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Message in a bottle: the wine terroir concept in Canada, from an earth sciences perspective

A.P. Hamblin

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Canada

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ABSTRACT

Geology is an important, but less-recognized, scientific factor in the agriculture of long-lived, deep-rooted plant crops such as vineyards, orchards and forests. This report focusses on the concept of vineyard agriculture as one example of how geological factors may affect a resulting crop. While acknowledging the pre-eminence of climatic factors, Earth Science forms part of the multi-factor, holistic concept of "terroir", which can help to maximize the potential of wine quality in a cool-climate country like Canada. Key publications, such as Wallace (1972), Wilson (1998), the series launched by Haynes (1999), and Macqueen and Meinert (2006) have emphasized the role of geology in the terroir concept and set the scene for further study. Thinking conceptually, from the ground upward, the main components of the Terroir concept can be divided into:

1) Geological (bedrock geology, surficial geology, soil, groundwater, topography and bodies of water);
2) Climatological (latitude, macro-climate, rainfall, sunshine, temperature and micro-climate);
3) Biological (vineyard age, grape varietal, microorganisms, nutrients and yeast); and,
4) Agricultural (viticultural techniques, management practices) (although this last is not dealt with in this report).

While not an exhaustive study, this report is meant to bring together and organize a preliminary summary of relevant information and sources, in order to suggest areas of study where geoscience may be able to contribute to improved understanding. Although this report focusses on wine terroir, the principles are equally applicable to other, similar long-lived, deep-rooted plant systems such as fruit orchards (particularly cider production, which is closely-related to wine-making), olive orchards and forests. Each of the terroir factors (including the geological ones) needs to be studied, and new understanding improved and applied within each wine region and sub-region of Canada, to maximize the potential for quality wine from our northern, cool-climate, constantly-evolving wine industry.

INTRODUCTION

Rationale

The science of geology intersects the everyday life of Canadians in many ways, some of which remain unrecognized by the general public. Exploration for oil, natural gas, metals, industrial minerals, aggregate and groundwater resources are obvious ways. And the geological organizations and professionals have been intimately involved in these activities for the good of all Canadians since before Confederation (2017 marked the 175th anniversary of the creation of the Geological Survey of Canada). In addition, many of the material goods, which we use each day, utilize these resources as raw materials or in processing to produce these products. It has been said that "if you can't grow it ***in*** the ground, you must mine it ***from*** the ground", a thumbnail summary of human life which might surprise most Canadians. But it is also true that many of those things grown in the ground are actually directly or indirectly affected by the ground in which they are grown, i.e. the underlying geology. This is obviously most important for crops involving perennial plants, which remain growing in one place on one plot of geology for an extended lifetime, especially the most long-lived, deep-rooted plant groups such as forests, tree fruit orchards, and wine vineyards. These are plants which extend their complex root systems downward through the soil, the sub-soil and even into the bedrock layers to tap water and nutrient supplies. These are high-value crops, where maximizing the productive potential of each long-lived, deep-rooted individual plant is paramount, so the stakes are higher in "getting it right". Clearly, agriculture, and particularly the maximizing of positive benefits for these crops, is one endeavour wherein geology can intersect with the daily life of all Canadians - but this connection has not yet been fully embraced. In the interest of beginning the conversation on collaborative science (and following a long-standing personal interest), I have chosen to focus this report on introducing the geological aspects of vineyard agriculture as a starting point (with some comments on the closely-allied cider orchard example), and as one obvious example of the application of the terroir concept. This concept has been extensively discussed in some parts of the world, but generally less so in our country (with a number of well-informed exceptions), and yet Canada is at a crucial moment in its wine-producing history, when new and more scientific approaches may provide a stepping stone to higher quality products and reputations.

This report is more about fundamental farming and dirt, rather than the connoisseur taste-testing notes and cultured palates which make up most wine discussions. I have attempted to gather many of the widely-scattered relevant concepts together in one place, and synthesize/summarize them in relatively simplistic terms to be as readable as possible.

Background

Canada, a northern, cool-climate viticultural country at the margins of the wine-growing world, will never compete internationally based solely on volume of fine wine produced: the acreage available for vineyard planting is limited (although our currently naturally-warming climate will expand this somewhat) and is only a fraction of that available in California, Argentina, or Australia. Indeed, a single vineyard owned by Penfold's in Australia covers more acreage than all of Canada's wineries combined. In addition, our domestic market is relatively small and cannot support a mass-industry on its own. But that does not mean that Canada cannot have a thriving premium artisanal wine industry or cannot be a significant force in the wine world. Simple production of high ***quantity*** yields "commodity wines" which can flood the market and generate profits; whereas production of high ***quality*** yields "estate or boutique or artisanal wines", which can command respect and price. Likewise, Canada's climate is conducive to an expanding premium cider industry. According to a recent report to the Canadian Vintner's Association, the wine industry already contributes a very significant $6.8 billion of overall economic impact to the Canadian economy (Rimmerman, 2013; Wines of Canada, 2015). For the Canadian wine industry to continue to be successful and expand, it must emphasize the quality, individualism and uniqueness of its wines – effectively attracting niche audiences, both at home and abroad – with their individual "gout de terroir". Fine wine almost always carries a signature of a place.

The recent internationalization, or homogenization, of wines globally over the past 3 decades has tended to marginalize the natural subtleties of grape variety and vineyard locality (Gillmor, 2006; Lukacs, 2012; Crosariol, 2013). Instead, there has been an emphasis on heavy-handed vintner manipulation (especially in the "New World" regions) to produce bold, stereotypic versions of a limited number of specific wine grape varieties, regardless of place of origin. There was a tendency in New World regions to pick crops late to create over-ripe, high-alcohol "impact" wines which overwhelm subtle foods (MacLean, 2006). For example, for a time winemakers insisted on extended aging of chardonnay in heavily-charred oak barrels to produce big, buttery, vanilla-rich "oak bombs". However, it is the mineral tastes and textures (imparted by the terroir factors) which give wine a density and concentration that is different from the power and heat of high alcohol content (MacLean, 2006). Consequently, there is a more recent trend back toward more specialization, and recognition of leaner, more delicate and localized flavours to allow boutique wines to express their own natural, more individualistic, terroir and varietal subtleties (MacLean, 2006; Lukacs, 2012). As Crosariol (2016) put it, there was an eventual public backlash (referred to as ABC: "Anything But Chardonnay") against these "McChardonnays" which all seemed to "taste like a mango on a smouldering two-by-four." (Crosariol, 2016).

The current trend back to true terroir-based wines can portend an expanding role for the Canadian wine industry in future, as Canadian wines become more widely recognized for quality and distinctive character. As global climate warms in future decades making Canada's wine regions more viable and reliable (and perhaps even opening new regions), the Canadian wine industry needs to be poised to take advantage of this trend toward recognition and appreciation of terroir as an important factor in wines. Serious application of science allows us "to better understand the physical environment that affects grape and wine quality" (Meinert, 2006). As MacLean (2006) said, "the new revolution will be in the vineyard".

The Canadian wine industry, although it represents less than 1% of the global wine industry, is rapidly growing and has a significant place in the national economy. In 2015, the industry created $9 billion of economic impact, employed 37 000 people, generated $1.7 billion in federal and provincial taxes, and attracted 3.7 million tourists spending $1.7 billion (Agriculture and Agri-Food Canada, 2013; Canadian Vintner's Association, 2017; Wines of Canada, 2015). Whereas only 30% of wine currently sold in Canada is home-grown, there is clearly great potential for growth (Wines of Canada, 2015). Although this industry represents a small part of the national economy, it certainly is significant in particular regions, and could increase in importance and value through more careful matching of grape variety to local conditions and naturally-warming climates, and careful attention to maximizing the returns from the geological aspects of grape growing. In addition, other traditional perennial, long-lived, deep-rooted crops (e.g. cider-apple and other fruit orchard trees) can also benefit from careful scientific analysis of non-biological/non-climatological factors which affect fruit quality and distinctiveness. Establishment of regional identities based partly on the recognition and quality of all local products can help strengthen the agricultural and touristic economies of that region, transforming the face of a rural economy. Whereas in Europe, each wine region grows only the grapes best suited to that locale, discerned through 2,000 years of trial-and-error, and so only produces a few wine types, in Canada we are still in a phase of trying "everything everywhere" to find those matches (Aspler, 1984).

"There is a great deal of science and artistry in each bottle of wine" (Sommers, 2008), and behind this is biology, climatology, chemistry, geography and, yes, geology. The concept of "Terroir", and optimizing its influence on wine quality, may represent an important factor in the future of the Canadian wine industry, the cider industry, and the entire fruit-growing industry. Although climatic factors clearly exert the most profound effect on wine production, geological factors are also prime components of that concept (Jones et al., 2006). Geology is a foundation factor underlying all those terroir factors, the very "bedrock", so to speak, of the vineyard. By making the effort to understand these factors scientifically, earth scientists may be able to help maximize the quality aspects of grape crops in each location. Terroir is about an intimate understanding of the land and what its best uses are (Brown, 2001), and can be applied to any crop grown on the land, especially those derived from perennial plants. It is a concept uniquely-suited to maximizing the efforts of small-scale agriculture, making it potentially important for most agricultural endeavours in most settings of Canada.

Structure of This Report

It takes generations of skill and a critical mass of exacting producers to put most wine countries on the map, to make the wines of that country a "postcard" from there to the rest of the world (Crosariol, 2013c). Advances on this front have been made in the Niagara region of Ontario (Haynes, 2000) and the Okanagan region of B.C. (Bowen et al., 2005), but further research is certainly required in these, and all other, areas. This report begins with an introduction to the historical aspects of wine (which may at first seem tangential and over-long, but is necessary background for a thorough introduction to the topic, and as background for later reports on the specific wine-growing regions of Canada) and continues on to provide some of the geological background and perspective to the important foundational concept of wine "terroir". The bulk of the report gives a brief introduction to the various Geological factors (standard earth science), Climatological factors (which are closely related to earth science) and Biological factors (which closely interact with the earth science factors) involved. It is arranged to emphasize 1) the foundational importance of the geological factors, and to emphasize 2) that each factor is simply one interactive component of the total "terroir" natural ecosystem at any given location. It ends with a very brief introduction to each Canadian wine region and its terroir factors, as a preamble to how each might better capitalize on those factors.

However, other aspects of vine-growing and wine making such as the winery techniques and cultural landscape, equally important in shaping the resulting nectar, are beyond the scope of this report. Obviously, a great deal of further, more systematic, research is needed to fully capitalize on the geological understanding of terroir factors and their effect on premium wine production. This is simply a first step toward elucidating our rich geological patrimony and its potential influence on the wines produced in this country. In future, as a long-term goal, I hope to assemble a "Geological Atlas of Wine Terroirs in Canada", which might perhaps encourage the further construction of detailed GIS models of the terroir potential for each wine region/appellation and sub-region, comparable to the effort already attempted in B.C.'s Okanagan Valley through the pioneering work of Bowen et al. (2005).

BRIEF HISTORY OF GRAPES, WINE AND WINEMAKING

Biology of Grape Vines

Grape vines belong to the Vitaceae family of woody climbing vines, with fossil seeds dating back nearly 50 MY to the mid-Eocene, and fossilized vines dating to 60 000 ybp. The wild Eurasian species *Vitis vinifera* (subspecies *sylvestris*) is the progenitor of all domesticated wine grapes (*Vitis vinifera* subspecies *vinifera,* the "Noble Grape") and is native to the Mediterranean region from Spain to central Asia, possibly originating in what is now the Republic of Georgia (Wilson, 1998; Lukacs, 2012; Robinson et al, 2012). The only significant difference between these two is that the domesticated subspecies *vinifera* is hermaphroditic, meaning all plants have both male and female flowers, happily making domestic cultivation and propagation much easier (Robinson et al, 2012). Most of the grape varieties known today (up to 10 000 types), all growing between latitudes ~ 30° to 50°, are actually nearly identical genetically, and really belong to only a very small number of "founder" varieties (e.g. The Pinot grape variety which encompasses both Pinot Noir and Pinot Blanc vines) (Robinson et al., 2012).

Grapes are similar to all broadleaf deciduous fruiting vines which compete for sunlight by climbing (up to 20 m if unpruned), and compete for nutrients by extending deep vertical roots (Encyclopedia of Life, 2016). These climbing vines require solid support, either as natural, living structures (trees) or as non-living structures (rock outcrops, human-constructed staking) to grow and develop properly (Cita et al., 2004). The older the vine, the deeper the rooting system, and consequently the better the vine is able to survive drought and find nutrients (Sommers, 2008). Budding begins when the average daily temperature reaches 10°C, and flowering begins about 2 months later, followed in a few weeks by the first immature berries (Sommers, 2008). From this point onward, sugars increase and acid decreases until the fruits are ripe enough to harvest. *V. vinifera* grapes contain a large amount of sugar (15 to 25%), with equal parts glucose and fructose, and both tartaric acid and malic acid (Encyclopedia of Life, 2016).

Humans and Wine

The history of human association with alcohol is one of an intimate symbiotic relationship between humans (in fact, all primates) and the group of single-celled fungi called yeasts, in particular the brewers yeast named *Saccharomyces cerevisiae* (Coghlan, 2006; Dunn, 2013). During Cretaceous time, when flowering plants began to develop fruits rich in sugar to encourage animals to eat those fruits and disperse their seeds, *S. cerevisiae* developed the parallel skill (fermentation) to convert those sugars into alcohol (which is toxic to most other microbes), in order to defend its territory and feed itself (Coghlan, 2006). Primates have always feasted on fruit and may have evolved to be attracted to the scent of alcohol which helped them locate ripe fruit in the thick forests (Coghlan, 2006). The domestication of cereal grains and fruiting vines in the Late Paleolithic Fertile Crescent around 10 000 ybp set humankind on the path to civilization and culture (Standage, 2005). Viticulture is one of the oldest agricultural endeavours, predating written history and practiced for at least the past 10 000 years (Meinert, 2004; Standage, 2005; Lukacs, 2012; Dunn, 2013). In fact, there is archeological evidence for a functioning winery in Armenia dating from more than 6,000 ybp (Meinert, 2018). In the unsanitary conditions of early settled communities, fermented drinks provided potable, nutritious beverages, since ethanol kills most bacteria (Dunn, 2013). There is also biological evidence of this long-standing unique relationship between humans and yeasts: alone among primates, and unlike our close higher ape relatives, the enzyme which metabolizes ethanol is overwhelmingly concentrated in our livers where all imbibed alcohol is processed (Dunn, 2013).

In the ancient world, wine was valued for its apparently divine origin, rather than for its taste: it was a gift from the Gods, a liquid within which the Gods' spirits resided, that apparently appeared through magical transformation (yeast-induced fermentation) and had miraculous effects (Lukacs, 2012). It was primarily drunk for complex religious reasons, valued for its spiritual power, and sacred for its divine energy: to be under the influence of wine was to be in a state of spiritual communion or religious rapture with the Gods (Lukacs, 2012). Perhaps some modern imbibers still experience this perception.

In the past, the most important factor identifying quality and taste was the place where the grapes were grown. In fact, prior to the second half of the 20^{th} C, few people knew the names of grape varieties because most wines were identified ***only*** by their place of origin: their "terroir". It is only in recent decades that varietal labelling, beginning in California, became dominant throughout the "New World" outside Europe. In many regions, this has become the familiar norm, rather suddenly relegating the place of origin to a disturbingly minor role (Robinson et al., 2012). However, an even more recent trend, away from mass-market industrial homogenization and back toward more traditional recognition of local terroir and premium quality, has been developing (Lukacs, 2012; Crosariol, 2013).

History of Wine-Making

Vitis vinifera growing represents one of the oldest fruit crops in the world (Encyclopedia of Life, 2016). According to ancient Greek myth, Dionysus (the god of fertility and wine) invented winemaking on the island of Crete. However, the earliest archaeological evidence of vine agriculture dates to 8,000 BC in eastern Turkey (Lukacs, 2012). Reddish wine residue (tartaric acid) from pottery jars dated to 5400 BC is present at Hajji Firuz Tepe in the Zagros Mountains of northwestern Iran (McGovern, 2003; Standage, 2005). Viticultural discoveries near the town of Shiraz in ancient Persia date to 3500 BC (Meinert, 2004). Certainly by about 2500 BC grape vines for wine production were thriving and being cultivated in the Nile Delta and throughout Greece and the islands of the Aegean (Lukacs, 2012; Encyclopedia of Life, 2016). The climate and terrain of Greece proved ideal for viticulture, which began to spread out from Arcadia and Sparta after 1700 BC (Standage, 2005): there are more grape varieties native to Greece (3000+) than anywhere else on Earth. The nurturing of vines, originally grown intertwined on olive or fig trees, was gradually subjected to more scientific approaches, leading to vineyards in neat rows on staked trellises, and to the invention of the wine press (Standage, 2005), concepts which still form the basis of viticulture today. In the ancient world, white wines were generally more highly-valued than red wines.

By Classical Greek time, vineyards and winemaking were profitable commercial ventures, spread throughout the Mediterranean by seafaring Greek and Phoenician traders, including to the Etruscans of Italy and to the Celtic people of France (Wilson, 1998; Meinert, 2004; Cita et al., 2004; Standage, 2005; Lukacs, 2012). The region of southern Italy colonized by the Greeks became known as "Oenotria" (the land of staked vines) (Cita et al., 2004), and was recognized as a prime producer by ~140 BC. Wine was the lifeblood of Mediterranean civilization and was the basis of a vast, seaborne trade network which also spread the then-new Greek concepts of rational philosophy, politics, law, art, science, architecture and literature from Greece throughout the known world (Standage, 2005). Nearly three thousand years later, these conceptual children of the first wine culture still represent the foundation principles of modern Western thought.

The subsequent Roman conquests, during the influential natural Roman warm climatic phase, spread wine culture through the rest of Europe, including all the now-renowned viticultural regions of Europe (Meinert, 2004). Interestingly, the Celts of Gaul enthusiastically embraced both grape vineyards and apple orchards into their culture, two of the crops most associated with France and most associated with the terroir concept. The Romans also invented oak barrels as prime storage containers for wine.

During the Dark Ages cool phase, grape growing declined throughout most of Europe, but resurfaced again in the hands of monks and monasteries throughout the Medieval Warm Optimum (10^{th} to 13^{th} C, with climatic maximum around 1100 AD) (Meinert, 2004). In particular, the Benedictines of Cluny and the Cistercians of Cîteaux, both located in Burgundy, were instrumental in this revival (Wilson, 1998). Wine was important to Medieval Europe because it provided warmth, calories and sterile fluids in a time when most people were under-nourished and much water was contaminated (Lukacs, 2012). These common medieval necessities, and secularization of wine into an everyday drink, represent the beginning of wine's conversion into its modern guise. Throughout the Middle Ages, the mild climate conducive to intense vine growing, the great increase in population, the vast expansion of vineyards under the care of Christian monks and monasteries, and the slow emergence of a new social class of wealthier bourgeois merchants/traders all conspired to allow people to think of wine as more of a pleasure and a choice than a necessity – especially in the trade-driven worlds of Britain and northern Europe (Lukacs, 2012). This led to the development of the terroir concept, as described below.

The natural climatic extremes of the Little Ice Age during the 16th to 18th C (climatic minimum around 1650) destroyed the indigenous vineyards and wine industries of England and northern Europe, forcing the British in particular to continuously search southern European regions for quality wines, and consequently driving the demand and recognition for certain wines and certain terroirs (Lukacs, 2012). This in turn led to the rise to prominence of the terroir-driven wines of Burgundy and Bordeaux, Sherry and Port. The 19th C. "Golden Age of Wine" emerged as the modern trend of naturally-warming climate exerted itself, the early Industrial Revolution made consumerism possible, and as wines became linked to the emerging trends of the new "restaurants", "cuisine" and "gastronomy".

However, a series of disasters in the 1850-1950 period (1845-1860 powdery mildew plague; 1860-1870 *Phylloxera vastatrix* plague, of an aphid-like louse which attacked the vine roots; 1870-1880 downy mildew plague; 1880-1890 black rot; 1914-1918 First World War; 1939-1945 Second World War) destroyed this wine culture in an apparent run of pestilence after pestilence of near-Biblical proportions, many of which were eventually traced to importation of North American *Vitis labrusca* vines as exotic species (Wilson, 1998; Lukacs, 2012). The *Phylloxera* root louse first appeared in Europe in a greenhouse vine near London in 1863, but was devastating vineyards in southern France a few years later, and quickly killed 40% of France's vineyards in only 15 years (Bryson, 2010). The solution to the devastating *Phylloxera* plague was eventually discovered to be importing resistant North American *labrusca* rootstocks and grafting native European *vinifera* vinestocks onto them (Wilson, 1998). This is now standard industry practice all over the world. Fortunately, a few vineyards located in particularly remote and isolated regions (parts of Australia, South Africa and Chile) or with very sandy soils (where *Phylloxera* larvae cannot survive) endured the onslaught and now produce from truly "Old Vines". *Phylloxera* continues to exist in most wine areas of the world, but has difficulty maintaining its life cycle in sandy soils and where rootstocks are resistant, although natural selection and evolution within the insect genus may be slowly creating new strains which can survive (Wilson, 1998). These multiple pest crises collapsed supply, led to large-scale industrial production and market-flooding of poor-quality wines of no distinction, the rise of other beverages (such as distilled spirits, absinthe, etc.) and finally complete collapse of demand as wine fell out of favour and became the province only of "peasants and degenerates" (Lukacs, 2012).

Wine's Second Golden Age, as part of the post-WWII global economic boom, has been characterized by two separate and very divergent trends: 1) a re-emphasis throughout the European "Old World" of wine, on traditional approaches, tight governmental control on quality, emphasis on niche products tuned directly to their origins, and recognizing specific places as sources of specific wines, and 2) the "New World" revolution with an emphasis on specific grape varieties, massive-scale growing and intense industrialization of the winemaking processes, manipulating to maximize the intensity of fruit flavours, and slipping the shackles of traditions which were seen to define or confine wines. Although both these key trends have played out somewhat separately to the present day, they may yet begin to converge toward a unified 21st C. perspective, still to emerge.

History of Wine in Canada

To most Canadians' surprise, the wine industry in Canada is over 200 years old. The first known winery in Canada was established in Ontario in 1811 (by Johann Schiller, first in Cooksville, Mississauga, later in the Niagara area) and in 1867, on the same property, Justin de Courtenay produced Gamay red wine which won a prize at the Paris Exposition (Aspler, 1984; Bell, 2014; Crosariol, 2010; Pope, 2016a). In 1866 three Americans planted 12 ha of vines at Vin Villa Estate on Pelee Island in western Lake Erie: Canada's first known commercial winery took full advantage of the 42° latitude location and one of the longest growing season in Canada, and supplied demand in both Ontario and U.S.A. (Aspler, 1984; Bell, 2014; Henderson and Henderson, 2012; Pope, 2016a). Pelee Island wine won a Bronze Medal at an exhibition in Paris in 1878. By 1890, 23 wineries operated in southwestern Ontario and by the turn of the 20th C, there were 41 commercial wineries in Canada, mostly in Essex County of Ontario along the north shore of Lake Erie, operated by Europeans (Aspler, 1984; Gillmor, 2006; Bell, 2014; Pope, 2016a). Likewise, in 1859 Father Charles Pandosy planted the first vineyards in British Columbia near Kelowna, although the first commercial winery there was not established until 1932 (Bell, 2014).

However, the early activities, positive results and promise were not sustained into the 20th C. Early Canadian wines were produced primarily from native and hybrid grapes of *Vitis labrusca*, such as Concord, Catawba and Isabella grapes, all either too low in fructose or too high in acidity to consistently create truly fine wines, but they were prolific and disease-free (Aspler, 1984; Bell, 2014). In addition to World War I, Prohibition (an attempt to forbid the sale and drinking of alcohol) although short-lived in Canada, still set back the development of the Canadian wine industry by several decades, followed by the Depression and World War II (Bell, 2014). Meanwhile, in British Columbia, the B.C. Growers Wine Company planted the first commercial vineyards in Kelowna in 1926 and started Calona Winery in 1932 (Bell, 2014; Fulton, 2011).

However, in the 1940s and 1950s Bright's Winery (first established in 1876), in the Niagara region, hired a winemaker from France and imported French hybrid and *vinifera* vines in an attempt to establish a significant estate winery focussing on quality (Aspler, 1984). In the Okanagan Valley of B.C., Joe Busnardo first planted European *vinifera* grapes on the site of present-day Hester Creek Winery in 1968 (Crosariol, 2011). Although covering only about 2,000 ha of original grassland or parkland forest, the B.C. industry has grown in succeeding years to over 225 commercial vineyards and over 60 commercial wineries (Fulton, 2011). Unfortunately, these stellar efforts to improve Canadian wines were hijacked by the arrival in the 1960's and 1970's of the ubiquitous, popular, big-selling, sweet, blended sparkling wines of the Cold Duck/Baby Duck/Lonesome Charlie era (Aspler, 1984; Gillmor, 2006). Partly in a backlash to these "soda-pop" wines and with the advent of free trade, government subsidies introduced in Ontario in the late-1970s and in B.C. in the 1980s (Taylor et al., 2006), encouraged re-planting vineyards in European *Vitis vinifera* varietals on hardy, disease-resistant North American *Vitis labrusca* rootstocks, immensely improving the vineyards and the grapes coming into the wineries. The birth of the modern Canadian wine industry can be dated from these plantings. One of the most successful and influential of these efforts was the inception of Inniskillin Wines in 1975, in the Niagara region, by Karl Kaiser and Don Ziraldo, based on European cold-hardy Riesling, Chardonnay, and Gamay vines (Mackay, 2017).

Icewine, first attempted in Roman times and certainly made regularly in Germany for the past several centuries, was first produced in minor quantities in B.C. and Ontario in the 1970s, and in commercial quantities by Inniskillin Winery in Ontario in 1984, and has since become a hallmark of the Canadian wine industry worldwide (VQA Ontario; Mackay, 2017). Because international law requires grapes to be harvested ***naturally-frozen*** on the vine (i.e. -8°C or colder), no other country can consistently produce high-quality icewine (Pope, 2016b). Unfortunately, inauthentic copies have appeared in some parts of the world, masquerading as the real thing.

The Vintner's Quality Alliance (VQA) was established in 1988 in an attempt to increase efforts to develop fine home-grown wines, although membership is strictly voluntary. In 1991, Karl Kaiser was instrumental in the creation of the Cool-Climate Oenology and Viticulture Institute at Brock University in St. Catherines (Mackay, 2017). From 1990 onward, Canadian vintners have continued to demonstrate that fine grape varieties in cool-climate settings can potentially rival the complexity, structure, quality and ageing potential of more famous wine growing regions of the world. For example, chardonnay wines are enjoying a renaissance due to the emergence of more elegant, delicate, balanced, crisper, complex versions with good acidity from Canada and other cool-climate regions which more closely compare to the original homeland of this noble grape variety (Crosariol, 2013d). The Southern Ontario region (42° to 44°N), known particularly for its good soils, has had excellent success with white wines, whereas Southern B.C. (49° to 51°N), known particularly for its good climate profile, has produced notable whites in the north and reds in the south. In 2009, Le Clos Jourdane winery from Niagara beat 13 other top chardonnays from France and California in a blind taste test (Pope, 2016b). The cooler air temperatures in Canadian wine regions lend our wines a fresh aromatic elegance that is very food-friendly (Pope, 2016b).

Currently, the Vintners Quality Alliance (VQA) recognizes 9 distinct wine appellations within Canada (4 in Ontario, 5 in B.C.) with numerous sub-appellations, as well as established wine regions in Quebec and Nova Scotia (Pope, 2016b). Yet virtually all Canadian vineyards are less than 40 years old and serious viticulture has only been widely-practiced for about 30 years (Fulton, 2011). Rather than toiling through 2,000 years of trial-and-error as in Europe, or 200 years of growing as in California, Canada can learn from those experiences and modern science to leap-frog over much of that time and compete in quality (Aspler, 1984). In 1999, Geoscience Canada began a new series of scientific papers, under the direction of Simon Haynes of Brock University on the relationship between geology and wine. In addition, a session of papers was convened at GSA in Seattle in 2003. All these contributions, and several more, were eventually collected into a single volume (Macqueen and Meinert, 2006), which stands as a firm foundation for future geologically-oriented terroir research.

Canada, with its geologic, geographic and climatic diversity, has now established an expanding premium wine industry with the potential to contribute increasingly to the country's economy, and especially to a variety of local economies. Better understanding of the geological background and influential factors behind this could be a major contribution to enhancing the quality of wines produced. The same is true for the apple cider, and other orchard fruit, industries.

THE MANY DEFINITIONS OF "TERROIR"

The place where grapes are grown, the soil they're grown in, the weather, the air, the sun and the growing techniques all affect the character and quality of the resulting wine. Wine thrives on regional nuance, and its finest interpretations and expressions are decidedly regional: wine is at its best when pushed to be increasingly site-specific (winebc.com, 2013). But, it's a somewhat unfamiliar concept today when we've come to expect standardization in products as a guarantee of quality.

The concept of Terroir, the guiding principle of wine quality in the European tradition, is actually something invented by humans, as well as discovered by them (Wilson, 1998; Lukacs, 2012). However, as Gladstones (2011) observed, Terroir is "much spoken-of but nobody, to the best of my knowledge, has attempted a comprehensive definition and integration of its elements in the light of modern science". Nevertheless, virtually every wine author or researcher has attempted to provide a working definition. The concept of terroir attempts to relate the sensory attributes of wine to the environmental conditions in which the grapes were grown (Van Leeuwen and Seguin, 2006). MacLean (2006) wrote: "Great wine is a subtle expression of the landscape, soil and climate from which it was produced, not a confection of lab techniques".

In fact, the word "terroir" was a 14th C Burgundian French expression, derived from the Latin "terratorium", describing the philosophy that sees wine as an expression of a specific soil and climate, of a geographical and even a cultural presence (Wilson, 1998; Gillmor, 2006; Meinert, 2018). The French use it as a shorthand for the holistic interrelationship of all the physical and cultural factors that go into making a wine from a particular vineyard taste the way it does: the winemaker aims to allow the wine to express its sense of place (Brown, 2001). It is an interactive combination of immutable natural factors describing the vine's entire natural environment, and is fairly unique to each vineyard or local area (Van Leeuwen and Seguin, 2006; Gladstones, 2011). Terroir is difficult to study on a scientific basis because so many mutually-interacting factors are involved (i.e. too many independent variables), and to focus on only one or two of these factors is to misunderstand the essential synergy of the aggregate fusion of all (Van Leeuwen and Seguin, 2006). This intimate connection between a grape variety and the vineyard's geology, soil, topography, climate, microbes, and neighbouring vegetation is crucial to the concept (Van Leeuwen and Seguin, 2006). The ultimate point is to produce the best wine that can be crafted from the grapes that thrive and fully ripen in this particular soil and climate. The entire basis of the concept of terroir tells us that "place" matters; that what we taste is a product of localized environmental forces and cultural decisions (Sommers, 2008).

Terroir is an integrated holistic concept involving the assemblage of special characteristics that the unique geography, geology, and climate of a certain place, interacting with the plant's genetics, impart to local agricultural products. It is a "sense of place", and at its core is the assumption that the land from which the crop is grown imparts a unique set of characteristics and quality that is specific to that growing site (Wilson, 1998). "Terroir describes the ineffable qualities of a wine-making area: the way that geography, topography, climate, air quality and soil collude to give a wine its sense of place" (Zimmerman, 2007). As Johnson (1997) stated, "the land itself chooses the crop that suits it best". As Haynes (1999) put it: "The very essence of terroir is that the wine produced from a particular vineyard is a fundament of the complex interrelationships of all factors above and below the ground surface that affect the grape during growth, including meteorological, physiographic, pedalogical, geological and viticultural factors". The important thing is that a wine's defined origin conveys a meaningful message to consumers (Gladstones, 2011). Thus, terroir is a relatively simple term used to describe the very complex interplay of physical factors that influence the character and quality of wine (Meinert, 2004). But even more importantly, terroir is the ***integration over time*** of these individual factors that contribute to wine quality (Meinert and Busacca, 2000).

In his now-classic book, Wilson (1998) summarized: "The term terroir has no precise translation but encompasses all aspects of the physical environment of vine cultivation underlying and shaping the character and quality of the wine, including meteorological, physiographic, pedalogical, geological and (often) viticultural controls. In Burgundy, the boundaries of vineyards that produce the best-quality wines correspond almost exactly to stratigraphic boundaries. What ties terroir studies together is the application of science to better understand the physical environment that affects grape and wine quality. Terroir is a concept, not easily grasped, but includes physical elements of the vineyard habitat – the vine, subsoil, siting, drainage, and microclimate. Beyond the measurable ecosystem, there is an additional dimension – the spiritual aspect that recognizes the joys, the heartbreaks, the pride, the sweat and the frustration of its history". Clearly, terroir isn't just a single, tightly-defined concept; it is more of a set of allied complementary ideas and principles, a holistic philosophy or unifying theory encapsulating a certain approach to wine that encompasses the almost metaphysical circle of soil, nature, appellations and human activity (Goode, 2013). But it does encapsulate the "thumbprint" of the local growing conditions, specific to that locale or region (Goode, 2013; Szabo, 2016). The great wines of the world are the result of skilled grape-growers and winemakers working together to bring out the unique qualities of the grapes that nature provides (winebc.com, 2013).

Like great real estate, a great vineyard is all about "Location, Location, Location!", but there are many factors which enter that equation. While the quality of the wine produced in any viticultural region is highly-dependant on the quality of the grapes grown, the quality of the grapes themselves is the result of the combination of five main physical factors: climate, topography, geology, choice of grape variety, and vineyard management (Jones et al., 2006; Jefford, 2016). Terroir, it seems, is the integrated ecology of a vineyard, the total inter-related environment wherein a grapevine is cultivated. This has brought applied geology research more explicitly into the range of influential factors, beyond the usually-considered climatic factors. In fact, assessing an area's physical terroir may be the most important process when considering a new vineyard, affecting the matching of grape varieties, the yield, the quality of wine and the vineyard's long-term profitability (Jones et al., 2006). The point is to maximize the potential which is derived from the relation between a certain grape variety and rootstock to its physical and biological and climatic environment (Jefford, 2016). However, the great need now is for solid scientific data/information upon which to base decisions, rather than anecdotal suggestions.

Perhaps the most satisfying definition of terroir, from an earth scientist's perspective is that provided by David Jones, as quoted by Gee (2004). "What you are tasting in a bottle of wine is a hundred million years of geologic history".

ORIGINS OF THE TERROIR CONCEPT

Ancient Beginnings

The original "terroir", the geographical birthplace of wine culture is traditionally placed in the lush valleys and slopes of the Trans-Caucasian region between the Black Sea and the Caspian Sea (eastern Turkey, northern Iran, Armenia, Georgia, Azerbaijan) north of the original Fertile Crescent (indeed, Judeo-Christian tradition declares Noah the first vintner with a vineyard near Mount Ararat) (Standage, 2005; Lukacs, 2012). This area, in the foothills of the Caucasus Mountains at the juncture of the Afro-Arabian and Eurasian plates, is underlain by Jurassic and Cretaceous limestones, with minor basaltic lavas (Wilson, 1998). Wine grew to become a key spiritual touchstone and a pervasive part of all ancient Mediterranean cultures.

The wealthy, noble citizens of Classical Greece were the first to value specific wines from specific locations, judging that the finest wines came from the Aegean Islands of Rhios, Kos, Lesbos and Thasos, so in essence these islands were the first recognized "terroirs" (Standage, 2005; Lukacs, 2012). Greek merchants would stamp different, distinctively-shaped amphorae with the particular seal of the region they came from (i.e. the first wine labels), thereby establishing reputations based on the quality and consistency of their wines (Standage, 2005; Wikipedia, 2013 – Terroir). In Classical Rome, wine appreciation had reached a whole new level of sophistication, and the nectars from southern Italy were always valued more highly than those from the north. In particular, Falernian wines were especially celebrated (an aged, late-harvest, high-alcohol white wine from vines grown exclusively on the mid-slopes of Mt. Falernius in Campagnia) (Standage, 2005; Lukacs, 2012). This included the legendary "Opimium Vintage" of 121 BC, said to be the finest in the world by Pliny The Elder (Lukacs, 2012), and still drinkable more than 100 years later (Standage, 2005).

History has shown that viticultural regions developed when and where climate was most conducive (Meinert, 2004; Jones, 2017). For example, during the Medieval Warm period, temperatures were up to 1°C warmer than today, allowing vineyards as far north as southern England, but conversely, during the Little Ice Age northern vineyards died out and even harvesting grapes in southern Europe was difficult (Meinert, 2004). The medieval Church established new vineyards wherever climatically-possible, clearing the forests of central France and bringing vines to Germany, right out to the geographic limits of viable viticulture: as Christianity spread, so spread viticulture (Lukacs, 2012). Most wines produced in these regions were green, vegetal, shrill and sour, but were more sterile and more nourishing than the often-contaminated local water. Thus, wine drinking became an everyday necessity for the burgeoning population of Europe. Even in these times, the sweet high-alcohol (Falernian-style) wines made from raisined grapes in the ancient terroirs of southern Italy, Greece and the Middle East (brought back by Crusaders, and known as "Romney's") were highly-prized because they were impossible to produce in the cool-climate regions of Europe (Lukacs, 2012). The continuous warming in climate toward the peak of the Medieval Warm Epoch allowed the re-establishment and re-invigoration of vineyards throughout Europe, including in southern England, but deleteriously affected wine-making in the traditional, hotter, southern regions. Incidentally, one thousand years later and in the grip of the current natural warming cycle today, we are experiencing similar trends. During the High Middle Ages at the height of the Medieval Warm, the dynamic religious, political and military history of Europe actively affected the establishment of new proto-terroirs that would later become the important foundation terroirs of the modern wine world, as follows.

Burgundy

Founded in 1098, the Cistercian Order (from Cîteaux Abbey) built a new monastery south of Dijon, planting vineyards on the gentle, east- and south-facing, well-drained hillsides of Burgundy, underlain by golden marine limestones of Middle – Upper Jurassic age (Wallace, 1972). Through large-scale and long-term observation of the wine produced from many varied parcels of land, these white-habited monks soon began to recognize that certain wines from certain vineyards tasted differently from others, with particular characteristics that repeated vintage after vintage (Lukacs, 2012; Wikipedia, 2013 – Terroir). They insisted on identifying these vineyards (and the wines produced from them) as distinct and consistently-recognizable entities, and began to build stone walls around the best patches to create a "clos" (cloistered vineyard), which would produce a particular "cru" (growth) (Lukacs, 2012). The most famous of these is the 50.6 ha Clos de Vougeot, walled-off in 1336 (Figure 1) (Wikipedia, 2013 – Burgundy Wine, Clos de Vougeot), and still producing and accessible today (although now split among more than 80 owners; Wikipedia – Clos de Vougeot). The finest wines produced from this legendary vineyard were based on Pinot Noir grapes grown on a gentle slope with good drainage, in the light, chalky, gravelly soils resting on Jurassic oolitic limestone (Wilson, 1998). These characteristic tastes changed the perception of wine throughout Europe, and were the first non-Mediterranean wines to taste good enough and different enough, to be widely admired and recognized. The Cistercians of Burgundy were the first in the "modern" world to recognize, care about and nurture the terroir aspects of their wines, and this fundamental attitude was soon taken up by vintners elsewhere as prices for these wines skyrocketed.

Figure 1. Front gates of the legendary Clos Vougeot vineyard (in Burgundy, France), first enclosed in 1336, and the site of the first formal recognition of the Terroir concept.

Bordeaux

The Romans had planted vines along the Atlantic coast of Gaul, but they languished until Eleanor of Aquitaine married Henry Plantagenet of England (Henry II) in 1151, and the Bordeaux wines of her homeland which were cheap to transport to Britain, became the court drink in London (Wallace, 1972). By the 1300s, Bordeaux exported the equivalent of 110 million bottles of "clairet", and the English consumers of these bottles demanded and ensured that Bordeaux wines evolved to become the best in the world (Wallace, 1972; Lukacs, 2012). These wines are primarily grown on Middle Oligocene marls overlain by Quaternary coarse sand and gravel of the Gironde alluvial terraces (Wallace, 1972). In the 1600s, the Bordeaux family which owned the Haut Brion estate insisted that wine from their vineyard could never be blended with any other because their wine was so distinctive and derived its taste directly from that place (Lukacs, 2012). Following this lead, many local vintners throughout the region began propagating only the most superior vines and Bordeaux wine quality rapidly increased, but also the wines began to adhere to a standard stereotype, recognizable and characteristic of that particular place (Lukacs, 2012). This highly-structured and -regulated approach to quality is still in place today.

Rhineland

Meanwhile, although the Romans had introduced vines to the Trier area along the Mosel valley, and Cistercians had re-introduced vines to the Rhineland of Germany in the 1100s, it was the chance planting of a new and cold-resistant variety, Riesling, in the 1400s, which yielded superior wines with a new refreshing taste and excellent longevity due to its high acidity which acted as a preservative (Lukacs, 2012). Clinging to steep, south-facing slopes and rooted directly in Lower Devonian cleaved and fractured black slates, these vines reside among the steepest vineyards in the world (Wallace, 1972). These German wines were stored in giant wooden casks ("tuns") which limited the exposure to air, maintaining their quality for long periods and allowing nuanced flavours to slowly develop over time which fully expressed the unique terroir of the vineyards (Lukacs, 2012). One of the most distinctive characteristics which typifies these wines is the subtle, petroliferous aroma, clearly inherited from the organic-rich bedrock.

Iberia

However, the Hundred Years War between England and France pushed Bordeaux into decline, and England sought reliable sources in Spain and Portugal. Consequently, during the 1400s after the Christian Reconquista of Muslim Spain, warm, sunny Andalucia began to specialize in strong, sweet wines grown in white chalky soils, which were stable enough to survive lengthy sea transport to England from the town of Jerez. These came to dominate the British beverage scene and were identified by a mispronunciation of their place of origin, as "Sherry" - or "Sack" (so much enjoyed by Shakespeare's Falstaff, named after sacer, or sugar). Similarly, full-bodied, tannic red wines with added brandy from the steep, black Precambrian metamorphic and granite river banks of the Douro Valley in Portugal, and shipped to England through the town of Porto during the 1700s, became a staple in upper-class London homes (Wallace, 1972). These wines were labelled and forever identified solely with their region of origin, as "Port" (Lukacs, 2012).

Champagne

During the depths of the Little Ice Age, in the 1530s near Limoux in Languedoc, monks were deliberately crafting fizzy white wines sealed in cork-stoppered bottles (a revolutionary discovery) by allowing winter-halted fermentation to restart in the spring within the bottles (Crosariol, 2013b). Although this rare "Blanquette de Limoux" was popular in Paris for a time, a similar sparkling wine from the chalky terroir of northern France, developed and mass-marketed more than a century later as warming climate began to spread northward, gets all the credit. In the late 1600s, monks in northern France were still struggling against cold weather to grow their vines on the Upper Cretaceous chalk of the Paris Basin (Wallace, 1972), but harsh temperatures stopped the fermentation in the middle of winter. Dom Perignon, of the Benedictine Order, first recognized that the fermentation was beginning again each spring within the bottles, and learned to control the process by allowing the secondary fermentation to continue in new, strengthened, bottles which had originated in the emerging glass industry of England, and originally were used in the same way for extended bottle-fermentation of cider (Lukacs, 2012; Brown and Bradshaw, 2013; Crosariol, 2013a). This new style of wine which soon became the "toast of the town" in Paris, Versailles and London, was identified solely with its place of origin: "Champagne". It is now the most highly-controlled, and most famous, agricultural product on Earth.

Modern Emergence

Although the European population had multiplied during the Medieval Warm Epoch, greatly expanding the market for wine, as the 1500s and 1600s wore on and climate naturally degraded into the Little Ice Age, many northern European wine-growing areas collapsed, and the crucial, but invisible, wine-producing boundary shifted southward (Lukacs, 2012). However, these five regions, Burgundy, Bordeaux, Rhineland, Iberia and Champagne had established themselves as the key locations where special wines of the modern world first became identified and linked to the particularities of grape and place, and in which people first began to understand the complex interplay of climate, soil and culture which constitutes the modern concept of "terroir" (Lukacs, 2012). Over time, the vintners in these areas began to evolve the belief that the role of the winemaker is to bring out the expression of a wine's terroir (Wikipedia, 2013 – Terroir). The stage was set for new developments when wine growing was re-established as Europe re-emerged from the Little Ice Age, economies/wealth/populations recovered, climate warmed again and that invisible wine-producing boundary once again shifted northward. As Europe moved into the balmier 18th and 19th C, almost unconsciously, the concept of specific wine terroirs, and their link to quality, had come to dominate the wine world (Lukacs, 2012).

The dawn of the 19th C. saw an emergence of a new consumerism, made possible by the wealth creation of the early Industrial Revolution, and the resulting emergence of the modern cultural tastes of artistic Romanticism, modern gastronomy and cuisine (including wine appreciation) (Lukacs, 2012). The concept that superior wines displayed characteristics unique to their origins became entrenched: a great wine had to taste like itself, and taste as it should taste, and above all, reflect its distinctive origins (Lukacs, 2012). Although this philosophy had first developed in Burgundy centuries before, Bordeaux became the new centre of the ideology. With the classification of the region's "top" wines by the Bordeaux Chamber of Commerce for the famous and well-attended 1855 Paris Exposition, this area became considered as **the** prime terroir in the world. In the 1920s and 1930s, France established its famous appellation system to officially recognize specific places as the sources of specific wines, a system which eventually spread worldwide. By the 1970s, the idea of wine as a natural expression of a particular piece of earth had emerged again and people began again to associate quality with origin. In 1978, new European Economic Community rules distinguished "quality wines produced in specific regions", an explicit recognition of the close link between terroir and taste (Brown, 2001; Lukacs, 2012). "Terroir" again became officially recognized as an integral part of a wine's identity – as it had been for the medieval Cistercian monks of Burgundy six centuries before.

Through trial and error, over many centuries, European winemakers came to recognize that certain soils and microclimates produced finer wines than others, but this perspective is still evolving in newer wine growing regions (Hubbard et al., 2006). However, much global wine-making of the 1970s to 1990s sought to reverse that tradition by maximizing the volumes and intensity of flavours, with an emphasis on irrigation and grape variety, rather than terroir, in a stylistic internationalization led by New World vintners (Gillmor, 2006; Lukacs, 2012). Conversely, a feeling has developed recently that a "cookie-cutter" effect on industrial-mass-produced wines made from certain popular varietals has masked many terroir characteristics through the use of intensive and invasive winemaking techniques (Wikipedia, 2013 – Terroir).

But it is possible that the grape varieties are merely a vector for expressing what the soil and climate are all about (Zacharkiw, 2011). Although many consumers in the New World stringently base their wine purchases on particular "favourite" grape varietals mentioned on the label, in reality this may be a deceptive conditioned response: in controlled taste tests, most people actually preferred several different wines from a particular region, rather than the same grape type derived from several different regions (Zacharkiw, 2011). If generally true, this would be a clear expression and demonstration of the importance of the terroir concept.

In the new millennium, the trend is back toward more specialization, to allow boutique wines to express their own natural varietal and regional terroir subtleties (Gillmor, 2006; Lukacs, 2012). Perhaps the old maxim "Great wine is grown, not made" will again be preeminent, or as MacLean (2006) put it, "Nature, not us, should control the vineyard". Winemakers in Burgundy do not believe that they are producing Pinot Noir that happens to be grown in Burgundy, but that they are producing unique Burgundian wines that happen to be made from the well-adapted Pinot Noir grape (Wikipedia, 2013 – Terroir). To them, and to many people, this is the true essence of "terroir".

CIDER AND TERROIR

Brief History of Cider

Cider may be the world's most misunderstood drink. It has a long history dating back to the patrician landowners of Rome, is still considered equivalent to wine in northwestern France and northern Spain, and was once admired as "English Wine". In fact, cider ***is*** wine: a drink made from a fermented fruit crop (and has no relation to beer, a common misconception held especially in North America). As such, it can provide another related example of the terroir concept in action. Craft cider and industrial cider is happily making a strong popular comeback worldwide in recent decades.

The earliest archeological evidence of humans eating apples dates from seeds from 6,500 BC excavated at Çatal Huyuk in Turkey (Bruning, 2012). Modern domestic apples descended from a natural hybridization, about 10 000 ybp in the Caucasus region, between *Malus sylvestris* (European crab) and *Malus pumila* (Asiatic crab) (Bruning, 2012). The Romans planted *Malus domesticus* and made cider throughout their conquered lands of Europe until 400 AD (Brown and Bradshaw, 2013). The conquered Celtic people (who regarded the apple as the legendary fruit of magic/revelation) studiously nurtured their orchards and the resulting golden elixir (Brown and Bradshaw, 2013). Throughout Charlemagne's Frankish Empire of the 8th and 9th C (stretching from Asturias and Cantabria to Brittany, Normandy, and across Germany, with a capital at Frankfurt) orcharding and cider-making was specifically recommended for landowners and became the standard drink for both kings and commoners (Brown and Bradshaw, 2013). The use of oak barrels to store and age wine appears to have been derived from the ancient Celtic practice of storing and aging cider in oak barrels (Cita et al., 2004).

In the 900s the Vikings took over Normandy, and studiously nurtured the orchards because for them apples were a symbol of immortality. Cider making crossed to Britain with the Norman Conquest at the height of the Medieval Warm Phase where orchards throve throughout the UK and Ireland at the same time as vineyards were producing fine wines. With the start of the Hundred Years War in 1337 and loss of access to French wines, Britain became primarily a cider-drinking nation (Bruning, 2012). The succeeding deterioration of growing conditions through the 1400s and 1500s as the world slipped into the Little Ice Age, decimated the vineyards of Britain, northern France and Germany, whereas extensive re-planting of orchards allowed these areas to focus on cider as their standard drink (Brown and Bradshaw, 2013).

During the 1500s and 1600s, cider essentially became the "National Drink" of Britain, and was the ship-board drink of the British Navy (before the advent of Caribbean rum) because it retained freshness much longer than water and offered more scurvy-fighting properties than beer (Bruning, 2012). As well, it had become the standard drink of ordinary workers, a status which it surprisingly maintained right up until the 1940s, only **after** which beer became more popular (Bruning, 2012; Brown and Bradshaw, 2013). Although the Aspall cidery in Suffolk is the oldest continuously-operating cidery in the world, it was the Gaynor family starting in Norfolk in 1870, and the Bulmer family (Strongbow brand) in Herefordshire starting in 1887 who turned cider from a secondary farm activity in Britain to a modern industry (Bruning, 2012; Brown and Bradshaw, 2013). Finally, Magner's cider, first produced in Clonmel, Ireland in 1934, is credited with the 21st C revival of popular craft cider poured over ice starting in 2006.

France also drank more "cidre" than wine, right up until the wine crops recovered from the multiple disasters of the Little Ice Age, the *Phylloxera* scourge and the devastation of two World Wars. In the Basque area of northern Spain, "sidra" with its dry, tannic, acidic flavour profile has always been a staple along with complementary pintxos (tapas). The German apfelwein industry began in Frankfurt in the 1600s but German apples tend to lack tannins so cider making has always been secondary to beer brewing (Brown and Bradshaw, 2013). Likewise, cider was the standard drink for most people in the U.S. in the 17th and 18th C, until more recent mass immigration of Germans to the cities in the 1870's transformed the country to a beer-drinking nation (New York City was called "The Big Apple" because it had been the centre of the apple orchard and cider industry) (Brown and Bradshaw, 2013). Most people today would be surprised to know that, outside the immediate Mediterranean region, the Western World had been primarily a cider-drinking world for 500 years until the 20th C when wine and beer finally displaced it again.

Orchard Terroir

Unfortunately, there has been less study and fewer published references on the terroir aspects of apple orchards, and the concept has yet to become an important factor in understanding craft cider (The Cider Journal, 2014) (https://ciderjournal.com/). Until the post-WWII period, cider has naturally been thought of as a wine-like (rather than a beer-like) beverage, which is still true in northern France and Spain, where vintage cider is produced from the orchards of elegant chateaux, served from refined bottles and expertly paired with local foods. Obviously, applying the terroir concept to this traditional product is entirely appropriate, even if it is unfamiliar to North Americans.

Although apple trees clearly do well on good, rich farmland in temperate climates such as northern France, southern England and parts of Canada, orchards also thrive on land which is difficult to farm for other crops, particularly grains (Bruning, 2012). The trees are content to live on relatively steep slopes, in heavier clay-rich soils, thriving through cool, rainy springs, and the practice of grazing livestock under them, adding copious manure to fertilize them, made these orchards highly-economical secondary crops (Bruning, 2012). Because apples are a crop of relatively cooler climate regions, sloping ground in the orchard allows good cold air drainage. Apple trees flower relatively late, so spring frosts are not usually a problem, but heavy spring winds can blow away the blossoms before they are fertilized, seriously affecting fruit yields. Ideally, long, warm summers, cool nights in autumn and adequate humidity promote good yields. As with grapes, soils less rich are preferable, encouraging deep rooting to capture nutrients. Well-drained sandy loam to sandy clay loam, with pH in the 6.0 to 7.0 range (ideally 6.0 to 6.5) is excellent.

Many of the world's 7,000 apple varieties are culinary dessert apples (i.e. "eating apples"), not suitable for cidering. However, the best apples for cider-making are the traditional bittersweet and bittersharp varieties: small, harder fruits with high concentration of sugars, phenolics and tannins, which also impart a more desirable mouth feel. These varieties were chosen through centuries of trial-and-error in the traditional cider-making regions (just as in traditional wine-growing areas), for their high sugar content paired with balanced tannins, polyphenols and acidity. The west of England and Normandy are generally based on Paleozoic limestone and sandstone soils, which lend a soft mellowness to their ciders, whereas in Brittany the cidres grown on granitic soils have a stronger, drier and more minerally taste (Brown and Bradshaw, 2013). The sidre of northern Spain is even drier and stronger.

The adage that "if things grow together, they go together" fits perfectly for cider. Hard apple cider usually measures only 4 to 8% alcohol, ranges off-dry to medium sweet, has a light effervescence, pairs well with many foods, is an excellent summer sipping choice, and is a gluten-free, vegan-friendly alternative to beer (Ejbich, 2015). In Normandy, fine vintage ciders are commonly paired with egg dishes and soft cheeses produced from the chickens and cows which graze on the grasses beneath the apple trees themselves. Because cider has residual sweetness that most wines don't, and the acidity that beer lacks, it excels at pairing with white meat, pork, cream sauces, seafood, cheeses, spicy foods and Asian foods (Brown and Bradshaw, 2013).

Cider in Canada

The world of cider in Canada has been shaped by the dual influences of Britain and France, two of the world's greatest cider nations. Although many Canadian ciders of the past were made primarily from sweet dessert apples, a new craft cider ethos springing up in several provinces has begun to move away from this tendency to sweetness, allowing blending of apple types and fuller fermentation to achieve stronger and more balanced flavours (Brown and Bradshaw, 2013). The Annapolis Valley of Nova Scotia benefits from mild winters, cool gentle springs, warm summers and acidic soils. The first apple trees may have been planted near Port Royal in the early 1600s (Conlin, 2008). The first apples in Quebec were planted in 1617 by colonists from Normandy, and around 1650 Sulpician priests planted Quebec's first full orchard with accompanying cider mill on the slopes of Mount Royal near Montreal (SAQ, 2017). The appearance of "ice-cider" in the 1990s opened the Quebec industry for successful artisanal cider making. Southern Ontario grows many UK-derived classic varieties on Burgundy-like limestone-based soils in a good apple-friendly climate. B.C. has been home to industrial cider making since the establishment of Growers Cider Co. in 1927 but now has respected craft cideries in the Okanagan Valley and on Vancouver Island. Currently, new Canadian cideries are appearing across the country, aiming to utilize less tannic local apples to reflect regional terroir and tap into new trends of gluten-free, sugar-free locavorism (Sisimondo, 2016a). In fact, contrary to its previous reputation in North America, many of today's ciders are artisanal, farm-to-table, small- batch heirloom products (Wilcox, 2015).

Terroir and Other Products

Forests

Forests are composed of long-lived, deep-rooted plants which interact throughout their lives with the terroir factors of the region. Forests are a valuable resource providing food, shelter, diverse wildlife habitat, fuel, water filtration, scenic landscapes, medicinal ingredients and paper, but also act as key links between the geosphere, atmosphere and hydrosphere, providing an enormous on-land carbon storage sink and play an important role in balancing the Earth's CO_2 supply and exchange (Canadian Forest Service, 2017). With 347 million hectares (nine per cent of the globe's total) (Economic Development Canada, 2017), Canada's forests have always been crucial to our economic success. Abundant research on climatological and biological aspects of forests has produced an enormous scientific literature. But how much has been focussed on the underlying geological factors and their effects on maximizing our forest ecosystems?

Beer

Although beer is not normally thought of as a product with a strong terroir aspect (relying on shallow-rooted, single season crops like grains), there is one factor which may express a closer relation to the land: Beer is 90% water, usually derived locally, and the mineral chemistry of the waters result directly from the geology that water percolates through (Rossbacher, 2013). Areas with softer (mineral-poor, especially Ca-poor) water produce excellent lagers (such as Czech Pilsner) and dark ales, whereas those with harder, more mineral-rich waters (especially those with high sulfate content that enhances the flavour of hops) are better-known for pale, hoppy beers (such as India Pale Ale) (Rossbacher, 2013). All provinces in Canada are experiencing a renaissance in small, craft breweries, which may benefit from attention to the terroir concept.

Olive Oil

A nascent olive-growing industry has started on the Gulf Islands of British Columbia, responding to the current interest in the local food movement (Adams, 2015). Throughout the original Mediterranean region, olive groves and vineyards go hand-in-hand, as long-lived, deep-rooted crops with similar climatic requirements. Olive trees were first planted on Pender Island in 2001, with additional groves currently producing culinary olives and extra virgin oil on Salt Spring and Saturna islands (Adams, 2015; Olsen, 2017). These islands represent an area of unique climate in Canada, with long, warm, sunny growing seasons and mild winters (Olsen, 2017). As with wine and cider, this crop may benefit from further study/application of the terroir concept, including the geological factors.

GEOLOGY AND TERROIR

No one can dispute that climatic and biological factors represent absolutely fundamental controls on where and how grape vines can be grown, and Jones (2017) recently has provided an excellent summary of many of these factors. However, it is clear that geological factors also play a foundational role in the results. Without minimizing the clear importance of the climatological, biological and agricultural factors contributing to the terroir concept, the purpose of **this** report is to focus on the geological factors.

At the 24th International Geological Congress in Montreal, a paper was presented discussing the relationship of geology to wine in various parts of Europe (Wallace, 1972). Encountering and reading this paper, a few years later as a young geologist was a watershed moment for me personally. For the first time, I realized how my science might interact with agriculture to have an impact on the everyday lives of humans. Although generally ignored in the Americas, this paper was considered a seminal contribution in Europe (Haynes, 1999). Although many "experts" insist that the only significant aspect of terroir to be considered is climate, Brown (2007) noted that many regions of the world have warm weather and moderate rainfall, but few of them actually produce fine wines, suggesting that geologically-based factors may also be important. The fact that trace element fingerprints can discriminate wines by region suggests that regional environmental factors such as geology and soil chemistry must have some influence on the composition and therefore the aroma and taste of wine (Taylor et al., 2003). The publication of *Terroir: the Role of Geology, Climate and Culture in the Making of French Wines* (Wilson, 1998) was a major step forward in modern understanding of the concept of terroir. However, until recently, the role of geology and terroir has been downplayed in the New World where emphasis on maximizing full-bodied fruit flavour from specific desired grape varietals, through the intervention techniques of post-harvest winemaking, have held sway. The series of papers published in Geoscience Canada (Haynes, 1999), a session held at the 2003 Geological Society of America conference in Seattle, and publication of the resulting book *Fine Wine and Terroir* (Macqueen and Meinert, 2006) were recent attempts to redress this disparity, and provide excellent foundations upon which to continue the geologically-based study of terroir in North America. In particular, Haynes (2000) presented an outstanding exposition of the geological foundations of a possible terroir classification in the Niagara region of Ontario.
In British Columbia, Roed and Greenough (2005) and Roed and Fulton (2011) also discussed the relationship between geology and wine in the Okanagan Valley region.

It is now evident that the worlds of wine and cider can be fertile ground for research in the science of geology, the study of the physical environment in which vines/orchards are grown, and how it came to be the way it is. Sommers (2008) said that "geography is in every drop of wine we drink", but that could equally be said, perhaps even more fundamentally, of geology. Certainly, earth science in its most general and comprehensive form, is the root of understanding of all crops grown in the ground, but especially for those long-lived and deep-rooted crops, like fruit orchards, grape vineyards and forests which are profoundly influenced by the underlying geology. Typically, these long-lived, valuable crops have also expressed strong influence over their local human culture through time. The need to examine the relationship of geology to wine, and the role of geology as an integral part of the terroir of a vineyard has never been more compelling (Haynes, 1999). The need to maximize each factor which contributes to "terroir" in order to obtain the best wine possible in a cooler climate or marginal setting suggests that incorporation of good science in Canadian vineyards may be of paramount importance. The same can be said for the other long-lived, deep-rooted crops mentioned above. Landscapes are not just things to be admired, but they can be "read": we can understand their evolution through time, and their effect on what is grown in/on them.

It is a common, but incorrect, fallacy to point to a single factor as the most important consideration, but the true concept of terroir is as a long-term integrated interplay of all environmental factors (Meinert and Busacca, 2002). It is true that high quality wines typically result from conditions that encourage only moderate vine vigour, either through moderate water stress or low nitrogen supply, and

that these conditions are most frequently met on soils with good drainage in moderately dry climates (Van Leeuwen and Seguin, 2006), but surely we can assemble knowledge allowing us to be more specific about individual regions and sub-regions. In addition, the over-riding geological perspective of deep time and the variability through time of terroir factors is a concept that can be well-understood by geologists. As Cita et al. (2004) suggested, wine producers must learn to "read the landscape with the eyes of a geologist", in three-dimensional space, plus its evolution through the fourth dimension of time.
This perspective of time, and the way it can shape important factors which are essentially invisible to we humans who live strictly at the surface, mostly indoors, and for such short lifetimes, is an aspect where earth scientists can contribute to the understanding of these distinguished crops.

The natural factors or components which contribute to the understanding of the terroir concept can be divided into 4 main categories, here listed "from the ground up" rather than by rank of importance. These are:

1) Geological (bedrock, surficial deposits, soils, nutrients, topography/drainage, groundwater, bodies of water);
2) Climatological (macroclimatic trends, vineyard microclimate, latitude, temperature, sunshine, rainfall);
3) Biological (soil microorganisms, vineyard age, grape varietals, yeast variety; and,
4) Agricultural (human experimentation, human understanding, viticultural practices).

I will discuss each of these separately below, but in an order which emphasizes the most fundamental to those of lesser contribution to the concept of terroir.

As Wilson (2002) said, *"The spread of the concept of terroir encourages the greater recognition of geology and geological processes … to the benefit of wine quality"*. And, incidentally, the field work involved is most pleasurable. Below is a preliminary attempt to provide a brief summary of some of the factors which might affect the wine terroirs of Canada.

COMPONENTS OF TERROIR
(from the base upwards)

Geological Factors

Bedrock Geology (The Phanerozoic Foundation)

Underlying everything, both figuratively and in reality, is geology. Geology is a science of the three dimensions of space plus the fourth dimension of time: a way to understand how natural earth processes have worked (and are still working) through vast spans of time: an intricate mystery puzzle to be unravelled using only a few observable clues. Geology is, in fact, the unifying science which brings together all the other sciences (biology, chemistry, physics, astronomy, climatology) into a comprehensive understanding of the entire natural world around us, integrated over time spans much greater than human lifespans. As stated by Wallace (1972) in one of the first geological papers to deal with the concept of terroir, "the quality and special characters of a wine are strongly influenced by the geology of the vineyard", a fact which is "all too-often forgotten". The underlying source bedrock, not only directly affects the vines, but also affects the glacial deposits that form the subsoil, the compositional chemistry, structure and texture of the soil, the water table and subsurface flow of groundwater, the topography and drainage, proximity to bodies of water, possibly the local climate and microclimate, exposure to sun and wind, the complex ecological/biological community of the vineyard, and the varietals which will fare best in that setting (Costantini et al., 2010). Too often, wine experts who are not geologists, think only in terms of the surface layer of soil as the only important geological component. Because grape vines root so deeply (up to 20 m; MacLean, 2006), bedrock geology is literally the foundation of winemaking and terroir. Geology is in every drop of wine we drink. As David Jones said, "What you're tasting in a bottle of wine is a hundred million years of geologic history". Yet, this factor, the parent of all others, is probably the least-studied of those that contribute to terroir in most locations. The influence of local bedrock on these many terroir factors in Canada is obvious in places such as the Niagara escarpment, or the Okanagan Valley.

The nature of the bedrock governs the amount of deep drainage, root penetration and groundwater quality. The degree of resistance to root penetration derives from bedrock type and the presence of planes of weakness, their spacing and orientation (Constantini et al., 2010). The presence of subsurface porosity and permeability, definable fabric or natural fractures may render apparently-impenetrable solid rock more easily-exploited by deep and long-lived root systems (Wilson, 1998). In addition, geology governs the amount and quality of groundwater available to the crop (Costantini et al., 2010). As Wilson (1998) stated, an enormous amount of fine wine is produced on Mesozoic and younger-aged rocks, especially Jurassic-aged limestones. Is this simply coincidence?

The earliest publication which specifically dealt with the bedrock geology of wine was that of Wallace (1972), wherein the quality and characteristics of several classic fine wine regions of Europe were directly related to the bedrock geology of the vineyards (e.g. the cool-climate whites of the Rhine-Mosel valleys of Germany grown on black, heat-absorbing, fractured and easily-drained Devonian slates; the celebrated Grand Cru Pinot Noir reds of the Cote d'Or in France, grown on the Jurassic golden limestones of Burgundy; the exquisite Chardonnays of the Champagne region of northern France, grown on Eocene shales overlying Cretaceous chalk, and processed and cellared for years within caves in the chalk). That same Burgundy-Champagne geological terroir stretches across the Channel to southern England where a vibrant cool-climate wine industry is re-emerging as climate gradually warms to levels not seen for almost 1,000 years (Sisimondo, 2016b).

When granite is subjected to physical weathering, it crumbles to a sandy regolith, commonly referred to as "granite wash", where the quartz crystals remain as sand grains and the feldspars and micas are subject to chemical weathering reducing them to component trace elements and clays (Wilson, 1998). Likewise, sandstone typically weathers to a sandy, somewhat acidic soil with some components of silt, clay and organics. Conversely, limestones and dolostones are more subject to chemical weathering, releasing trace elements and abundant carbonate ions, yielding natural alkalinity and good water retention (Wilson, 1998). Macro-nutrients are the elements required by plants in large quantities (O, N, P, K, Ca, Mg, S, C, H) and are most-easily-accessed in a neutral to slightly alkaline environment: conversely, critical micro-nutrients (Fe, Z, Mn, Cu, B, Mo, Cl) are most-easily accessed in slightly acidic environments (Wilson, 1998). As crucial examples of the importance of these elements, Wilson (1998) notes that each molecule of chlorophyll requires one atom of magnesium, so its abundance is mandatory, whereas iron is usually present in appropriate amounts but can be inaccessible in an alkaline environment where it precipitates in a poorly-soluble oxide form. The presence of fracturing in underlying bedrock enhances water storage, root extension and access to mineral nutrients (Wilson, 1998).

Vineyards are often situated in locations and on soils that are less than ideal (from the perspective of most crops) because this stresses the vine, forces the roots deeper and promotes fruit development rather than foliage development. When a vine is stressed, it focusses its efforts on making more fruit, not more leaves or stems: this concentrates the mineral and trace element expressions of terroir into whatever fruit is actually produced. In this way, the resulting wine carries an indelible imprint of the geological terroir factors. For example, grapes grown on calcareous bedrock tend to have higher sugar and polyphenol content (therefore higher alcohol and richer flavours) with more intense colour (Constantini, 2010). Likewise, potassium content increases grape acidity and therefore flavour (Costantini, 2010).

Some examples of the bedrock characteristics of classic wine areas are given below.

Granitic Terrains (Classic examples: northern Rhone Valley, Alsace, South Africa)

Granite (molten rock intruded subsurface within older rocks) is 40 to 60% quartz, 30 to 40% feldspar (both high-K and high-Na/Mg types) with various amounts of hornblende, mica and other trace minerals. It is generally hard and coarsely crystalline until weathered: the quartz into sand-sized grains, and the feldspars and mica into clays (Wilson, 1998). By the well-known process of "sieving" the finer grained particles tend to winnow their way downward, leaving the coarser quartz grains at the surface, providing good drainage (Belding, 2010). Granite terrains warm quickly and retain heat, and they tend to be highly acidic which minimizes acid levels in the grapes. Granite generally has poor porosity and permeability except where heavily fractured.

Volcanic Terrains (Classic example: Washington/Oregon)

Volcanic geological terrains (molten rock extruded onto the surface), and the soils derived from them, are extremely variable in chemical composition and texture, with typical high Fe, K, S, Ca and Mg, but variable silica (from basalt with less than 50% to rhyolite with much more) (Szabo, 2016). Soils overlying lava, ash or tephra tend to be thin, mechanically, texturally and chemically immature resulting in relatively infertile rubbly, rocky surfaces on relatively steep slopes with very good drainage, poor organic content and poor water availability (Szabo, 2016). Basalts tend to be darker colours and therefore absorb heat. The semi-starved vines planted in these rather inhospitable settings tend to get well-balanced micronutrient nourishment, but in small quantities at a very low rate, producing less fruit, smaller bunches, with thicker protective skins (where most aroma and flavour compounds are stored) and result in more concentrated flavoured wines with high acid and strong earthy characters (Szabo, 2016).

Metamorphic Terrains (Classic examples: Rhineland, Mosel Valley)

Most metamorphic rocks (rocks which have been transformed by heat and/or pressure) have poor porosity and permeability, except where heavily cleaved or fractured. Slate is dark coloured, metamorphically-altered shale, which retains heat well and warms up quickly in cooler climates, but has poor water retention unless fractured. The Mosel Valley in western Germany with all vineyards located on steeply-southward-facing slopes, is a type locale. Schist is laminated crystalline rock which is very friable and flakey, rich in Mg and K but poor in N or organics, and retains heat well.

Sedimentary Carbonate Terrains (Classic examples: Burgundy, Champagne)

Limestone and dolostone (primarily created by chemical precipitation from ancient seawater) have high Ca and Mg, and may have abundant fossil fragments, and so typically are consistently alkaline which neutralizes acidity in soil and works well with high-acid grapes. Carbonate rocks, often with mudstone, marly and organic-rich interbeds can supply abundant nutrients. However, many carbonate terrains lack particular minerals which are common in other rock types, which may lend unique characteristics to wines based on these rocks. These rocks are commonly pale coloured and reflect heat, retaining cooler substrate temperatures. This aspect might delay ripening (which increases acidity in wine), which may be positive or negative, depending on the climatic location of the vineyard. Carbonate breccias and conglomerates are another possible rock type. Carbonate substrates commonly provide good drainage (either through matrix, or fracture, or karstic permeability) with some water retention. Chalk is a very soft and porous limestone through which roots can easily penetrate, and has good drainage. Flint is a very siliceous accessory rock type in carbonate terrains which may impart a flinty aroma to wine, as in the Loire Valley.

Sedimentary Clastic Terrains (Classic examples: Napa Valley, South Africa)

Areas dominated by clastic rocks (primarily created by erosion of older deposits and deposition in a variety of settings) usually include a wide variety of rock types, grain sizes and compositions, but quartz is usually the dominant mineral. Coarser grained types are commonly porous and permeable, but may have lesser nutrient content, whereas finer grained types may have lesser porosity and permeability, but increased organic and nutrient content. Mudstone/shale is fine-grained, dense, commonly cool in temperature, and high in acidity. These rocks offer good fertility, good organics, and may have good water retention, but poor drainage and might even create a barrier to root penetration, or act as a water table. When exposed at the surface they might break into fragments. Siltstone is relatively fine-grained, modest in fertility and organics, with good water retention, but poorer drainage. Sandstone is coarser, quartz-dominated and is a warm material, with good heat retention and heat reflection which increases ripening resulting in higher alcohol content, Sandstones commonly have good drainage, but lesser water retention. These rocks are also acidic, and have high soil pH which can reduce the acidity level of wine. Greywacke is a rock type which has high feldspar and clay, is dark coloured and retains heat. Conglomerate is very coarse-grained, with pebble to boulder size clasts commonly of quartz or varied rock type compositions, can be very porous and deeply penetrated by roots and is very well drained. Conglomerates may include a matrix of sand, silt and clay size material which lends some fertility, but may decrease porosity and permeability.

Surficial Geology (The Quaternary Anchor)

Over the past 1.8 million years, Earth's history has been characterized by severe global climatic cooling and severe reduction in atmospheric CO_2, and continental glaciers have repeatedly extended and contracted over the landmass of Canada, as the culmination of a 50 million year cooling phase.
The Quaternary Period included 4 major continental-scale glaciations each spanning about 100 000 years (the last being termed the Wisconsinan Glaciation), and separated by shorter, 10 000 to 20 000 year interglacial intervals, including the present Holocene, characterized by slightly higher temperature and atmospheric CO_2 (Prest, 1972). As a result, approximately 97% of Canada has been subject to glacial erosion (Prest, 1972), and to deposition of Quaternary-aged glacial debris and non-glacial deposits which mantle the scoured bedrock surface of most of southern Canada's agricultural land to varying depths. These processes have formed the modern landscapes which we are surrounded by and live on today: thus, our heritage of glacial and glacially-related surficial deposits is fundamental to the very character of Canada and Canadians (Prest, 1972). This material may directly reflect the underlying bedrock, but in

fact, much of it has been transported some measurable distance from sources which may or may not be similar: thus the Quaternary deposits may have compositions and characteristics unlike the local bedrock, or be mixtures of local and regional influences (Wilson, 1998). The upper surface of these deposits has been altered by pedogenic (soil-forming) processes during the succeeding Holocene Interglacial to form the modern soils that help sustain all agriculture.

As the Wisconsinan ice sheets decayed and the ice fronts retreated, the land surface and sub-glacial topographic landforms were uncovered and exposed to boreal conditions. Meltwater features, ponded water, and associated sediments were re-distributed across the new landscape to create a complex set of glacial and post-glacial surficial deposits at any given location (Prest, 1972). For example, the modern Great Lakes and Niagara Escarpment of southern Ontario wine regions owe their existence and configuration to these processes. The same result was occurring in the classical wine areas of France/Germany and New Zealand, all of which were also affected by Quaternary glaciation. However, that geological result is very different from the bedrock and substrate conditions of other wine areas such as Italy, Greece, California or Australia which were never glaciated. In those unglaciated areas, vine roots penetrate and access directly into bedrock.

In a recent study of quality wines of the Côte d'Or in Burgundy, it was determined that the one factor which separated Grands Cru wines from all others was the high proportion of gravelly colluvial hillwash sediment in the sub-soil parent material (Atkinson, 2011). The over-riding importance of glacial outwash/fluvial gravel and sand as a pre-eminent substrate for fine wines (Bordeaux, Napa, New Zealand) and of limestone as a substrate for fine wine (Burgundy, Champagne) is evident.

The influence of Quaternary glaciation in Canada is profound. It affects everything from the origin of topography and water bodies to the compositions and textures of subsoil substrates everywhere. These, in turn, affect regional climates precipitation, groundwater aquifers and flow, and soil development. Surficial deposits provide the substrate for all agriculture, and most human development, in Canada (Prest, 1972). The ideal substrate condition for a vine is a thin layer of topsoil over a substrate that sufficiently supports the root structure, includes sufficient minerals and nutrients that can be accessed by the roots, and can retain moisture but also influences drainage so that the roots do not become overly-saturated (Wikipedia, 2016). Surficial deposits have a direct bearing on water resources because they determine the rate of runoff, amount of near-surface water storage, rate of near-surface aquifer replenishment, geometry of water courses, control of erosion and landscape development (Prest, 1972). So, the Quaternary surficial deposits are one of the prime places where geology and viticulture intersect in Canada.

Some examples of various Quaternary deposit characteristics which might influence wine growing areas in Canada are given below.

Outwash Terrains (Classic examples: Bordeaux, Rhone Valley, Marlborough)

Gravel is unconsolidated coarse-grained clastic material, with pebble to boulder size clasts commonly of quartz or varied rock type compositions. Thick and extensive occurrences of these deposits are commonly present as pro-glacial meltwater outwash in valleys associated with modern or Pleistocene-aged glacial activity, and as large gravel terraces in drowned estuaries which may be of much greater age (Wilson, 1998). Some of these may be classed as older bedrock terrains, whereas many are actually unconsolidated surficial deposits of Quaternary age. They are typically very porous and permeable and are easily deeply-penetrated by roots. They tend to be very well drained and have poor water retention, but may include a matrix of sand, silt and clay size material which lends some fertility.

Marine/Lacustrine Shoreline Terraces (Classic example: Okanagan Valley)

As Pleistocene glaciers began to melt and ice fronts receded, they left significant linear shoreline ridges around marine and meltwater lake coastlines. Many of these are topographic prominences with considerable lateral extent which represent ancient beaches which were well-washed by wave action, and are composed of well sorted and stratified sandy to gravelly facies. They are likely to present reliable porosity and permeability for drainage and groundwater flow.

Moraines and Eskers

Terminal moraines are typically long, linear ridges of poorly sorted, fine to coarse-grained unstratified debris pushed up at the farthest extent of a glacial advance. These topographic ridges may have fair to poor porosity and permeability, but diverse compositions and grain sizes, and in Canada they may preferentially have south-facing slopes. Eskers are meandering, water-deposited, generally steep-sided sediment ridges that form within a subglacial stream channel. Subsequent melting of the glacier exposes the deposit. They are generally composed of stratified, well sorted sand and gravel, with porosity and permeability, and can range up to many kilometres in length and tens of metres in height.

Till

Glacial till is the most common and most variable deposit left by the advancing and retreating Wisconsinan glaciers, and covers vast areas of Canada. It is composed largely of a low-topography plain of unsorted and unstratified accumulation of mixed heterogeneous materials of different size grades and compositions, ground up and deposited directly by glacier ice. Because of these processes, this substrate may have poor drainage, but may possess abundant nutrients and so may have variable success for wine crops.

Soil (The Holocene Veneer)

Soil can be a pivotal factor in "terroir" because the physical and chemical properties of soil can directly affect the health of grapevines and the characteristics of the grapes/wine they yield. Yet, being rather thin and very complex, soil can vary over short distances, which might be reflected in the taste of the resulting product (Brown, 2001).

Although "soil" is colloquially thought of as simply the ground surface, a soil is defined as a body of unconsolidated mineral and organic matter at the surface, derived from the disaggregation of older parent material, which was altered *in situ* in response to variations of mechanical and chemical weathering and biogenic action (Clayton et al., 1977; Retallack, 1981; INQUA, 1990). Soil displays particular "horizons", or layers, extending down from the surface to underlying, relatively unaltered geological material. Soil is really a metastable complex system of mineral and biological components, resulting from the interplay of mechanical and chemical weathering, translocation upward and downward of components, and multiple biological processes, integrated over significant periods of time (Wilson, 1998; Costantini et al., 2010).

Soil-Forming Processes

Physical mechanical weathering cracks the bedrock through the agents of water, ice, heat, gravity and roots to create multiple surfaces which can then be attacked by various forms of chemical weathering, utilizing moisture air and microorganisms (Wilson, 1998). Soil can be thought of as a mixture of mineral particles, organic particles, air, water and the organisms which inhabit this subsurface world. Soil is actually a complex and dynamic metastable system resulting from a succession of physical and biological processes during which rocks and sediments are transformed into a new material (Clayton et al., 1977; Constantini et al., 2010). The main soil-forming processes, which normally act in combination, are:

a) physical weathering;
b) chemical weathering of minerals and clay formation;
c) downward leaching of soluble materials in humid areas;
d) upward concentration of soluble salts, especially carbonates, in arid areas;
e) incorporation of decomposing organic matter;

f) redox reactions (gleying);
g) downward translocation of solid particles (illuviation);
h) downward movement of organics and iron (podzolization); and
i) bioturbation, argilliturbation, cryoturbation (Bronger and Catt, 1989; INQUA, 1990).

Soil formation is a normal and continuous process in terrestrial settings during residence time in the weathering zone near the surface. Topography, water, climate, organisms and time are the environmental factors influencing the creation of soil.

Texture and Horizonation

Soil "texture" refers to the proportions of different sizes of particles. Somewhat coarser textures help promote drainage and combat soil compaction, but the presence of some finer material is desirable for water retention and nutrient content: hence, a mixture of pebbles, sand, silt and clay is best (Wilson, 1998). Clay-rich soil has good water retention, but poor drainage, often very high acidity and tends to be very cool. Siliceous soil reflects and retains heat well, warming up quickly, and is alkaline, thereby reducing the acidity of the resulting wine. Gravelly soil has good drainage but poor water retention and poor fertility, encouraging deep rooting, wines are generally less acidic than calcareous soils. Loam is the best mixture but actually is usually too fertile and therefore less conducive to high quality wines which need to limit yields to concentrate flavours. In addition, soil "structure" refers to the way those particles are arranged in space as layers, and can influence water movement, water storage, and root penetration (Wilson, 1998). From top to bottom, an ideal soil displays the following layers:

1) **O Horizon**, the thin surface organic-rich layer;
2) **A Horizon**, the near-surface relatively coarse-grained mineral layer with some organics, but subject to the loss of some clays/organics/minerals through the process of downward leaching/eluviation;
3) **B Horizon**, the main relatively finer-grained mineral layer enriched in some clays/organics/minerals by the process of depositional illuviation and with some soil structure such as columnar peds and clay cutans; and,
4) **C Horizon**, the moderately-altered mineral layer immediately overlying the parent substrate (Clayton et al., 1977; Agriculture Canada Expert Committee on Soil Survey, 1987).

These layers overlie the parent substrate (surficial Quaternary deposits in most of Canada) and the bedrock. The clay fraction (less than 0.0039 mm. grain size) is the most important of the mineral components because it is the most mobile, is the most chemically-active, is the storehouse of moisture and plant nutrients, controls porosity and permeability, and generally determines the character of the soil (Clayton et al., 1977). Montmorillonite and illite are alumino-silicate clays which can absorb and store moisture thereby promoting plant health, whereas kaolinite and chlorite clays are much less absorptive.

Soil colour is another primary soil characteristic, ranging from bright white calcareous soils to black soils generated from underlying slate. Soil colour affects the quality and quantity of light reflected back upward into the grape bunches and leaf canopy, thus influencing fruit (Costantini et al., 2010). Pale-coloured soils reflect heat during the day and the growing season, whereas dark-coloured soils warm quickly and store heat, which can be re-radiated at night and during the autumn ripening season (Costantini et al., 2010). Soil texture and its surface characteristics can also influence light reflection and heat retention, and so gain in importance in cooler climate locations (Sommers, 2008).

Soil texture is extremely important because it determines the ability of the soil to hold/drain moisture and access nutrients, by controlling infiltration rate into the soil, percolation rate through the soil, and porosity amount and distribution to provide storage space and absorption time (Sommers, 2008; Costantini et al., 2010). Soil structure also controls the ability of plant roots to penetrate and access/absorb the moisture and nutrients (Wilson, 1998). Essentially, porosity and permeability are crucial aspects to understand. Capillary water with dissolved nutrients is held in the pore spaces, available for plant use. It is necessary to have enough clay to slow the groundwater movement and retain it and absorb nutrients, but also enough sand/gravel to provide storage space and allow capillary movement. About 25% + of sandy or coarse pebbly material allows good root penetration, good groundwater flow and avoids too much compaction (Wilson, 1998). Interestingly, coarser grained, sandy soils are also more resistant to the *Phylloxera* root louse (Wilson, 1998). However, too much sand/gravel and drainage will suck away all moisture (and nutrients) before the plant can utilize it, but conversely, too much clay will limit porosity/permeability and the water will be less accessible (Sommers, 2008).

The best soil for grapevines is a natural mixture called "loam": approximately equal parts of sand (40%) and silt (40%), plus some clay (20%) and some organics. The ideal medium is a thin topsoil, well drained, easily penetrated and rather less fertile than that for most crops, forcing the vines to root deeply and work hard. In fact, some experts summarize the situation with the phrase "bad soil = good grapes". This limits the abundance of foliage and fruit production, thereby maximizing concentrated flavours. Studies have indicated that, rather than focussing on soil type analysis, the substrate texture and structure, which are the result of geological processes and are the primary controls on grape quality and character (by controlling drainage and accessibility to water) are much more important than identifying soil type (Swinchatt, 2003). Immature soils in semi-arid climates produce good wines in many parts of the world: perhaps it is the level of developmental maturity of a soil which will have the most bearing on a produced wine in that region.

Mineral Nutrients

The mechanical and chemical weathering processes make the useful compounds more available to plant roots. As with many plants, Mg is important for chlorophyll, Fe for photosynthesis, and K for strong roots. Nutrient availability in soils for most important trace elements needed by vines is optimized in the pH range of 6.5 to 7.5 (Ker, 2013). Soils derived from granitic or sandstone bedrock substrates tend to be coarser grained and slightly acidic, due to the absence of carbonate ions in the parent material (Wilson, 1998). Conversely, soils derived from limestones tend to be slightly alkaline, which actually favours chemical availability of mineral nutrients and biological activity (Wilson, 1998). Soil pH may also be an important factor. For example, in the ornamental species Hydrangea, the flowers are blue when grown in acid soil (lots of Al), pink in alkaline soils (lack of Al), so the lack of a key element causes a significant change. Perhaps a similar relationship obtains in grape vines, where the flavour profile is influenced by the lack of some key element(s) in certain terroirs. The organic components are primarily products of decomposition of organic matter which provide nutrients and help retain moisture (Sommers, 2008). For Merlot grapes, a clay-rich soil is best. The famous Chardonnay grapes of the Chablis area grow in limestone/clay soils overlying Kimmeridgian-aged limestone bedrock full of fossil oysters. Not surprisingly, Chablis wines pair perfectly with oysters (Firth, 2008).

Soils and Plants

Most soils in Canada have developed only over the past 10 000 to 12 000 years: the Holocene Interglacial. Under certain conditions, a well-developed soil profile can develop in only a few centuries, but many require several thousand years to become well-established. Therefore, soils in Canada tend to be relatively thin, perhaps mostly in the range of 20 to 100 cm, but ranging locally up to several metres. Soil is very specific to a place – and thus forms one of the geological backbones of the terroir concept – but because grape vine roots extend deeply and the bulk of the root mass resides below the soil profile in Canada, the actual soil component may be less important than the geology of the Quaternary substrate or bedrock it is derived from. In addition, most grape-growing areas of Canada have been subjected to agricultural development for decades or centuries, rendering their soils less pristine than their original state. Soil formation proceeds through discrete stages bounded by definite threshold states (Robinson et al., 2000). Initially, destratification destroys the original layering of the parent material through direct action of roots and infauna, mixing by shrinkage/swelling of expandable clays, and freeze/thaw expansion and contraction (Allen and Wright, 1989). Over time, the removal of matter from one horizon ("eluviation") and concentration of that matter into a lower horizon ("illuviation") begins to dominate pedogenesis (Allen and Wright, 1989). This downward translocation of clays to form a distinctive B Horizon may take thousands of years to complete. The variation in soil composition and characteristics with depth is advantageous for deep-rooting plants such as grape vines because each soil horizon offers something different for the plant (Sommers, 2008).

Grapes can root to depths exceeding 2 m, commonly up to 6 m, and are particularly adept at tapping the inorganic constituents which dominate lower soil horizons, so the thin upper organic-rich horizons of a soil profile may not be as important for this crop as for many others. However, those organic-rich upper layers provide some nutrients and hold whatever precipitation moisture is available (Sommers, 2008). Vines will grow in a wide variety of substrates, varying from clayey to sandy, acidic to neutral, slightly saline, or high pH. The inorganic constituents of a soil may relate directly to the underlying *in situ* bedrock, or they may result from weathering of material transported (by streams, glaciers, etc.) to that site.

The most important Soil Orders present in producing wine regions of Canada are:

1) Brunisolic (brownish, cool to mesic temperature, relatively humid climate, well- to poorly-drained, weakly developed horizonation, underlying forests), common in Prince Edward County and Vancouver Island;
2) Chernozemic (well- to poorly drained, cool temperature, subhumid to semiarid, well developed horizonation, frozen during part of the winter and dry during part of the summer, well developed A Horizon with abundant organics, underlying grasslands), common in the Okanagan Valley;
3) Luvisolic (pale coloured, well- to poorly drained, subhumid to humid climate, mild to cold temperature, well developed B Horizon with abundant silicates and clays, underlying forests), common in Annapolis Valley, St. Lawrence Lowlands, and Niagara Peninsula (Clayton et al., 1977; Agriculture Canada expert Committee on Soil Survey, 1987).

However, within these larger families, there are numerous sub-categories. For example, vineyard soils from Niagara are classified as "alfisols" with a deeper layer of silicate clay accumulation, whereas soils from the more arid Okanagan are classified as "inceptisols" with weakly-developed subsurface horizons (Taylor et al., 2003).

Groundwater (The Plumbing)

Groundwater is defined as all water which infiltrates into the subsurface, and resides in a zone of continuous saturation below the water table trapped and stored in pore spaces and fractures within unconsolidated surficial and consolidated bedrock aquifers (Brown, 1972; Rivera, 2014). Groundwater represents about 30% of the world's available freshwater (glaciers include 69%, but it is not easily accessible), whereas rivers and lakes account for less than 1% (Rivera, 2014). An aquifer is a natural body of permeable material which can store and transmit significant quantities of water, and may be either a) unconsolidated and permeable (e.g. gravel), or b) consolidated and permeable (e.g. sandstone), or c) consolidated and impermeable but subsequently fractured (e.g. granite) (Rivera, 2014). Precipitation and surface water enters aquifers, through the universal hydrologic cycle at points of recharge. Water is stored in aquifer porosity, either in intergranular pore spaces between material grains, or within fracture spaces (Brown, 1972). Groundwater flow through aquifers is controlled by permeability, the size and interconnectedness of the intergranular pores, which depends on the sedimentological characteristics of the soil or rock medium (Rivera, 2014). These characteristics are heterogeneous in three dimensions and may vary laterally over short distances. Subsurface groundwater flow is controlled by topography, and moves (very slowly) by means of aquifer permeability, either through interconnected intergranular pores, or along fractures (Brown, 1972; Rivera, 2014). In some areas, multiple aquifers are present and combined into Groundwater Flow Systems which are spatially- and hydraulically-interconnected stratigraphic units of different origins, but with the ability to store and transmit water resources (Rivera, 2014). These occur at different scales in space and time, and may be a) regional (greater than 1,000 km^2), b) local (100's km^2), or c) site-specific (less than 100 km^2) (Rivera, 2014).

The geology of aquifers and groundwater has been studied in Canada by the Geological Survey of Canada and other agencies since the late 19th C. Although it is much less obvious to the layman, subsurface water resources are approximately 30 times those of surface rivers and lakes (Brown, 1972). Groundwater always "flows" in dynamic ways by gravity, from a location of high hydraulic head at higher elevation toward low hydraulic head at lower elevation (Brown, 1972; Rivera, 2014). Also important are aquitards (poorly-permeable layers which restrict groundwater flow) and aquicludes (non-porous, non-permeable layers that completely forestall groundwater movement) (Rivera, 2014). Although we in Canada develop and use groundwater resources extensively, we commonly do so with little regard for geological understanding of, or the dynamics of recharge, vulnerability and sustainability of important aquifers (Rivera, 2014).

As with any agricultural crop, healthy vines rely on root access to adequate water supply, in the form of rainfall, groundwater or irrigation, at the right times of the growing year. A vine's roots are the vital link between plant and soil, and if not coddled with too much water and fertilizer, those roots will thrust deeply, making the vine more resistant to drought and disease (MacLean, 2006). Therefore, depending on local conditions, the water table accessed by vine roots should be deep, forcing roots to penetrate deeply. The irrigation additions may come from surface water sources or from subsurface groundwater. The subsurface hydrogeological characteristics are a key terroir component.

The presence, depth and distribution of both aquifer layers (allowing vertical or lateral groundwater flow) and aquitard layers (barriers to vertical or lateral groundwater flow) in the near-subsurface may have important effects on the health of vines, especially in semi-arid areas where irrigation is used. In some semi-arid regions, water table levels have dropped considerably due to irrigation since vine growing became an important activity. However, vineyard grapes are actually less-water-intensive than many other crops, and in some regions the wine industry has been at the forefront of developing more "sustainable" agriculture. Conversely, in some classical areas, such as France, irrigation is not allowed.

In addition, another factor to be considered in studies of the groundwater system is the potential leaching of pesticides and fertilizers into the subsurface aquifers.

Topography/Slope/Exposure/Drainage (The Lay of the Land)

Geology profoundly influences the shape of the landscape, the altitude, slope and exposure to sun and winds. Recrystallized or extensively-cemented bedrock, or fully consolidated surficial deposits, can create steeper slopes, whereas poorly-consolidated substrates may encourage erosion and gentler slopes. The shape of the land and its relationship to the sun at the latitude of the vineyard are key factors in determining the hours of sunlight, degrees of warmth, timing of maximum heating, and length of growing season. The angle, aspect and elevation are all important factors, and grape vines enjoy sloping topography which maximizes drainage and sun exposure. For example, Burgundy's Côte d'Or ("slope of gold") faces east, absorbing early morning warmth by day (to recover after nighttime coolness) and releasing heat over night for slow maturation, while gaining soft morning sunlight which ripens the grapes more gradually than the hotter afternoon sun (Wilson, 1998; MacLean, 2006).

Topography and slope control drainage, soil erosion and deposition, and in typically sloping vineyards, erosion commonly exceeds deposition of new soil formation. As a result, vineyards commonly have rocky surface soils impoverished of nutrients. This is not necessarily a negative circumstance because vines produce better fruit in these poorer soils, having to work harder and be more resourceful (MacLean, 2006), and the rocky surfaces better absorb and retain and re-radiate heat in cooler climate settings (Sommers, 2008). In Burgundy, soils are continuously eroded at the top of the slope, leaving less fertile substrate there, whereas the eroded material collects at the base of the slope creating soils that are very deep and fertile, but producing thinner, flabby wines (MacLean, 2006). The best wines are grown within the mid-slope belt where soils are poorly to moderately fertile and drainage is good, vines struggle for enough water and nutrients, sending their roots very deeply to tap into a far greater spectrum of nutrients and minerals from many soil and bedrock layers (Wilson, 1998; MacLean, 2006). Topography also generally controls the profile of the underlying water table, which typically tends to become a subdued replica of the overlying ground surface (Rivera, 2014).

Good drainage relies on water being able to move into, out of, and through the soil at a rate fast enough to avoid water-logging, but not so fast as to remove water before the roots can use it (Brown, 2001). Elevation can profoundly affect the temperature, the precipitation and the length of the growing season. The lapse rate for the change in temperature is approximately 0.55° per 100 m of elevation, suggesting that vineyards in cool climate settings should be as close to sea level as possible (Sommers, 2008). Additionally, because cold air drains downslope and tends to settle in hollows, low-lying areas at the bottoms of river valleys or at the base of slopes are the most frost-prone (Wilson, 1998).

In Burgundy, the home of the terroir concept, along the Côte d'Or, the slope faces east to southeast, and rises to about 130 m elevation, but all the "grand crus" sit side-by-side across the mid-slope (Wilson, 1998; MacLean, 2006; Cooke, 2012). Anyone who has visited the Rhine and especially the Mosel wine regions of Germany will have seen just how important the lie of the land can be, with the almost-impossible steepness (up to 65° slope at Bremm) of the south-facing slopes, catching the maximum sunlight and creating a warmer terroir than would be suggested from the raw climate data. Hills can also protect the vineyards from chilling winds, and slopes allow cold air to roll down through vineyards to settle into frost hollows at the base (Brown, 2001). In addition, on flat land, roots remain shallow and get "lazy", creating a crop with abundant fruit but flabby flavours. On steep slopes, the roots work harder, producing less fruit but much more intense flavours. Moreover, grape vines dislike "wet feet" and so good drainage is essential (Haynes and Grant, 2004).

Slope can influence the angle of incoming sunlight radiation, soil moisture, wind exposure and cold-air drainage, and therefore elevation can have a profound effect on temperature, precipitation and length of growing season. The average temperature lapse rate is about 0.6°C per 100 m above sea level, which is of vital importance in marginal regions where climate is cooler (plant closer to seal level) or hotter (plant at higher elevations) than ideal (Sommers, 2008).

Bodies of Water (The Thermostat)

Proximity to a body of water can regulate temperature and minimize temperature swings, and moderate frosts (Sommers, 2008). Many of the great wine regions of the world are adjacent to significant bodies of water (both fresh- and saltwater) which act as heat retention sinks and heat re-radiators (e.g. Bordeaux, Rhine/Mosel, and Napa). This is also true for Canadian wine regions such as the Gulf Islands, Okanagan, Niagara, and the Bay of Fundy. But the physical presence, size, depth, input and drainage of those bodies of water represent the long-term operation of fundamental geological processes and evolutions, such as tectonics, erosion and deposition. Not only can contiguous water store heat and release it during cooler periods, but it can also reflect significant amounts of heat and sunlight back onto the adjacent vineyards. In fact, most of the current and potential wine growing regions of Canada reside near significant bodies of water. The Great Lakes/St. Lawrence system, the Interior Lakes of B.C., the Bay of Fundy/Northumberland Strait, and the Salish Sea/Strait of Georgia system are all artefacts of geological processes which now profoundly influence local climates and vineyards. Of course, the same body of water that provides temperature benefits may also produce excess moisture problems (Sommers, 2008).

Climatological Factors

Latitude (Location, Location, Location)

Wine production occurs over a relatively narrow geographical and climatic range, and individual wine grape varieties have even narrower ranges (Jones and Webb, 2010; Jones, 2017). It is not an overstatement to say that climate components of terroir are **critical** and form "the baseline factors in the continuum of terroir influences, controlling what can be grown, where and how" (Jones, 2017). Primarily, and traditionally, the recognized great wine regions of the world are located within the belt 30° to 45° north and south of the equator, with Bordeaux at 45°N (Wilson, 1998; Sommers, 2008), although Burgundy, Champagne and the Rhineland were always outside that typical zone. However, presently, as climate gently warms back toward the temperatures enjoyed during the Medieval Warm Optimum, the geography of world wine regions will change, and cool-climate areas in England and Canada are now extending to 51°N (Jones, 2017). Lamb (1977; 1984) quotes abundant historical evidence that vineyards were maintained to 53°N in England during the MW phase. One thousand years ago, at the height of the Medieval Warm, southern England (aided by the adjacent warm Gulf Stream) was the "vineyard of Europe", and may again become so over the next century. In Canada, the wine areas of Southern Ontario reside at 42° to 44°N (about the latitude of Rioja, Languedoc, Provence, Chianti in Europe), the Okanagan spans 49° to 50°15'N (about the latitude of Champagne or Pfalz in Europe), and the Kamloops/Thompson area (*see* Figure 5), where pioneering wineries are now producing, lies at 50° 30'N (Bisby, 2014). Jones (2017) rightly made the point that comparisons based solely on latitude are dubious. However, the further north of 45°N latitude, the lower the angle of the sun in the ripening season, and so the more critical is the orientation and location of the vineyard, requiring a more southerly or southeasterly exposure to warm the vines after a cool night (Wilson, 1998). At 50°N, the maximum angle of summer sun is only 65°, and is only 49° at the autumnal equinox, so these effects are important (Wilson, 1998). Differences between wine regions within the same latitude zone clearly depend on a full range of additional terroir factors (Haynes and Grant, 2004). Another, generally under-appreciated, latitude factor is that locations at the more northerly margins of the range actually receive more hours per day of sunshine during the summer growing season than those (warmer) areas to the south (Meinert and Busacca, 2000). As long as late-spring and early-autumn frosts can be avoided, this effect could be very important.

Macro- and Meso-Climate (The Trend)

Throughout human civilization, climate has played a crucial role in the development of culture and agriculture, largely controlling production and quality and economic sustainability of most crops (Jones and Webb, 2010). The well-being of every plant, including grape vines, is intimately connected to climate. Climate is the average of all the weather experienced in a region over a span of decades to centuries to millennia – but doesn't highlight the individual critical weather events that can determine whether crops are viable or not (Gribben, 1991; Brown, 2001). Both short-term climate variability and longer-term climate trends will affect the cultivation of vineyards (Jones and Webb, 2010). Long-term climate trends have always varied over wide ranges through 3 billion years of geologic time (Lamb, 1977), and every geologist understands (even if those with little relevant scientific training do not) that global climate continuously varies, in somewhat-predictable patterns, over a number of superimposed scales of cycles, ranging from decadal to multi-millenial. These entirely-natural patterns, which have been in effect over vast spans of time, have seriously impacted virtually all aspects of our natural world, including bedrock geology, Quaternary geology, soil development and all plant and animal life.
In addition, climate trends, both decadal and millenial, have profoundly influenced virtually all aspects of human activity and culture, especially including agriculture. From the point of view of grape growing and terroir, the most important macro-climatic trends of recent millennia are the well-known identifications of the Greek Cool Phase, the Roman Warm Epoch, the Dark Ages Cool Phase, the

Medieval Warm Epoch, the Little Ice Age, and the Modern Warm Epoch, for all of which there is abundant scientific and historical evidence (Lamb, 1965; 1977; 1984; Easterbrook, 2011).

The monumental compilation/documentation of the scientific and cultural/historical bases for continuously changing, natural, predictable climatic patterns by Hubert Lamb (1977; 1984), the father of modern climatological history, places viticultural history in context. Lamb (1977; 1984) quotes copious evidence to demonstrate that southern England and northern Germany were prolific producers of wine in the 950 – 1300 AD period (MWE) and that temperatures in southern England were approximately 1 – 1.5°C warmer at that time than in the 20th C. Further, temperatures and wine harvests decreased as climate slipped down into the Little Ice Age, and at the depths of the LIA were as much as 2°C colder than the 20th C, with grape harvest dates about 1 month earlier (Lamb, 1977; 1984; Wilson, 1998; Pfister et al., 1999; Fagan, 2000). Indeed, Lamb (1984) suggested that the extent of snow and ice throughout the world attained a maximum in this period as great as at any previous period in the Holocene. Not surprisingly, the modern natural warming trend, already 350 years and counting in duration from the depths of the LIA (Easterbrook, 2011), has also affected some classical wine areas: harvest time shifted two weeks earlier in Bordeaux, and a full month earlier in the Rhône valley, over the 20th C (Last, 2010; Trichur, 2011; Nicholas, 2015). And, interestingly, southern England is again becoming a well-developed wine producer (Nicholas, 2015), duplicating its reputation established 1,000 years ago during the last major warm period. In fact, the slight, but definite, recent temperature increase in southern England has moved cultivation of Burgundy grape varietals "from the wrong side of marginal to the right side of marginal", allowing the emergence of a new English Champagne-style sparkling wine industry (Sisimondo, 2016b). The centuries-long natural warming trend which we are currently experiencing is slowly shifting viticultural zones farther north in the northern hemisphere (where there is abundant new land available for new crops), and farther south in the southern hemisphere (where some countries may run out of viticultural land in future, e.g. South Africa) (Trichur, 2011). We can expect this natural warming trend to continue for another 100 to 150 years before the succeeding natural cooling trend begins to take hold.

The basic formula for wine making is heat = ripeness = sugar = alcohol, but as global climate warms, alcohol contents are rising measurably (Bordeaux wines have increased from 12% to 14% on average over the past century), which consumers generally do not like because it overpowers the more subtle flavour compounds, and accompanying acidity levels have fallen (Last, 2010; Nicholas, 2015; Jones, 2017). Harvesting sooner is not a solution because grapes appear to require a specific length of "hang-time" (about 4 months) for all parts of the grape to become physiologically ripe together, and attain balanced flavours (Last, 2010; Nicholas, 2015).

To produce grapes for quality winemaking we need a long but not blazingly hot growing season, a cool-to-cold winter that is short and not too severe, freedom from late-spring frosts which destroy flower buds, an adequate amount of spring and early-summer rainfall, sufficient summer sunshine and warmth, warm and dry conditions in late summer and fall, and no early-fall frosts (Lamb, 1977; Sommers, 2008; Last, 2010). Grapes have evolved to require annual thermal excursions with a warm summer growing season, dry summer/fall conditions and a 2 to 3 month cool winter dormancy period (Cita et al., 2004). The long, slow ripening during weeks of warm days and cool nights gives the ideal combination of mature sugars/skins/tannins/acids, producing a wine with balance and structure (MacLean, 2006).

The classic regional climate for grape growing is the sub-tropical zone, especially regions with a Mediterranean climate (cool wet winter/hot dry summer) where the deep root system can tap water stored deep underground while the warm sun promotes growth and ripening. In addition, Marine West Coast climates which are somewhat cooler and wetter, located next to and poleward of Mediterranean climates are positioned on the west coasts of continents in low to mid latitudes where westerly winds off the oceans moderate the temperatures (Sommers, 2008).

It is important to remember that it is the environment at root level which has the most long-term effect on vine health and so the best terroirs are ones that effectively buffer the unpredictable excesses of day-to-day weather and allow the roots to exist in a "regime that more closely resembles the smooth curves and plotted trends of climatic means" (Atkinson, 2011).

As grapes ripen, sugar levels rise and acidity drops with the peak acid: sugar ratio occurring about 4 months after flowering, normally coinciding with the peak flavour profile, and signalling the ideal time for harvest (Wilson, 1998; Nicholas, 2015). However, as global climate continues to warm from the depths of the Little Ice Age toward the impending peak of warmth, the ideal ratio for picking is already occurring earlier in the season. Inevitably, some wine areas will have to begin shifting their mix of grape varietals from cooler climate (e.g. Pinot Noir) to warmer climate (e.g. Cabernet Sauvignon), as is already happening in California (Kirk, 2015; Nicholas, 2015).

Rainfall/Humidity/Irrigation (The Lifeblood and Manna from Heaven)

Moisture available to a plant is also a key aspect of climatic influence (e.g. humid Burgundy vs. semi-arid Spain). Not only the amount of rain (total precipitation), but when it falls (timing), are crucial factors: about 700 mm. of rain, falling mostly in the spring, is very beneficial, but essentially dry autumns are also important (Wilson, 1998; Shaw, 2012; Jones, 2017). Baciocco and Davis (2014) found that the primary factor which distinguishes quality differences is the amount of precipitation during the spring flower bloom period. While bad for other types of agriculture, mild drought at certain times of the year is good for grapes, and typical of many well-known wine regions (Jones, 2017). *"Grapes are like people. A little bit of suffering builds character."* (N. MacLean, 2013). Only moderate vine vigour is desirable, either through moderate water deficit stress or moderate nitrogen supply (Leeuwen and Seguin, 2006). Water stress impedes vine respiration, but a slight deficit between flowering and veraison will benefit the fruit development (Atkinson, 2011). Too much rain in the spring can lead to rot and disease, and too much in the autumn means there is less sunshine at the crucial fruit-ripening period: an overall average of about 680 mm., or a semi-arid climate, is beneficial (Wilson, 1998). Rainwater is naturally slightly acidic, obtaining a measure of carbonic acid while falling, through interaction with CO_2 in the air.

Vine roots are an important storehouse for starch, with reserves being carried over from one season to the next, so periodic drying of coarser-grained soils which encourages dense and deep root colonisation, will result in more vigourous root systems, a better root:shoot ratio and stronger vines (Atkinson, 2011). Humid or waterlogged soils and water-retentive clay-rich soils can have the opposite effect. Jones (2017) described the concept of "soil-water balance" as an integration of many climate parameters which could be used to estimate the overall water requirements of a plant. This analysis would also have to be reconciled with the geological aspects of the local root environment.

With extensive irrigation, desert areas can produce good grapes, and with careful management of frosts and summer/fall moisture, marginal continental climates may also prove successful (Sommers, 2008). Irrigation has become nearly standard in many New World wine regions, although not in the Niagara region of Ontario. As a result, in some more humid locations, purposeful withholding of irrigation water may reduce fruit yields, but increase fruit quality: a technique which may enhance overall wine quality. Conversely, irrigation is not allowed in France, hence, every vine must be fully adapted to the unique conditions of its unique local environment. With these strictures, it is not surprising that the "terroir" concept originated, and is paramount, in France.

Sunshine (The Energy)

As Galileo said, "Wine is sunshine, held together by water". The amount of solar radiation received by the vines is critical to maintaining proper photosynthesis, especially during bloom and berry ripening (Jones, 2017). In order to convert light to chemical energy, only certain wavelengths excite the molecular components of chlorophyll: chlorophyll a absorbs violet and red ends of the spectrum, while chlorophyll b absorbs blue light (Wilson, 1998). A rule of thumb has been that grapes require 1500 hours of sunshine during the growing season. A bright sunny day has light levels 2 to 3 x the saturation level required for photosynthesis (Sommers, 2008).

Through the catalytic medium of photosynthesis, the energy of sunlight is harnessed to break the chemical bonds of CO_2 and H_2O (with its transported minerals) to re-assemble as carbohydrates and other compounds which create the vegetable and fruit matter of the resulting plant (Wilson, 1998).
Waste oxygen and water vapour are released back into the atmosphere by all plants through transpiration, a 3 billion-year-old process which has created a warm and oxygenated greenhouse atmosphere in which animals like we humans can thrive and enjoy the fruits of the vines' labours.

The further north of 45° latitude, the lower the angle of sun and the more critical factors such as orientation of the vineyard and slope and microclimate become. In most of Canada, a southward, southeastward, or southwestward exposure will be beneficial, especially for early spring budding and late autumn ripening. Ironically, the Canadian wine growing region least able to provide this orientation is that of the well-known Niagara area, the area with the longest history of wine production. For quality grape ripening/maturation, direct sunshine is best. However, in hotter climates, leaves may be allowed to shade the western sides of the vines from hot afternoon sun, extending the ripening period. Conversely, lack of sunshine can delay vine development to the point where some late-ripening varieties (e.g. cabernet sauvignon) might not attain full ripeness and flavour profiles. Likewise, diseases such as downy mildew may proliferate in such conditions. On the other hand, wet, overcast conditions might benefit early-ripening varieties (e.g. the famous Burgundy grapes like chardonnay and pinot noir) by slowing hang time to allow more complete phenolic ripeness and flavour complexity (Crosariol, 2017).

Temperature (The HVAC System)

Grapes must be grown within specific temperature and precipitation ranges in order to optimize their ripening and flavour profiles (Trichur, 2011; Jones, 2017). Excessively warm temperatures can hurt the quality of white grape types and the cooler climate reds and the prospects for Icewine production so important to Canada, and also promote the proliferation of pests and the possibility of excessive drought (Trichur, 2011). On the other hand, longer growing seasons and strategic expansion into new areas are positive outcomes of the currently warming climate (Trichur, 2011). Cool-climate wine regions, such as those in Canada, on the margins of current commercial viticulture, are likely to benefit from the gradual warming trend toward a warmer and more consistent overall climate (Shaw, 2017).

Temperature partly controls which grape variety can be grown optimally in a given location (Jones, 2017). It also controls when vines break their winter dormancy in the spring, when growth and fruit ripening occur, the amount of acid present and the amount of sugar present in the grape (Nicholas, 2015). Winter dormancy does not break until the mean daily temperature reaches 10°C, at which time photosynthesis can begin (Wilson, 1998). Photosynthetic processes peak at about 25°C, but drop off quickly at temperatures above 30°C (Wilson, 1998). Jones (2017) states that quality wine production requires the ideal temperature range of 13° to 21°C for virtually all commonly-vintaged grape varieties, and that the average growing season for quality wines is in the range of 170 to 190 days. The average temperature, the mean maximum temperature during the growing season, the mean temperature during the ripening phase and the diurnal temperature range are all important factors in quality grape production (Shaw, 2012; Baciocco and Davis, 2014).

A common practice is to use Heat Summation of Growing Degree Days (GDD) which describe the number of hours the local temperature is above 10°C during the growing season, and reflect the total heating over the entire growing season. Each degree in excess of 10°C (the approximate temperature where grape vine photosynthesis begins in earnest) for each day of the growing season is added to a running total (Wilson, 1998; Sommers, 2008). The formula is Daily GDD = Mean Daily Temp. - 10°C : totalling these Daily GDD's for the entire growing season (April to October in the northern hemisphere) should fall in the 1100 to 2200 range for the most successful vineyards (if less than 1000 or more than 2500, then the chances of success are slim). Totals falling outside the ideal range (both cooler and hotter) may still yield quality wines under certain circumstances (Sommers, 2008). The concept of Heat

Summation has been summarized into a five-part system referred to as the Winkler Regions (after Amerine and Winkler, 1944):

I. 1000 – 1400 GDD (Champagne, Burgundy, Rhine Valley, middle to northern Okanagan) (suited to Riesling, Chardonnay, Pinot Noir, Gamay);
II. 1400 – 1600 (Bordeaux, Alsace, Oregon, New Zealand, southern Okanagan, Niagara) (suited to Chardonnay, Sauvignon Blanc, Pinot Noir, Merlot, Cabernet Franc);
III. 1600 – 1950 (Rhône Valley, Piemonte, Napa Valley, Australia) (suited to Sauvignon Blanc, Semillon, Cabernet Sauvignon, Syrah, Zinfandel, Grenache);
IV. 1950 – 2200 (Tuscany, Spain, Greece) (suited to Zinfandel, Tempranillo, Sangiovese); and
V. 2200+ (Sicily, Algeria) (Meinert and Busacca, 2000; Easton, 2010).

However, the concept of GDD can be somewhat misleading because of the importance of sunshine to the photosynthetic processes and the fruit ripening processes, whereby a warm sunny day is much more useful to the plant than a warm cloudy day (Wilson, 1998). In fact, warm sunny days during the September fruit maturation period (when sugars increase and acidity decreases) are the most important for creating positive effects on taste (Wilson, 1998). Diurnal temperature variation can also be important because cooler nights help grapes retain some natural acidity, producing crisper and more complex wines (Meinert and Busacca, 2000).

Temperature is central to all aspects of viticulture, controlling the vine's rate of physiological development from flowering to fruit setting to ripeness (Gladstones, 2011). The growth of temperate zone plants, including grape vines, is essentially nil below 10°C (delaying budbreak and fruit setting until the worst danger of spring frosts has ended) and above 40°C (reducing evaporative losses and degradation of fruit), and peaks around 22° to 25°C, and a relatively narrow diurnal range is optimal (Gladstones, 2011). Photosynthesis optimizes at about 25°C, but is inhibited above 30°C because higher temperatures cause instability of important enzymes and closure of stomata (Wilson, 1998). Many vines will die at temperatures above 40°C. However, higher temperatures lead to higher evaporation and transpiration rates, which in turn encourage increased nutrient uptake from the soil substrate (Ker, 2013). On the other hand, warm temperatures above 22°C during fruit ripening encourage vapourization and loss of flavour compounds, many of which have a lower molecular weight than water: higher relative atmospheric humidity at this time tends to limit this vapourization and loss of flavour (Atkinson, 2011). According to Jones (2017), the last 30 days before harvest are crucial to full development of flavour and aroma compounds. At the other end of the scale, temperatures of -10°C can kill vines, and at -25°C virtually all vines will expire. Late spring frosts during bud break, or early autumn frosts during fruit ripening will cause severe damage to the resultant crop. Hail storms can be devastating. Of course, excessive winds can cause rapid temperature drop and have a significant drying effect as well (Wilson, 1998). Just as important is the presence of an actual winter period of dormancy, so the plant can rest and re-generate (Lamb, 1977; Sommers, 2008).

Flowering and setting of fruit buds requires avoidance of late-spring frosts (Crosariol, 2017b). Fruit ripening depends primarily on daytime warmth, sun exposure and avoidance of too-intense summer heat (which over-accelerates fruit ripening) and of early autumn frosts (Crosariol, 2017b). Sun-exposed grape clusters attain temperatures many degrees higher than the surrounding air because the dark berries absorb light and, unlike leaves, have few stomata for cooling (Gladstones, 2011). Photosynthesis can only occur between 10°C and 37°C, and optimizes at about 25° to 27°C (Sommers, 2008). Grape variety also is important with respect to temperature: Jones et al. (2004) presented a chart of maturity-ripening temperatures for various grape varieties, showing that a Pinot Gris grape can ripen with average growing season temperature as low as 13° to 15°C, whereas a Zinfandel requires 19° to 24°C.

The Heliothermic Index of Branas (1946) multiplies 1) the summation of mean temperatures exceeding a 10°C base times 2) the day-lengths through the growing season, and has long been the defining standard for determining the northern limit of viticulture in Europe. In Canada, plant hardiness zones have shifted approximately 1 Hardiness Zone warmer over the past 50 years (Canadian Geographic, 2016), as expected from the general warming trend of the past 350 years since the low point of the Little Ice Age.

In cool-climate settings, such as most of Canada or the Burgundy area of France, characterized by cool-to-cold winters and warm-to-hot summers, grapes preserve more prominent acidity and less tannin, which enhances a crisp, fruity, minerally liveliness and complexity (provided the vintner does not overwhelm this by lengthy aging in toasted oak barrels) which is pleasing to most palates and pairs well with a variety of foods (Crosariol, July 8, 2016; Firth, 2016; Sisimondo, 2016b). Examples of this are the Chablis of northern Burgundy, the Sauvignon Blanc of New Zealand, the Riesling of western Germany or potentially the Chardonnays and Pinot Noirs of Canada (Firth, 2016). Of course, cool-climate-adapted grape varietals like Chardonnay and Pinot Noir must also contend with the yearly threat of early-autumn frosts, which could impede full ripening (Sisimondo, 2016b).

Microclimate (The Here and Now)

In the grape-growing world, the term "microclimate" generally refers to phenomena at the scale of individual vines up to the whole vineyard scale (Wilson, 1998). As humans, we tend to observe and measure climate factors a few metres above ground surface – but the temperature down at the soil level, among the plants where there is little air circulation even when there is a breeze, can be very much higher, easily 5°C or more (Wilson, 1998). Similarly, in winter, ground frosts are more common and achieve a lower temperature at soil level where the vines disrupt air movement, than air frosts above the vines (Brown, 2001). Although daily temperature fluctuations penetrate only a few 10's of centimetres, seasonal trends penetrate much deeper (to where the roots reside) and regulate the overall growth/dormancy periods.

Dark soils warm up more quickly than light coloured ones, and so can reach critical growing temperatures earlier in the spring, and retain them longer in the autumn: the equivalent of several hundred kilometres and several degrees of latitude can be compensated for by the colour of the soil alone. Stony surfaces also can influence the temperature by warming up in the sun by day, and then releasing that heat through re-radiation during the night, which can counteract late spring and early autumn frosts in cooler settings (Wilson, 1998; Brown, 2001).

Moist, but not wet, soils absorb heat about 15% more efficiently than dry soils, significantly affecting fruit maturation (Wilson, 1998). In addition, stony surfaces tend to retain subsurface moisture by reflecting light and heat. Retaining heat is an important consideration when the goal is to plant early, grow late in the fall and avoid evening frosts: some surfaces, with high albedo, reflect a lot of the incoming radiation (Sommers, 2008).

Other Weather Factors (The Unexpected)

Sometimes the unpredictable vagaries of local weather can be unkind – in vineyards, as in most agricultural crops. Late spring frosts (below -5° to -20°C, depending on grape variety) can damage leaf and flower/fruit tissue while early autumn frosts can rupture the grapes themselves (Jones, 2017). Advection frosts occur when a regional cold front passes, whereas ground frosts occur during local temperature inversions (usually during cloudless nights) and can affect vines if rows are planted across the slopes or if there is no lower ground to receive cold-air drainage (Jones, 2017). Hailstorms are generally catastrophic in vineyards, as is true with most crops. Cool, drying winds can have a negative affect by leading to dessication of tissues and fruit, but may also have a positive affect by reducing the occurrence of fungal diseases (Jones, 2017).

Biological Factors

Vineyard Age (The Maturity)

Most grape vines don't produce fruit until about 3 – 5 years old, and peak in volume produced during the 6 to 20 year age period, after which the amount of fruit per vine decreases (Robinson, 2012). However, the quality and flavours of the wines produced typically increases with vine age because the older root systems are so highly developed, so well-acclimated to their setting/climate, so extensive and so deep that they can withstand year-to-year variations and tap into the very essence of the location (Robinson, 2012). At 30 years old, vines begin to produce fruit that imparts more character to the wine and at 50 years old, wines take on the deep complex flavours of superior wines, although yields are curtailed (MacLean, 2006). It is therefore surprising that most vines in most well-known wine areas are uprooted and replaced every 25 to 30 years in order to keep production volume up – but at the expense of wine quality. Conversely, in Bordeaux, little wine is produced from vines under 15 years old, large volume wines are produced from vines 15 to 40 years old, and the vines greater than 40 years old yield the acknowledged fine wines. By comparison, in Canada, the oldest vines currently in production are just reaching that magic 40-year age now. The only regions on earth with significant areas of truly "old vines" are in California, Australia, Chile and South Africa, regions where *Phylloxera* did not penetrate, and many exist only because they were totally neglected for many decades. More recently, these unique terroirs are belatedly receiving the recognition for quality and taste that they deserve.

Grape Varietals (The Crop)

Whereas most of this report focuses on the physical factors involved in the terroir concept, many wine drinkers today feel that a wine's ability to be true to a varietal style is more important than its ability to be true to its terroir origin (Lukacs, 2012). Although, this is an attitude unique to the non-European world of the post-WWII era, and is actually a departure from the past 2,000 years of wine history, it still represents an important choice, and an important biological factor of terroir. To maximize quality, the viticulturist's careful choice of varietal to plant in any given location should match the local physical factors discussed above.

Although all grapes are 85% water, the other components are important in creating the tastes associated with each grape type. The climate of the Rhine/Mosel River basin is not an ideal location for grape growing, but with the use of cool-weather-adapted varietals such as Riesling (documented from 1435) and Sylvaner, and utilizing the best sites, this area has been a producer of fine wines for centuries (Sommers, 2008). Jones et al. (2004) and Jones (2017) presented a chart of maturity-ripening temperatures for various grape varieties, showing that (for example), a Pinot Gris grape can ripen with average growing season temperature as low as 13° to 15°C, whereas a Zinfandel requires 19° to 24°C.

Here is a list of a few of the most common and well-known grape varieties, with some typical characteristics in point form, as derived from Laube and Molesworth (1996).

Cabernet Franc – often overshadowed by Cabernet Sauvignon which is its genetic offspring, classic Loire Valley red and an important component of Bordeaux reds, warm climate, full-bodied, less tannic, savoury, smoky, fruity, herbal: pair with robust fish dishes, lighter meats, vegetarian

Cabernet Sauvignon – "Noble Grape", classic Bordeaux, gravel outwash terrains, easily grown in many locations, warm to hot climate (16° to 20°C), late ripening, thick skins, complex and bold flavours, full-bodied, prominent acidity, big tannins, often blended with gentler varietals, may be oaked, ages well: pair with meats, rich foods

Chablis – classic northern Burgundy, cooler-climate, Kimmeridgian limestone/clay soil, mineral overtones, austere, steely: pair with oysters/seafood

Chardonnay – "Noble Grape", classic Burgundy, synonymous with the term "terroir", easily grown in many locations, warmer to cooler-climate (14° to 18°C), can withstand humidity, Kimmeridgian limestone/clay/chalk terrains, complex and bold rich intense flavours, apple/fruity flavours in cool climates, tropical/pineapple flavours in warm climate, mineral-rich, drier, may be oaked, ages well, richer, mellow, buttery, vanilla overtones: pair with butter, cheese, cream, chicken

Gamay – classic Beaujolais, granitic slopes, temperamental and not easily grown, light, fruity, low alcohol, high acidity, doesn't age well

Gewurztraminer – classic Alsace, cooler climate, temperamental to grow, deep colours, crisp acidity, floral aromas, potent spiciness, makes excellent dessert wine when left for late harvest: pair with spicy foods

Malbec – originally Bordeaux, now a signature wine of Argentina, hot and sunny, but temperamental and not very hardy, strong, fruity, tannic, stains the glass, ages well: pair with beef

Merlot – "Noble Grape", classic Bordeaux, tolerant of cooler climate, clay-rich soil, large grapes with thin skins, lighter, medium weight, paler colour, fruity, softer tannins, cherry and chocolate overtones, can be oaked, ages well: pair with most foods

Pinot Blanc – a workhorse grape, tolerant of many conditions, similar flavours and textures to Chardonnay, intense concentrated flavours, dry, crisp, high acidity, good complexity, tree fruits and citrus overtones, doesn't age well, often ignored in past: pair with most foods

Pinot Gris/Pinot Grigio – mutated from Pinot Noir, northern Italy and Alsace, cooler climate, aromatic, soft tannins, dark skins therefore deeper colour than Pinot Blanc, low acidity, medium to full bodied: pair with rich foods

Pinot Noir – "Noble Grape", classic Burgundy, synonymous with the term "terroir", cooler-climate (14° to 16°C), can withstand humidity, thin skins therefore rather delicate, can be temperamental and challenging to grow, gentle slopes, limestone/chalk soils, paler colour, lighter, softer tannins, medium to high acidity, rich, fruity with dark fruit and spice and earthy overtones, elegant, ages well: pair with butter, cheese, cream, beef

Riesling – "Noble Grape", the grape of Germany and Alsace, cooler-climate, very hardy and resistant to frost, slatey terrains, ripen slowly, dry to sweet, high acidity, light bodied, low alcohol, floral and mineral accents, crisp, flinty, petroliferous aroma, strongly reflects terroir, ages well, can be elegant, makes excellent dessert wine when left for late harvest and *Botrytis* "Noble Rot": pairs well with most foods, especially pork, duck, soft cheeses, Asian, spicy

Sauvignon Blanc – originated in Loire Valley, but now associated with New Zealand, prolific producer, distinctively crisp and refreshing, high acidity, medium bodied, fruity and herbal overtones, may have grassy aromas, can have mineral notes, doesn't age well: pair with fish and seafood

Syrah/Shiraz – hot climate, originated in northern Rhone valley, clay soil, relatively easy to grow, rich and complex, deep colour, soft tannins, medium to full-bodied, peppery and spicy accents, ages well, fruity: pair with grilled meats

Zinfandel – Italian/Croatian origin, hot climate, challenging to grow, late ripening, widely planted in many locations, dark colours, full-bodied, intense flavours, firm tannins, ages well, dark fruit and spicy flavours, can be earthy or spicy: pair with grilled meats, pasta

Microorganisms (The *"Bugs"* and the *"Wood-Wide Web"*)

Soil is not an inert, dead sheet of mineral material, but is a living, breathing complex containing many species of active plant and animal organisms. The small volume of soil accessed by each grape vine contains billions of microorganisms, most of which are generally beneficial to the plant (Wilson, 1998; Wohlleben, 2015). These include fungi (molds and yeasts), algae, a variety of invertebrates (annelid worms, insects, etc.) aerobic bacteria and anaerobic bacteria, many of which function in concert

(Wilson, 1998). These organisms churn the soil day and night, thriving especially well in slightly alkaline soil conditions (pH 7 to 8, which favours availability of mineral nutrients) and when they die they release nitrogen and carbon to the root environment (Wilson, 1998).

The ground-breaking research of Simard et al. (1997) has elucidated the role of networks of symbiotic mycorrhizal fungal networks surrounding and connecting to the root systems of many higher terrestrial plant communities, forming an interface between the roots and the soil, and the roots of neighboring plants. This work, conducted primarily on temperate forest trees in B.C., plus the further extensions by Wohlleben (2015), have shown unequivocally that considerable amounts of carbon-based nutrients, mineral-based nutrients, and even electrical signals flow through the hyphae of shared fungal systems that intimately surround root systems (i.e. below-ground transfer through the mycorrhizal network) from adjacent plant to plant of the same species, and even between different species of plants within the same plant community. In fact, these mycorrhizal fungal networks have been demonstrated to be commonly utilized in active shuttling/subsidizing of nutrients by mature "mother" plants to less mature/less healthy nearby seedlings to help one another survive and thrive: a giant redistribution network slowly built to maximize the health and benefits to all members (Simard et al., 1997; Wohlleben, 2015). This invisible, below-ground network of tightly-linked plant-fungus-soil components with bi-directional transfer and communication has been termed the "wood-wide web" (Wohlleben, 2015), and may be one of the most crucial recent discoveries for understanding how long-lived plant communities actually function.

In addition, Wohlleben (2015) also described how forest communities of trees/fungal networks actively control the temperature, humidity and winds within the community for the benefit of all members.

In addition, the role of symbiotic *Metarhizium* fungus in the nitrogen cycle is being studied at Brock University (Walker, 2017). This bio-insecticidal fungus inhabits soil around plant roots, kills and mummifies many insect pests, pumps nitrogen from the bodies to the plant roots and receives carbohydrates in return from the plant (Walker, 2017).

Could it be that the long-lived, deep-rooted grape vines within an established, mature vineyard are also connected through extensive mycorrhizal fungal networks which unite and protect the plants of that community? Should this be another terroir factor which we need to explore, understand and nurture to maximize the health and productivity of vineyards?

Nutrients (The Diet)

Water and nutrients limit vine growth and productivity: the former does this through its role in evapo-transpiration promoting nutrient uptake by the roots and its presence in the substrate as a transport medium to enable roots to do that vital job (Ker, 2013). Nutrients are primarily characteristic of the soil/substrate/bedrock which the vine roots can access. In fact, since most mature grape vine roots penetrate several to many metres, it is most important to understand what nutrients and what concentrations are available at that level, rather than what are available at surface (Taylor et al., 2003). Plant roots sip on mineral-rich solutions created by dissolution in groundwater from bedrock and soils and the best vineyards are located on terrains with the best balance of water and nutrient availability.

Most nutrient ions have a positive charge, whereas most clays have a negative charge, encouraging uptake from groundwater and transport to roots (Wilson, 1998). Whereas early season growth is based on stored nutrients from the previous year, further growth and fruiting requires access to new nutrient supply and the water transport for root uptake. Nutrient deficiency leads to decreases in cell division, photosynthesis, hardiness, fruit quality and overall health (Ker, 2013).

The main macronutrients, needed in high quantity include O, N, C, H, P, K, Mg, Ca, S; essential micronutrients include Fe, Mn, B, Cu, Z, Mo, Cl (Wilson, 1998). Nitrogen, the most important, is responsible for photosynthesis and for root, stem and leaf growth and drought tolerance. Phosphorus and potassium are particularly important for root growth, fruiting and drought tolerance and Mg transport. Magnesium is important in photosynthesis and fruit growth: indeed, each molecule of chlorophyll requires one atom of Mg (Wilson, 1998; Ker, 2013). Most macronutrients and micronutrients are most easily-assimilated from neutral to moderately-alkaline soils (pH = 6 to 9), whereas only Fe, Zn, Mn, and Cu can be easily-harvested from acidic soils (Wilson, 1998). Among micronutrients, iron, manganese and copper and zinc are important in chlorophyll and photosynthesis and growth, while boron and zinc are important in germination, seed growth and fruit setting (Ker, 2013).

High contents of Ca encourage high sugar and polyphenol content and high colour intensity (Costantini et al., 2010). High K content tends to decrease acidity in the resulting wine (Costantini et al., 2010). Ca helps neutralize soil pH because limestones are consistently alkaline, so planting grapes of higher acidity level is good. Fe is essential for photosynthesis, Mg is an important component of chlorophyll, P encourages root development and K improves plant metabolism. High levels of Ca and Mg in calcareous soils cool the root temperature which delays ripening and produces more acidic wine, provide good water retention and drainage, and neutralize natural acidity of soils. For yeasts to fully ferment grape juice to wine, they require adequate N, Mg, P and K in the juice, and especially in the skins (Robinson, 2006). Schists and slates are laminated, rich in Mg and K but poor in organics, have good heat retention, but allow deep rooting along cleavage.

Maltman (2013) has elucidated a fundamental misunderstanding about tastes in wine. He states that the chemical analysis of wines confirms that most associated flavours are due to content of ***organic*** molecules, rather than ***mineral*** nutrient elements (typically metallic cations which are entirely tasteless and present in miniscule amounts), and therefore are only distantly related to the presence of particular geological minerals (which are complex chemical compounds) in vineyard soils. However, the notion that "flinty" or "mineral" character and flavour can originate from vines grown in well-drained, nutrient-poor substrates may still represent an indirect, complex process by which these vineyard geological factors influence vine metabolism and physiology, root depth and type of groundwater accessed by roots, the uptake and production of specific organic compounds within the vine and fruit, or yeast-grape interactions (Maltman, 2013). Certainly, as with most crops, deficiencies of key nutrient elements such as nitrogen, phosphorus, potassium and magnesium rapidly lead to clear and specific vine health setbacks – proving the fundamental importance of these constituents to vine and fruit growth (Ker, 2013).

Cations, like K, Ca, Mg, Fe, have a positive charge and are required for production of chlorophyll and foliage, whereas anions, like P and S have a negative charge and are necessary for root development (Sommers, 2008). There are several minerals which are vital to the health of vines: Ca to neutralize soil pH, Fe is essential for photosynthesis; Mg is an important component of chlorophyll, N which is assimilated in the form of nitrates, P which encourages root development, K which improves vine metabolism (Wikipedia, 2016). Finally, red wine grapes require water deficit stress and relatively low N supply, whereas white wine grapes require more regular but moderate water supply and moderate N supply to produce high quality wines (Leeuwen and Seguin, 2006).

Clay minerals are the "glue" that holds soils together and allows them to develop and maintain structure. The platy latticework structure of clays encourages very strong molecular attraction horizontally within the lattice plates, but is weak between the plates, allowing water and other cations to be easily absorbed and released as long as there is sufficient moisture present. Thusly, clays have a high Cation Exchange Capacity (due to their lattice structure) and therefore are good sources of nutrients, whereas sand has a low CEC and is not: silt lies between the other two (Sommers, 2008; Maltman, 2013). CEC is vital to plant function because this is how plants receive and utilize nutrients, and how they eliminate toxins (Wilson, 1998). The lack of a diversity of minerals in highly-sorted, or clean bedrock or substrates can adversely affect wine flavours by reducing these functions. Although kaolinite is the most common clay mineral in soils, the best clay minerals for agricultural soils are montmorillonite and vermiculite (with their high CEC and swelling, water retention character) (Wilson, 1998).

Yeasts (The Trigger)

Aside from the grapes themselves, the second crucial biological factor in wine-making is yeast. As Pasteur discovered in the 1850s, in the absence of oxygen, yeasts convert sugars into alcohol and CO_2

through the process of fermentation (Robinson, 2006; Robinson et al., 2012). This occurs primarily through the action of the many strains of *Saccaromyces cerevisiae*, which is also important in the making of bread and beer (Robinson, 2006). Different yeast strains, their interaction with particular grape varieties, or the lack/addition of certain compounds during fermentation may affect the flavour profile of the resulting wine, over and above the physical terroir factors (Meinert, 2018). As global climate warms, encouraging higher alcohol contents (Nicholas, 2015), new specific yeasts strains are being developed designed to re-direct sugar metabolism to produce less alcohol without sacrificing flavour or body (Last, 2010). In addition, selection of certain yeast strains encourages the production of glycerol as a by-product, which favourably increases the body and texture of the resulting wine.

Agricultural Factors

Vineyard/Viticultural Techniques/Spacing/Trellising/Pruning/Harvesting (The Day-to-Day Work)

Although not the focus of this report, a few comments are offered here on the farming practices which affect wine. Until very recently, wine growing and wine making procedures had not changed significantly for millennia (Cita et al., 2004). Even in antiquity, vines were staked, trellised, pruned to reduce vegetative growth and reduce evapo-transpiration (Cita et al., 2004). Virtually all decisions made during the planning, planting, row orientation, trellising, growing, pruning and maintaining of a vineyard (and the chosen wine-making techniques) might affect, either positively or negatively, the expression of terroir in the produced wine. Many of these decisions are typically made only once in the long life cycle of a vineyard, and therefore need to be carefully planned with a view to the long-term climate trend (Nicholas, 2015).

Planting rows up and down the slope and keeping the vines well-pruned can make it easier for cold air to flow downhill and drain out of the vineyard, and to obtain the most advantageous exposure to sunlight for that property (Sommers, 2008). Vines must be pruned in order to focus their energy into optimizing fruit production (Ejbich, 2016). In many vineyards, leaves are pruned away to expose fruit to warming sunshine. Grapevines will survive all but the wettest environments, but perform best in drier settings and the drier the climate, the wider spacing the rows should be planted in order to allow each vine to tap the maximum cubic subsurface space for moisture (Sommers, 2008). In parts of Canada (e.g. Prince Edward County) it may be necessary to hill up mounds of soil over *vinifera* canes in winter for protection, and monitor spring temperatures in order to uncover after risk of frost damage has passed (Ejbich, 2016).

It is profitable in the end to snip off and discard many of the grapes while they are still green, thereby concentrating all the natural sugars into the fruit that remains to mature on the vine.

Precision Digital Agriculture (The Future)

The recently-promoted concept of "precision agriculture" perfectly suits the practices of viticulture. Indeed, this is actually just a modern expression of the epitome of the concept of terroir: to carefully and purposefully observe and understand the sum total of the growing conditions and suit the crop intimately to the immediate environment and practices. In recent years the concept of "precision" or "digital" agriculture has appeared, which is a farm management technique based on observation and multi-spectral measurement in real-time of environmental data in order to monitor and optimize crop production and minimize environmental impact (eVineyard, 2015; Networked Society Institute, 2017).

These techniques are especially well-suited to application for high-value crops (such as vineyards) because of the up-front expense and labour to initiate. These methods can include satellite remote sensing, in-ground and above-ground distributed sensor networks, small/inexpensive aerial autonomous drones with infrared cameras and GIS positioning, and decision-support software (Cornell, 2015; eVineyard, 2015). Terroir factors which can be monitored daily (or even hourly) include detailed micro climate data, soil temperature, soil moisture, groundwater salinity, groundwater pH, crop growth rate, stress levels, water distribution, fertilizer applications, pest infestations and fruit ripeness (Cornell, 2015; Networked Society Institute, 2017). Surely, in the dynamic and profitable world of wine, these techniques will continue to expand.

Cultural Aspects (The Human Factor)

The French concept of Terroir goes beyond the physical factors and adds human sensibilities into the equation too. Culture can be as crucial to the final result as any given physical factor. Terroir is about an intimate understanding of the land and what its best uses are, what crops or varietals are best suited, what best-reflects the local origin. Applying the concept of terroir to management practices forces growers, especially small growers, to think about maximizing quality (Brown, 2001).

Whereas it is true that fundamentally Sugar + Yeast = Alcohol + CO_2, the natural landscape is also the backdrop for the activities of people in the cultural landscape: the concept of terroir is something that has evolved through time from the interplay between humans and nature (Sommers, 2008).

TERROIRS IN CANADA

Within the totality of natural and man-made components which make up the tantalizing concept of terroir, geology dictates much of the overall rock types, landscape, landforms, exposure, drainage, subsoil and soils (Johnson, 1998). Due to their training and experience in interpreting past landscapes, geologists instinctively want to "see" through the surface soil layer into the subsurface habitat where a plant's roots reside and gather water and nourishment (Wilson, 1998).

Canada has a very long and very complex geological history, spanning almost the entirety of known geologic time and known rock types. As proven by experience in other parts of the world, grapevines can thrive in a variety of environments and on a variety of substrates (Cita et al., 2004). Perhaps the great variability in the geology of Canada's widely-dispersed viticultural regions, and a naturally warming climatic trend, may bode well for the terroir concept and the future of high-quality and unique wines in Canada. The young, and rapidly-evolving, Canadian wine industry may be perfectly situated at exactly the right time to capitalize on this newer terroir-friendly trend to produce "unique wines from unique areas".

Wine has gained a prominent place in Canada's agricultural, gastronomical and cultural landscapes (VQA Ontario, 2017). However, as a northern, cool-climate country, on the current margin of the wine growing world, and a country which must emphasize artisanal quality rather than quantity, Canada needs to optimize each factor which could improve the quality of the resulting product. This report has been an attempt to set the scene for more thorough study of the possibilities and potential of terroir research in Canada, particularly of the basic geological foundations involved. Below is a very brief introduction to the wine growing regions of our country, as a preamble to more detailed reports to follow. I have only included here the areas which are currently commercially producing grapes and wine: a number of emerging areas, that will soon become viable and important, will be detailed in future reports.

VQA/APPELLATIONS/WINE REGIONS

Nova Scotia

The Nova Scotia wine growing region lies between latitudes 44°30'N to 46°00'N, within the cool-climate belt, never more than 20 km from the ocean, and generally enjoys a temperate climate with cool humid winters and warm humid summers, moderated by the closely-adjacent ocean waters of the Bay of Fundy and Northumberland Strait. Although grapes were apparently cultivated here since the 1600s by the Acadians, only recently has a Wine Appellation been designated: the Tidal Bay Appellation which focusses solely on crisp, aromatic whites (Wines of Nova Scotia, 2017) (Figure 2). Grapes are also grown along the shore of Northumberland Strait.

A) Tidal Bay

Canada's easternmost wine area, primarily about 100 km west of Halifax in the Annapolis Valley (a designated World Heritage Site landscape), is characterized by cool temperatures and humidity, long growing seasons, modest sunshine, and climate moderation by adjacent ocean waters. Low topography sheltered by the higher elevation of North Mountain ridge, is underlain by local geology involving well-drained fine to coarse-grained surficial deposits overlying sandstones, siltstones and shales of Middle to Late Triassic age (Wines of Nova Scotia, 2017).

B) Northumberland Shore

A single winery has been established since the late 1980's on the sheltered Malagash coastline adjacent to the warmest ocean waters in eastern Canada. However, the area may be prospective for additional vineyards in future. Cool temperatures, high humidity and a long growing season are coupled with local geology involving well-drained, fine to coarse grained surficial deposits overlying sandstones, siltstones and shales of Late Carboniferous age.

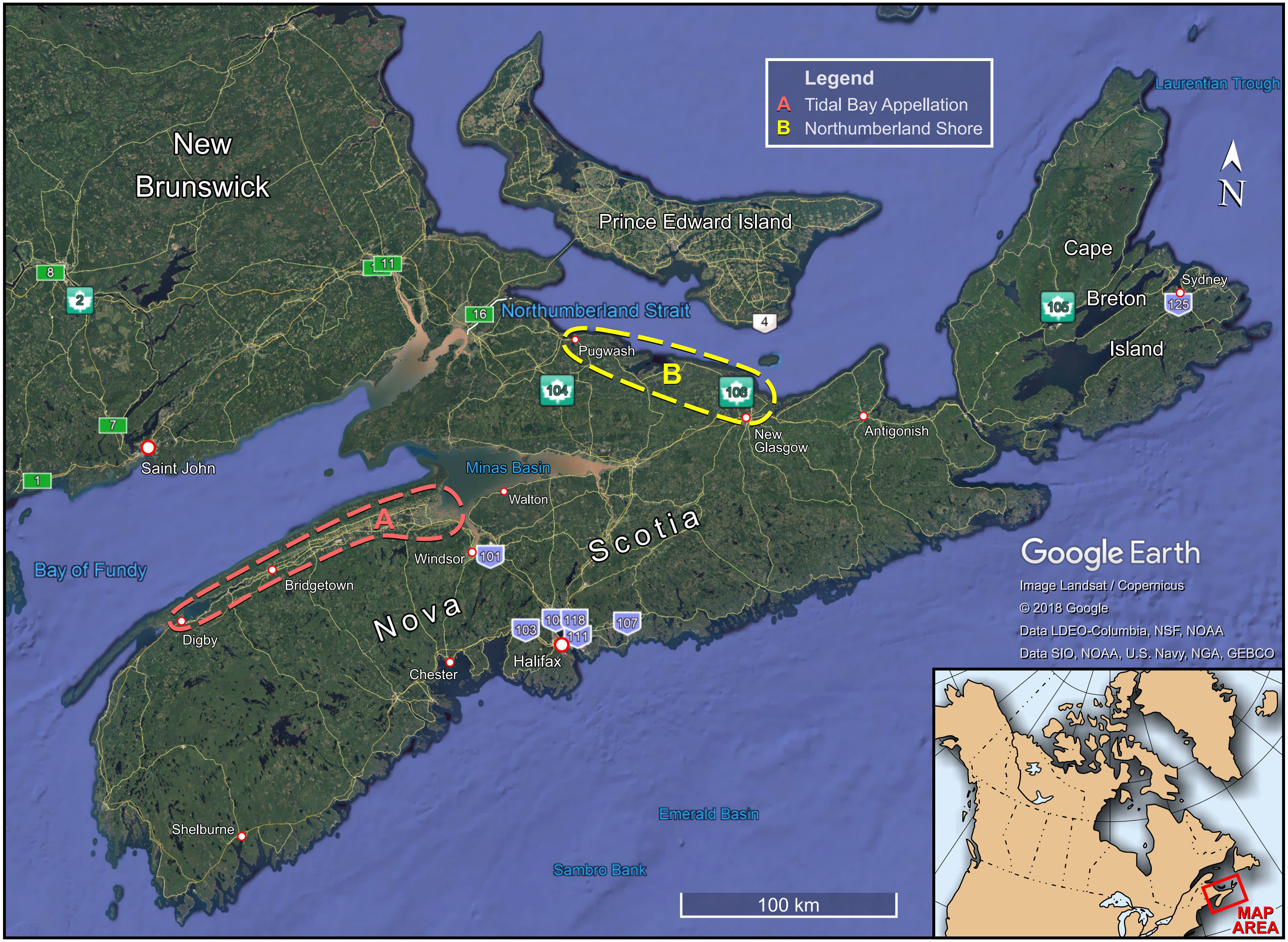

Figure 2. Wine growing areas of Nova Scotia (from Wines of Nova Scotia, *winesofnovascotia.ca*).

Quebec

The southern Quebec wine growing region lies between latitudes 45°00'N and 46°00'N, within the cool-climate belt, and generally enjoys a temperate climate with cold humid winters and hot humid summers, with some modification by the adjacent St. Lawrence River. Although grapes have been cultivated here for centuries, and serious production was attempted in the 1860-1870s, it is only in the last 20 years that a commercial industry based on small, family-run artisianal vineyards and hybrid grape varieties has developed (vinsduquebec.com, 2016); QuebecWines.com, 2017). Almost all wines produced are sold right at the wineries and therefore are not well-known outside the region, and little specific information is available. Several regions have been designated (Bell, 2014; QuebecWines.com, 2017) (Figure 3):

A) Eastern townships
B) Montérégie
C) Centre du Quebec
D) Basses Laurentide
E) Lanaudière
F) Quebec City/Capitale

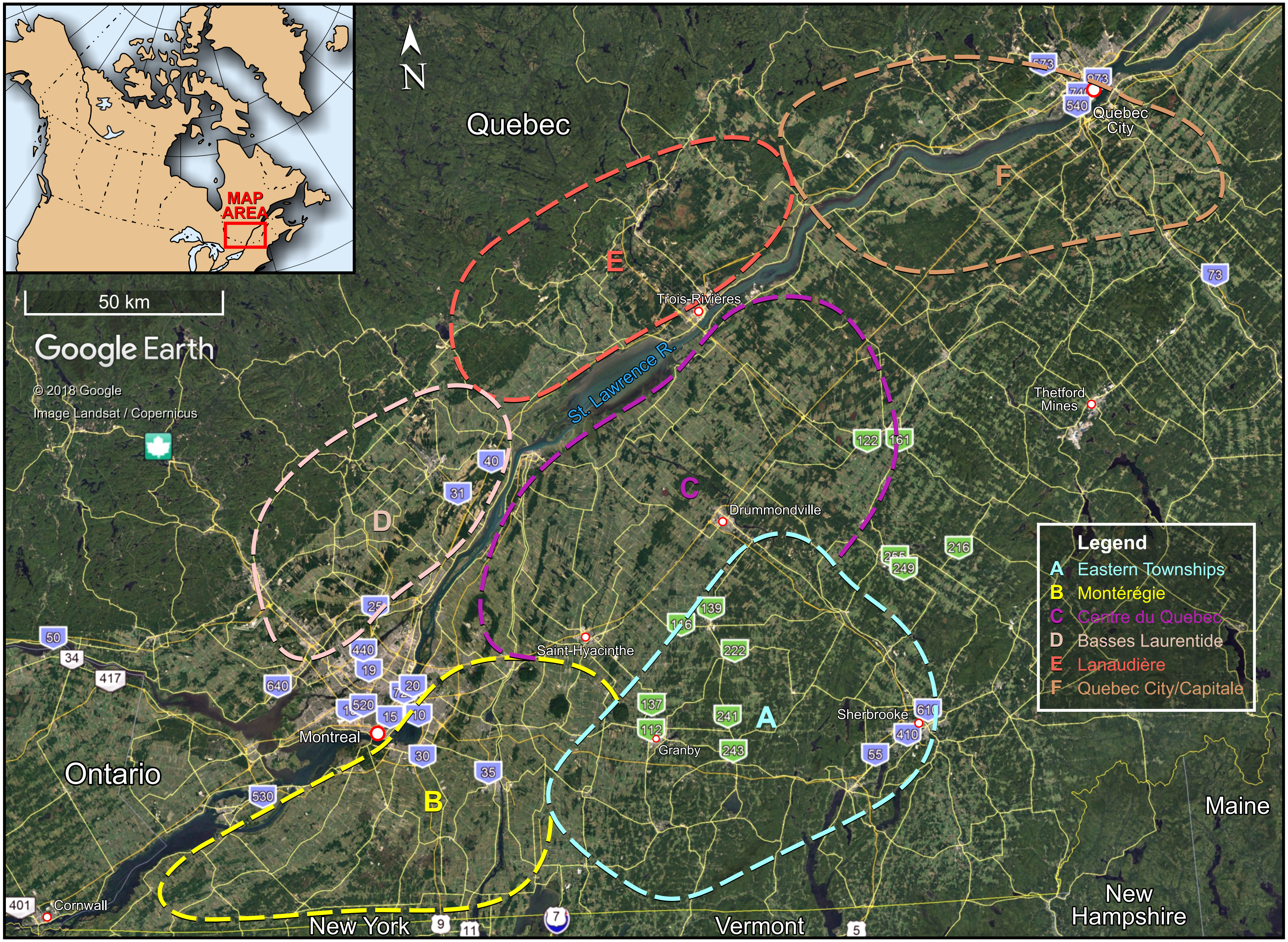

Figure 3. Wine growing areas of Quebec (QuebecWines.com, www.quebecwines.com).

Ontario

The Southern Ontario wine growing region lies between latitudes 41°45'N to 44°10'N, within the cool-climate belt, and generally enjoys a temperate climate with cool humid winters and hot humid summers, modified by the adjacent Great Lakes. Within the varied areas of Canada's oldest commercial wine growing region, four Wine Appellations have been designated. These are A) Lake Erie North Shore, B) Niagara Peninsula, C) Niagara-on-the-Lake, and D) Prince Edward County (VQA Ontario, 2017) (Figure 4). In addition, a few small wineries have sprung up outside these designated areas and may be harbingers of new, emerging wine regions (Wine Country Ontario, 2016).

A) Lake Erie North Shore

Ontario's southernmost wine area (42°N latitude), 250 km southwest of Toronto along the north shore of Lake Erie, is characterized by warm temperatures, long growing season, abundant sunshine, climate moderation by the surrounding Lakes Huron and Erie, and low topography (Wine Country Ontario, 2016). With overall south-facing slopes, the local geology involves well drained, fine- to coarse-grained, glacio-lacustrine surficial deposits overlying shale and limestone bedrock of Middle to Late Devonian age. It includes the *South Islands Sub-Appellation,* 20 km off the Lake Erie shoreline to the south (southernmost point in Canada) (VQA Ontario, 2017).

B) Niagara Escarpment

Along with Niagara-on-the-Lake, this represents Ontario's oldest and largest wine areas (Wine Country Ontario, 2016), characterized by cool-climate lakeside vineyards, at about 43°N latitude. It is part of the UNESCO World Biosphere Reserve. High topographic relief of the north-facing Niagara Escarpment, diurnal temperature variation, moderate sunshine, and climate moderation by adjacent Lake Ontario, all combine with well-drained, rich and fertile soils overlying diverse and complex glacio-lacustrine surficial deposits which in turn overlie multi-layered bedrock units of limestone/dolostone/sandstone/shale of Late Ordovician to Middle Silurian age. Six Sub-Appellations are designated along the east-west oriented belt including *Beamsville Bench*, *Creek Shores*, *Lincoln Lakeshore*, *Short Hills Bench*, *Twenty Mile Bench*, *Vinemount Ridge* (VQA Ontario, 2017).

C) Niagara-on-the-Lake

Along with Niagara Escarpment, this represents Ontario's oldest and largest wine areas (Wine Country Ontario, 2016), characterized by cool-climate vineyards adjacent to the Lake Ontario shoreline and the Niagara River at about 43°N latitude. The area is considered the bitrthplace of the modern Ontario wine industry and is a region of great Canadian historical interest. Climate moderation by adjacent water bodies combines with well-drained surficial deposits overlying multi-layered bedrock units of limestone/dolostone/sandstone/shale of Late Ordovician to Middle Silurian age. Four Sub-Appellations are designated including *Four Mile Creek*, *Niagara Lakeshore*, *Niagara River*, *St. David's Bench* (VQA Ontario, 2017).

D) Prince Edward County

Ontario's newest and northernmost wine area, 200 km northeast of Toronto along the Lake Ontario shoreline and rapidly expanding, is characterized by cool-climate lakeside vineyards (Wine Country Ontario, 2016), at about 44°N latitude. It is virtually completely surrounded and moderated by Lake Ontario, has varied and rugged topography with overall south-facing slopes, well-drained thin sandy/stony soils overlying thin gravelly surficial deposits, in turn overlying well-stratified limestone and shaley limestone bedrock of Middle to Upper Ordovician age (VQA Ontario, 2017).

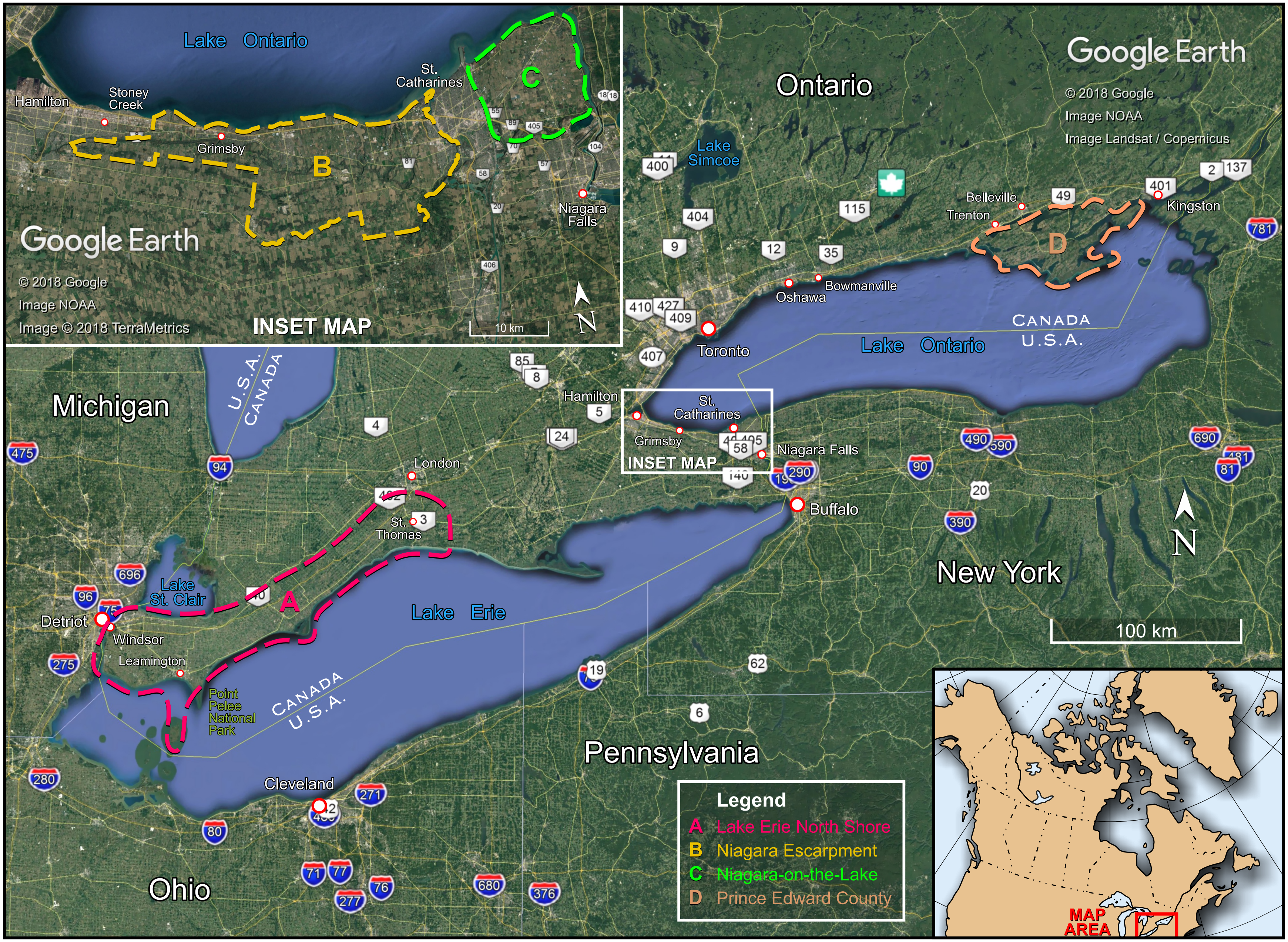

Figure 4. Wine growing areas of Ontario (Lake Ontario and Lake Erie) (VQA Ontario, www.vqaontario.ca).

British Columbia

The British Columbia wine growing region is a complex grouping of areas lying between latitudes 48°20'N to 50°45'N, within the cool-climate belt, and generally enjoys a temperate to Mediterranean climate with mild humid winters and warm dry summers, modified by the adjacent river, lake and ocean waters. Within these varied areas, five Wine Regions have been designated. These are:
A) Vancouver Island, B) Gulf Islands, C) Fraser Valley, D) Similkameen Valley, and E) South and F) North Okanagan Valley (Wines of British Columbia, 2017) (Figure 5). In addition, four further emerging areas have recently been recognized: G) Shuswap, H) Thompson Valley (at above 50°N latitude, one of the most northerly wine areas on earth), I) Lillooet, and J) Kootenays (British Columbia Wine Institute, 2017).

A) Vancouver Island

A relatively large area with a long history stretching north-south over 150 km from Victoria to Courtney/Comox, on the east side of the Island in the rain shadow, adjacent to the moderating influence of Georgia Strait and Cowichan Lake (British Columbia Wine Institute, 2017).
Long growing seasons, low topography with east and south facing slopes are characterized by mild humid winters and warm dry summers. Well-drained thin sandy to gravelly soils overlie thin to thick sandy to gravelly surficial deposits, in turn overlying complexly-faulted sandstone and shale bedrock of Cretaceous age.

B) Gulf Islands

B.C.'s newest wine area scattered over a number of small islands within the sheltered and climate-moderating Georgia Strait (British Columbia Wine Institute, 2017), immediately east of southern Vancouver Island within the rain shadow. Long growing seasons, characterized by mild humid winters and warm dry summers combine with well-drained thin sandy to gravelly soils overlying thin to thick sandy to gravelly surficial deposits, in turn overlying complexly-faulted sandstone and shale bedrock of Cretaceous age.

C) Fraser Valley

A relatively newer area nestled in the agricultural Fraser River valley stretching for about 100 km eastward from Vancouver, near the ocean coast with low topography, and characterized by mild humid winters and warm dry to wet summers (British Columbia Wine Institute, 2017). Thick fertile fine-grained delta soils overlie thick fluvio-deltaic sandy to gravelly surficial deposits which in turn overlie bedrock sandstones and shales of Cretaceous and Tertiary age.

D) Similkameen Valley

This small narrow valley area immediately west of Okanagan Valley just north of the 49th parallel, is bounded by steep mountains on both sides, no moderating lake, and is characterized by cold winters and hot dry summers with persistent winds (British Columbia Wine Institute, 2017). The rugged topography and west-facing slopes support well-drained sandy to gravelly soils overlying thick sandy to gravelly surficial deposits, in turn overlying bedrock of metamorphosed sedimentary rocks of varied Paleozoic ages.

E and F) Okanagan Valley

B.C.'s oldest and largest wine area, and one of the more northerly established wine regions in the world (equivalent to the Champagne/Mosel Valley regions of France and Germany) (British Columbia Wine Institute, 2017), stretches 200 km north-south along a moderating chain of lakes in Canada's Pocket Desert within a rain shadow. Great climatic variation is apparent from south to north, characterized by cool-to-hot-climate lakeside vineyards with long dry growing seasons, varied and rugged topography, and east/west/south facing slopes. Well-drained thin sandy/stony soils overlie benches of thick silty to sandy to gravelly glacio-fluvial and glacio-lacustrine surficial deposits, in turn overlying a complex bedrock suite of Jurassic granites, Eocene volcanics and sandstone/shale, and Miocene plateau basalts (see Bowen et al., 2005 for much more detail). There is one designated Sub-Region of *Golden Mile Bench* and several unofficial sub-regions (British Columbia Wine Institute, 2017).

Other Regions including G) Shuswap, H) Thompson Valley, I) Lillooet, and J) Kootenays

These four regions have recently been officially recognized as areas that now produce wines that are certified by the B.C. Vintners Quality Alliance (VQA) as outlined in the "Wines of Marked Quality Regulation." Each of these regions have unique microclimates which give *"special character to its wines"* (British Columbia Wine Institute, 2017).

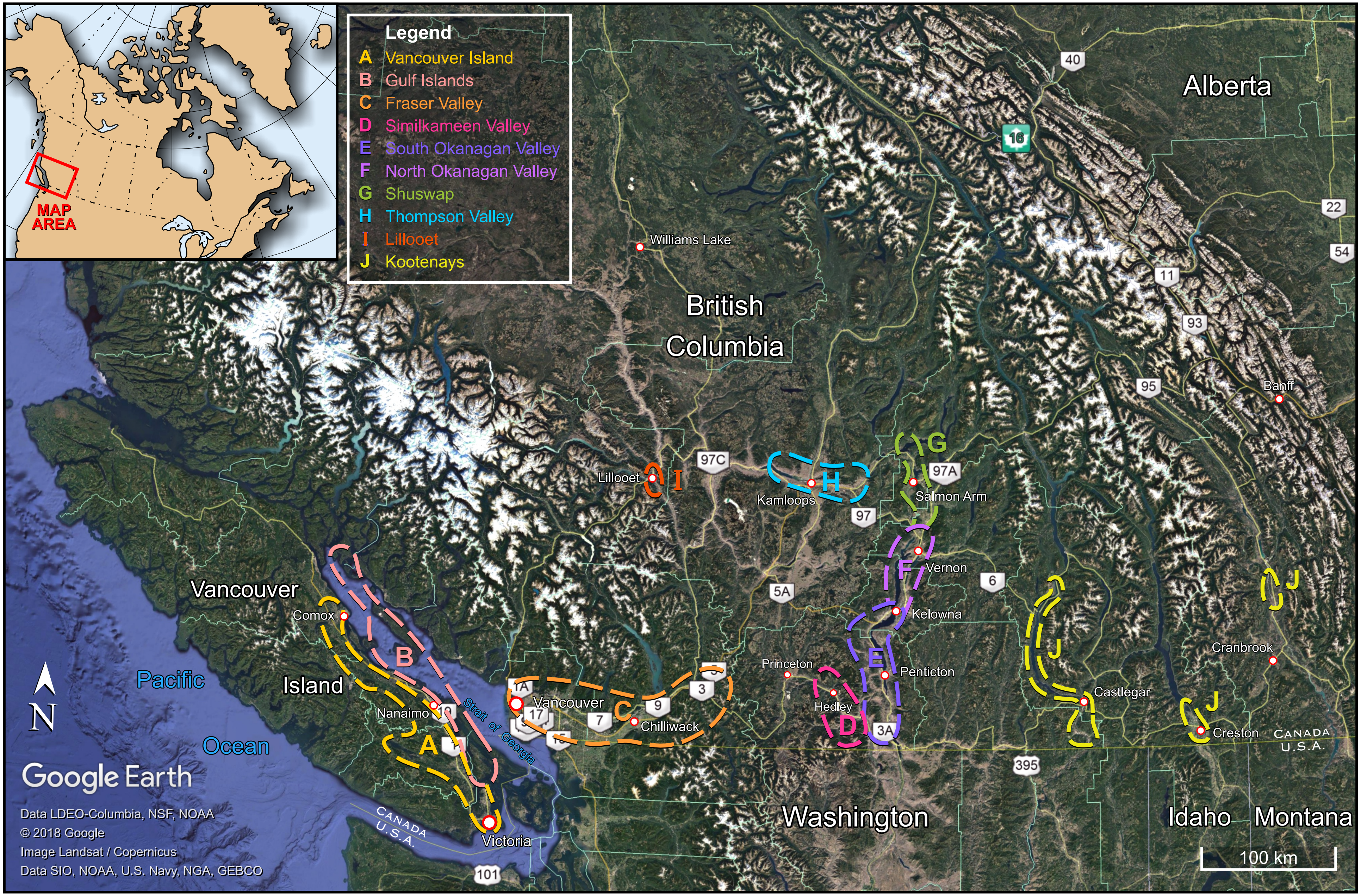

Figure 5. Wine growing areas of British Columbia (from British Columbia Wine Institute, www.winebc.com).

CONCLUSION

The foregoing discussion clearly suggests that to understand and utilize the concept of terroir to advantage in the cool-climate, developing vineyards of Canada requires multi-dimensional and multi-layered analysis of any given site and the varietals which suit it. Taking into account the independently varying multiple geological layers, the loosely-related climatological factors, a logical (rather than fashion-driven) choice of grape varietals and biological factors, and intelligent, thoughtful application of agricultural vineyard techniques should result in better wines in the long run.

Understanding the terroir factors on a property, and which grape varieties will best suit them, will help a viticulturist to work with the land to grow the best crops possible. Utilizing terroir thinking is an approach uniquely suited to small growers who can know and work their land intimately (Brown, 2001), but is just as useful for large producers. Building a regional identity, a reputation for quality and uniqueness, perhaps even developing a "caché" based on the strength of all local products will help to strengthen that local economy and attract gourmet tourists. Using the terroir concept to inform the management of the land helps all growers to focus on maximizing quality. In fact, investigating the terroir components of an area might even suggest alternative land uses and high value crops that could transform the face of the rural economy. For example, never a country to flood markets with bargain swill, New Zealand has focussed its relatively young industry on quality and unique terroir-driven taste, and today boasts the world's highest average selling price for exported wines (Crosariol, 2013c).
The "Paradox of Terroir" is that, although the human recognition and appreciation of unique tastes usually takes place in a socially-sophisticated urban setting, that same distinctive taste actually originates (and must be understood) in the basic, dirt-and-roots, natural science of the rural setting of the vineyard (Lukacs, 2012).

Because Canadian wine regions are technically "cool-climate", have short growing seasons, with potential late spring and early autumn frosts, it is even more important to utilize the terroir concept to get the most out of the endowed natural conditions at our disposal, to maximize our scientific analyses of those factors, to carefully match the best grape varietals with each region and terroir regardless of short-term commercial consumption trends, and to enhance our terroir knowledge base to maximize viticultural output of quality wines. As I have tried to demonstrate in this brief review, an understanding and appreciation of the geological characteristics of the landscapes involved, and how they interact with the climatological and biological aspects are key ingredients for success. Most importantly, in a wine world where Canada can never compete in production volume, and should not try to compete with warm-climate varieties, the philosophical emphasis should be on understanding our natural geological, climatological and biological patrimony to attain, promote and capitalize on that "signature of place" which so characterizes the finest examples of terroir-driven wines.

As of 2011, the wine industry contributed a significant $6.8 billion impact to the Canadian economy (Wines of Canada, 2015). The future of the wine industry in Canada rests on the quality of the vines in the ground, the understanding of the science behind the suite of terroir factors which influence vine growth and grape production, and the expertise of our viticulturalists in matching grape varieties to the many individual terroirs present in our wine-growing regions. And, of course, the same statements apply to the other terroir-influenced crops mentioned here.

As climate naturally warms over the next decades, how will Canada's established wine regions evolve and adapt and thrive, and which new regions will become able to support a new wine culture? Will concerted scientific analysis of terroir factors help our viticulturists to improve the results for vineyard and orchard products in Canada? Over time, perhaps we will discover the answers to these questions in the liquid beverages themselves. As Pliny The Elder wrote in about 60 AD (translating from an ancient Greek proverb), surely the oldest quote involving wine, "In Vino Veritas" – In wine, there is truth.

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