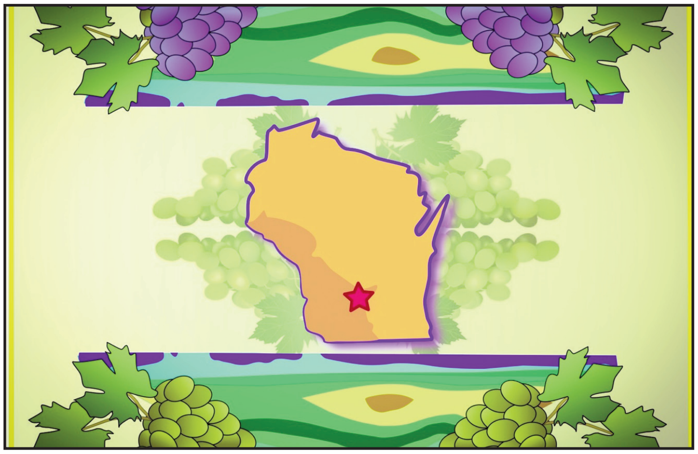
SERIES



Geology and Wine 14. Terroir of Historic Wollersheim Winery, Lake Wisconsin American Viticultural Area

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SUMMARY
The viticultural history of Wisconsin started in the 1840s, with the very first vine plantings by Hungarian Agoston Haraszthy on the Wollersheim Winery property located in the Lake Wisconsin American Viticultural Area (AVA). This study examines the terroir of historic Wollersheim Winery, the only winery within the confines of the Lake Wisconsin AVA, to understand the interplay of environmental factors influencing the character and quality as well as the variability of Wollersheim wines. Soil texture, chemistry, and mineralogy in conjunction with precision viticulture tools such as electromagnetic induction and electrical resistivity tomography surveys, are utilized in the Wollersheim Winery terroir characterization and observation of spatially variable terroir at the vineyard scale. Establishing and comparing areas of variability at the plot level for two specific vineyard plots (Domaine Reserve and Lot 19) at Wollersheim Winery provides insight into the effects of soil properties and land characteristics on grape and wine production using precision viticulture tools.

The viticultural future of Wisconsin looks quite favourable, as the number of wineries keeps rising to meet the demand for Wisconsin wine and local consumption. As climate change continues to affect the grape varieties cultivated across the world's wine regions, more opportunities arise for Wisconsin to cultivate cool-climate European varieties, in addition to the American and French-American hybrid varieties currently dominating grape production in this glacially influenced wine region.

RÉSUMÉ
L'histoire viticole du Wisconsin a commencé dans les années 1840, avec les premières plantations de vigne par le Hongrois Agoston Haraszthy sur la propriété du vignoble Wollersheim situé dans la région de l'American Viticultural Area (AVA) du lac Wisconsin. Cette étude porte sur le terroir historique du vignoble Wollersheim, le seul à l'intérieur de l'AVA du lac Wisconsin, qui soit soumis à l'interaction des facteurs environnementaux qui influencent le caractère, la qualité et la variabilité des vins Wollersheim. La caractérisation et l'observation des variations spatiales du terroir à l'échelle du vignoble Wollersheim se font par l'étude de la texture du sol, sa chimie et sa minéralogie en conjonction avec des outils de viticulture de précision comme l'induction électromagnétique et la tomographie par résistivité électrique. En définissant des zones de variabilité au niveau de la parcelle et en les comparant pour deux parcelles de vignobles spécifiques (domaine Reserve et lot 19) du vignoble Wollersheim on peut mieux comprendre les effets des propriétés du sol et des caractéristiques du paysage sur la production de raisin et de vin.

Le nombre de vignoble augmentant pour répondre à la demande de vin du Wisconsin et à la demande locale, l'avenir viticole du Wisconsin semble assez prometteur. Comme le changement climatique continue d'influer sur la variétés des cépages cultivés dans les régions viticoles du monde, c'est l'occasion pour le Wisconsin de cultiver des variétés européennes de climat frais, en plus des variétés hybrides américaines et franco–américaines qui dominent actuellement la production de raisin dans ce vin glaciaire région.

Traduit par le Traducteur

INTRODUCTION
The state of Wisconsin is perhaps best known for cheese and beer, invoking placid images of lush pastureland, clear lakes, and the north woods, but in the last decade, there has been a significant increase in the number of wineries established

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across this Midwestern state. Although Wisconsin has a long winemaking history, the Wisconsin grape growing and wine industry has experienced rapid growth in recent years. The viticultural history of the state of Wisconsin extends back to the 1840s, when the illustrious nobleman Agoston Haraszthy, a Hungarian-born immigrant who subsequently became a pioneer in California's grape and wine industry, first settled in south-central Wisconsin. Haraszthy planted the first vines in 1847 and 1848 and built a 40-foot cellar on the prairie bordering the Wisconsin River – the current location of Wollersheim Winery, which has become a National Historic Site. The traditional European vines planted by Haraszthy did not survive the harsh Wisconsin winters. At the end of 1848 he followed the gold rush to California, where he founded some of the first productive vineyards (including Buena Vista Winery in Sonoma), introduced over 300 varieties of imported European vines, and ultimately became known as the founder of the California wine industry (Pinney 1989). Agoston Haraszthy's vine planting and cellar digging efforts on the hill of Wollersheim Winery in Prairie du Sac, Wisconsin, mark the humble beginning of the state's viticultural history.

Wine production in Wisconsin has always been minimal due to its climate, which is susceptible to extremes of temperature (the record low of –48.3°C, or –55°F, was reported in February 1996), making Wisconsin's mesoclimates incompatible with the cultivation of most Vitis Vinifera varieties. Overall, average annual minimum temperatures in the state of Wisconsin range between –2°C and 3°C, and average annual maximum temperatures vary from 10°C to 14°C. Data from the Wisconsin State Climatology Office show that Wisconsin's continental climate, moderated by Lake Michigan and Lake Superior, is characterized by a short growing season of 140 to 150 days in the east-central Lake Michigan coast and southwestern valleys and even shorter in the central portion of the state, as a result of inward cold air drainage. These cool-climate conditions commonly limit yield and quality of grapes because of occasional spring freezes, which can occur from early May in southern counties and Lake Michigan coastal areas to early June in northern counties, and fall frosts, which can occur from late August/early September in northern and central lowlands to mid-October along the Lake Michigan coastline. Based on a long-term climatological temperature average (calculated using the 1981–2010 U.S. Climate Normals), a total of 2264 Growing Degree Days (GDD, base 50°F) were calculated for Wisconsin from April 1st to October 31st, which puts Wisconsin in Winkler's Region I (2500 or less GDD). The Winkler scale, which is a method of classifying climate of grape growing regions based on heat summations (one degree day per degree Fahrenheit over 50°F), includes five climate regions: Region I (≤2500 GDD); Region II (2501–3000 GDD); Region III (3001–3500 GDD); Region IV (3501–4000 GDD); and Region V (>4000 GDD). Because Vinifera vines typically cannot survive the cold Wisconsin winters, mostly cold-resistant native American and French-American hybrid varieties, such as Marechal Foch, Leon Millot, Edelweiss, La Crosse, Frontenac, St. Peppin, Seyval Blanc, Marquette, and many other resilient varieties, are cultivated in Wisconsin. Many Wisconsin winemakers procure grapes from other areas of the USA (California, Washington, New York), and also make wine from other types of fruit, including cherries, strawberries, blueberries, raspberries, cranberries, peaches, apples, and pears. Most Wisconsin wineries make a combination of grape and fruit wines, and increasingly more producers make wine from locally grown cold-climate grapes.

In spite of the Midwestern USA climatic challenges, the Wisconsin grape industry has expanded exponentially in the last decade, as most vineyards were planted between 2005 and 2010. The number of Wisconsin wineries keeps climbing, with over 100 wineries to date (2016) across the state, according to the Wisconsin Winery Association. As global temperatures continue to increase, the current areal extent of grape growing regions will shift accordingly, allowing new varieties to be cultivated in certain regions, as well as limiting the production and affecting the quality of established cultivars in other regions. As climate change continues to affect the selection of grape varieties that can be cultivated in Wisconsin, some grape growers are starting to experiment with Vitis Vinifera varieties; cool-climate Riesling is the frontrunner.

In 2012, Wisconsin grape growers and winery owners were surveyed regarding grape-growing practices, winery operating practices, and sales and production performance in order to establish industry baselines and quantify economic contribution. The survey was conducted by Tuck and Gartner (2014) as part of the United States Department of Agriculture (USDA)-funded Northern Grapes Project. Based on the survey results, approximately 708 acres of vines were planted and approximately 1400 tons of grapes harvested in 2011. Of the 71,699 planted vines in the state, the majority (58,300) are cold-hardy vines, comprising 34,400 red cultivars and 24,000 white cultivars. The top three red cultivars are Marquette, Frontenac, and Marechal Foch, constituting 42%, 26%, and 9%, respectively, of the total planted cold-hardy red varieties. The top three white cultivars are Frontenac Gris, Brianna, and La Crescent, representing 27%, 19%, and 15%, respectively, of the total planted cold-hardy white varieties (Tuck and Gartner 2014). As evidenced by these survey results, Wisconsin is a very small grape producer. For comparison, the top 13 United States grape producers are listed in Table 1, based on data from the Crop Production Report (ISSN: 1936-3737) released on August 12, 2015, by the National Agricultural Statistics Service (NASS), Agricultural Statistics Board, USDA. California leads the way with 6,822,000 tons (89%), followed by Washington with 512,000 tons (5%), and New York with 188,000 tons (2%) of total production in 2014.

The state of Wisconsin is divided into five distinctive wine regions: the Northwoods Region, Fox Valley Region, Glacial Hills Region, Door County Region, and Driftless Region, and within these five wine regions, there are three established American Viticultural Areas (AVAs), including the Lake Wisconsin AVA, the Upper Mississippi River Valley (UMRV) AVA, and the Wisconsin Ledge AVA (Fig. 1). The Lake Wisconsin AVA, established on February 4, 1994, is situated in the south-central part of the state and encompasses approximately 130 square kilometres (km^2) in two counties. It includes within its

Table 1. Summary of 2014 US grape production showing the top 13 United States grape producers.*

State	Total Grape Production (tons)
California	6,822,000
Washington	512,000
New York	188,000
Pennsylvania	91,000
Michigan	63,300
Oregon	58,000
Texas	9,400
Virginia	8,800
North Carolina	6,000
Missouri	4,030
Georgia	4,000
Ohio	3,810
Arkansas	1,490

*Source: Crop production report (ISSN: 1936–3737) released August 12, 2015, by the National Agricultural Statistics Service, Agricultural Statistics Board, United States Department of Agriculture.

boundaries the location of the historic Wollersheim Winery. The UMRV AVA, established on June 22, 2009, is the largest designated appellation in the world, stretching approximately 78,000 km^2 across southeastern Minnesota, southwest Wisconsin, northwest Illinois, and northeast Iowa, and it includes within its boundaries the Lake Wisconsin AVA. The Wisconsin Ledge AVA, established on March 22, 2012, is located in the northeastern part of the state, covering approximately 9800 km^2 in 11 counties, and is part of the Niagara escarpment corridor, stretching along the Lake Michigan shores.

This research study examines the terroir of historic Wollersheim Winery, the only winery within the confines of the Lake Wisconsin AVA, to understand the interplay of environmental factors influencing the character, quality, and variability of Wollersheim wines.

OVERVIEW OF THE TERROIR OF LAKE WISCONSIN AVA

Lake Wisconsin AVA is situated in south-central Wisconsin, approximately 70% in Columbia County and 30% in Dane County. The AVA is bordered to the west and north by the Wisconsin River and Lake Wisconsin, respectively, to the east by Spring Creek and State Highway 113, and to the south by Mack Road and State Highway Y (Fig. 2); its boundaries are defined by federal regulations (GPO Electronic Code of Federal Regulations 2015). The climate within the Lake Wisconsin AVA displays minor variability. The Wisconsin River and Lake Wisconsin moderate the temperatures, and average annual precipitation ranges from approximately 762 to 813 mm, which is lower than most of the state. The number of frost-free days ranges from 125 to 170 across the AVA and represents the number of days in the interval between the last spring day and the first autumn day with freezing temperatures. Based on a 30-year climatological temperature average using data from Columbia and Dane counties weather stations, Lake Wisconsin AVA falls in the low range of the Winkler Region II (2501−3000 GDD), with an average of 2555 GDD. The geology of the Lake Wisconsin AVA comprises Precambrian bedrock units consisting of crystalline igneous and metamorphic rocks, overlain by lower Paleozoic (Cambrian and Ordovician) sedimentary rocks. Specifically, Cambrian sandstone interbedded with secondary dolostone and shale constitute the Elk Mound, Tunnel City, and Trempealeau groups, whereas Ordovician dolostone with secondary sandstone and shale is assigned to the Prairie du Chien Group (Oneota and Shakopee formations).

The Lake Wisconsin AVA extends along the eastern margin of the Driftless Area or Paleozoic Plateau, which remained unglaciated during the last glacial advance. The USA upper Midwest region was covered by ice during four glacial stages: the Nebraskan, Kansan, Illinoisan, and Wisconsinan. The most recent major glacial advance of the North American Laurentide Ice Sheet was the Wisconsinan, which lasted from approximately 25,000 to 15,000 years ago (Attig et al. 2011). The glacial lobes of the Laurentide Ice Sheet extended down into the northern and eastern parts of the state, covering its terrain

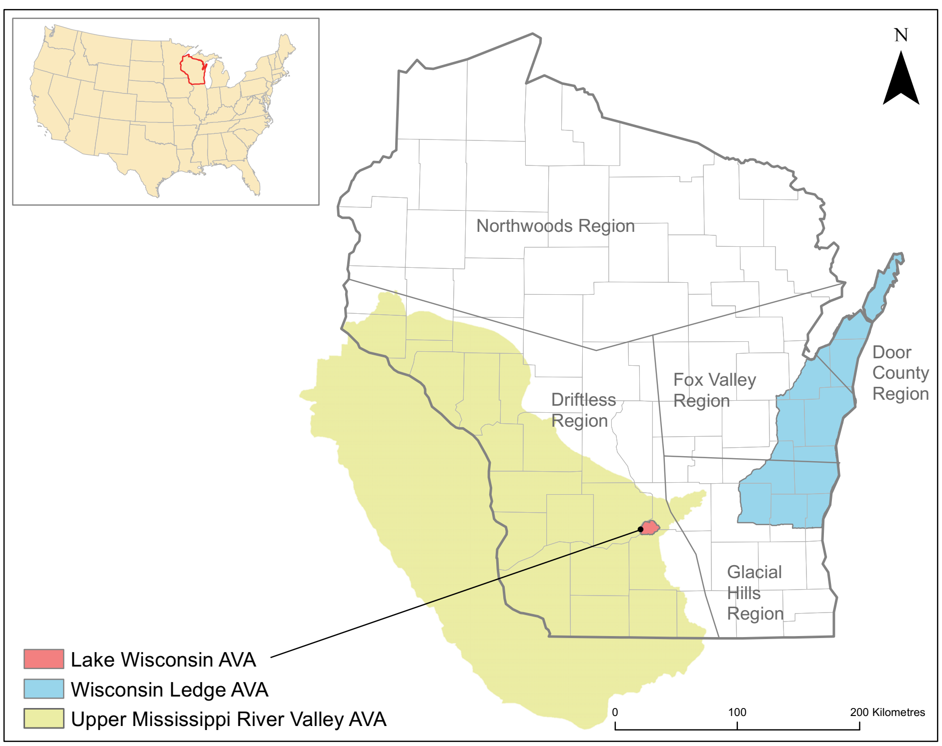

Figure 1. Map showing the five Wisconsin Wine Regions (Northwoods, Fox Valley, Glacial Hills, Door County, and Driftless) and the three American Viticultural Areas (AVA; Lake Wisconsin, the Upper Mississippi River Valley, and the Wisconsin Ledge).

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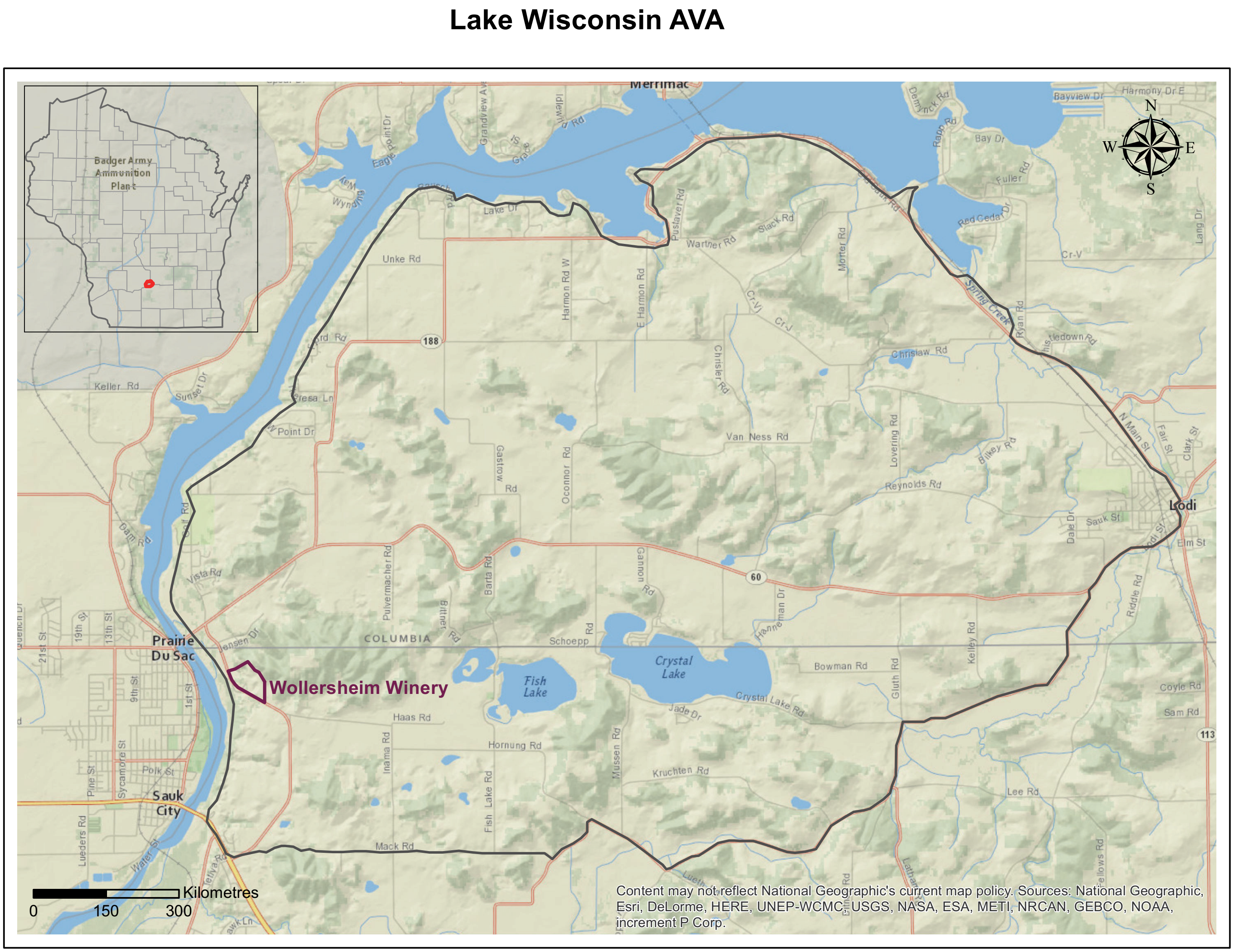

Figure 2. Map depicting the boundaries of the Lake Wisconsin American Viticultural Areas (AVA) and the location of historic Wollersheim Winery, the only winery in the Lake Wisconsin AVA.

in glacial drift, but never reached the Driftless Area in the western and southern parts of the state. The Driftless Area is characterized by a lack of glacial drift and an erosional topography consisting of flat-topped hills, steep forested slopes, and a well- developed, dendritic drainage system. The landscape is dissected by a network of steeply-cut valleys developed by stream erosion during the roughly 420 million years between the Silurian and Quaternary periods. In contrast, to the east of the Driftless Area, the land was glaciated, and the topography consists of small, gently undulating hills, a less developed drainage system, and numerous lakes, wetlands, and marshes. Although glaciers never reached the Driftless Area during the Quaternary (Mickelson et al. 1982), the effects of glaciation are observed in its peripheral deposits and landscapes, which were affected by periglacial processes (Stiles and Stensvold 2008).

The Lake Wisconsin AVA is situated in the transitional zone between the glaciated topography to its east and the unglaciated, driftless topography to its west. Its landscapes are part of the glacially-derived Holy Hill Formation, comprising the Horicon and Mapleview members (Fig. 3). The deposits consist of terminal moraines – large ridges of glacial debris that accumulated at the glacial limit – and outwash deposits of stratified sand and gravel found in the valleys of rivers that carried large volumes of glacial meltwater. Generally, postglacial deposits include sand, silt, clay, and organic materials deposited in stream valleys and lowlands, whereas glacial stream deposits include outwash and hummocky sand and gravel. Silt-sized loess, windblown from the floodplains of glacial meltwater rivers, was deposited on top of the land surface during the Wisconsinan Glaciation, but was subsequently eroded from many areas, and is now present as a thin discontinuous cover on uplands and slopes (Clayton and Attig 1997). Figure 3 depicts the glacial features across the state of Wisconsin, including the extent of the Horicon and Mapleview members

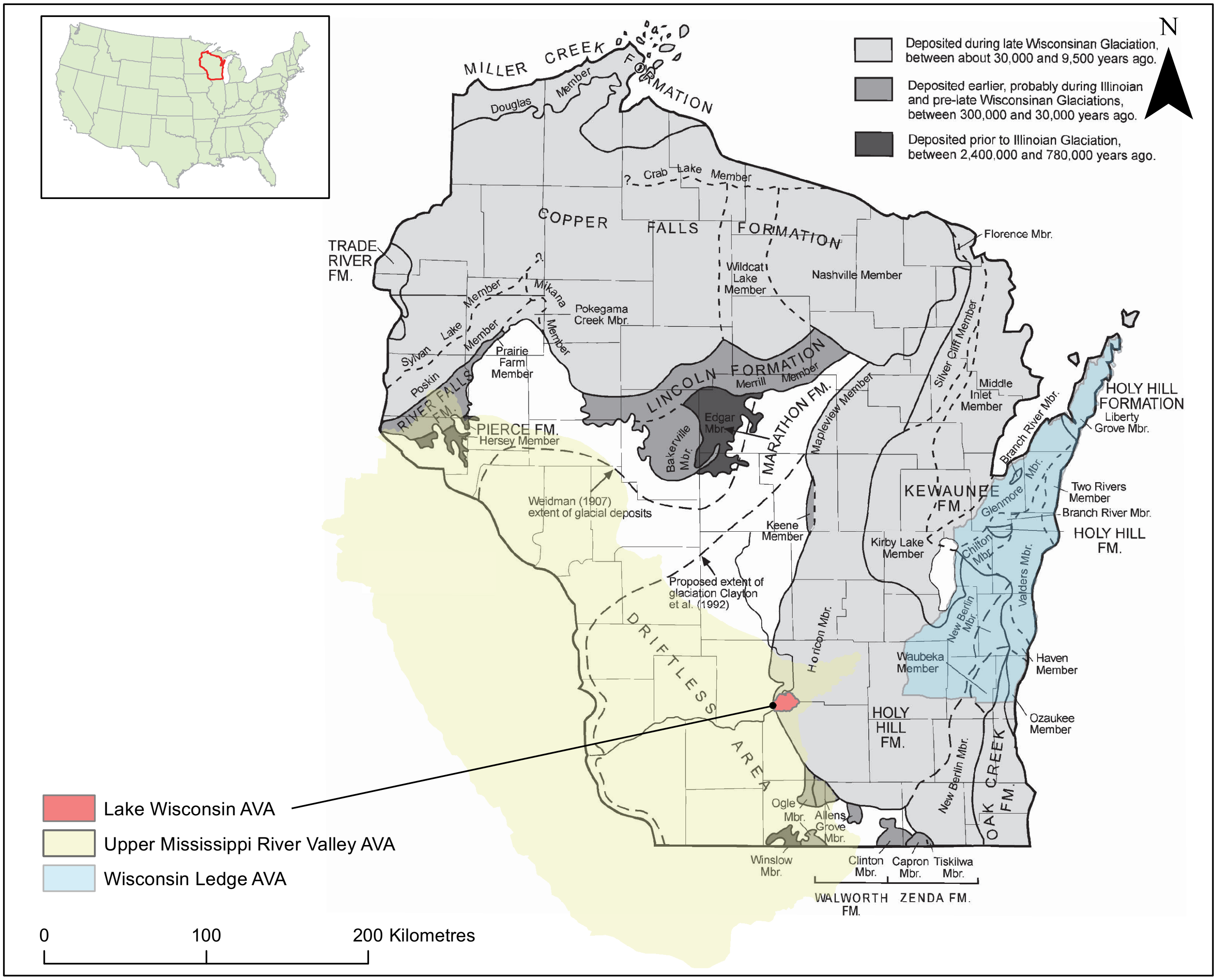

Figure 3. Map depicting the glacial features of the state of Wisconsin in relation to the locations of the state's three American Viticultural Areas (AVA). (from Syverson and Colgan 2004).

of the Holy Hill Formation, as well as the non-glaciated Driftless Area, in relation to the locations of the state's three AVAs.

The soils across the Lake Wisconsin AVA were developed on top of various types of parent materials, ranging from sandstone and dolostone bedrock to glacial till, outwash, and loess deposits. The parent materials covering the largest proportions of the AVA are calcareous sandy loam till, loess over glacial loamy till, silty sediments over stratified silts and sands, loess and/or silty slope alluvium, loess over calcareous sandy loam till, and loess over glacial till (USDA Natural Resources Conservation Service, Web Soil Survey data). Most cultivated soils in the region have developed in loess, making these windblown silt deposits the foundation of agriculture (Clayton and Attig 1997).

GLACIALLY INFLUENCED TERROIR IN OTHER VINE-GROWING REGIONS

Worldwide, many wine regions located where soils developed on glacially transported parent materials are known for producing outstanding wines. Generally, ice and glacial meltwater are the primary agents of deposition of the soil parent material, generating glacial till and glaciofluvial/ glaciolacustrine deposits, respectively. Windblown silt-sized loess deposits can also be generated from the floodplains of glacial meltwater rivers.

In New Zealand, vast portions of the North and South islands are covered by Quaternary glacial and fluvial sediments, and extensive outwash deposits are distributed across the lowlands. The majority of vineyards are planted on alluvium and outwash gravels. In the Central Otago region, nearly half of the planted vineyards are located on glacial gravels; in Hawkes Bay, which includes the Gimblett Gravels wine region, approximately 63% of vineyards are located on outwash deposits; and in the Marlborough and Waipara wine regions, most vineyards are planted on alluvium and outwash gravels (Imre and Mauk 2009).

In Canada, the soils of the Niagara Peninsula wine region developed on glacial till resulting from the advance and retreat of ice during Quaternary continental glaciations, and on glaciolacustrine and glaciofluvial deposits formed during interglacial periods. The Niagara vineyards planted on these soils define two distinctive terroirs: the flat area of the Lake Iroquois Plain extending between Lake Ontario and Lake Iroquois, and the Escarpment, consisting of the Lake Iroquois bench terraces and the slopes above the Niagara Escarpment (Haynes 2000). In the Canadian Okanagan and Similkameen valleys of British Columbia, many glacial advances generated soil parent materials consisting of unconsolidated glacial deposits. In the Okanagan Valley, the thickness of Pleistocene glacial deposits is nearly 100 m, and glaciofluvial deposits cover the sides of the valley (Taylor et al. 2002). Most vineyards in the Okanagan and Similkameen valleys are planted on soils derived from these glacial sediments, which include glaciofluvial, fluvial fan, and glaciolacustrine deposits (Bowen et al. 2005).

In the USA, the Columbia Valley AVA, which encompasses several other AVAs in Washington and Oregon, has soils derived from Quaternary glacial sediment and aeolian deposits. Recurring Pleistocene glacial outburst flooding events, known as the Missoula floods, generated glacial flood sediment deposits known as Touchet beds, which accumulated in river valleys and covered the landscape (Meinert and Bussaca 2000, 2002; Pogue 2009). Deposits of windblown loess of varying thickness overlie the Touchet beds. Most vineyards in the Columbia Basin are planted on soils derived from deposits of loess and glacial flood sediments (Pogue 2009). In the Finger Lakes AVA of New York state, vineyards are planted on soils consisting of varied accumulations of gravel, sand, silt, and clay produced by glacial processes (Swinchatt 2012). The Devonian bedrock, which is now covered by Pleistocene glacial deposits, was scoured repeatedly during glacial advances. The retreating glaciers generated the glacial meltwater that formed the Finger Lakes and carved a landscape of moraines, glacial till, and glacial outwash (Meinert and Curtin 2005).

In France, the landscapes of the Rhone Valley and Bordeaux wine regions have abundant glacial sediments originating from the Alps. In the Rhone Valley, alpine glaciers descended from the Alps, scouring valleys and leaving behind an assortment of glacial till and moraine deposits. Meltwater and subsequent glacial floods re-sorted some of these deposits into extensive terraces and gravel plateaus where many vineyard sites are located (Wilson 1998). In the Bordeaux wine region, Medoc and Graves vineyards are located on gravel terrace mounds. The gravel-rich soils of these areas developed on the outwash deposits associated with the Garonne River interglacial floods and the moraine deposits generated during the Pleistocene glaciation (Wilson 1998).

These glacially influenced wine regions produce exceptional wines in a unique terroir consisting of soils developed on transported, glacially derived parent materials. The glacial soils provide distinct vineyard sites and are characterized by good internal drainage and moderate fertility and water-holding capacity, controlling vine vigor and promoting grape ripening.

TERROIR CHARACTERIZATION OF WOLLERSHEIM WINERY

Historic Wollersheim Winery Background

Wollersheim Winery is a National Historic Site, with a history extending back to the 1840s, when the legendary Hungarian nobleman Agoston Haraszthy first settled on the estate. One of Wisconsin's largest wineries, top wine producers, and a leader in the Midwestern wine industry, Wollersheim Winery produces approximately 240,000 gallons or 1.2 million bottles annually, which corresponds to approximately 1410 tons of grapes. Most are custom-grown grapes, including Sangiovese, Chardonnay, Riesling, Pinot Noir, Seyval Blanc, Carignan, and Muscat from Washington (335 tons), California (10 tons), and New York (783 tons); however, approximately 20% (282 tons) are Wisconsin-grown grapes, including 25 acres of vineyards located on site. Four winter-hardy hybrid grape varieties are cultivated on the Wollersheim Winery estate, including two French-American red hybrids (Marechal Foch and Leon Millot) and two Wisconsin-native American white hybrids (St. Pepin and LaCrosse), producing eight different estate wines made entirely from Wisconsin-grown grapes. Specifically, the grapes grown in the young, flat vineyards produce light-bodied wines (Prairie Blush, Eagle White, Prairie Sunburst Red, and Ice Wine); grapes from the medium-aged vines planted on medium-sloped vineyards produce medium-bodied wines (Ruby Nouveau, Bon Vivant, and Domaine du Sac); and grapes from the oldest and steepest-sloped vineyard produce the rich, full-bodied Domaine Reserve wine.

Best known for its distinctive regional wines, Wollersheim Winery has received numerous medals and awards in national and international wine competitions. Some of the most recent Wollersheim Winery accolades include the 2012 Winery of the Year award at the San Diego International Wine Competition and the 2015 Small Winery of the Year award at the Riverside International Wine Competition. It has also won many awards for its estate wines, such as the 2015 Prairie Blush, which most recently was awarded the Chairman's Trophy at the 2016 Ultimate Wine Competition in Hawthorne, New York, and gold medals at the 2016 New World International Wine Competition in Ontario, Canada, the 2016 Winemaker Challenge International Wine Competition in San Diego, California, and the 2016 Dan Berger's International Wine Competition in Sonoma County, California. Other estate wines, including Domaine Reserve, Domaine du Sac, Eagle White, and Prairie Sunburst Red, have consistently won awards at numerous competitions; a listing of the various awards can be found on the winery's website (http://www.wollersheim.com).

This research study provides a terroir characterization of the Wollersheim Winery vineyards, and utilizes analyses of soil type, texture, geochemistry, and mineralogy to understand the interaction of environmental factors influencing the character and quality of Wollersheim wines. The study further examines local-scale vineyard variability between two plots (Domaine Reserve and Lot 19) that are cultivated with the same grape variety (Marechal Foch) to determine the controls on small-scale variability in grape quality and Wollersheim wines.

Materials, Methods, and Data Acquisition

Total major and select minor and trace element compositions were determined on powdered rock samples and on the fine fraction of vineyard soil samples, which were powdered and fused for x-ray fluorescence (XRF) analysis. Loss on ignition (LOI) was determined by heating 1 gram of sample for 10 minutes in a muffle furnace at 1050°C and calculating the mass difference. The major element and select minor and trace element compositions were obtained from glass disks fused at 1050°C in a Claisse M4 fluxer and analyzed using a Bruker S4 Pioneer XRF in the Department of Geosciences, University of Wisconsin–Milwaukee. Plant-available soil chemistry analysis was conducted by the University of Wisconsin Soil Testing Laboratory in Madison, Wisconsin, to determine concentrations of phosphorus, potassium, calcium, magnesium, sulfur, zinc, manganese, and boron, as well as pH, cation exchange capacity, and organic matter. Soil texture was determined by grain size analysis using a Malvern Mastersizer 2000E laser diffraction particle-size analyzer. In the laser diffraction method, a laser beam is passed through a sample to measure the angular variation in scattered light intensity, which is used to evaluate the particle size distribution within a sample. Soil and rock mineralogy were determined non-quantitatively on a portion of each powdered sample by x-ray diffraction (XRD) analysis. Random mounts were prepared by packing the fine powders to a flat surface onto a cavity mount sample holder capable of assuming different orientations. Samples were analyzed in the Department of Geosciences at the University of Wisconsin–Milwaukee using a Bruker D8 Focus XRD system (Cu Ka radiation, 4 s per 0.01° 2θ, 2°–60° range, Sol-X energy dispersive detector). Minerals were identified by searching the International Centre for Diffraction Data (ICDD) database of standard X-ray powder diffraction patterns for a match with the pattern of the unknown.

Vine trunk circumferences were measured at two plots, Lot 19 and Domaine Reserve, on September 14, 2014. Vine trunk circumference measurements can be used as an indicator of vine vigor variation (Imre and Mauk 2011). The measurements were collected from every vine at every other row, approximately 20 cm from the ground surface at the narrow part of the vine.

Geophysical surveys, including electromagnetic induction (EMI) and electrical resistivity tomography (ERT) were conducted at two plots, Lot 19 and Domaine Reserve, on May 18, 2014. The EMI surveys were carried out with a Geonics EM-31-MK2 ground conductivity meter, which has a fixed coil spacing (3.66 m) and a single frequency (9.8 kHz) generating the primary magnetic field, with depths of exploration of 3 m in the horizontal dipole mode and 6 m in the vertical dipole mode. The Geonics EM-31-MK2 ground conductivity meter is calibrated for a standard operating height of 1 m above the ground, which is approximately waist height. The EMI surveys were performed at walking speed, and apparent electrical conductivity (ECa) measurements were collected from 104 locations at each plot along alternating transects between every other row of vines, for a total of 9 transects completed at each plot. ECa measurements in the horizontal and vertical dipole modes were read directly from the integrated data logger, and the measurement locations were georeferenced by means of a GPS receiver. The ECa datasets for both plots were downloaded with the Geonics DAT31W software program and interpolated using the ordinary kriging method with the Esri ArcGIS Desktop software program.

The ERT survey was conducted using a GF Instruments ARES-G4 unit, with a standard survey line of 115 m consisting of three cables and a total of 24 electrodes. The electrodes were spaced 3 m apart in the Wenner array, attaining a maximum exploration depth of 14 m. The Wenner array consists of four electrodes spaced equally in a straight line at ground surface; current is applied to the two outer (current) electrodes and the potential difference measured at the two inner (potential) electrodes. The ERT method records the contrast in apparent electrical resistivity (ER) in soil, providing an estimate of the horizontal and vertical lithological variations. Two profiles were completed at each plot, one near the top row and one near the bottom row of vines. The profiles were used to determine lateral changes in resistivity, identifying the lateral continuity of layers. The ER data for all profiles were downloaded with the GF Instruments ARES v5.0 program and exported into RES2DINV (Geotomo) inversion program for processing. A common logarithmic scale was applied to all profiles for appropriate comparison.

Results and Discussion

The Wollersheim Winery vineyards are located on a hill overlooking the Wisconsin River, at elevations between approximately 213 and 306 m, on south and southwest-facing gentle slopes. The vines are planted 2 m apart and the distance between rows is 3 m, which allows sufficient space for farming equipment. The 25 acres of bearing vineyards consist of approximately 700 vines per acre for a total of 17,500 vines on site. The landforms are streamlined hills and valleys shaped by glaciers and glacial stream deposits consisting of outwash and hummocky sand and gravel (Mickelson 2007). The glacial deposits are part of the Horicon Member of the Holy Hill Formation, which is characterized by glacial till comprising brown gravelly, clayey, silty sand, and dolomite derived from Ordovician formations; these glacial deposits are overlain by loess (Clayton and Attig 1997).

The climate is moderated by the Wisconsin River, and air drainage in the river valley inhibits frost in the vineyards. In the Wollersheim Winery area, where the average growing season ranges from April 1st to October 31st, a total of 2382 (base 50°F) GDD were recorded in 2014. Based on a 30-year climatological temperature average (1981−2010), Wollersheim Winery falls in the low range of the Winkler Region II (2501−3000 GDD) with an average of 2652 GDD. In comparison, Napa, California falls in the middle range of the Winkler Region III

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Figure 4. Location map of Wollersheim Winery vineyards illustrating the distribution of soil types, and soil sample and resistivity profile locations.

(3001–3500 GDD) with an average of 3297 GDD, and Walla Walla, Washington falls in the high range of the Winkler Region II (2501–3000 GDD) with an average of 2959 GDD.

Vineyard Soil Properties

To characterize the terroir and assess vineyard variability at Wollersheim Winery, a total of 12 soil profiles were examined and sampled throughout the vineyards (Fig. 4). Two rock samples were also collected in the vicinity of the vineyards. The first was from a sandstone outcrop exposed along Highway 60, approximately two kilometres to the north-northeast of the Wollersheim vineyards; the second was from a representative dolostone boulder (approximately 2 x 4 x 2 m) at the top of the Domaine Reserve plot that was transported from the Ordovician Prairie du Chien Group dolostone bedrock bordering the east boundary of the vineyards. The elevations of the soil sample locations range from 236 to 286 m, and the maximum depths of the soil profiles range from 50 to 70 cm below ground surface, across horizons A, E, and B.

Based on the USDA taxonomic classification, the vineyard soils are Alfisols, which is a soil order characterized by moderately weathered and leached clay-rich soils having high to medium base saturation, relatively high native fertility, and abundant iron and aluminum. The soils are further classified as the subgroup Udalfs (Alfisols found in humid climates) and the great group Hapludalfs (Udalfs with minimum horizonation). Specifically, the soils are Typic and Mollic Hapludalfs in a mesic soil temperature regime and udic soil moisture regime, indicating that the soils are similar to other Alfisols (Typic) or have a darkened and organic-rich surface horizon (Mollic). Based on a water budget analysis using the National Oceanographic and Atmospheric Administration's National Climate Data Centre climate normals and the USDA Official Soil Series descriptions (textures and profile thicknesses) to determine the water status of soils over the growing season, the soils are seasonally moist in normal years, and generally experience a surplus throughout the year. Recharge periods extend from April through October, when temperatures are generally above 5°C. Although droughts likely alter the water balance, drought years do not represent 'normal years' in this region.

Based on the USDA Official Soil Series descriptions, the soils are part of the Gaphill−Rockbluff complex, and Boyer, Kegonsa, and Seaton Series, which are characterized by very deep, well-drained soils. Based on the grain size analysis, silt- and sand-sized grains dominate the soil samples collected throughout the vineyards, with average silt and sand compositions of 59% and 34%, respectively. The soils plot in the silty loam and sandy loam fields of the USDA soil texture triangle (Fig. 5), and these textures are in general agreement with the USDA taxonomic classification for these soils. Soil samples collected from the highest elevations in the northern and eastern parts of the property (DR-1, DR-2, and Lot 10A/B) contain the highest silt content (79–80%) and correspond to areas of steeper slope, thinner soil, and shallower depth to bedrock.

Most of the vineyard soils are silty loams developed on parent materials consisting of windblown loess deposits; these soils are represented by 8 of the 12 soil samples collected and cover approximately 42% of the property. The vineyard soils in the northern and central parts of the property, represented by soil samples Lot 10A/B, Lot 14, and Lot 20, underlie approximately 27% of the property, and consist of sandy loams derived from loamy outwash and glaciofluvial deposits underlain by outwash. Along the eastern property boundary, in a small area covering approximately 4% of the property and characterized by the highest elevations and steepest slope, soil sample DR-1 is a sandy loam developed on loamy colluvium and sandy deposits overlying sandstone bedrock. The remainder of the property (approximately 25%) consists mostly of a centrally located gravel pit developed in gravelly outwash.

Vineyard Soil Chemistry and Mineralogy

Soil chemical analyses were carried out for organic matter, cation exchange capacity, and pH, along with plant-available macronutrients (potassium, calcium, magnesium, phosphorus, and sulfur) and micronutrients (boron, manganese, and zinc) that are essential elements necessary for completion of the plant life cycle (Table 2). All these elements have important roles in the metabolic functions of vines and require that minimum levels be maintained. The physical and chemical characteristics of the vineyard soils, such as texture, pH, organic matter, and cation exchange capacity, affect the nutrient pool, availability, adsorption, and retention potential. Fine-grained, clayey soils can reduce the availability of potassium to vines, whereas coarse-grained, sandy soils are prone to leaching and can drain nutrients from the soils (Lambert et al. 2008). The silty loam and sandy loam vineyard soil samples are dominated by silt- and sand-sized grains, providing a good balance between drainage and water holding capacity. The pH values of the vineyard soil samples, ranging from 5.6 to 7.6, indicate moderately acidic to slightly alkaline conditions, which provide good nutrient availability and balance for the health of the vines. Soils rich in organic matter are generally high in available nutrients, as decomposition of organic matter adds nutrients to soil and improves water-holding capacity. Cation exchange capacity, which is influenced by the soil's organic matter and clay content, affects the ability of soil to hold positively charged nutrients for plant uptake (Dami et al. 2005). The highest organic matter percentages and cation exchange capacities, ranging from 1.1−1.3% and 12−13 cmol/kg, respectively, correspond to vineyard soil samples containing the highest silt content collected from the vineyards located in the northern and eastern parts of the property.

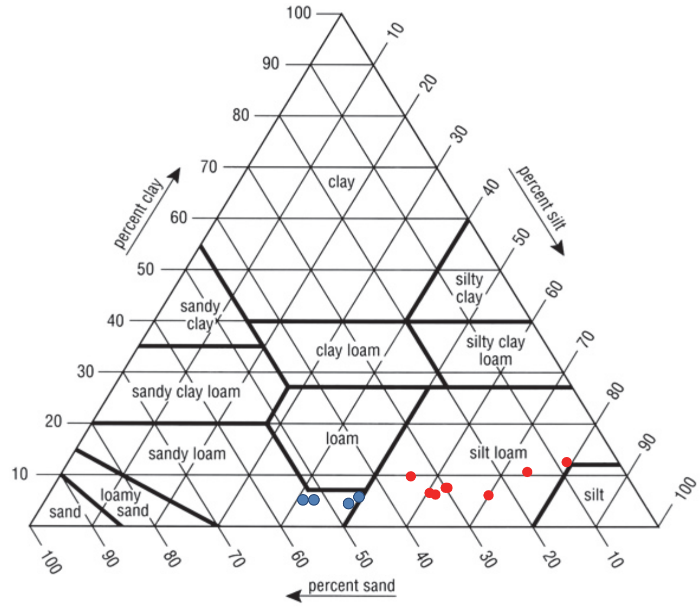

Figure 5. Ternary diagram showing the vineyard soil textures plotting in the silt loam and sandy loam fields of the United States Department of Agriculture (USDA) Soil Texture Triangle.

The concentrations of plant-available macronutrients potassium (24–112 ppm), calcium (278–1587 ppm), magnesium (62–658 ppm), phosphorus (7–49 ppm), and sulfur (1–5 ppm), and micronutrients boron (0.2–0.6 ppm), manganese (13–89 ppm), and zinc (0.4–2.1 ppm), indicate significant variability in the vineyard soils. Some of these nutrient concentrations are outside the ranges specified by Moyer et al. (2014) in their pre-plant soil fertility guidelines for establishing productive vineyards, and by Dami et al. (2005) in the Midwest Grape Production Guide. However, when assessing the nutrient requirements of established vineyards, analyzing vine tissue samples in conjunction with soil samples is critical in determining vine nutrient status and identifying potential deficiencies (Moyer et al. 2014). Overall, the plant-available soil chemistry shows the most variability for calcium, magnesium, and potassium; the highest concentrations of these elements are found in soils having the highest silt content in the northern and eastern parts of the property, i.e. in areas of steeper slope, thinner soil, and shallower depths to bedrock, where the vineyards producing the lowest yields and highest quality grapes are planted.

The XRF total elemental analysis conducted on the fine fraction (silt and clay) of the soil samples indicates some variation in the chemical composition of the vineyard soils (Table 3). These elemental abundances represent the total concentrations in the soil and are indicative of the general vineyard soil conditions, whereas plant-available essential elements (Table 2), which are necessary for the completion of the plant life

Table 2. Summary of plant-available soil chemistry and texture. The variability in nutrient levels is influenced by the vineyard soil properties, which affect the nutrient pool, availability, adsorption, and retention potential.

Sample ID	DR-1	DR-2	Lot 5	Lot 6	Lot 7	Lot 8	Lot 9	Lot 10A/B	Lot 14	Lot 19-1	Lot 19-2	Lot 20
Depth (cm)	50	50	65	65	70	60	55	50	55	50	50	50
Soil Type	1145F	SmC2	SmB	SmB	SmB	SmB	SmC2	BoD2	BoD2	KeB	KeB	BoC2
Parent Material (USDA WSS)	Loamy colluvium over sandy residuum weathered from sandstone	Loess and/or silty slope alluvium	Loess and/or silty slope alluvium	Loess and/or silty slope alluvium	Loess and/or silty slope alluvium	Loess and/or silty slope alluvium	Loess and/or silty slope alluvium	Loamy outwash over sandy and gravelly outwash	Loamy outwash over sandy and gravelly outwash	Loess over sandy and gravelly outwash	Loess over sandy and gravelly outwash	Fine-loamy fluvial deposits over sandy-gravelly outwash
Clay	5.8	12.3	7.3	7.3	5.0	5.5	4.2	10.4	6.3	4.9	6.0	9.5
Silt	70.3	79.6	62.4	63.0	41.0	49.7	48.7	74.2	60.6	42.7	61.7	56.0
Very Fine Sand	10.0	4.2	10.8	7.8	12.4	12.5	12.9	8.3	10.0	7.1	11.7	7.6
Fine Sand	8.7	2.0	14.6	12.0	26.4	20.5	20.0	5.0	9.9	17.3	11.0	12.7
Medium Sand	5.0	1.8	4.8	9.3	14.7	11.5	13.0	2.1	6.8	21.4	7.3	11.3
Coarse Sand	0.21	0.1	0.0	0.59	0.46	0.34	1.2	0.006	5.9	6.4	2.2	2.9
Very Coarse Sand	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.56	0.06	0.10	0.03
pH	7.6	5.6	5.7	6.0	6.1	5.9	5.9	6.0	7.1	7.0	7.3	7.0
OM %	1.3	1.1	0.7	0.6	0.3	0.4	0.7	1.1	1.0	0.7	1.0	1.3
CEC (cmol/kg)	12	9	3	4	2	2	2	13	9	4	9	10
P (ppm)	7	28	35	28	34	28	49	8	28	24	16	8
K (ppm)	70	95	50	49	34	24	37	112	79	44	63	79
Ca (ppm)	1587	994	465	567	278	354	482	1384	1234	689	1172	1211
Mg (ppm)	469	373	96	150	68	62	66	658	442	225	515	586
B (ppm)	0.5	0.3	0.3	0.3	0.2	0.2	0.2	0.4	0.4	0.3	0.4	0.6
Mn (ppm)	13	27	36	25	14	21	89	35	30	43	29	28
Zn (ppm)	0.9	0.4	1.5	0.7	0.4	0.4	2.1	0.5	1.2	1.5	1.0	1.0
S (ppm)	3.5	2.0	3.3	1.2	1.0	2.3	3.5	2.3	5.0	2.3	2.3	1.8

Notes:
1145F - Gaphill-Rockbluff complex, 30 to 60% slopes; SmC2 - Seaton silt loam, 6–12% slopes, eroded; SmB - Seaton silt loam, 2–6% slopes; BoD2 - Boyer sandy loam, 12–20% slopes, eroded; KeB - Kegonsa silt loam, 2–6% slopes; BoC2 - Boyer sandy loam, 6–12% slopes, eroded; USDA WSS - United States Department of Agriculture Web Soil Survey (http://websoilsurvey.nrcs.usda.gov); OM - Organic matter; CEC - Cation exchange capacity

cycle, must be dissolved in an ionized water solution to allow uptake into the metabolism of the vines. Overall, the most variability in total concentrations is noted for SiO_2 (45.16–78.73%), CaO (0.67–9.82%), MgO (0.5–.94%), Al_2O_3 (8.13–13.30%), and Fe_2O_3 (2.36−7.22%). The vineyard soils contain average total concentrations of K_2O, CaO, MgO, and P_2O_5 of 2.55%, 2.03%, 1.64%, and 0.14%, respectively; and Fe_2O_3, MnO, Ni, and Zn are present in the vineyard soils in average total concentrations of 38,650 parts per million (ppm), 1200 ppm, 25.2 ppm, and 67.5 ppm, respectively. The dolostone rock sample consists primarily of CaO (32.77%), MgO (20.72%), and SiO_2 (2.25%), whereas the sandstone sample is dominated by SiO_2 (53.77%), CaO (14.12%), and MgO (9.51%). The variation in the chemical composition of the vineyard soils reflects the diversity of parent materials in which the soils have developed.

The XRD analysis indicates that the soil mineralogy is dominated by quartz, plagioclase (albite/anorthite/laboradorite), orthoclase (microcline/sanidine/adularia), dolomite, and minor biotite, hornblende, and various clay minerals (vermiculite, montmorillonite). The dolostone consists primarily of dolomite, along with minor quartz and clay minerals, whereas the sandstone is composed of quartz and dolomite, and minor clay minerals, indicating that it is a dolomite-rich sandstone. Unpublished field notes from Road Materials Investigations Reports prepared by the Wisconsin Geological and Natural History Survey show that dolomite is the most common pebble lithotype in the Holy Hill Formation, based on analyses of rock types present in deposits of sand and gravel throughout Dane County. East of Sauk City (Fig. 2), more than 50% of the pebbles in glacial till consist of coarse-grained, mafic igneous rock to depths of at least 15 m (Clayton and Attig 1997). Consistent with chemical analyses indicating elevated MgO and CaO, soil samples DR-1, Lot-19-2, and Lot 20 contained dolomite, which may indicate the influence of weathered dolostone and dolomite-rich sandstone in the soils located in closest proximity to the bedrock outcrops. The relatively high Fe_2O_3 content in the soils relative to the rock samples may result from the oxidation of ferromagnesian minerals such as hornblende and biotite from mafic igneous rocks.

The compositional variation of the soils is illustrated graphically on plots of major element oxides versus SiO_2 (Fig. 6), and spatially on maps depicting interpolated concentrations across the study area (Fig. 7). The plots show that SiO_2 has a strong inverse correlation with CaO and MgO; high coefficients of determination explain 80% of the variation. The soils are highly depleted in CaO and MgO relative to the dolostone sample and slightly depleted relative to the dolomite-rich sandstone sample. Fe_2O_3, P_2O_5, and MnO are also inversely correlated with SiO_2, and have lower coefficients of determination that account for 40–60% of the variation. The soils are highly enriched in Fe_2O_3, slightly enriched in P_2O_5, and have similar

Table 3. Summary of total elemental soil analysis and mineralogy. The variation in the chemical and mineralogical composition of the vineyard soils is indicative of the diversity of parent materials in which the soils have developed and the influence of the dolostone and dolomite-rich sandstone weathering in the soils located in closest proximity to the bedrock outcrops.

Sample ID	DR-1	DR-2	Lot 5	Lot 6	Lot 7	Lot 8	Lot 9	Lot 10A/B	Lot 14	Lot 19-1	Lot 19-2	Lot 20	Dolostone	Sandstone
Elevation (m)	286	276	275	274	272	272	264	276	261	236	236	244	286	286
Al_2O_3	9.70	11.18	9.18	9.83	9.49	9.27	8.13	11.60	10.47	10.08	8.96	13.30	0.62	0.59
TiO_2	0.57	0.73	0.76	0.74	0.77	0.71	0.72	0.74	0.65	0.79	0.47	0.75	0.02	0.06
Fe_2O_3	3.63	3.77	2.70	3.13	3.15	2.90	2.36	4.21	3.87	4.47	4.97	7.22	0.32	0.88
K_2O	3.14	2.55	2.46	2.48	2.57	2.51	2.37	2.52	2.40	2.68	2.21	2.73	0.27	0.19
MgO	4.01	0.85	0.67	0.77	0.74	0.70	0.50	0.99	1.32	0.90	6.94	1.27	20.72	9.51
CaO	5.43	0.67	0.72	0.69	0.78	0.77	0.83	0.79	1.61	1.08	9.82	1.14	32.77	14.12
Na_2O	0.65	1.04	1.14	1.16	1.18	1.23	1.20	1.05	1.20	0.97	0.62	0.72	0.0	0.0
P_2O_5	0.16	0.11	0.12	0.10	0.12	0.10	0.13	0.07	0.14	0.17	0.21	0.20	0.03	0.09
MnO	0.10	0.10	0.08	0.08	0.06	0.08	0.14	0.12	0.10	0.19	0.21	0.19	0.09	0.05
Zr	427.28	441.49	490.58	510.92	556.97	526.00	617.09	497.27	484.21	509.67	250.06	458.42	<10.9	62.48
V	75.20	81.36	57.73	68.01	64.95	71.75	47.08	100.57	63.27	77.14	80.58	150.72	<14.0	<14.6
Zn	47.04	68.15	66.26	69.20	58.09	58.73	49.77	59.41	72.86	66.39	86.83	115.75	<16.9	<16.3
Ni	32.50	31.76	14.71	35.01	11.11	6.41	7.20	28.08	35.15	30.07	18.89	51.61	<13.2	<14.2
Cr	59.37	79.62	68.24	68.55	61.57	67.43	67.04	54.60	55.52	51.27	61.96	96.12	18.54	18.36
Ce	123.08	143.75	146.38	131.08	125.58	141.23	77.48	138.92	235.29	237.17	181.14	161.72	<49.6	107.36
Sr	143.69	129.88	125.59	121.99	175.41	192.21	123.04	128.12	139.22	118.17	118.96	110.97	125.73	50.02
Ba	410.43	587.53	647.02	614.41	626.27	605.32	684.42	519.50	499.99	541.91	369.69	492.74	<47.1	<47.0
Quartz	xxx	xxx	xxx	xxx	xxx	xxx	xxx	xxx	xxx	xxx	xxx	xxx	x	xxx
Plagioclase[1]	x	x	xx	xx	x	x	xx	xx	x	xx		x		
Orthoclase[2]	xx	xx	x		x	xx	x	xx	x	xx	x	xx		
Dolomite	xx										xx	x	xxx	xxx
Biotite	x	x	x	x	x	x	x	x	x	x		x		
Hornblende		x						x	x		x	x		
Clay[3]	x	x	x	x	x	x	x	x	x	x	x	x	x	x

Notes:
Concentrations are in weight % for oxides and ppm for elements.
[1]Plagioclase - Albite, Anorthite, Labradorite
[2]Orthoclase - Microcline, Sanidine, Adularia
[3]Clay - Vermiculite, Montmorillonite
Relative mineral abundance based on visual evaluation of peak height and intensity (xxx = most abundant; x = least abundant)

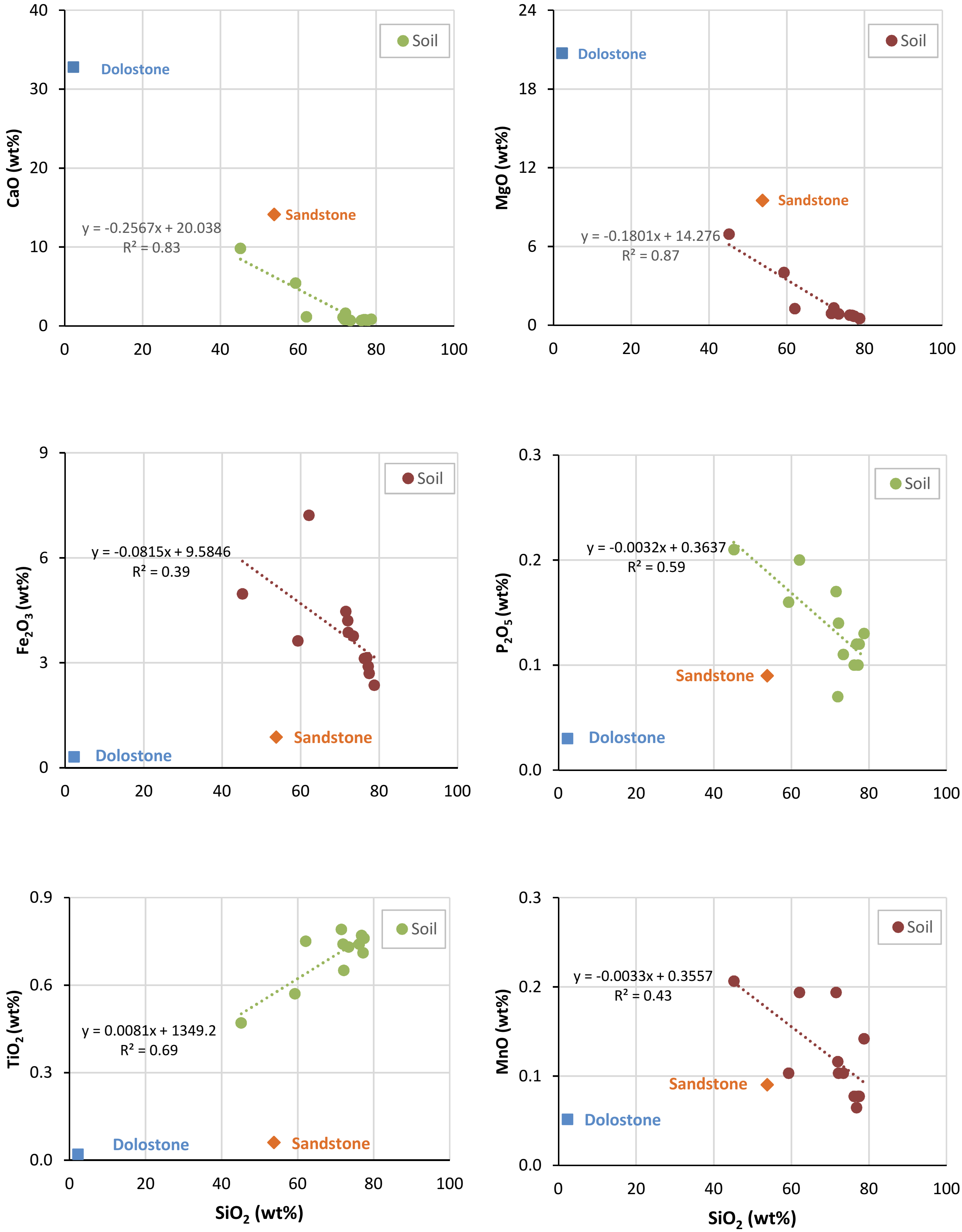

Figure 6. Harker diagrams depicting the compositional variation of selected major elements in soils relative to bedrock samples, reflecting the diversity of soil parent materials and the influence from the dolostone and dolomite-rich sandstone bedrock.

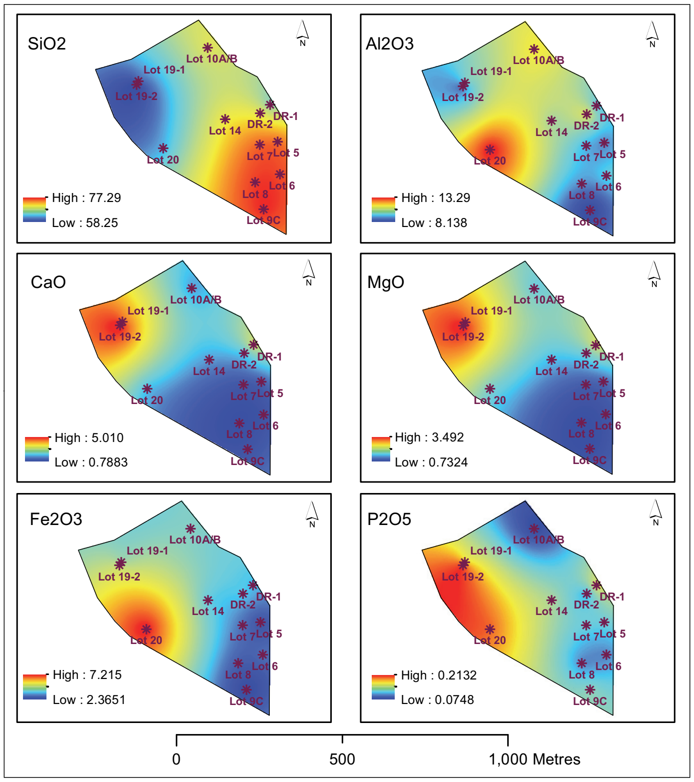

Figure 7. Map showing the spatial distribution of selected major elements in the Wollersheim Winery vineyards (see Figs. 2, 4), reflecting the variety of parent materials in which the soils formed.

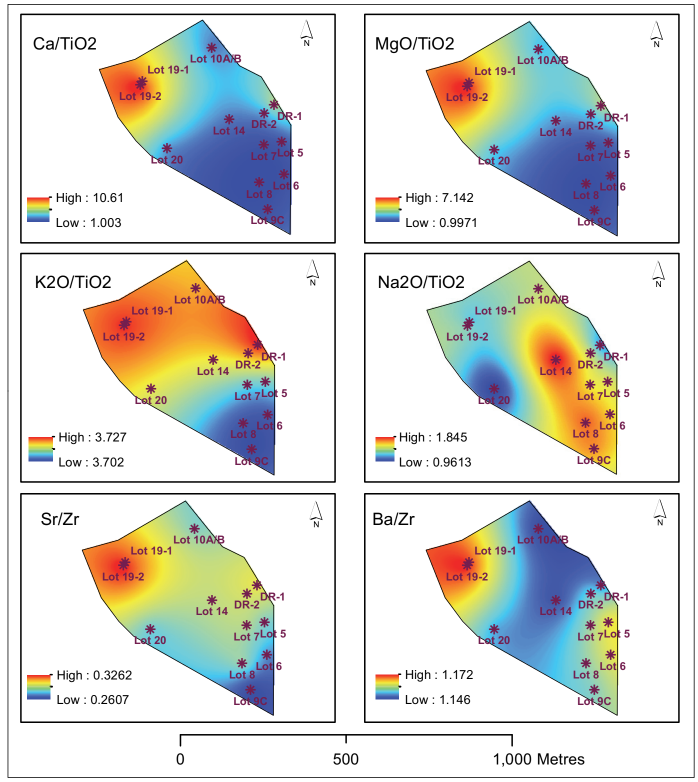

Figure 8. Map showing the spatial distribution and degree of chemical weathering in the Wollersheim Winery vineyards (see Figs. 2, 4), using ratios of selected mobile to immobile elements. More extensive chemical weathering is associated with vineyards in the north, east, and south.

MnO compositions relative to the dolostone and sandstone samples. TiO_2 and SiO_2 are positively correlated, with a coefficient of determination that accounts for 70% of the variation. The soils are significantly enriched in TiO_2 relative to the bedrock samples. Additionally, SiO_2 has a strong positive correlation with Zr and Ba; high coefficients of determination explain 80–90% of the variation (not shown). Again, these compositional differences reflect the diversity of parent materials, which include windblown loess, loamy outwash and glaciofluvial deposits underlain by outwash, and loamy colluvium and sandy deposits overlying sandstone bedrock.

Figure 7 depicts the spatial compositional variability in soils, based on interpolated concentrations across the study area. Overall, the soils with the highest SiO_2 contents are found in the southern half, whereas the lowest SiO_2 contents occur in the northwest corner of the study area. Conversely, the soils with the highest CaO and MgO contents are present in the northwest corner and the lowest CaO and MgO contents are in the southern half of the study area. The highest Fe_2O_3 and Al_2O_3 compositions are found in soils from the west and north-central parts of the study area, and the highest P_2O_5 contents are located in the west and northwestern corner. Of note are soil samples DR-1, Lot-19-2, and Lot 20, which contain the lowest percentages of SiO_2 (62.09−45.16%), the highest LOIs (7.95−19.09%), and elevated concentrations of MgO (1.27−6.94%) and CaO (1.14−9.82%) relative to the rest of the soil samples. These compositions reflect the dolostone and dolomite-rich sandstone bedrock influence on the soils of these vineyard plots, caused by dissolution of primary minerals during rock weathering. Forested ridges underlain by dolostone of the Ordovician Prairie du Chien Group border the east boundary of the vineyards, and weathered outcrops of dolomite-rich sandstone are observed approximately 2 km to the northeast, along Highway 60.

The major element chemistry was used to assess the general spatial distribution and degree of chemical weathering at the local scale in the vineyard soils (Fig. 8). Ratios of mobile elements (Ca, Mg, K, Na, Sr, and Ba used as proxies for primary minerals) to the immobile elements Ti and Zr were calculated and interpolated across the study area. Generally, the ratios of CaO/TiO_2, MgO/TiO_2, Sr/Zr, Ba/Zr, and to a lesser degree K_2O/TiO_2, representing minerals such as calcite, dolomite, plagioclase, hornblende, and mica, increase toward the northwest, indicating greater chemical weathering in the northern, eastern, and southern areas of the property. In the north and east, greater chemical weathering correlates with areas of steeper slope, thinner soil, shallower depth to bedrock, and highest soil silt content, where the vineyards producing the lowest yields and highest quality grapes are located. Wollersheim Winery winemaker, Philippe Coquard, states that the grapes from these vineyard plots (Lots 10A/B, 11 [not sampled], and Domaine Reserve) consistently produce the lowest yields and reach the highest sugar levels. With average Brix (estimated concentration of dissolved sugar) values of 21.5, average pH values of 3.31, and average yields of approximately

5 to 6 tons per acre, these grapes consistently achieve a perfect balance of sugar and pH levels at harvest, and produce wines with robust fruit flavors and concentrated aromas (P. Coquard personal communication March 15, 2016). In the southern part of the property, the vineyards are characterized by soils with higher sand content, intermediate elevations, and flatter slopes; these vineyards produce the highest grape yields (approximately 7 to 8 tons per acre) and softer wines with delicate, lighter flavours (P. Coquard personal communication March 15, 2016). Overall, these are typical economic crop yields for hybrid grapes that have been optimized and proven successful for Wollersheim Winery in terms of maintaining a balance between profitability and grape and wine quality, while meeting the demand for sensible local wines.

Vineyard Variability Study at Domaine Reserve and Lot 19

The 1.6-acre Domaine Reserve and 1.4-acre Lot 19 plots, both planted with Marechal Foch grapes, were selected for further investigation by means of geophysical methods and vine trunk circumference measurements. Both plots have a southwesterly aspect, with slopes of 21% at Domain Reserve and 10% at Lot 19. The geophysical surveys provide measurements of apparent ECa and its inverse, ER, which are correlated with soil moisture, clay content and mineralogy, rock fragments, bulk density, porosity, and other soil properties (André et al. 2012). Vine trunk circumference measurements can be utilized to assess subsurface variability at the plot level and as a proxy for vine vigor, which can be correlated with grape characteristics (Imre and Mauk 2011).

Vine Trunk Circumferences

Vine trunk circumferences were measured at Domaine Reserve and Lot 19 in September 2014. The Domaine Reserve vines were planted in 1974, and the Lot 19 vines were planted in 1987. Measurements were collected from every vine on every other row, for a total of nine rows at each plot. The number of measurements collected was 437 at Domaine Reserve and 477 at Lot 19. Generally, vine trunk circumferences were similar between the two plots: median circumferences were 170 mm at Domaine Reserve and 190 mm at Lot 19 (Fig. 9). The Domain Reserve vine circumference data displayed slightly more variation, with a range of 300 mm compared to a range of 260 mm for the Lot 19 data.

Smaller vine trunk circumferences were observed at the uppermost three rows, at higher elevations near the top of the slope at Domaine Reserve. As uniform management practices are implemented at both plots, the variation in vine trunk circumferences between them reflects vine age, soil conditions (type, texture, and drainage), and topographic conditions (slope, elevation); it is also observed in grape yields, which are approximately 5 tons per acre at Domaine Reserve and 6 tons per acre at Lot 19. Wollersheim Winery's Philippe Coquard considers the age of the vines to be the dominant factor in the variation of vine trunk circumferences, although he insists that it is the combination of these factors (vine age, soil conditions, and topographic conditions) that ultimately creates these differences (personal communication, March 15, 2016). Larger circumferences in older vines may be expected if vine age alone were a determining factor, but the actual average measurements indicate that the younger vines of Lot 19 have the larger circumferences; it is clear, therefore, that the effects of age, soil, and topographic conditions combined outweigh the effects of vine age by itself.

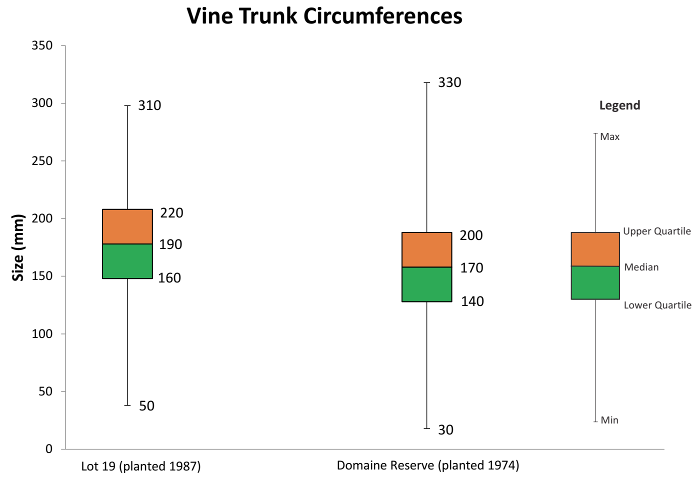

Figure 9. Box and whisker plots showing the trunk circumference measurements collected from Domaine Reserve and Lot 19; variations between the plots are a result of different vine ages, soil conditions, and topographic conditions.

Geophysical Surveys

EMI and ERT surveys were completed at Domaine Reserve and Lot 19 in May 2014. The survey measurements were utilized to determine spatial variations in the subsurface that can be used to map soil variations within each plot. The soils were likely saturated by spring precipitation at the time of the survey.

Figure 10 presents the horizontal (3 m) and vertical (6 m) soil ECa at 9.8 kHz measured in May 2014. Overall, the ECa values were relatively low, ranging from 7 to 68.75 millisiemens per metre (mS/m), and spatially correlated areas of similar ECa were noted at both plots. These areas generally coincide with the distribution of different soil types, as established by the USDA. The horizontal ECa measurements were generally similar between the two plots, ranging from 5 to 27.25 mS/m at Lot 19 and from 7 to 30.75 mS/m at Domaine Reserve, indicating relatively sandy surficial soils. Vertical ECa values ranged from 7.25 to 18 mS/m at Lot 19 and from 8 to 68.75 mS/m at Domaine Reserve. The highest vertical ECa values were encountered at Domain Reserve in the northeastern corner of the plot, which is underlain by the Gaphill – Rockbluff complex (well-drained sandy loams developed from loamy or sandy colluvium), and has steeper slopes and shallower soil (Fig. 11). An inverse relationship between ECa and depth to bedrock is observed here because soils developed from the underlying bedrock are generally more conductive than the bedrock, and groundwater at or above the bedrock interface may also increase conductivity. Philippe Coquard of Wollersheim Winery confirms that the shallow depth to bedrock restricts rooting depth and limits grape yields in this northeast

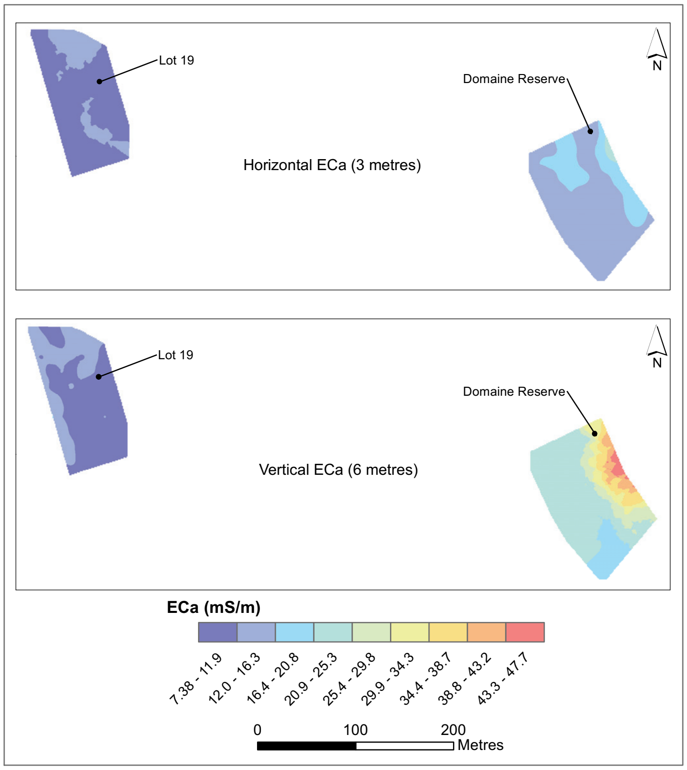

Figure 10. Map depicting the horizontal (3 m) and vertical (6 m) apparent electrical conductivity (ECa) measurements in soils at Domaine Reserve and Lot 19, demarcating areas of similar soil type at each plot. mS/m: millisiemens per metre.

portion of the plot, which also coincides with smaller vine trunk circumference measurements in this area.

Figures 12 and 13 illustrate the two resistivity profiles completed at each plot: one profile near the top row, and one profile near the bottom row of vines. Overall, the ER measurements can be correlated with the ECa data of the plots, with areas of high conductivity corresponding to low resistivity and vice versa. At Lot 19, the ER values were generally similar between the top (53–7433 ohm-m) and bottom (51−3850 ohm-m) rows. Although the top row of the Domaine Reserve plot revealed ER measurements (26−2821 ohm-m) similar to those observed at Lot 19, much higher resistivity values (25−31,551 ohm-m) were noted for the bottom row of vines, indicating the presence of a more resistive layer at lower elevations, near the foot of the slope. This highly resistive layer is encountered at a depth of approximately 12 m near the bottom row of vines at Domaine Reserve, indicating an increase in coarser soil textures with depth. These coarser textures at depth coincide with the centrally located gravel pit, consisting of stratified sand and gravel, and covering approximately 25% of the property. Based on well-log information from private wells drilled on the property, the stratified sand and gravel layer is laterally continuous and extends from 2 to 29 m below ground surface in the centre of the property and from 9 to 15 m below ground surface in the northeast part of the property. Based on the ER data, Lot 19 has a more homogeneous subsurface, compared to the Domaine Reserve plot, which shows much more variability between the top and bottom rows.

Overall, the ECa data corroborate the ER data at the Domaine Reserve plot, depicting more conductive/less resistive soils near the top row of vines, proximal to the Gaphill−Rockbluff complex, and more resistive/less conductive soils approximately 12 m deep near the bottom row of vines at Domaine Reserve. This indicates an increase in coarser soil textures with depth and coincides with the location of the stratified sand and gravel pit.

In addition to the differences established by geoelectrical methods, other plot characteristics such as elevation, slope, and vine age variations further differentiate the two plots. Specifically, the Domaine Reserve plot is situated at elevations of 259−305 m, has an average slope of approximately 20%, more soil textural variability across the plot, higher average clay and silt content, and vines approximately 42 years old. The grapes from Domaine Reserve have consistently higher sugar levels, with average Brix values of 21.13, average pH values of 3.29, and average yields of approximately 5 tons per acre, producing the best wines with robust fruit flavors and bold, concentrated aromas. In contrast, Lot 19 is located at lower elevations (213−259 m), has a gentler average slope of ca. 10%, less soil textural variability across the plot, higher average sand content, and younger vines approximately 29 years old. The grapes from Lot 19 attain intermediate sugar levels, have average Brix values of 20.07, average pH values of 3.28, average yields of approximately 6 tons per acre, and produce medium-bodied wines with pleasant fruit flavors and balanced aromas.

CONCLUSIONS

Wollersheim Winery is the birthplace of Wisconsin viticulture, a National Historic Site, and a leader in the Midwestern USA wine industry. Its location on a hill bordering the Wisconsin River marks the transition zone from glaciated terrain to the east to non-glaciated terrain to the west. The Wollersheim vineyards, with south and southwest-facing slopes and good air drainage, have well-drained soils dominated by silt- and sand-sized grains (silty loams and sandy loams). The vineyard soils are developed on parent materials consisting of windblown loess deposits, loamy outwash and glaciofluvial deposits underlain by outwash, and loamy colluvium and sandy deposits overlying sandstone bedrock.

The plant-available chemistry of the vineyard soils shows that the most variability and highest concentrations of calcium, magnesium, and potassium correspond to vineyard soils having the highest silt content in the northern and eastern parts of the property. The XRF total elemental chemistry of the vineyard soils reveals the most variability in SiO_2, CaO, MgO, Al_2O_3, and Fe_2O_3, reflecting the variety of parent materials in which the soils have developed. The soil mineralogy consists primarily of quartz, plagioclase, orthoclase, and dolomite, minor biotite and hornblende, and various clay minerals. The soil samples with the lowest SiO_2 compositions and the highest LOIs have elevated MgO and CaO contents, indicating a contribution from the weathering of dolostone or dolomite-rich sandstone bedrock in the soils of these plots, which are located in closest proximity to the bedrock outcrops. Based on a preliminary evaluation of chemical weathering

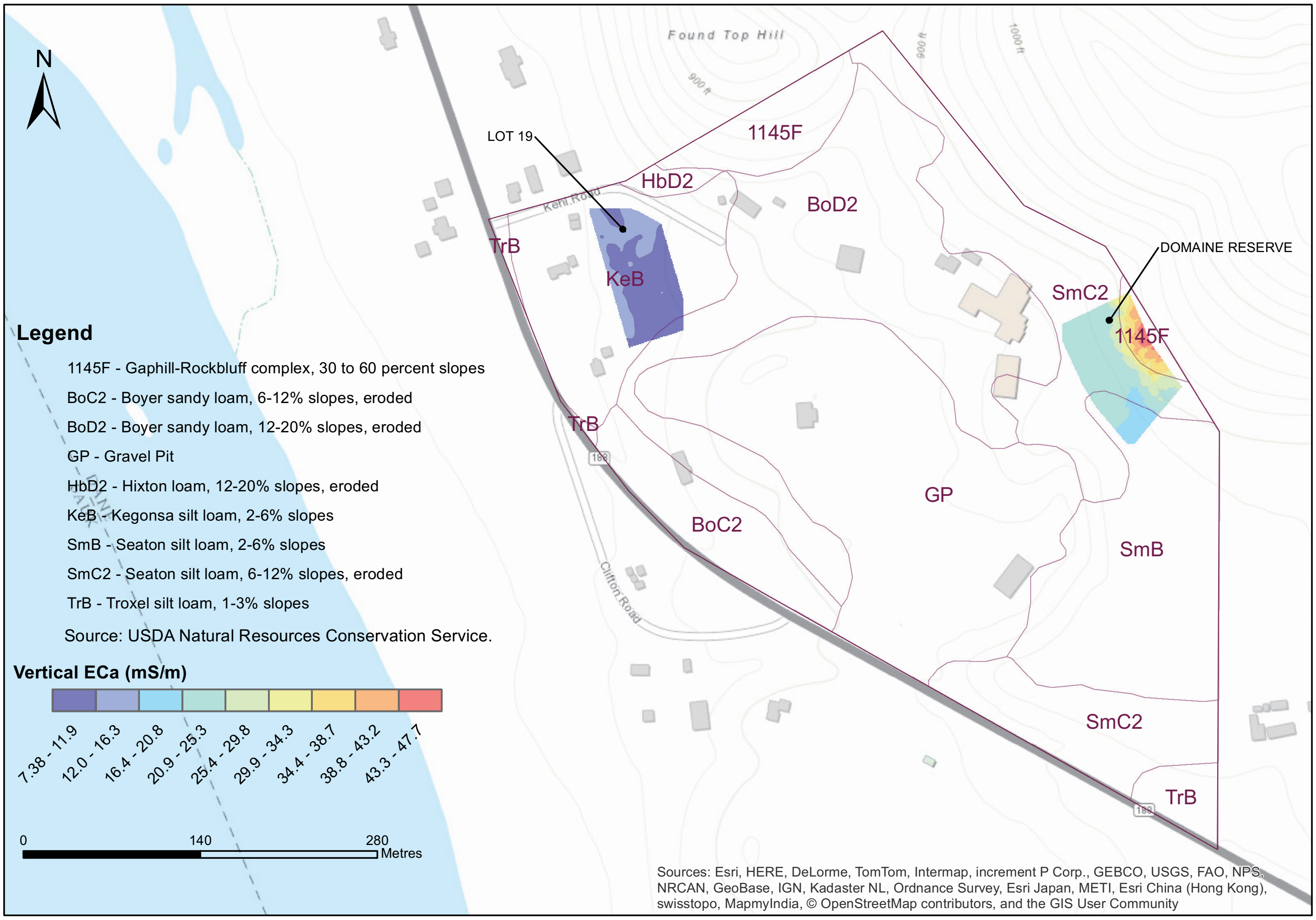

Figure 11. Map depicting the vertical (6 m) apparent electrical conductivity (ECa) measurements and soil types at Domaine Reserve and Lot 19; the area of highest ECa (the Domaine Reserve plot) coincides with steeper slope and shallower soil depth, restricting rooting depth and limiting crop yields in this area. mS/m: millisiemens per metre.

using ratios of mobile to immobile elements in the vineyard soils, an overall increase in chemical weathering is noted in the northern, eastern, and southern parts of the property. The areas of greater chemical weathering in the north and east are characterized by steeper slope, thinner soil, shallower depth to bedrock, and most silt-rich soils. They also display the highest plant-available calcium, magnesium, and potassium, and coincide with the location of vineyards producing the highest quality grapes.

Vineyard geophysical surveys at the Domaine Reserve and Lot 19 plots demonstrate spatial variations within the subsurface at the plot level, demarcating soil variations within each plot. The ECa data corroborate the ER data, indicating more soil textural variability and higher average clay and silt content for the Domaine Reserve plot, and less textural variability and higher average sand content for Lot 19. Additional characteristics, such as elevation, slope, and vine age variations further differentiate the two plots. Thus, the terroir of the Domaine Reserve plot, consisting of more heterogeneous soils with a greater degree of chemical weathering, higher elevation, steeper slope, and older vines, produces the lowest yields, the best quality grapes, and the rich, full-bodied Domaine Reserve wine, whereas the terroir of Lot 19, comprising more homogeneous soils with the lowest degree of chemical weathering, lower elevation, gentler slope, and younger vines, produces slightly higher yields, good quality grapes, and the medium-bodied Domaine du Sac wine.

With an increasing demand for wine and an expanding local consumption movement across the state, the future of viticulture in Wisconsin looks promising, with new wineries opening and larger acreage of grapes being cultivated throughout the state to meet the demand for Wisconsin wine. As climate change continues to affect the selection of cultivated grape varieties, Wisconsin holds a great potential for cultivating quality cool-climate European varieties, in addition to the American and French–American hybrids currently dominating the state's grape production. Future work focused on selecting the proper hybrid not only for the appropriate climatic conditions, but also for the specific soil type, will aid in further refining our understanding of the optimal terroir conditions for cultivating quality cold-climate grapes.

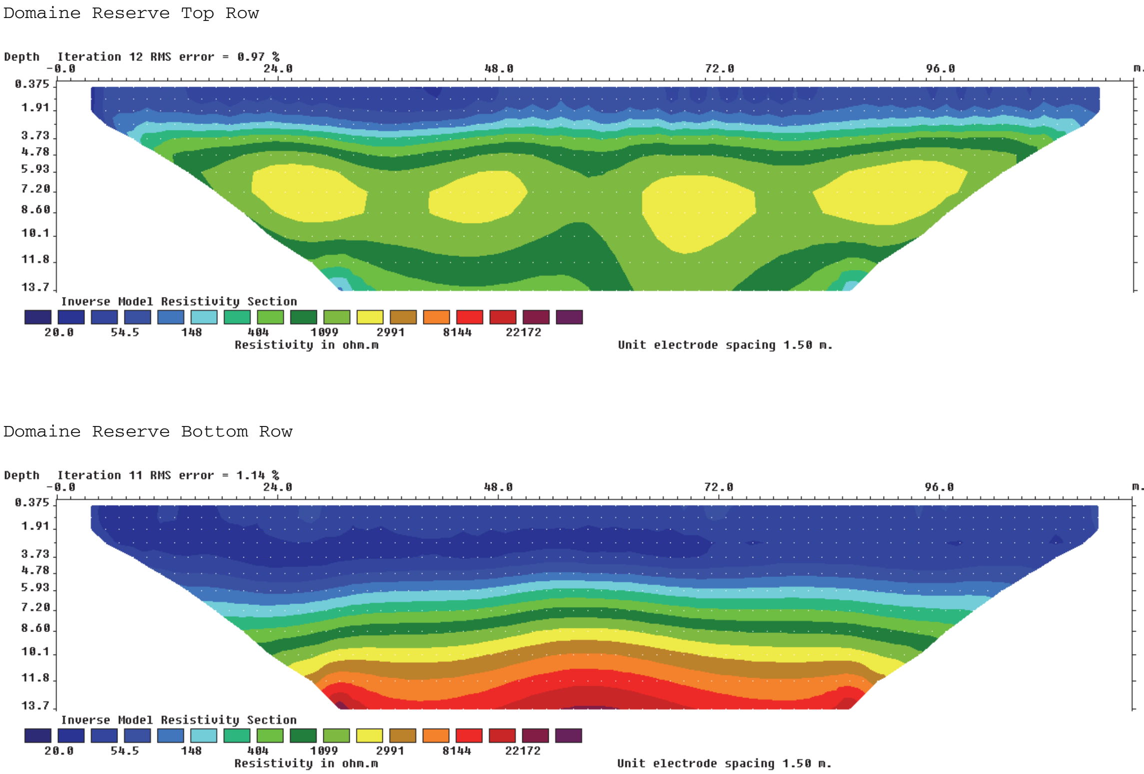

Figure 12. Figure illustrating the soil apparent electrical resistivity (ER) measurements (in ohm-m) for the two resistivity profiles completed at Domaine Reserve; the highly resistive layer at Domaine Reserve's bottom row indicates an increase in coarser soil textures with depth.

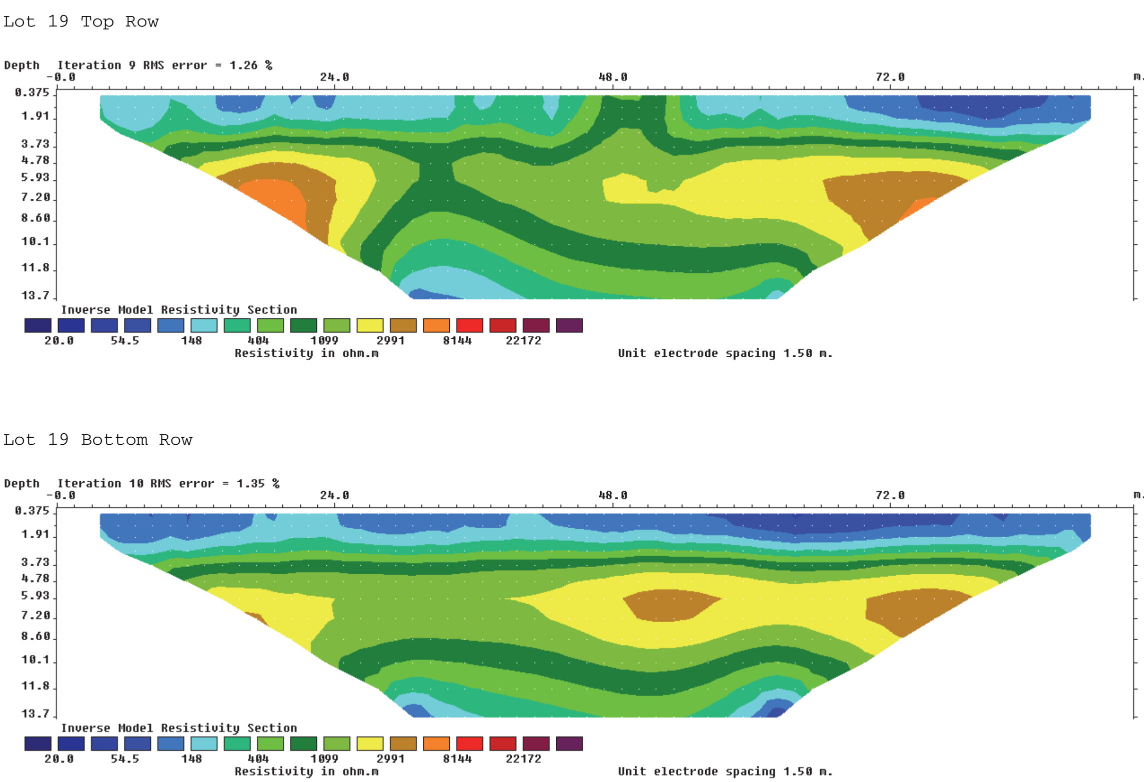

Figure 13. Figure illustrating the soil apparent electrical resistivity (ER) measurements (in ohm-m) for the two resistivity profiles completed at Lot 19; similar ER values between the top and bottom rows indicate a homogeneous subsurface.

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REFERENCES

André, F., van Leeuwen, C., Saussez, S., Van Durmen, R., Bogaert, P., Moghadas, D., de Rességuier, L., Delvaux, B., Vereecken, H., and Lambot, S., 2012, High-resolution imaging of a vineyard in south of France using ground-penetrating radar, electromagnetic induction and electrical resistivity tomography: Journal of Applied Geophysics, v. 78, p. 113–122, http://dx.doi.org/10.1016/ j.jappgeo.2011.08.002.

Attig, J.W., Bricknell, M., Carson, E.C., Clayton, L., Johnson, M.D., Mickelson, D.M., and Syverson, K.M., 2011, Glaciation of Wisconsin [fourth edition]: Wisconsin Geological and Natural History Survey, Educational Series, v. 36, p. 4.

Bowen, P.A., Bogdanoff, C.P., Estergaard, B.F., Marsh, S.G., Usher, K.B., Smith, C.A.S., and Frank, G., 2005, Geology and Wine 10. Use of geographic information system technology to assess viticulture performance in the Okanagan and Similkameen valleys, British Columbia: Geoscience Canada, v. 32, p. 161–176.

Clayton, L., and Attig, J.W., 1997, Pleistocene geology of Dane County, Wisconsin: Wisconsin Geological and Natural History Survey Bulletin, v. 95, p. 64.

Dami, I., Bordelon, B., Ferree, D.C., Brown, M., Ellis, M.A., Williams, R.N., and Doohan, D., 2005, Midwest grape production guide: Ohio State University Extension, Bulletin 919, Columbus, OH, 155 p.

GPO Electronic Code of Federal Regulations, 2015, Approved American Viticultural Areas: 9.146 Lake Wisconsin: Electronic Code of Federal Regulations, U.S. Government Publishing Office, Washington, DC. Accessed 05/10/2015.

Haynes, S.J., 2000, Geology and Wine 2. A geological foundation for terroirs and potential sub-appellations of Niagara Peninsula wines, Ontario, Canada: Geoscience Canada, v. 27, p. 67–87.

Imre, S.P., and Mauk, J.L., 2009, Geology and Wine 12. New Zealand Terroir: Geoscience Canada, v. 36, p. 145–159.

Imre, S.P., and Mauk, J.L., 2011, Geophysics and wine in New Zealand, *in* Dar, I.A., *ed*., Earth and Environmental Sciences: InTech, online access: http://cdn.intechweb.org/pdfs/24548.pdf.

Jordan, T.D., Pool, R.M., Zabadal, T.J., and Tompkins, J.P., 1981, Cultural practices for commercial vineyards: New York State College of Agriculture and Life Sciences, A statutory college of the State University, at Cornell University, Miscellaneous Bulletin 111, 70 p.

Lambert, J.-J., Anderson, M.A., and Wolpert, J.A., 2008, Vineyard nutrient needs vary with rootstocks and soils: California Agriculture, v. 62, p. 202–207, http://dx.doi.org/10.3733/ca.v062n04p202.

Meinert, L.D., and Busacca, A.J., 2000, Geology and Wine 3. Terroirs of the Walla Walla Valley appellation, southeastern Washington State, USA: Geoscience Canada, v. 27, p. 149–171.

Meinert, L.D., and Busacca, A.J., 2002, Geology and Wine 6. Terroir of the Red Mountain appellation, central Washington State, U.S.A.: Geoscience Canada, v. 29, p. 149–168.

Meinert, L.D., and Curtin, T., 2005, Terroir of the Finger Lakes of New York (Abstract): The Colorado College, Extended Abstracts, 18th Keck Symposium, Colorado Springs, p. 34–40.

Mickelson, D.M., 2007, Landscapes of Dane County: Wisconsin Geological and Natural History Survey Educational Series v. 43, p. 36; map (07-6).

Mickelson, D.M., Knox, J.C., and Clayton, L., 1982, Glaciation of the Driftless Area: An evaluation of the evidence, *in* Knox, J.C., Clayton, L., and Mickelson, D.M., *eds*., Quaternary history of the Driftless Area: Wisconsin Geological and Natural History Survey Field Trip Guidebook, v. 5, p. 155–169.

Moyer, M., Moulton, G., and Henick-Kling, T., 2014, Growing winegrapes in maritime western Washington: Washington State University Extension, EM068E, 29 p.

Pinney, T., 1989, A history of wine in America: From the beginnings to prohibition: University of California Press, Berkeley, CA, p. 269–285.

Pogue, K., 2009, Folds, floods, and fine wine: Geologic influences on the terroir of the Columbia basin, *in* O'Connor, J., Dorsey, R., and Madin, I., *eds*., Volcanoes to Vineyards: Geologic Field Trips through the dynamic landscape of the Pacific Northwest: Geological Society of America Field Guide 15, p. 1–17.

Stiles, C.A., and Stensvold, K.A., 2008, Loess contribution to soils forming on dolostone in the Driftless Area of Wisconsin: Soil Science Society of America Journal, v. 72, p. 650–659, http://dx.doi.org/10.2136/sssaj2007.0112.

Swinchatt, J., 2012, Finger Lakes a new-found source of great intrigue: The world of fine wine, v. 38, p. 60–66.

Syverson, K.M., and Colgan, P.M., 2004, The Quaternary of Wisconsin: A review of stratigraphy and glaciation history, *in* Ehlers, J., *ed.,* The glacial stratigraphy of the northern U.S.: Elsevier, p. 289–305.

Taylor, V.F., Longerich, H.P., and Greenough, J.D., 2002, Geology and Wine 5. Provenance of Okanagan Valley wines, British Columbia, using trace elements: Promise and limitations: Geoscience Canada, v. 29, p. 110–120.

Tuck, B., and Gartner, W., 2014, Vineyards and wineries of Wisconsin: A status and economic contribution report: Regents of the University of Minnesota, Extension Center for Community Vitality, 51 p.

USDA. United States Department of Agriculture Natural Resources Conservation Service, Web Soil Survey data, http://websoilsurvey.nrcs.usda.gov/. Accessed 03/29/2015.

Wilson, J.E., 1998, Terroir: The role of geology, climate and culture in the making of French wines: University of California Press, 336 p.

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