill University (Canada); Mark Caddick, Virginia Polytechnic and State University (USA); and Adam Simon, University of Michigan. Bryan C. Chakoumakos, Oak Ridge National Laboratory (Tennessee, USA), continues in office as Secretary. Continuing Councilors for 2019 will be Sarah K. Carmichael, Appalachian State University (USA); Sarah C. Penniston-Dorland, University of Maryland (USA); Jay J. Ague, Yale University (USA); and Donna L. Whitney, University of Minnesota (USA). Members of the MSA should have received voting instructions to their current e-mail addresses. Those who do not wish to vote online can request a paper ballot from the MSA Business Office. The voting deadline is 1 August 2018.

At the GSA Meeting in Indianapolis (Indiana, USA), to be held 4–7 November 2018, MSA will have its Awards Lunch; Awards Lectures; MSA Presidential Address; Joint Reception of the MSA, the Geochemical Society, and the GSA’s Mineralogy, Geochemistry, Petrology, and Volcanology (MGPV) Division; Annual Business Meeting; MSA Council Meeting; and breakfasts for the Past Presidents and Associate Editors. The exhibit hall will be open Sunday (2–7 PM), Monday–Tuesday (10 AM–6:30 PM), and Wednesday (10 AM–2 PM).

The MSA Awards Lunch is Tuesday, 6 November 2018, at which the Roebling Medal will be presented to E. Bruce Watson, Rensselaer Polytechnic Institute (New York, USA); and the Dana Medal to Joerg Hermann, University of Bern (Switzerland). The 2017–2018 MSA Distinguished Lecturers will also be recognized: Zachary D. Sharp, Clara S. Chan, and Jon Blundy. The MSA Awards Lectures, the Presidential Address, and the Annual Business Meeting session are later in the day at the Indiana Convention Center. The Roebling Lecture will be given by E. Bruce Watson 3:00 PM; the Dana Medal Lecture by Joerg Hermann at 3:40 PM, and the MSA Presidential Address by Michael Brown at 4:20 PM. The MSA Annual Business Meeting is at 5:00 PM and the MSA/GS/MGPV Joint Reception follows, from 5:45 PM to 7:30 PM. The 2018 MSA Awardee is Laura Nielsen Lammers, University of California, Berkeley (USA). Presentation of her award and her MSA Award Lecture is delayed until 2019.

Topical sessions have been proposed for awardees:

- **T136.** “Tick Tock in the Rock: Elucidating the Time Scales of Geologic Processes and Honoring the Contributions of Bruce Watson, 2018 Roeblimg Medalist.” **Organizers:** Frederick J. Ryerson, Mark Harrison, Julia E. Hammer, Sumit Chakraborty, and Calvin F. Miller

- **T139.** “Work on the Zircon, Highlight the Apatite: Wielding the Power of Accessory Minerals and Honoring the Contributions of Bruce Watson, 2018 Roebling Medalist.” **Organizers:** Calvin F. Miller, Mark Harrison, Sumit Chakraborty, Frederick J. Ryerson, and Julia E. Hammer

- **T140.** “Frontiers in Mineralogy, Petrology, and Geochronology: A Session in Honor of Dana Medalist Jörg Hermann.” **Organizers:** Bradley Hacker, Marc M. Hirschmann, and Hugh St.C. O’Neill

表决 2018 MSA Elections

Michael Brown, 2018 MSA President
There are also sessions in honor of a Past MSA President (2013), and of the MSA itself:

- **T114.** “Apatite, from Magma to Medicine: In Honor of John M. Hughes.” **Organizers:** John Rakovan and Jessica J. Barnes
- **T115.** “Mineral Evolution and Ecology: Potential Directions for the Next 100 Years with the Mineralogical Society of America.” **Organizers:** Edward S. Grew and Robert M. Hazen
- **T142.** “Metamorphic Petrology Past, Present, and Future: Preparing for the Next 100 Years with the Mineralogical Society of America.” **Organizers:** John M. Cottle, Sarah Penniston-Dorland, and Mark J. Caddick

J. Alex Speer, MSA Executive Director
jaspeer@minsocam.org

### 25-YEAR AND 50-YEAR MSA MEMBERS

The following individuals will reach 25 or 50 years of continuous membership in the Mineralogical Society of America during 2018. Their long support of the society is appreciated and is recognized by this list and by 25- or 50-year pins mailed this year. If you should be on this list and are not, or have not received your pin, please contact the MSA Business Office.

#### 50-year Members
- Hans Annersten
- Gustaf O. Arhenius
- Philippa M. Black
- George A. Desborough
- G. Nelson Eby
- Gerhard K. Hentschel
- Lincoln S. Hollister
- Carol M. Jantzen
- R. James Kirkpatrick
- W. John McLean
- Arthur Montana
- Yoshikazu Ohashi
- Richard O. Sack
- Samuel E. Swanson
- Alan Bruce Thompson
- Robert J. Tracy
- David J. Vaughan
- David J. Von Bargen
- Hans-Peter Weber
- James A. Whitney

#### 25-year Members
- Ivan K. Bonev
- Claude Dalpe
- Dolores G. Durant
- Dori J. Farthing
- Bruce Paul Gaber
- Terrence M. Gerlach
- Ben A. Grguric
- R. Brooks Hanson
- Dan G. Holtstam
- Cliff Johnston
- Ursula E. D. Kelm
- Konstantinos Kitsopoulos
- Ingrid M. Kjarsgaard
- Jacob Teunis Kloprogge
- Nikolas Koukouzas
- Keiji Kusaba
- Claudio Mazzoli
- Konstantin K. Podlesskii
- Kevin M. Rosso
- Hirohito Shinjo
- Thomas C. Simonon
- Richard Spiess
- George H. Swihart
- Yoshiharu Watanabe
- Alan B. Woodland

## MSA UNDERGRADUATE PRIZE FOR OUTSTANDING STUDENTS

The MSA welcomes the following exceptional students to the program’s honor roll and wishes to thank the sponsors for enabling the Mineralogical Society of America to join in recognizing them. MSA’s Undergraduate Prize (MSA–UP) is for students who have shown an outstanding interest and ability in mineralogy, petrology, crystallography, and geochemistry. Each student is presented with a certificate at an awards ceremony at his or her university or college and receives an MSA student membership, which includes a subscription to *American Mineralogist, Elements,* and either a volume of the Reviews in Mineralogy and Geochemistry or an MSA Monograph chosen by the sponsor, or the student, or both.

Past MSA–UP awardees are listed on the MSA website, as well as instructions on how MSA members can nominate their students for the award.

- Antoineta Ashauer, Goethe University (Frankfurt, Germany). **Sponsored by** Dr. Frank E. Brenker.
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- Sarah K. Powers, University of Vermont (USA). **Sponsored by** Dr. Julia Perdrial.
- Catherine Sangster, University of Otago (New Zealand). **Sponsored by** Dr. J. Michael Paulin.
- Emma Scanlan, University of Otago (New Zealand). **Sponsored by** Dr. J. Michael Paulin.
- Cole Sitar, University of California-Santa Barbara (USA). **Sponsored by** Prof. Roberta L. Rudnick.
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- Zachary D. Tomlinson, University of Oklahoma (USA). **Sponsored by** Dr. David London.
- Jessica Ann Wheeler, Furman University (South Carolina). **Sponsored by** Dr. William A. Ranson.
- Jodie C. Wilse, University of Victoria (Canada). **Sponsored by** Prof. Dante L. Canil.
- Caroline Cominey Wolcott, Furman University (USA). **Sponsored by** Dr. William A. Ranson.
- Peiyu Wu, University of Washington (USA). **Sponsored by** Dr. Fangzhen Teng.
2018 EAG AWARDS

Urey Award to Susan L. Brantley
Sue Brantley (Pennsylvania State University, USA) has developed exceptional insight into the physico-chemical processes that operate at the Earth’s surface. Sue has ventured from her background in low-temperature aqueous geochemical kinetics into numerous other disciplines: geomorphology, microbiology, and geophysics. Her work on the time-scale dependence of mineral dissolution rates and of how weathering fronts advance have provided fundamental insights into the functioning of the weathering zone. Sue has written numerous book chapters and initiated the US NSF National Program of Critical Zone Observatories, which is a network of observatories that study the critical zone across the US. She is one of those few outstanding geochemists who have initiated a field of substantial size and significance.

Shackleton Science Innovation Award to Jess Adkins
Jess F. Adkins, Professor of Geochemistry and Global Environmental Science at the California Institute of Technology (Caltech; USA), has been awarded the 2018 Science Innovation Award, Shackleton Medal. Jess was awarded the medal for pioneering the field of deep-sea coral paleoceanography (which has helped us to understand the role of deep ocean in climate change and abrupt climate change) and for major contributions to our understanding of the controls on ocean salinity at glacial–interglacial timescales, the controls on precipitation and dissolution of biogenic carbonates, and the effect of sulfide weathering on atmospheric carbon dioxide concentrations. With these accomplishments and his ongoing research, Adkins truly follows in the footsteps of Sir Nicholas Shackleton.

Houtermans Award to Morgan Schaller
Currently an assistant professor at Rensselaer Polytechnic Institute (New York, USA), Morgan Schaller is a geochemist, stratigrapher, and sedimentologist who specializes in stable isotope research and vapor inclusion analysis in relation to deep-time atmospheric gas variations. He is best known for documenting major changes in atmospheric CO2 through 32 million years of the Early Mesozoic, including CO2 changes associated with the weathering of Triassic–Jurassic basalts, and, most recently, his discovery of impact spherules at the Paleocene–Eocene boundary, which he reported in Science and for which the Houtermans award has been bestowed. Dr. Schaller received his bachelor’s degree in geology and biology in 2005 from Binghamton University (New York, USA), his MS in hydrogeology, and his PhD in geochemistry in 2012 from Rutgers University (New Jersey, USA).

KNOW OF ANY DESERVING SCIENTISTS?
Nominate them for one of the 2019 EAG awards by 15 November 2018 at http://www.eag.eu.com/awards/nomination/.

2017 EAG–GS OUTREACH PROGRAM TO AFRICA
As part of the 2017 EAG–GS Outreach Program to Africa, I [Alex Hofmann] travelled to Earth science departments in Ghana, Ethiopia, Tanzania, and Nigeria to give a three-day short course with the title Early Earth Life and Mineral Systems. The course explored the relationship between surface processes, the evolution of life, and the formation of mineral deposits on the early Earth. Africa has a rich record of Archaean geology, and I aimed to outline some of the geochronological and geochemical tools available to tap into this record. Beside promoting geochemistry in Africa, a more personal goal of the course was aimed at intensifying Pan-African collaboration – I myself am based in Africa, at the University of Johannesburg (South Africa).
contact the geology department at the University of Nairobi in Kenya fell on deaf ears, possibly because of student unrest at the time. Staying five days in Addis Ababa (Ethiopia) was a pleasant experience due to blue skies, cool air, and Ethiopian hospitality at the university, which had been arranged by Profs. Dereje Ayalew and Gezahegn Yirgu. A group of ~15 postgraduate students attended the course, which was a sizeable number when keeping in mind that Ethiopia’s basement rocks are mainly Neoproterozoic in age. The following week was spent at the University of Dar-es-Salaam (Tanzania), where ~35 postgraduate students and members of the Tanzania Geological Society (TGS) followed the course. Because of the abundance of Archaean rocks in the Tanzanian craton, there were some lively discussions on early Earth processes. Drs. Elisante Mshiu, Ernest Mulaya, and Emmanuel Kazimoto hosted me, and the TGS sponsored refreshments and a joint lunch. Thank you all. Being in Tanzania in December, I used the opportunity to travel around the country for a year-end holiday, trying to avoid as much as possible the rather pricey national parks.

In January, teaching in Nigeria was back to normal, so I decided to complete my lecture tour by visiting the universities of Zaria, Ibadan, and Lagos. Thanks to Profs Tavershima Najime (Ahmadu Bello University, Zaria), Olugbenga Ehinola (University of Ibadan), and Samuel Olobaniyi (University of Lagos) for arranging for my tour. A diverse mix of ~40 postgraduate students and staff, coming from as far as Kano, attended in Zaria, well known for its ancient walled town and Precambrian basement geology. The Zaria university campus is surrounded by peaceful agricultural land and, therefore, far away from the hustle-and-bustle commonly encountered in Nigerian cities. Thanks to Harmattan winds, the weather was pleasant, albeit too cool for residents. At Ibadan, the audience included many PhD students from around Africa. The University of Ibadan is the oldest Nigerian university, and the geology department is host to the Life and Earth Sciences Unit of the Pan-African University. Certificates of attendance were handed out, like at most other departments, and I got my own certificate too. I had to use it later as proof of my workplace and for having travelled to Nigeria for work and not for wheeling and dealing! The last stop was at the University of Lagos, where more than 100 predominantly undergraduate students tested my patience. I hope that I was able to arouse some interest in them in the evolution of the ancient Earth as a system. There is an interesting array of Precambrian rocks in Nigeria, and I am specifically referring to the schist belts here, which appear largely undated. Much field-based research, in combination with geochronology and geochemistry, is required. There is no shortage of students there to do the job, but access to analytical facilities and trained technical staff are needed, which applies to most of the departments I visited.

The EAG–GS Outreach Program to Africa provides useful guidance by which African universities can offer advanced (and practical) research opportunities for students. A big thanks to Marie-Aude Hulshoff, Bernard Marty, the EAG and the GS for making this tour through Africa possible.

Axel Hofmann, 2017 Outreach Lecturer
The first “hard rock” description onboard the drilling vessel D/V Chikyu: a historical collaboration between the Oman Drilling Project of the International Continental Scientific Drilling Program (ICDP) and the International Ocean Discovery Program (IODP)

The drilling vessel D/V Chikyu (“chikyu” is Japanese for “Earth”) is the first riser drilling-equipped scientific research vessel capable of drilling up to 7 km beneath the sea bed. This is far deeper than any other scientific drilling vessel. Although Chikyu has successfully recovered core samples from several previous scientific targets – such as the Nankai Trough Seismogenic Zone (Araki et al. 2017), the Tohoku earthquake slip surface (Ujiie et al. 2013), and examined biomass of sub-seafloor microbial life (Inagaki et al. 2015) – she has never drilled cores from significant depth in “hard rocks”.

The Oman Drilling Project (http://www.omandrilling.ac.uk/) of the International Continental Scientific Drilling Program (ICDP) aims to understand oceanic plate formation and the alteration of that plate, including active serpentinization and its relationship to the deep biosphere (Kelemen et al. 2013). During the first phase of the drilling project (late December 2016 until the end of March 2017), 1.5 km of core were obtained from four boreholes into the crustal and mantle sections of the Samail ophiolite, with 100% recovery. Three boreholes were drilled into the lower crustal section of this ophiolite (GT1, lower gabbros; GT2, foliated gabbros; GT3, dike–gabbro transition). One borehole (BT1) passed through the basal thrust from the mantle sections of the Samail ophiolite, with 100% recovery. Three boreholes were drilled into the lower crustal section of this ophiolite (GT1, lower gabbros; GT2, foliated gabbros; GT3, dike–gabbro transition). One borehole (BT1) passed through the basal thrust from the listvenite section [listvenites being carbonated peridotites interlayered with partially serpentinized peridotites], through the fault zone, and terminated in the fine-grained mafic volcanics and sediments of the metamorphic sole. Geophysical properties and geological descriptions of the Oman Drilling Project cores were carried out for the first time on board the Chikyu from 15 July 2017 to 15 September 2017 by shipboard scientists from all over the world (nicknamed ChikyuOman) (Fig. 1). The analytical methods closely followed those used during IODP Expeditions 304/305, 309/312, 335, 345, and 360 by JOIDES Resolution and IODP Chikyu Expeditions 322, 348.

A series of carefully structured preparations and tests were followed on the ship. All core sections are shrink-wrapped and run through the X-ray computed tomography (X-ray CT) scanner to obtain X-ray CT images. Natural gamma radiation and magnetic susceptibility were subsequently measured using a whole-round multi-sensor core logger. The X-ray CT scan is a routine measurement used during IODP research, and it was applied to the Oman Drilling Project core on Chikyu. It enables the non-destructive observation of the internal structure of core samples. The X-ray intensity varies as a function of X-ray path length and the linear attenuation coefficient of the target material, which is dependent on its chemical composition and density. The X-ray CT images that are obtained can provide information on chemical compositions and densities of the cores, which can be used to assess sample locations and the quality of the whole-round samples. An example of an X-ray CT image taken from a section of Hole C5701A (Section 805-C5703A-7Z) is shown in Figure 2. Additional measurements of gamma ray attenuation density, P-wave velocity, and non-contact resistivity were also taken. Information generated from these instruments form part of the J-CORES database of the Chikyu-curated section lengths done for each core section. A comprehensive discussion of methodologies and calculations used in the Chikyu Physical Properties Laboratory (except for the X-ray computed tomography) is given by Blum (1997). In addition to these analyses, a Caltech imaging spectrometer system was used to scan the entire 1.5 km archive half of the core from all four boreholes at ~250 µm/pixel. Representative samples, and some specific samples, were subjected to X-ray diffraction analysis; X-ray fluorescence (to analyze for major, trace, and minor element concentrations); inductively coupled plasma mass spectrometry (using mixed acid/alkali-fusion digestion); loss on ignition; and an elemental analyzer (to assess volatile element concentrations of H, C, N, S). Routine shipboard paleomagnetic and magnetic anisotropy experiments were carried out within the ship’s shielded room. All the data collected are being used to link together petrological observations (background characters, structure, alteration, and veins), representative thin section information, measurements made by downhole wireline geophysical logging, and regional geological survey results.
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JOURNAL OF MINERALOGICAL AND PETROLOGICAL SCIENCES

Vol. 113, No. 2, April 2018

Original Articles

Dissolution of diamond crystals in a heterogeneous (metal–sulfide–silicate) medium at 4 GPa and 1400 °C – Anatoly I. CHEPUROV, Valeri M. SONIN, Egor I. ZHIMULEV, Aleksei A. CHEPUROV, Boris S. POMAZANSKY and Aleksei L. ZEMNUKHOV

Formation of triple-layer coronas between corundum and hornblende from the Lützow–Holm Complex at Akarui Point, East Antarctica – Yuki MORI and Takeshi IKEDA

Bayesian probabilistic reconstruction of metamorphic P–T paths using inclusion geothermobarometry – Tatsu KUWATANI, Kenji NAGATA, Kenta YOSHIDA, Masato OKADA and Mitsuhiro TORIUMI


Letter

In situ X-ray diffraction studies of hydrous aluminosilicate at high pressure and temperature – Ryota ABE, Yuki SHIBAZAKI, Shin OZAWA, Itaru OHIRA, Hiromu TOBE and Akio SUZUKI

Laboratory measurements of electrical conductivity in a gabbro of the Oman ophiolite at high pressures and high temperatures: implications for interpretation of resistivity structures of lower oceanic crust – Satoshi SAITO and Nikolai S. BAGDASSAROV

MINERALOGICAL DATABASES AND DATA PLATFORMS: TOOLS SUPPORTING THE SPREAD OF MINERALOGICAL KNOWLEDGE IN THE EU

Collecting data into structured databases, managing these databases, and integrating them into larger units (platforms) are practices that are becoming increasingly urgent today. This urgency is due to the increasing demand for access to various types of data by a wide range of diverse users, from scientists to political decision-makers. Harmonizing data, organizing regular updates, and guaranteeing good data quality are now the tasks of many European Union (EU) projects. Keeping mineralogical databases up-to-date is becoming increasingly important.

Of the many operating mineralogical databases, the two best-known contain basic mineralogical data such as composition, structure, and geographic occurrence: Mindat (https://www.mindat.org) and WebMineral (http://webmineral.com/). A third database, Minerant (www.minerant.org/), consists of information relevant to collectors. Mindat and WebMin support newly generated databases that cover a wide thematic range. A more specialized database dedicated to spectral data is the RRUFF Project (http://rruff.info/about/about_general.php). This project has a complete set of high quality spectral data from well-characterized minerals. It is addressed to mineralogists, geochemists, gemologists and the general public interested in Earth sciences and planetology.

New mineral databases expand the information needed to support decision-making in regard to mineral exploration, exploitation, production, trade activity, policy, and legislation. Such databases need to provide information regarding the location and spatial distribution of minerals. Both primary and secondary minerals are objects of industry interest. Exploration and exploitation of mineral resources, as both primary and secondary deposits, are critical issues for the modern economy. Within the EU, various institutions have emerged whose aim is to provide tools that will help in mineral exploration and exploitation. One of those is GeoERA (http://geoera.eu/), which its website means, “Establishing the European Geological Surveys Research Area to deliver a geological service for Europe (GeoERA)”. GeoERA regularly announces calls for European Geological Survey research projects. These calls have included “Raw Materials Specific Research Topics” and “Improving and Sustaining the Raw Materials Knowledge Base by Periodically Delivering a Minerals Yearbook and Inventory Information System”. The idea of the mineral yearbook was introduced in 1933 in the US with the publication of an annual report that reviewed minerals and materials from the US and many other countries. The European Minerals Yearbook continues this idea and develops it for European needs.

Another EU minerals platform is the European Minerals Knowledge Data Platform (EU-EMKD) (http://minerals4eu.bgrm-rec.fr/). This platform is defined on their website as “A simplified, user-friendly and efficient access to all available and new data related to mineral resources through the ‘Minerals4EU’ Knowledge Data Platform.” Indeed, the Minerals4EU project was developed to implement the EU mineral intelligence network structure in a form suited to the EU-EMKD platform, the European Minerals Yearbook, and various predictive studies.

Two other platforms need to be mentioned: the Raw Materials Information System (RMIS) (http://rmis.jrc.ec.europa.eu/) and the more versatile system that is the European Geological Data Infrastructure (EGDI) (http://www.eurogeosurveys.org), which is governed by EuroGeoSurveys. However, all these mineral platforms and databases pose something of a challenge: how can we unify them and create useful and necessary connections between them? And then, of course, how can we manage that integrated system itself?
The Mineralogical Association of Canada (MAC) awarded 14 student travel and research grants in 2017 that totaled $10,000: one went to an undergraduate student, five to MSc students, and eight to PhD students. Congratulations to these deserving individuals! Excerpts of their reports follow.

Jamie Cutts is a PhD student at the University of British Columbia (Canada) under the supervision of Drs. Matthijs Smit and James Scoates. He received the MAC Student Travel Grant to visit the Vegacenter at the Swedish Museum of Natural History in Stockholm to conduct U–Pb analyses on rutile using a laser ablation multi-collector inductively coupled mass spectrometer (LA–MC–ICP–MS). These analyses are crucial to one of the chapters of his PhD dissertation, which involves constraining rates of exhumation for deeply buried continental crust. This study relies on U–Pb geochronology of rutile to investigate exhumation rates, specifically using the well-constrained closure temperature to Pb-diffusion at the rim of rutile grains (~500°C). Cutts also attended the 2017 International Eclogite Conference, which was held in Åre (Sweden).

Garrett Harris is an MSc student at the University of Alberta (Canada) under the supervision of Dr. D. Graham Pearson. Harris used his travel grant to attend the 11th International Kimberlite Conference in Gaborone (Botswana) in 2017. The conference included five days of technical sessions, including the topics of emplacement and economics, diamond substrate, diamonds, kimberlites and related magmas, and exploration and mining. Garrett presented his MSc research as a poster titled, “Mantle Composition, Age, and Geotherm beneath the Darby Kimberlite Field, West Central Rae Craton.” This is the world’s leading conference on the topic of diamonds and kimberlites, and Harris felt deeply honoured to receive the best student poster award. Furthermore, he attended a post-conference field trip to major mines in Botswana, which was an invaluable experience. Attending the 11th International Kimberlite Conference will be the highlight of his Master’s degree.

Kelsey Lamothe is an MSc student at McGill University (Canada) under the supervision of Dr. Galen Halverson. Lamothe traveled to the Metal Geochemistry Center at Yale University in New Haven (Connecticut, USA) to measure chromium isotope ratios in a suite of shale samples from the late Mesoproterozoic Bylot Supergroup. The acquired Cr isotope data will help constrain when, during the Proterozoic, the atmosphere started to become significantly oxygenated. This can be done because isotopic fractionation of Cr occurs during terrestrial weathering when atmospheric oxygen levels are above a known threshold. Sample preparation was done in at McGill University, including major and minor element concentration measurements, and suitable samples were selected for Cr isotope analysis. During the two weeks Lamothe spent at Yale University, she was able to learn column chemistry in a world-class laboratory and had the invaluable opportunity to ask questions of leading experts in Cr biogeochemistry. The results of this study will be published soon.

Rebecca Lynch is a PhD student at the University of Victoria (Canada) under the supervision of Dr. Dante Canil. The MAC travel grant has allowed her to continue her research into volcanic trace metals (e.g. Cu, Zn, V, Mo, Cd, As, which are volatile trace metals that degas from volcanoes) that are liberated to the atmosphere. Laboratory experiments allowed Lynch to collect trace metals as condensed microscopic crystal phases. To analyze and help identify the crystals, she imaged the condensates on the scanning electron microscope (SEM) at the University of Victoria. This SEM work provided information about the crystal shape and variability of the trace-metal species in her experiments and may help to identify key variables that control trace-metal behaviour in volcanic gases. The MAC grant also helped her produce publication quality images of her experimental products.

Svieda Ma is an MSc student at Queen’s University (Canada) under the supervision of Drs. Dawn Kellet and Laurent Godin. Ma’s research aims to establish the deformation–temperature history of the Bathurst Fault (eastern Slave craton) through microstructural analysis and geochronology. The MAC grant allowed her to travel to the University of Massachusetts Amherst (USA) for in situ monazite dating using an electron microprobe. This method preserves the microstructural context of monazite grains such that ages can be linked to stages of ductile deformation in the host rock. Monazite U–Th–Pb dates from synkinematic monazites suggest that ductile shearing occurred at ~1,933 Ma and 1,895 Ma in rocks affected by the Bathurst Fault, which was subsequently overprinted by brittle deformation features such as fracture networks and cataclasis. The onset of brittle deformation was constrained to ≤1,839 Ma. Brittle deformation appears to have localized along the older ~1,933–1,895 Ma ductile high-strain zone parallel to the trend of the Bathurst Fault. The brittle Bathurst Fault likely behaved as a permeable basement structure capable of transporting ore-bearing fluids.

Emily Mick is an undergraduate student at the University of Ottawa (Canada) under the supervision of Prof. Olivier Nadeau. The MAC travel grant allowed her to present her research on the petrography and geochemistry of fresh and hydrothermally altered rocks from the Vulcano and Campi Flegrei volcanoes (Italy) at the 2017 GAC–MAC conference as a poster. This was her first time at a conference and was, thus, the first opportunity to show her research. Mick received invaluable feedback on her work, which she can apply going forward. From attending talks, seeing posters, and speaking to professionals over three days, she has been able to gain important insight into the industry that she hopes to join one day. She has learned a tremendous amount, which would not have been possible without this grant.

Rhea Mitchell is a PhD student at Carleton University (Canada) under the supervision of Profs. Sharon Carr and Robert Berman. The MAC travel grant allowed Mitchell to attend the 2017 European Geosciences Union General Assembly in Vienna (Austria) where she presented a poster based of her PhD research, “Prolonged Episodic Paleoproterozoic Metamorphism in the Thelon Tectonic Zone, Canada: an in-situ SHRIMP/EPMA Monazite Geochronology Study” at the session New Geochronological Approaches for Quantification of Geological Processes. Mitchell also participated in the pre-meeting Reviews in Mineralogy and Geochemistry short course entitled Petrochronology: Methods and Applications. Petrochronology is a field that...
of study that uses geochemistry, textural analysis, thermodynamics, and modeling to provide petrological context to geochronological ages. The short course provided a broad and thorough review of cutting-edge petrochronological techniques and applications, allowing her to network with international colleagues and to provide her with a solid foundation that she can apply to her PhD research.

Kevin Neyedley is a PhD student at Saint Mary’s University (Canada) under the supervision of Dr. Jacob Hanley. Neyedley attended the European Current Research on Fluid Inclusions (ECROFI) conference in Nancy (France), which was a great learning opportunity. Many of the presentations had a direct application to his current research project, entitled “Deciphering the Fluid and Melt History of the Caribou Lake Gabbro through the Analysis of Fluid and Silicate Melt Inclusions”. One presentation really stood out for him: mapping silicate melt inclusions using Raman spectroscopy. The presenter of this talk gave him excellent advice on how to approach a problem he has been having. It was also useful to talk with students and professors from around the globe to get their insight into his research. Networking at the ECROFI conference proved to be beneficial and may result in Neyedley participating in a summer internship.

Stéphane Poitras is an MSc student at the University of Alberta (Canada) under the supervision of Dr. Graham Pearson. Poitras attended the 4th International Diamond School in Bressanone/Brixen (Italy). His MSc research is on diamond exploration in part of the southwestern Northwest Territories (Canada). Poitras wants to understand the lithospheric mantle how diamonds form. processes. The school provided an excellent venue to update his knowledge of these research topics (i.e. cratons, diamonds, and kimberlites) and to meet individuals from the diamond industry. It was a rewarding experience, one that provided many new and interesting ideas regarding his thesis project, as well as future collaborative and mentorship opportunities. In particular, meeting professors Nick Sobolev and Malcolm McCallum, whose diamond research findings Poitras extensively employed in his own research, proved very insightful. Additionally, he was able to thoroughly discuss an upcoming publication with one of his peer-reviewers, Bruce Kjarsgaard from the Geological Survey of Canada. This was most instructive to talk about some of his kimberlite indicator mineral geochemical results and viable locations for source kimberlites within the Northwest Territories.

Marion Saby is a PhD candidate at the Université du Québec à Montréal (UQAM, Canada) under the supervision of Profs. Daniele L. Pinti (UQAM/Brixen) and Vincent Van Hinsberg (McGill University, Canada). She received a MAC grant to travel to Iceland and New Zealand. In Iceland, she analysed volcanic gases in Theistareykir, her study area. With the help of the Icelandic Geological Survey (ISOR) in Akureyri, she collected cuttings from geothermal wells drilled down to 2.5 km. From there, she met other ISOR geologists at the Krafla camp where she stayed for a week. Her study area was always thrilling, with geothermal wells blowing high-temperature vapours, and fumaroles and mud pots everywhere sounding like the Earth was breathing! She collected noble gases from boiling mud pots and fumaroles, water from hot and boiling springs and surface rocks in order to analyze elemental and isotope geochemistry. The results will help her decipher the sources and pathways of metals in magmatic–hydrothermal environments.

Gavin Tolometti is an MSc student at the University of Western Ontario (Canada) under the supervision of Drs. Gordon Osinski and Catherine Neish. Tolometti received a MAC travel grant to present his thesis work at the GAC–MAC 2017 in Kingston (Ontario, Canada). Being an international student from the UK, he found the Queen’s University campus to have a European cultural appearance, which made him feel right at home. The most exciting session was that on hydrothermal processes and alteration. Tolometti presented his own poster, “Variation in Petrography of Basaltic Lava Flows with Similar Surface Roughness”. The goal of this study is to use the Craters of the Moon National Monument and Preserve (Idaho, USA) as an analog for planetary lava and impact melt flows by comparing the petrography and surface roughness of the lava flows. The conference participants asked many questions and offered helpful comments on his poster.

Connor Turvey is a 4th-year PhD student at Monash University (Australia) under the supervision of Dr. Sasha Wilson. His PhD research is on the carbon sequestration potential of hydrotalcite minerals, anionic clays that can form and trap atmospheric CO2 within the waste material of some mine sites. The formation of these clays has the potential to increase the amount of CO2 that is being sequestered at ultramafic mine sites, however these clays remain relatively poorly understood. The MAC travel grant enabled Turvey to travel to the University of British Columbia (UBC) to conduct mineral dissolution experiments on hydrotalcites using a combined flow-through reaction chamber and an ICP-MS. This research will form part of his PhD thesis. While working at UBC, he was also offered a post-doctoral research position for 2018.

Ching-Pao Wang is a geophysics PhD student at the University of Western Ontario (Canada) under the supervision of Prof. Sean R. Shieh. His research uses a diamond anvil cell to study nitrogen solubility in the major mantle silicates, to explore nitrogen-bearing phases, and to evaluate nitrogen storage in the deep Earth. Wang’s research will first focus on the nitrogen solubility of olivine, wadeslyite, and ringwoodite, at different pressure and temperature conditions. High-pressure and high-temperature (HPHT) nitrogen solubility studies were performed at the 13-ID-D beam line of the Advanced Photon Source (APS) in Chicago (Illinois, USA). Four different nitrogen-infused olivine polymorphs were synthesized at 15–26 GPa, and 1,800–2,400 K. In situ X-ray diffraction patterns were taken on all synthesized samples to identify the different HPHT phases. Nitrogen analyses will be carried out at Department of Earth Sciences in Western University.

Tianqi Xie is a PhD student at the University of Western Ontario (Canada) under the supervision of Drs. Gordon Osinski and Sean R. Shieh. She received a MAC travel grant to present her work at the Lunar and Planetary Science Conference (48th LPSC) in Woodlands (Texas, USA). During her stay, she presented the poster “Raman Study of Shock Effects in Lunar Anorthite from the Apollo Mission.” Not only did she discuss her data with researchers from a wide variety of backgrounds, she also received valuable feedback from experts in the field. She attended a variety of talks on the Moon and Mars that affected her profoundly, and her future research path has now changed to research more on these subjects.
MINERALS WITH A FRENCH CONNECTION

The beautiful book *Minerals with a French Connection*, co-authored by our late colleague François Fontan (Toulouse, France) and by Robert F. Martin (Montréal, Canada), is now available at www.sfmc-fr.org (for Europe and Africa) and at www.mineralogicalassociation.ca (for the rest of the world). This book accurately and comprehensively describes how past and contemporary French scientists have contributed to making France the birthplace of mineralogy and crystallography and are keeping its vitality very much going, especially with regard to the mineralogic richness of the French territories. This French–Canadian co-production is an illustrated inventory of mineral species discovered in France or that are named in tribute to French citizens. The book also describes the properties and geological context of the minerals’ type localities. *Minerals with a French Connection* is an invitation to fabulous and unusual travel throughout the history of sciences.

The book was published in 2017 by TVA Inc, costs €72.00, has 588 pages, and the ISBN is 978-2-903589-08-0 or 978-0-921294-59-7.

PETROCHRO2018 SUMMER SCHOOL

The CNRS thematic workshop Petrochro2018 Summer School will be held 18–20 September 2018 in Sète (France). Petrochronology is a branch of geology that offers insights into such topics as geochemistry, petrography, and thermodynamics by integrating the information about timing and rates of geological processes that are contained in accessory minerals and which places all this into a rock’s wider petrogenetic context. The aim of this summer school is to review petrochronological tools (both theoretical and analytical) in order to illustrate how accessory minerals can be used to improve our understanding of magmatic and metamorphic processes. The SFMC will offer several grants to PhD students who wish to attend this event. More information, and registration details, are available at http://petrochro2018.gm.univ-montp2.fr.

FIRST WORKSHOP OF THE FRENCH CHAPTER OF THE INTERNATIONAL MEDICAL GEOLOGY ASSOCIATION

The French chapter of the International Medical Geology Association (IMGA) held its first workshop 29–30 March 2018, in the gorgeous location that is Les Pensières of the Mérieux Foundation on the shore of Lake Annecy (Haute-Savoie, France). About 50 scientists gathered to share their most recent work at the interface between the Earth sciences and medical science to provide a clearer picture of the dynamism of this growing community. The topics that were covered included the development of new isotopic markers for the early detection of cancers and neurodegenerative diseases, a geo-medical perspective on human exposure to nanoparticles and heavy metals, and the application of spectromicroscopy techniques to characterize altered tissues.

This workshop was organized by L. Charlet, A. Gourlan, and V. Balterand was sponsored by the following organisations: Université Grenoble Alpes, Institut polytechnique de Grenoble (GIMP), École normale supérieure de Lyon, Labex Lyon Institut des Origines, Institut des sciences de la Terre, and Région Auvergne-Rhône.
FIRST JOURNAL ISSUES APPEAR IN THE MINSOC–CAMBRIDGE PARTNERSHIP

After a slightly delayed start, issues of *Mineralogical Magazine* and *Clay Minerals* have begun to appear on Cambridge Core, the Cambridge University Press online journal system. See the March 2018 issues of *Clay Minerals*, and the February, April, and a supplementary 2018 issue of *Mineralogical Magazine*. The new system is working very well. Authors are happy and content is making its way well through the workflow.

Our entire journal archives from the 1800s to the present day will soon be available from a single source for the first time, and members have access to the entire archive. Brilliant!

Our journals continue to be an integral part of the GeoScienceWorld journal aggregate and are much-used by customers of that service.

HONORARY MEMBERS

Four new appointments have been made to the list of Honorary Life Fellows. These are D. Waters, J.N. Walsh, D.J. Vaughan and K. Brodie. Congratulations to them all, and welcome.

GRANULITES AND GRANULITES 2018

The fifth “G&G” takes place 10–13 July 2018 and will be held at the Macphail Centre in the beautiful fishing town of Ullapool in NW Scotland. Go to https://www.minersoc.org/2018-meeting-granulites-granulites.html for a complete copy of the programme. There are >100 delegates, but it may still be possible to register. Visit the site for information about late registration.

The pre-conference fieldtrip to Assynt (Scotland) and the post-meeting trip to SW Norway are both fully subscribed.

MAIN CONVENER: Tim Johnson (Curtin University, Australia)

CO-CONVENERS: Chris Clark (Curtin University), Kathryn Goodenough (British Geological Survey), Martin Hand (University of Adelaide, Australia), Simon Harley (University of Edinburgh, Scotland), Pete Kinny (Curtin University), Trond Slagstad (Geological Survey of Norway, NGU)

ORGANISERS: Mineralogical Society of Great Britain and Ireland

EUROPEAN MICROBEAM ANALYSIS SOCIETY (EMAS) 2018 WORKSHOP

4–7 September 2018

Bristol, UK

EMAS 2018 will present a workshop aimed at the earth-science research community to bring them up to speed with the latest advances in microbeam techniques as applied to their samples. It will be 20 years since the Mineralogical Society of Great Britain and Ireland (MinSoc) presented the Microbeam Techniques in Geology workshop in London and EMAS is joining MinSoc to present this current workshop.

Techniques covered will include scanning electron microscopy, electron probe microanalysis, cathodoluminescence, electron backscatter diffraction, transmission electron microscopy, Raman spectroscopy, Fourier transform infrared microscopy, laser ablation mass spectrometry, secondary ion mass spectrometry, Nano-secondary ion mass spectrometry, atom probe tomography, and synchrotron-based techniques. Each subject will include tutorials from analytical experts together with lectures from Earth scientists who will apply the various techniques to problems relating to their own materials.

The workshop is to be hosted in the conference facility at Wills Hall, part of the University of Bristol.

Note that the MinSoc and EMAS are offering a number of bursaries for this event. Details available at https://www.microbeamanalysis.eu/events/event/51-emas-2018-microbeam-analysis-in-the-earth-sciences.

SPECIAL INTEREST GROUP REVIEW

Starting in the next issue, we will have a focus on one of our Special Interest Groups. First up will be the society’s Applied Mineralogy Group. Watch this space.

ADMINISTRATIVE REVIEWS

And finally, the MinSoc is undertaking a review of its stance on several administrative areas, including data protection [because of the European Union's recently enforced General Data Protection Regulation (GDPR) legislation], health and safety, long-range planning, financial management and social media. If you would like to contribute to any of these areas, offers are welcome. Members are particularly welcome to contribute, of course, but input from non-members is also invited.

BOOKS FOR SALE


Go to www.minersoc.org and click on “Online bookshop”. Many of our titles are also available on Amazon.
Mineralological Organizations in Australia

Australia is home to one of the most mineralogically diverse localities on the planet, that of Broken Hill (324 mineral species, type locality for 24 of them). This extraordinary place also hosts the oldest known terrestrial mineral, the Hadean zircon from the Jack Hills. It is fitting for this country, rich in mineralogical exotica, that the last lunar mineral to be found on Earth, tranquillityite \([\text{Fe}^{3+}]_8\text{Ti}_3\text{Zr}_2\text{Si}_3\text{O}_{24}\), turned up in Western Australia in 2011. Australia also has some of the world’s greatest reserves of iron, copper and uranium as economic resources. Given the lack of Pleistocene glaciation, much of the continental bedrock remains concealed under a deep regolith cover; many more mineralogical surprises are doubtless waiting to be found. However, the lack of exposure, the sheer vastness of the country (similar to the lower 48 states of the USA in area) and the harsh desert climate prevalent over much of it, as well as the small overall population (currently just under 25 million), have kept mineral collectors relatively few in number.

The professional mineralogical community is small, but punches above its weight: between 2008 and 2014, Australia provided both the former Chairman (Peter Williams) and Secretary (Stuart Mills) of the International Mineralogical Association (IMA) Commission on New Minerals, Nomenclature and Classification.

Given the small population and strong cultural ties to long-established professional organisations in the UK and USA, there is no discrete mineralogical society as such. Mineralogical interests are catered for by the Geological Society of Australia (GSA) and its Specialist Group for Geochemistry, Mineralogy and Petrology, along with the mineralogical societies of the individual Australian states. The GSA is the host professional organisation for the IMA meeting that is to be held in Melbourne in August 2018.

Geological Society of Australia

The Geological Society of Australia (GSA, see www.gsa.org.au) was established as a non-profit organization in 1952 to promote, advance and support Earth sciences in Australia. The GSA’s members represent all Earth science professions, and come from the minerals and petroleum industries, government, research and education institutions, and consultancy groups. The GSA has a division in each state and territory, as well as a branch in the Hunter Valley. Biannual conventions are held Australia-wide, at which members may keep in touch with scientific developments, present the results of their work, and contribute to discussions on vocational and scientific topics. Specialist groups cater to different sectors of the Earth sciences, and organise dedicated conferences and excursions.

The GSA publishes periodicals for Earth scientists and the wider community. The Australian Journal of Earth Sciences is its official journal, which publishes papers on all aspects of Earth science. The Australian Geologist is GSA’s quarterly member magazine and includes technical and special features, society news, conference details, regular reports, book reviews and other items of interest to Earth scientists. The e-zine geoz is an Australian Earth science news service available free to GSA members.

The GSA encourages and recognizes excellence in the Earth sciences through awards, such as the A.E. Ringwood and W.R. Browne Medals, as well as divisional and specialist group awards for outstanding scientific contributions. The Specialist Group for Geochemistry, Mineralogy and Petrology (SGGMP) caters to GSA members interested in mineralogy, along with a larger community of geochemists and petrologists. The SGGMP hosts its own meetings and associated field trips on a quadrennial basis, the venue rotating among the states.

State Mineralogical Societies

There are currently six mineralogical societies established in Australia, on a state-wide basis. These are in New South Wales (the oldest of the six, founded in 1975), Queensland, South Australia, Tasmania, Victoria and Western Australia (www.mineral.org.au/socs/socs.html). All societies are based in the respective state capitals but have memberships which extend the breadth of Australia and beyond. Their membership includes both Earth-science professionals and amateur mineral enthusiasts at all levels of expertise. Although not connected by any formal constitution or agreement, the societies are informally bonded through their common ideals and interests. The societies assemble every year for a joint seminar on minerals and mineral collecting. Usually, this is held in early June, but it is flexible. In 2007, this group was expanded to include New Zealand, so the collective entity is now referred to as the Joint Mineralogical Societies of Australasia. The seminar venue is rotated among the states, and the host society decides on a theme topic. In 2018, the 41st joint seminar will be hosted by the state of Victoria (www.mineral.org.au/seminar/seminar18.html).

Australian Journal of Mineralogy

The Australian Journal of Mineralogy (AJM) was launched in 1995, is a joint publication of the six state societies, features all aspects of Australian mineralogy, and appeals to professional mineralogists, geologists and mineral enthusiasts (www.mineral.org.au/pubs/ajm.html). Articles range in scope from new mineral descriptions and the mineralogy of specific localities to mineral collections and mining history. In general, two issues per year have been published. Currently, the journal is produced in Western Australia and is a high-quality production that features excellent colour photography. For subscription information, please consult the AJM Facebook page (www.facebook.com/AJMPublications/) or contact the editor.

Andrew G. Christy (IMA National Representative, a.christy@uq.edu.au)

Peter Downes (AJM Editor, peter.downes@museum.wa.gov.au)
New for 2018!

• Early career workshops on career strategies, funding opportunities, communicating science, and more
• On-site child care is available for delegates’ children during the conference
• Conference social events at the Harvard Mineralogical & Geological Museum and Fenway Park
• Special session devoted to communicating science through education and outreach
Programme topics:

Early Earth
50 years of plate tectonics
Mountain building from depth to surface
Dynamics of core and mantle on Earth and other planetary bodies
Sedimentary systems
Neotectonics, earthquakes, impacts and natural hazards
Mineralogy, material science of the Earth
Climate change, climate dynamics and paleoclimate
Earth materials, resources, and waste management
Fossil ecosystems
Fossilization and the quality of the fossil record
Applied and industrial micropalaeontology
Applied geophysics
3D applications in the geosciences
Outreach, education, and the societal relevance of geosciences
Fluid-rock interactions
Open session

Pay early - it’s cheaper!
Deadline: 5 July 2018
<table>
<thead>
<tr>
<th>Date</th>
<th>Event</th>
<th>Location</th>
<th>Web page</th>
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<tbody>
<tr>
<td>June 1–2</td>
<td>AGU Fall Meeting</td>
<td>Seattle, WA</td>
<td><a href="http://www.agu.org/meetings">www.agu.org/meetings</a></td>
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<td>June 3–7</td>
<td>AAG (Asia Oceanica Geosciences Society) 15th Annual Meeting</td>
<td>Honolulu, HI</td>
<td><a href="http://www.aag.org/meetings">www.aag.org/meetings</a></td>
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<td>June 11–15</td>
<td>S5 Clay Minerals Society Meeting</td>
<td>Urbana-Champaign, IL, USA</td>
<td><a href="http://www.s5claymineralsociety.org">www.s5claymineralsociety.org</a></td>
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<tr>
<td>June 12–16</td>
<td>14th Pan American Conference on Research on Fluid Inclusions (PACROFI XIV)</td>
<td>Houston, TX, USA</td>
<td><a href="http://www.pacrofi.com/">www.pacrofi.com/</a></td>
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<td>June 14</td>
<td>Canadian Institute of Mining, Metallurgy and Petroleum (CIM)</td>
<td>Edmonton, AB, Canada</td>
<td><a href="http://www.cim.ca/">www.cim.ca/</a></td>
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<tr>
<td>June 15–19</td>
<td>Canadian Institute of Mining, Metallurgy and Petroleum (CIM)</td>
<td>Edmonton, AB, Canada</td>
<td><a href="http://www.cim.ca/">www.cim.ca/</a></td>
</tr>
<tr>
<td>June 17</td>
<td>Sixteenth International Symposium on Experimental Mineralogy, Petrology and Geochemistry (EMPG-XVI), Clermont-Ferrand, France</td>
<td>Clermont-Ferrand, France</td>
<td><a href="http://www.empg.org/">www.empg.org/</a></td>
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<tr>
<td>June 22</td>
<td>IMA Summer School: Stellar Variability in the Era of Large Surveys, Vatican Observatory, Vatican City</td>
<td>Saint-Petersburg, Italy</td>
<td><a href="http://www.ima2018.com/">www.ima2018.com/</a></td>
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<tr>
<td>July 1–5</td>
<td>Conference on Experimental Studies of Subduction Zone Processes, St. Louis, MO, USA</td>
<td>St. Louis, MO, USA</td>
<td><a href="http://www.esciencemag.org/">www.esciencemag.org/</a></td>
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<tr>
<td>July 3–7</td>
<td>15th International Conference on Research on Fluid Inclusions (PACROFI XIV)</td>
<td>Houston, TX, USA</td>
<td><a href="http://www.pacrofi.com/">www.pacrofi.com/</a></td>
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<tr>
<td>July 9–13</td>
<td>Geoanalysis 2018 Conference</td>
<td>Macquarie University, Sydney, Australia</td>
<td><a href="http://www.geoanalysis2018.org/">www.geoanalysis2018.org/</a></td>
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<tr>
<td>July 23–27</td>
<td>81st Annual Meeting of the Meteoritical Society, Moscow, Russia</td>
<td>Moscow, Russia</td>
<td><a href="http://www.metsoc81.moscow.ru/">http://www.metsoc81.moscow.ru/</a></td>
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<tr>
<td>July 29–August 2</td>
<td>International Union of Crystallography (IUCr) Commission on High Pressure Workshops, Honolulu, HI, USA.</td>
<td>Honolulu, HI, USA</td>
<td>hp2018honolulu.github.io/index.html</td>
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<td>August 9–10</td>
<td>Microscopy &amp; Microanalysis 2018, Baltimore, MD, USA.</td>
<td>Baltimore, MD, USA</td>
<td><a href="http://www.microscopy.org/events/future_clm">www.microscopy.org/events/future_clm</a></td>
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<td>August 26–27</td>
<td>Magnet Chamber Simulatoer Workshop, Boston, MA, USA.</td>
<td>Boston, MA, USA</td>
<td><a href="http://www.mcs.geol.ucsb.edu/">www.mcs.geol.ucsb.edu/</a></td>
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<tr>
<td>August 28–30</td>
<td>2018 Goldsmith Conference, Boston, MA, USA.</td>
<td>Boston, MA, USA</td>
<td><a href="http://www.mcs.geol.ucsb.edu/">www.mcs.geol.ucsb.edu/</a></td>
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<tr>
<td>August 31–September 4</td>
<td>Microscopy &amp; Microanalysis 2018, Portland, OR, USA.</td>
<td>Portland, OR, USA</td>
<td><a href="http://www.microscopy.org/events/future_clm">www.microscopy.org/events/future_clm</a></td>
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<tr>
<td>September 1–3</td>
<td>Late Mars Workshop, Houston, TX, USA.</td>
<td>Houston, TX, USA</td>
<td><a href="http://www.hou.usra.edu/meetings/latemars2018/">www.hou.usra.edu/meetings/latemars2018/</a></td>
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<td>September 1–5</td>
<td>Short Course: Application of diffusion studies to the determination of timescales in geochemistry and petrology, Bochum, Germany.</td>
<td>Bochum, Germany</td>
<td><a href="http://www.icafe.org/geochemistry/mineral-deposits-conference/2018/">www.icafe.org/geochemistry/mineral-deposits-conference/2018/</a></td>
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<td>September 7–9</td>
<td>IAGD Symposium, Salta, Argentina.</td>
<td>Salta, Argentina</td>
<td><a href="http://www.15iagods.org/">www.15iagods.org/</a></td>
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<td>September 12–14</td>
<td>89th Congress – SGI – SIMP (Italian Society of Mineralogy and Petrology), Catania, Italy.</td>
<td>Catania, Italy</td>
<td><a href="http://www.simp.it/meetings/">www.simp.it/meetings/</a></td>
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<tr>
<td>October 1–5</td>
<td>Short Course: Application of diffusion studies to the determination of timescales in geochemistry and petrology, Bochum, Germany.</td>
<td>Bochum, Germany</td>
<td><a href="http://www.icafe.org/geochemistry/mineral-deposits-conference/2018/">www.icafe.org/geochemistry/mineral-deposits-conference/2018/</a></td>
</tr>
<tr>
<td>October 7–9</td>
<td>GIA International Gemological Symposium, Carlsbad, CA, USA.</td>
<td>Carlsbad, CA, USA</td>
<td><a href="http://www.gia.org/giainternationalgemosympi/2019/">www.gia.org/giainternationalgemosympi/2019/</a></td>
</tr>
<tr>
<td>October 14–18</td>
<td>Materials Science &amp; Technology 2018, combined with ACRS 120th Annual Meeting (MS&amp;T18), Columbus, OH, USA.</td>
<td>Columbus, OH, USA</td>
<td><a href="http://www.acrs.org/meetings/">www.acrs.org/meetings/</a></td>
</tr>
<tr>
<td>November 4–7</td>
<td>Geological Society of America Annual Meeting, Indianapolis, IN, USA.</td>
<td>Indianapolis, IN, USA</td>
<td><a href="http://www.geosociety.org/meetings/">www.geosociety.org/meetings/</a></td>
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</table>

The meetings convened by the societies participating in Elements are highlighted in yellow. This meetings calendar was compiled by Andrea Koziol (more meetings are listed on the calendar she maintains at https://sites.google.com/a/udayton.edu/akoziol1/home/mineralogy-and-petrology-meetings). To get meeting information listed, please contact her at akoziol1@udayton.edu
Molten glass rained down from the sky over parts of Southeast Asia, Australia, Antarctica, and into the neighbouring ocean basins during the Pleistocene, about 790,000 years ago. These glass occurrences, long recognized to be remnants of melt formed during meteorite impact, are known as the Australasian tektites. Their distribution defines the largest of at least four known strewn fields across the globe, strewn fields being regions over which tektite glass are scattered from what are thought to be single-impact events. The three other big tektite strewn fields are associated with known source craters, including the Bosumtwi (1.07 Ma, Ghana), Ries (15 Ma, Germany), and Chesapeake Bay (35.5 Ma, USA) impact structures (Glass and Simonson 2013). At only 790,000 years old, the Australasian tektite strewn field (Fig. 1) is both the youngest and the largest known. Despite much effort, the source crater has yet to be discovered. The search to locate it represents something akin to a “holy grail” in impact cratering studies.

Australasian tektites vary in composition but are isotopically distinct from other tektites (Koeberl 1990). Generally, they have high-Si glass, with SiO$_2$ averaging ~73.5 wt%. Other major element oxides include Al$_2$O$_3$ (~11.5 wt%), FeO (~4.7 wt%), CaO, MgO, and K$_2$O (all between 2.0 to 3.5 wt%), NaO (1.3% wt%) and TiO$_2$ (0.7% wt%). Tektites differ from volcanic glass in several important aspects, including very low water content (~50 ppm OH). The presence of $^{18}$Be can be used as a unique tracer of tektite provenance (e.g. Ma et al. 2004), which is generally taken as near-surface material rather than excavated bedrock. A near-surface source, such as siliciclastic sediments (e.g. Koeberl 1990), is also consistent with the relict mineral assemblage represented by included detrital grains.

The formation mechanism of the Australasian tektites remains poorly understood (e.g. Koeberl et al. 1994) and this is further compounded by a lack of direct knowledge on the whereabouts of the source crater. Outstanding questions include, “How much melt was produced and subsequently ejected?” and “What were the target rocks?” Perhaps the most critical questions are “Where is the location of the source crater?” and “What is its size?” Many locations have been proposed, including sites in China, Antarctica, and Siberia, although most studies appear to favour a location in Southeast Asia. Modelling the crater size, based on tektite distribution, has resulted in estimated crater diameters ranging from ~40 km to >100 km. Wherever its actual location, it is widely agreed that the crater is young and large, and, thus, should be a conspicuous feature on Earth’s surface.

The discovery of shocked minerals in Australasian tektites has provided tantalizing clues to their origin. Shock-damaged quartz in Australasian tektites was recognized from X-ray data back in the 1970s, and coesite, the high-pressure SiO$_2$ polymorph, was later found in microtektites within a circular distribution around Southeast Asia (e.g. Folco et al. 2010). Most recently, evidence for the former presence of reidite, a high-pressure ZrSiO$_4$ polymorph, was later found in microtektites.
high-pressure ZrSiO₄ polymorph stable at 30 GPa, has been discovered in granular-textured zircon (Figs. 2C, 2D) in MN-type tektites from Thailand, again supporting a crater location in Southeast Asia (Cavosie et al. 2018).

Solving the mystery of where Australasian tektites originated is of broad interest, far beyond the interest of those only concerned with glass and shocked minerals. The event that created the Australasian tektites is the only potential environmentally catastrophic extra-terrestrial impact event possibly witnessed by anyone on the specifically human ancestral tree. While the northern latitudes were experiencing glacial conditions, many details of human evolution during the mid-Pleistocene are still debated. It is tantalizing to think that members of the Homo erectus lineage living in Asia, best known from the discovery of the Peking Man skull (Fig. 3), could have witnessed the Australasian impact.

The burial age of the sedimentary layer that Peking Man came to rest in (i.e. 770,000 ± 80,000 years old) (Shen et al. 2009), fully overlaps with the age of Australasian tektite formation at 785,000 ± 7,000 years (Schwarz et al. 2016). Did our distant ancestors see this event, perhaps as a second sunrise, or a flash in the night sky? Or did they wake up to shocked minerals. The event that created the Australasian tektites is interest, far beyond the interest of those only concerned with glass and crystallization. It might have witnessed the Pleistocene fireball that initiated the Australasian tektites. P. Koeberl and 5 coauthors (2010) determined the age of Zhoukoudian Homo erectus, some of whom might have witnessed the Pleistocene fireball that initiated the Australasian tektites. P. Koeberl and 5 coauthors (2010)

ACKNOWLEDGMENTS

Support was provided by the NASA Astrobiology program (NNA13AA94A), the Australian Research Council, and the John de Laeter Centre, the Space Science and Technology Centre, and The Institute for Geoscience Research at Curtin University.

REFERENCES


The Chemical Precipitates of Henry Sorby

Chris Hammond1, Robert Edyvean2 and Bruce Yardley1

1811-5209/18/0214-$0.00 DOI: 10.2138/gselements.14.3.214

Henry Clifton Sorby (1826–1908) is best known to geologists for his pioneering use of the petrological microscope and for instigating the systematic study of fluid inclusions. He also introduced microscopy to many other areas of science. Sorby belongs to that great tradition of amateurs who have made substantial contributions to science. Being unhindered by the needs of funding bodies, Sorby’s research ranged widely and touched on many topics that are still current today.

In 1879, Sorby published a short paper in the Mineralogical Magazine ‘On the Cause of the Production of Different Secondary Forms of Crystals’. He begins, ‘It has often struck me that much more might be learned from the study of the secondary forms of crystalline minerals than we now know respecting the circumstances under which they were produced. Some years ago, being chiefly acquainted with calcite as it occurs in Derbyshire, where the crystals are usually of the so-called dog-tooth shape, my attention was much attracted by the difference in the form of crystals in Devonshire and Cornwall, where we so often meet with six-sided prisms. … I could not give any more satisfactory explanation than that the conditions under which they were formed must have been very different in some important particular.’

Sorby goes on to describe a series of experiments in which he prepared aqueous solutions of ‘carbonate of lime in carbonic acid’, then evaporated them at different temperatures. He reported that differences in temperature, the presence of ‘foreign substances’ (Fe and Mg carbonate were sometimes added), and conditions of formation (including whether crystals formed at the surface or the bottom of the solution) ‘give rise to very varying secondary forms in the crystals…’ Sorby did note earlier in the paper that ‘I did not continue the experiments sufficiently to enable me to draw any complete detailed conclusions.’ Nevertheless, he offers the parting thought in relation to correlating the conditions of crystal morphology (‘secondary forms’) to the unknown formation conditions: ‘If this could be done, it would, I doubt not, be a great gain for geology.’

It appears that Sorby then abandoned this avenue of research, but he was always meticulous in preserving his microscopical preparations – sometimes publishing his results long after completion of the experimental work. For example, all his work on the microstructures of iron and steel were carried out during 1863–1865 but remained unpublished until 1886–1887. However, the preparations of the crystallisation experiments, upon which the 1879 paper is based, did not come to light until 2011 when one of us (RE) discovered, at the back of a store cupboard in the Department of Chemical Engineering at the University of Sheffield (UK), a cardboard box covered in blue-paper labelled ‘Chemical Precipitates &c’.

The box and its contents are shown in Figure 1. It contains sixty 40 mm square glass slides (with coverslips), all neatly engraved using a diamond-point with brief descriptions and the initials ‘H.C.S.’ and date (Fig. 2). Without doubt, these are the long-lost preparations. Most are conventional microscope slides and it appears that crystalline precipitates from the experiments were collected onto the slides and preserved with a coverslip. The slides are in immaculate condition, with little yellowing of the Canada balsam, and no detachment. Most of them are dated 1852, with a few from later years, up to 1862. There are also ten cavity slides (i.e. with a shallow well), all but one (undated) from 1858. The exact nature of the cavity slide experiments is unclear (see description for Fig. 2B). Most of the chemical precipitate slides precede the year 1855 in which Sorby commenced his research on fluid inclusions. The description on the later cavity slides may indicate that they were used for evaporating the leachates from crushed, fluid inclusion-bearing minerals.

The engraved notes on the slides are the only source of information about the experiments that generated these products, so we have a tantalising glimpse into the controls on crystalisation that Sorby investigated, without being able to reach any definite conclusions. The notes show that Sorby carried out a greater variety of experiments than described in his brief paper of 1879. As well as evaporating solutions of carbonates, he also added sodium carbonate to calcium chloride or the reverse.

We have re-examined the slides using optical microscopy but have not attempted to use any destructive techniques. There appear to be three main types of solid product, sometimes present together (Fig. 3). Many slides contain well-formed single crystals up to 20 µm across and with a rhomb-like morphology and high birefringence (Fig. 3A). In others, the precipitates are in the form of spherulites of highly birefringent radiating fibres with straight extinction (Fig. 3B). Spherulites often form ‘dumbbell shapes’, rather than simple spheres. A few experiments produced acicular crystals, and these invariably coexist with...

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Figure 1: Sorby’s original cardboard slide box: 165 mm square by 48 mm deep with three rows of edge-mounted slides. The coloured discs were added by this paper’s authors.

Figure 2: Examples of Sorby’s chemical precipitate preparations. Each slide is 40 mm square. (A) Slide 4, a standard side inscribed ‘CaO 2CO2. 3A). (B) Slide 52, cavity slide inscribed ‘Salts sol. in water in quartz of granite C, Cornwall’ and ‘H.C.S. 1852’. Perhaps this slide contains the remains of an early attempt to investigate fluid inclusions by crushing. Note the deterioration (yellowing) of the Canada balsam in the cavity slide.
rhombs. (Figs. 3D, 3E). Both the fibres in the spherulites and the acicular carbonate crystals have straight extinction, and are inferred to be aragonite, whereas the rhomb morphology is inferred to be calcite. Without knowing the starting compositions, we cannot be sure if other divalent carbonates may have precipitated, but slides from experiments with Fe-carbonate do show a slight orange discolouration.

The experiments that produced only rhombs involved evaporation of calcium bicarbonate solutions generally under mild conditions. In contrast, the precipitates in samples formed from mixing calcium chloride and sodium bicarbonate solutions are spherulites of highly birefringent radiating needles with straight extinction (Fig. 3B). Some experiments produced a mixture of spherulites and rhombs (Fig. 3C), and these are described as deriving from evaporation of carbonate solutions under relatively extreme conditions, including boiling and the addition of MgO and FeO. The experiments which produced distinct acicular crystals coexisting with rhombs (Fig. 3D) also involved relatively intense evaporation and include one experiment in which cotton was provided for the precipitates to grow on (Fig. 3E).

Sorby noted that crystal morphology sometimes varied according to whether the crystals formed at the surface or the base of the evaporating solution, but he did not provide more details. Some of the slides with mixed morphologies may reflect this phenomenon. In present-day terms, we can infer that spherulitic morphologies are indicative of growth from supersaturated solutions, while single rhombs would suggest a lesser degree of supersaturation.

What do we learn from Sorby's experiments? Are they relevant today? The short answer is that Sorby failed to find answers to the questions he set out to tackle, and, with the benefit of hindsight, it is not difficult to see why. He had no means of identifying his precipitates beyond the microscope, and it would be well into the twentieth century before crystal growth theory was able to provide an adequate framework for his observations. However, what is clear from his 1879 Mineralogical Magazine note is that he had realised that crystallisation can be very strongly dependent on subtle factors which may not appear to be at all significant at the outset. It was lessons like this which led to modern ideas of ‘good scientific practice’ where parameters are controlled to the point where experiments become reproducible.

Sorby's slides give us an intimate glimpse back into the early years of modern science, with a chance to see how an individual scientist was thinking and modifying his ideas while coming to terms with unexpected difficulties in his work. Sorby's experiments were a failure in their original terms, but not a waste. He bounced back from this frustration to embark on the study of fluid inclusions where he had a lasting impact.

FURTHER READING
Sorby HC (1879) On the cause of the production of different secondary forms of crystals. Mineralogical Magazine 3: 111-113

FiguRe 3 Photomicrographs of precipitates from Sorby's experiments, all taken under crossed polars. (A) Slide 4 (see Fig. 2A), example of coarse rhombohedral crystals, inferred to be calcite. (B) Slide 21, which is inscribed ‘CaCl in ex’ added to carb am’ ‘Fe2O3 present’ and ‘H.C.S. 1852’. These are examples of spherulites made up of fine needles with straight extinction. (C) Slide 35, inscribed ‘Bicarb, CaO.MgO FeO evap. at 80° F’ and ‘H.C.S. 1852’. Spherulite textures are represented by very thin, radial growths of fine needles that coexist with much thicker rhombs. (D) Slide 2, inscribed ‘CaCO3 cryst on glass from CaO & CO2 [indecipherable]’ and ‘H.C.S. 1852’. Acicular crystals, commonly twinned, coexisting with rhombs. Crossed polars with sensitive tint plate. (E) Slide 3, inscribed ‘CaO.2CO2 evap. at max. heat & crsyt on cotton’ and ‘H.C.S. 1852’. Both acicular crystals and rhombs occur adhering to cotton threads that were added by Sorby as seeds.
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