SERIES

Geology and Wine 6. Terroir of the Red Mountain Appellation, Central Washington State, U.S.A.

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SUMMARY

Red Mountain is the newest of five appellations in Washington State and like the majority of Washington vineyards its terroir is influenced by 1) the rain shadow effect and volcanic tephra of the Cascade Mountain Range, 2) soils derived from Quaternary glacial sediments and wind-blown loess overlying Miocene basalt, and 3) a warm, dry climate with abundant sunshine and cool nights due to high latitude (N 46°) and topography. Variations of rooting depth, textures, calcium carbonate content, and other properties of vineyard soils are directly influenced by Quaternary glacial flood deposits in the back-eddy of Red Mountain and by the variable nature of the loess and dune cover on the flood deposits. This is the first demonstration of the effect of paleohydrology on vineyard site characteristics. In the past two years, wines made from Red Mountain grapes have received nine scores of ≥ 94 out of 100 in independent blind tastings and merlot wine made from Red Mountain grapes has been ranked as the best in the United States for each of the past two years by two different national wine magazines.

Red Mountain is one of the warmest and driest viticultural sites in Washington State, having heat summation (growing degree days) and total sunshine similar to Napa Valley, California which is 1000 km farther south. Other wine regions that have been influenced by the worldwide glacial processes that were so important in the development of Washington vineyards include the gravel mounds that underlie most of the first growth vineyards of Graves-Médoc, Bordeaux, France and some of the outwash gravel plains of New Zealand.

RÉSUMÉ

L'appellation Red Mountain est la plus récente des cinq appellations de l'État de Washington et, comme c'est le cas pour la plupart des vignobles de l'État de Washington, son terroir dépend 1) de l'effet parapluie de la chaîne des monts Cascade et de ses cendres volcaniques, 2) des sols dérivés des sédiments glaciaires quaternaires et des loess éoliens recouvrant le basalte miocène et, 3) d'un climat chaud et sec avec un fort ensoleillement, avec des nuits fraîches dues à la latitude (N 46°) et à la topographie. Les variations de la profondeur d'enracinement, de texture, de contenu en carbonate de calcium et d'autres propriétés pédologiques des vignobles varient selon le patron de dépôt des alluvions glaciaires quaternaires par écoulement tourbillonnaire de Red Mountain et de la variation de composition du loess et de la couverture des dunes des dépôts alluvionnaires. Cela constitue la première démonstration des effets paléohydrologiques sur les propriétés des sites vinicoles. Au cours des deux dernières années, les vins des raisins de Red Mountain ont reçu neuf cotes de plus de 94% lors de dégustation anonyme, et les vins merlots provenant de raisins de Red Mountain ont été jugés les meilleurs aux USA pour chacune des deux dernières années, par deux revues spécialisées d'envergure nationale.

La région de Red Mountain constitue l'un des sites viticoles les plus chauds et les plus secs de l'État de Washington, possédant un bilan thermique (degré-jour de croissance) et un ensoleillement comparable à ceux de la vallée de Napa en Californie, laquelle est située à 1 000 km plus au sud. Parmi d'autres régions ayant subi l'influence de processus glaciairemondiaux et qui se sont avérés si déterminant dans le développement des vignobles de l'État de Washington, on retrouve celle des collines graveleuses constituant le lieux de croissance de la plupart des vignobles de première génération de Graves-Médoc de la région de Bordeaux en France, et d'autres sur des plaines d'alluvions en Nouvelle-Zélande.

INTRODUCTION

As described in other articles in this Geoscience Canada series (*e.g.,* Wilson, 2001), *terroir* involves the complex interplay of climate, soil, geology, and culture that influences the character and quality of wine. These factors are in addition to, or perhaps underlie, the substantial contribution of good viticultural practice and expert winemaking. One common illustration of the importance of terroir is the occurrence of adjacent or nearby vineyards that produce strikingly different wines, even where many of the measurable aspects of climate, viticulture, and winemaking technique are very similar. It is also common, although usually incorrect, to point to a single factor as the explanation: "It's the soil." "It's the water." "It's the limestone." Terroir is the integration of individual factors that contribute to wine quality, and to make matters even more complicated there is the variable of time. What may be good terroir in one year may be less so in another. For example, in years that are relatively warm and dry, vineyard "X" with a particular slope, elevation, sun angle, and soil type may produce better wine than vineyard "Y", whereas the reverse may be true in years that are cooler and wetter. Similarly, no matter how good the site, poor vineyard management or winemaking practices can result in bad wine.

Although the term originated in France, terroir increasingly is being used in other parts of the world to explore differences at the scale of appellations to individual vineyards to within-vineyard domains (Halliday, 1993, 1999; Wilson, 1998; Haynes, 1999, 2000). The goal of the present paper is to document the terroir of Washington's newest appellation, Red Mountain (Fig. 1) and to contrast it with other Washington appellations such as Walla Walla (Meinert and Busacca, 2000). At least one aspect of the terroir of the Red Mountain appellation is similar to that previously documented for Walla Walla, 75 km to the east: the strong control on soil materials and landforms exerted by cataclysmic glacial outburst floods. However, there are other factors that vary to different degrees, such as topographic patterns that control air drainage, soil texture, depth to bedrock, growing degree days, solar radiation, rainfall, and frost hazards.

Washington State has some of the world's largest and most spectacular flood basalts and glacial outburst flood deposits as well as widespread dune and loess fields. All of these contribute to the terroirs of Washington State wines. In addition, recent volcanic activity such as the well-known 1980 eruption of Mt. St. Helens continues to shape the oenological and geological landscape. Many Washington vineyard soils have a component of ash erupted from Mt. St. Helens and other Cascade volcanoes such as the much larger Mt. Mazama eruption (6,850 ^{14}C yr. BP), which formed present-day Crater Lake in Oregon (Busacca *et al.*, 2001).

Washington State is second only to California in terms of the volume of wine produced in the United States (www.nass.usda.gov/wa/grape02.pdf). Most Washington State vineyards are located between latitudes 45° and 48° N, well to the north of the more widely known California vineyards but parallel to the great French wine regions of Burgundy and Bordeaux. This northerly latitude provides up to two hours more summer sunlight than occurs in California wine regions, somewhat offsetting the generally shorter growing season (Gladstones, 1992). Arid conditions created by the large rain shadow of the Cascade Mountains allow vineyardists a high degree of control of soil moisture. Almost all commercial vineyards lie east of the Cascade Mountain Range (Fig. 1).

Although there is considerable local variability, most Washington vineyards are sited on soils formed from Quaternary sediments that overlie Miocene basaltic rocks of the Columbia River flood basalt province. Many of the Quaternary sediments were deposited during cataclysmic glacial outburst floods that formed the spectacular geomorphic features of the Channeled Scabland (Fig. 2). In fact, comparison of Figures 1 and 2 demonstrates that more than 90% of Washington vineyards are located in areas affected by the glacial outburst floods. This element of terroir, combined with the rain shadow effect of the Cascade Mountains, distinguishes Washington vineyards from other grape growing areas of the world and suggests that Washington wines may develop flavour and quality characteristics that are equally distinct.

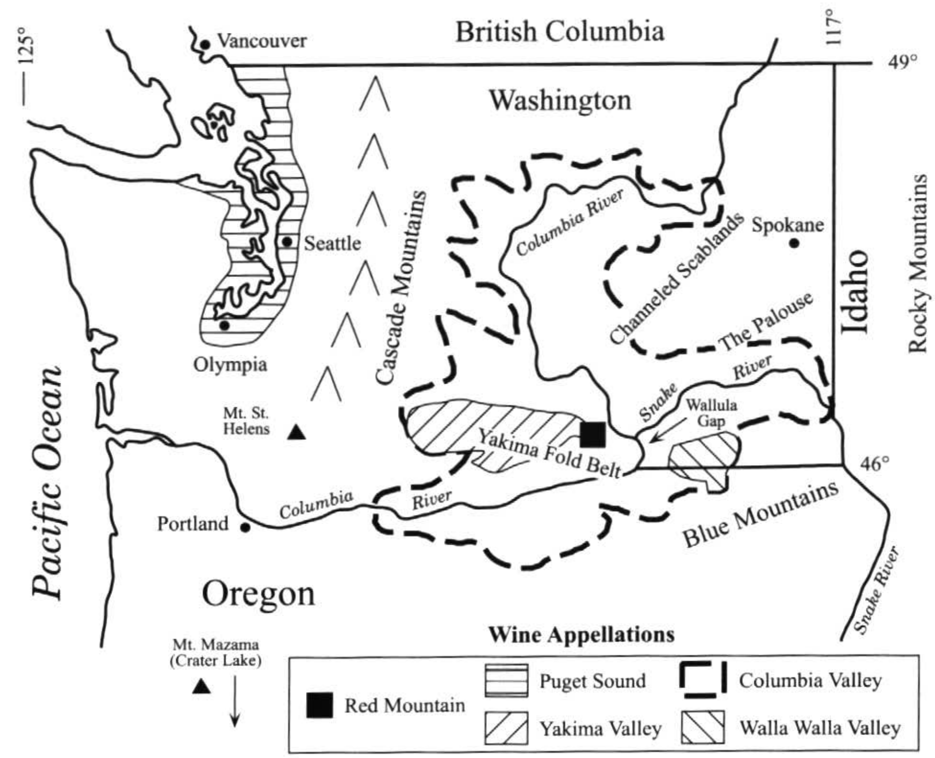

Figure 1 Location map of the Pacific Northwest showing wine appellations and major geological features described in the text.

OVERVIEW OF WASHINGTON STATE WINE GRAPE PRODUCTION

Washington State has five wine appellations called American Viticultural Areas (AVAs) by the Bureau of Alcohol, Tobacco, and Firearms (BATF), the chief regulatory agency of the wine industry in the United States. The current Washington State appellations (AVAs) are Columbia Valley, Puget Sound, Red Mountain, Walla Walla, and Yakima Valley (Fig. 1). Sub-appellations, that may someday become AVAs, include Alder Ridge, Canoe Ridge, Cold Creek, Columbia River Gorge, Horse Heaven Hills, Wahluke Slope, and Zephyr Ridge (Peterson-Nedry, 2000). Other areas, such as the north bank of the Columbia River near the small town of Paterson, also are becoming known for growth of premium grapes owing to their south-facing slopes and the mitigation of temperature extremes by proximity to Lake Wallula on the Columbia River.

As with most other wine growing regions, Washington AVAs can be nested such that the Columbia Valley appellation, which produces more than 90% of the state's wine grapes, includes the Yakima Valley, Walla Walla Valley, and Red

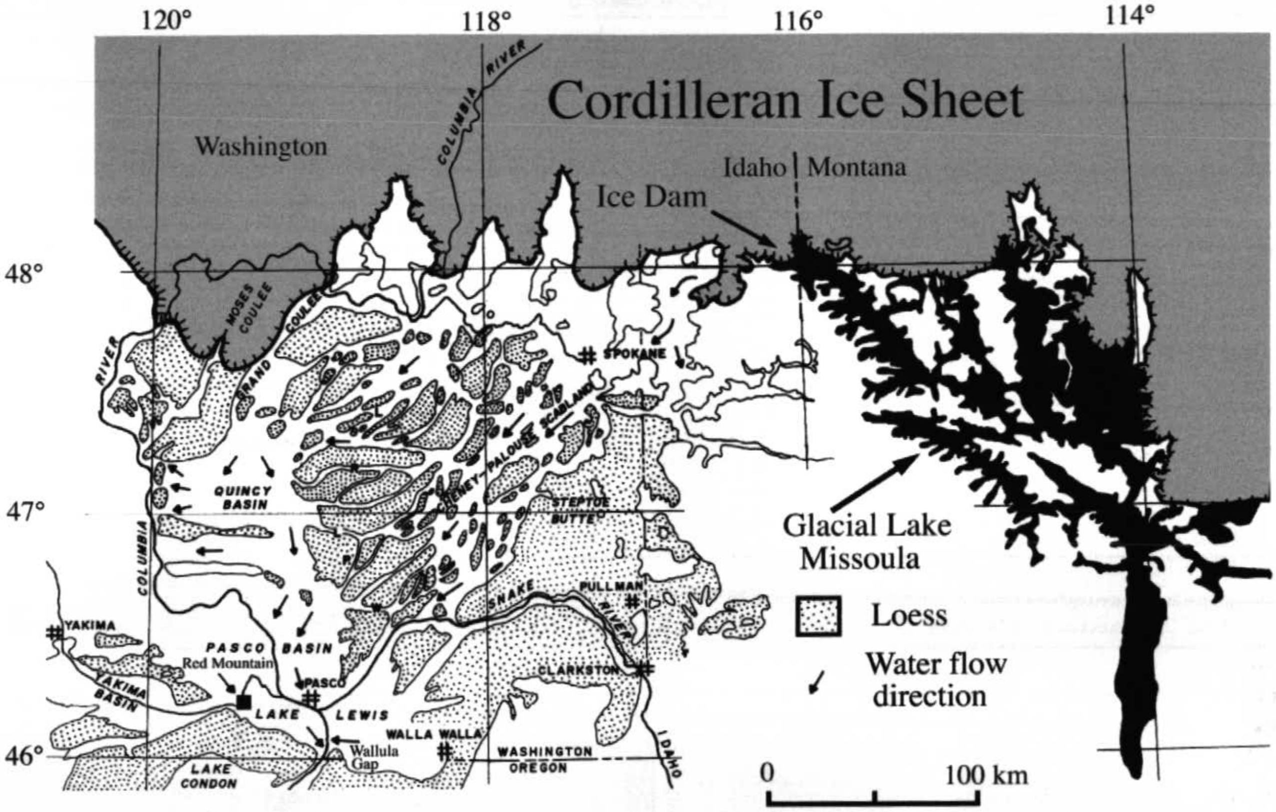

Figure 2 The Channeled Scabland of the Pacific Northwest showing the Cordilleran ice sheet in its approximate position at 15,000 years before present, glacial outburst flood channels, and the distribution of loess. Modified from Baker and Nummedal (1978).

Mountain appellations. The area available for future plantings is very large. In the 10.7 million-acre Columbia Valley appellation only about 16,000 acres are planted to wine grapes. Even the smallest appellation, Red Mountain, has room for expansion with approximately 710 acres planted to vines out of the 4040 acres of the AVA. In many cases the availability of water for irrigation is a larger limitation than the suitability of land for growing high-quality grapes.

Only about 18% of Washington's wine grapes are from vineyards more than 20 years old and from these older vineyards, white grapes (73%) predominate over red grapes (27%) (www.nass.usda.gov/wa/wine02.pdf). For example, prior to 1982 Riesling was the most widely planted white wine grape. In 1982, 54% of the current (2002) acreage was planted with Riesling grapes. In contrast, Cabernet Sauvignon, Merlot, and Syrah were the three most widely planted red grapes in 2002 and had only 12%, 5%, and 0%, respectively, of their current acreage planted prior to 1982.

In the summer of 2002, there were 212 wineries in Washington State. Total wine grape production in 2001 was 100,000 tons from 24,000 acres of bearing vineyards (Table 1). Wine grape production will continue to increase since there are an additional 6,000 acres of wine grapes planted that were not yet bearing fruit in 2001. Most grape vines start producing commercial yields in the third year. Of the wine produced in Washington State in 2001, there was an equal split between white and red wine, down from a 62% white wine majority in 1998. For example, the production of Semillon and Chenin Blanc in this three-year time period decreased 35% whereas the production of Cabernet Sauvignon, Merlot, and Syrah increased 200%. This trend towards a predominance of red wine production in Washington State likely will continue in the future because of the increased plantings of red varietals and the higher prices realized from red grapes in general (Table 1).

REGIONAL GEOLOGIC HISTORY

Red Mountain is located in the geographic center of the Columbia Plateau, which is bordered on the north and east by the Rocky Mountains, on the south by the Basin and Range Province, and on the west by the Cascade Mountains (Fig. 1). Red Mountain is part of a northwest-southeast-trending series of anticlinal ridges called the Olympic-Wallowa Lineament (OWL) that can be traced on topographic and geological maps for hundreds of kilometres (Fig. 3). The ridges result from the north-south-oriented compressional stress regime of south-central Washington State that has existed from the Miocene to the present day. Some anticlines in the Yakima fold belt have developed as much as 100 m of structural relief in the past 10 m.y. (Reidel *et al.*, 1992), and the Red Mountain area experienced an intensity VII (approximate Richter magnitude 6) earthquake on July 15, 1936 (Brown, 1937), most likely caused by movement on the Wallula fault zone (Mann and Meyer, 1993), which is subparallel to the Yakima Fold Belt (Fig. 1).

Erosion of some of the anticlinal ridgetops exposes bedrock of the Columbia River Basalt Group, which covers an area of about 165,000 km^2. The Columbia River Basalt Group was erupted mostly between

Table 1 Washington vinifera wine grape production 1997–2001 (data from http://www.nass.usda.gov/wa/wine02.pdf)

Variety	Tons Utilized					Acres planted	Acres bearing	Yield tons/acres	Average Price (US$/ton)				
	1997	1998	1999	2000	2001	2001	2001	2001	1997	1998	1999	2000	2001
Chardonnay	17,700	20,500	22,900	27,800	29,200	6,640	6,290	4.6	$1,055	$971	$882	$818	$788
White Riesling	10,100	11,500	9,800	10,100	10,600	2,200	1,940	5.5	$489	$533	$547	$590	$603
Sauvignon Blanc	3,300	3,900	3,400	3,400	3,300	710	680	4.9	$729	$750	$746	$728	$719
Gewurztraminer	1,700	1,600	1,300	1,600	2,200	670	540	4.1	$552	$629	$706	$684	$662
Semillon	2,800	3,100	2,600	2,700	2,100	550	540	3.9	$661	$625	$598	$571	$576
Chenin Blanc	1,800	2,300	1,700	1,500	1,400	450	450	3.1	$499	$488	$473	$494	$439
Other (*)	600	600	800	900	1,200	780	460	2.6	$789	$952	$777	$866	$834
Total White	38,000	43,500	42,500	48,000	50,000	12,000	10,900	4.6	$794	$772	$753	$736	$721
Merlot	12,800	14,100	14,300	21,400	23,400	5,980	5,630	4.2	$1,360	$1,197	$1,149	$1,060	$1,034
Cabernet Sauvign	7,800	8,300	8,400	13,000	16,700	6,050	5,130	3.3	$1,195	$1,204	$1,236	$1,144	$1,122
Syrah	#	#	800	2,200	4,400	2,100	1,610	2.7	#	#	$1,398	$1,343	$1,221
Cabernet Franc	1,100	1,700	2,000	3,300	3,300	750	720	4.6	$1,120	$1,102	$1,066	$994	$1,012
Pinot Noir	1,000	1,100	1,000	1,000	900	290	260	3.5	$653	$661	$647	$642	$689
Lemberger	500	500	500	500	500	230	180	2.8	$757	$760	$785	$790	$748
Other (+)	800	800	500	600	800	600	370	2.2	$1,400	$1,386	$1,152	$1,232	$1,286
Total Red	24,000	26,500	27,500	42,000	50,000	16,000	13,900	3.6	$1,255	$1,168	$1,152	$1,085	$1,073
Washington total	62,000	70,000	70,000	90,000	100,000	28,000	24,800	4.0	$972	$922	$910	$899	$897

* Includes muscat canelli, pinot gris, and viognier

\+ Includes gamay beaujolais, grenache, nebbiolo, sangiovese, and zinfandel

\# Included in "Other" Red Varieties for 1997-1998

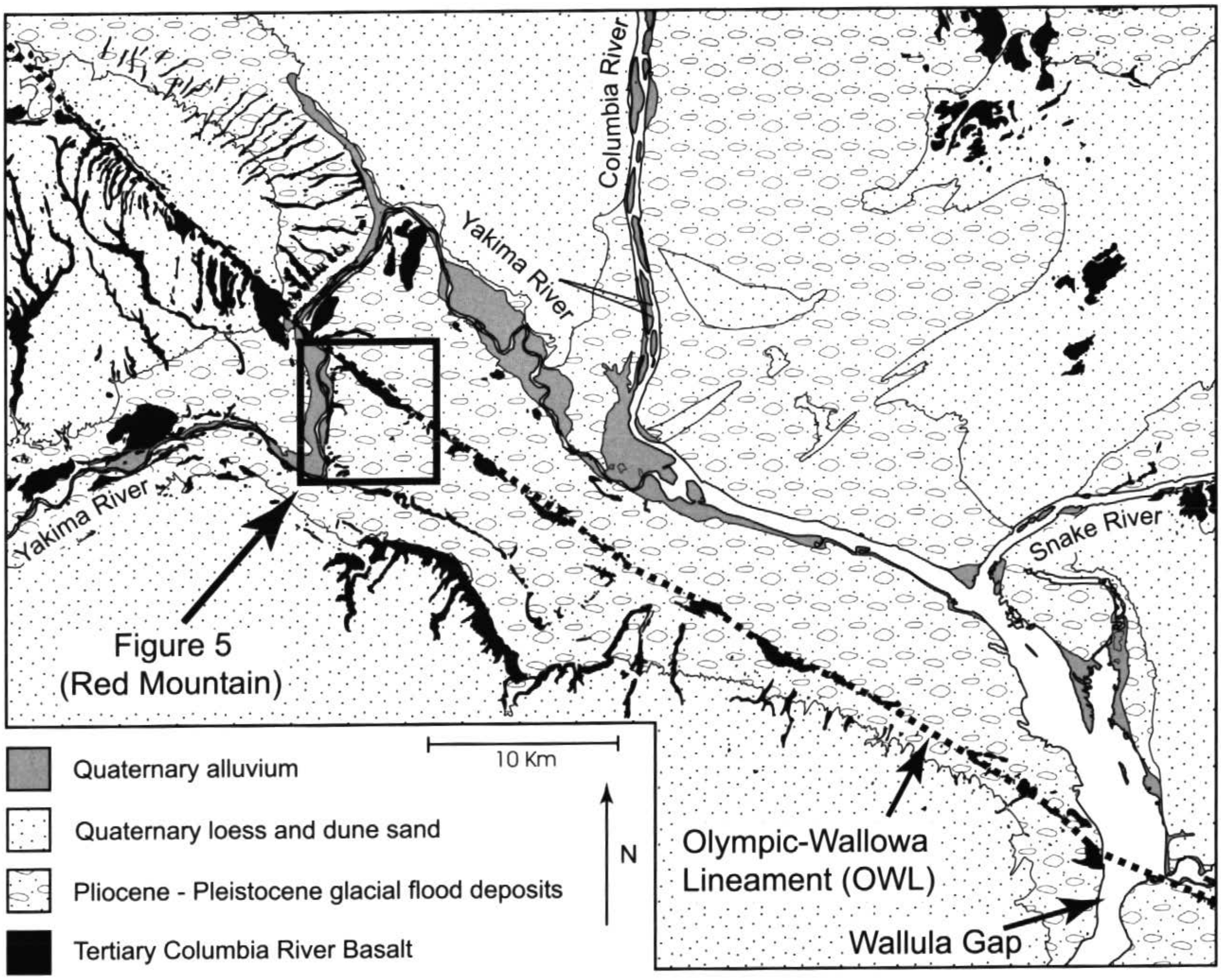

Figure 3 Regional geology of the Pasco Basin showing alignment of ridges along the Olympic-Wallowa Lineament (modified from Reidel and Fecht, 1994).

17 and 11 Ma (early Miocene) from north-south fissures roughly paralleling the present-day Washington-Idaho border. The Columbia River Basalt Group has individual flows with estimated eruptive volumes of at least 3,000 km^3, making them the largest documented lava flows on earth (Baksi, 1989; Landon and Long, 1989; Tolan *et al.*, 1989). This dwarfs the erupted volumes of typical Cascade volcanoes: even the explosive eruption of Mt. St. Helens in 1980 yielded only about 1 km^3 of volcanic material (Pringle, 1993). The basalt bedrock bedrock is overlain by unconsolidated sediments deposited by glacial outburst floods and eolian processes described in some detail in Meinert and Busacca (2000).

To briefly summarize: A lobe of the Cordilleran Ice Sheet blocked the Clark Fork River near the Canadian border in northern Idaho most recently about 18,000 Ka and created glacial Lake Missoula (Fig. 2), which covered 7800 km^2 of western Montana (Pardee, 1910). At the ice dam the water was approximately 600 m deep (Weis and Newman, 1989). The ice dam failed repeatedly, releasing the largest floods documented on earth (Baker and Nummedal, 1978). These floods overwhelmed the Columbia River drainage system and sent up to 2500 km^3 of water across the Columbia Plateau with each outburst (called jökulhlaups in Iceland where similar events occur). The floods eroded a spectacular complex of anastomosing channels, locally called 'coulees', into southwest-dipping basalt surfaces. They also eroded huge cataracts in the basalt now seen as dry falls and "loess islands" that are erosional remnants of an early thick loess cover on the plateau. The floods deposited immense gravel bars and ice-rafted erratic boulders at high elevations. Collectively these features make up the Channeled Scabland as detailed in the early work by Bretz (1923, 1925, 1928a,b, c, 1932).

In south-central Washington State, the many paths of the onrushing floods converged on the Pasco Basin where floodwaters were slowed by the hydrological constriction of Wallula Gap before draining out through the Columbia River Gorge to the Pacific Ocean (Figs. 1, 2). This constriction caused backflooding of local river valleys and basins that resulted in deposition of relatively fine-grained slackwater sediments characterized by rhythmically graded bedding; these graded rhythmites locally are called Touchet beds, and multiple sets, indicative of multiple floods, have been recognized (Flint, 1938; Waitt, 1980, 1985).

In the last stages of the Pleistocene (roughly from 15,000 to 10,000 yr. ago) and continuing through the Holocene (the last 10,000 yr., a time when climates worldwide were essentially similar to those of today), prevailing southwesterly winds eroded slackwater and other glacial sediments and redeposited them into the present thick blanket of loess that covers much of the Columbia Plateau (45°30' to 48°N and 116°30' to 120°W). These windblown soils form the backbone of agriculture in all of eastern Washington (Boling *et al.*, 1998). The loess is thickest in a 10,000 km^2 area northeast of Red Mountain called the Palouse (Busacca, 1991) (Fig. 1).

RED MOUNTAIN AVA

The Red Mountain American Viticultural Area (AVA) is defined by a combination of topographic contour lines and geographic markers (Fig. 4) and encompasses approximately 4,040 acres. Of this 4,040 acres there is potential for up to 2,700 bearing acres, of which 710 are currently planted. Red Mountain is home to Hedges Cellars, Kiona and several smaller wineries, including Blackwood Canyon, Sand Hill, Seth Ryan, and Terra Blanca. There are 16 vineyards in the AVA (Table 2) and 37 different Washington wineries currently use Red Mountain wine grapes, including Arc-en-Ciel, Andrake, Andrew Will Cellars, Apex Cellars, Barnard Griffin, Betz Family Winery, Bookwalter, Cadence, Camaraderie Cellars, Canoe Ridge, DeLille Cellars, Gibbons Lane, Foris Vineyards, Hedges Cellars, Hightower Cellars, JM Cellars, Januik, Kiona, Kestrel vintners, L'Ecole No 41, Matthew Cellars, McCrea Cellars, Mount Baker Vineyards, Owen-Sullivan, Quilceda Creek, Randall Harris, Ryan Cray, Sandhill, Seth Ryan, Seven Hills, Soos Creek, Terra Blanca, Three Rivers, Waterbrook, Wilridge, Woodward Canyon, and Yakima River Winery.

Compared to the rest of Washington state, Red Mountain has a much higher proportion of red (80%) versus white wine grapes (20%). Currently, there are 570 acres of red wine grapes (480 bearing) and 140 acres of white wine grapes (120 bearing). Most of these are relatively young plantings, with only 4% of the Red Mountain vineyards planted prior to 1982, comprising 10 acres each of Gewürztraminer, Riesling, and Merlot (www.nass.usda.gov/wa/wine02.pdf). Currently, the three most abundant grape varieties planted within the Red Mountain AVA are Cabernet Sauvignon (35%), Merlot (21%), and Syrah (10%).

RED MOUNTAIN GEOLOGY

Columbia River Basalt Group

In general, the vineyards of Red Mountain all share the same basic geology in that they are rooted in a stratigraphic package consisting of a thin but variable mantle of Pleistocene to Holocene loess and dune sands on top of Quaternary glacial flood sediments. These in turn overlie Tertiary Columbia River Basalt basement. In the Red Mountain area the Columbia River Basalt Group consists of the Saddle Mountains Formation, about 8.5 to 12 million years old, which can be subdivided into three members: the Ice Harbor (8.5 Ma), Elephant Mountain (10.5 Ma), and Pomona (12 Ma) members (Reidel and Fecht, 1994). Locally, these members can be subdivided further into individual flow units that are exposed along the ridgetop of Red Mountain and by incisions of the Yakima River on the west side of the Red Mountain AVA (Fig. 5). Compositions of representative rock units are illustrated in Table 3. As shown in Figure 6, subdivisions among individual flow units can be made on a compositional basis using a variety of major and trace elements (Hooper, 2000).

In drill intercepts, it is also possible to distinguish between individual basalt flows by the presence of locally persistent but regionally discontinuous shaly interbeds (Fig. 7) that developed during the 1 to 2 million year intervals between eruption of major basalt units. These interbeds, along with relatively porous flow tops and basal flow breccias, form the main aquifers in the Columbia River Basalt Group. Static water level is about 100 m below the surface in most of these wells, coincident with the upper shaly interbed. Because of this hydrological regime, the rooting zone of all Red Mountain vineyards is well above the water table.

Structure

The basalt bedrock in Central Washington has been folded into a series of NW-SE-trending anticlines and synclines. On a regional scale (Fig. 3) the anticlines are exposed in ridges that form elongate

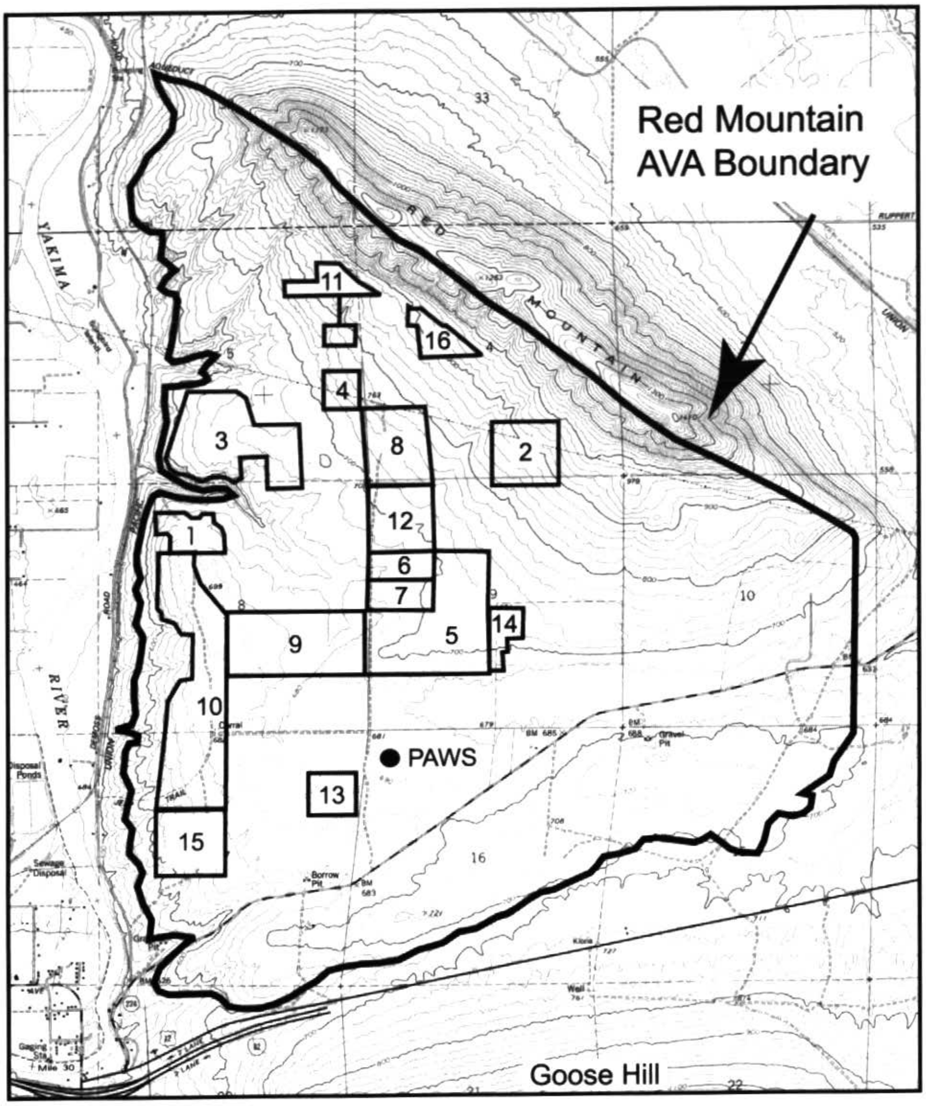

Figure 4 Location of vineyards and topography of the Red Mountain AVA. Base map is the 1:24,000 scale U.S.G.S. Benton City topographic map. Also shown is the location of the Washington State University Public Agricultural Weather System (PAWS) station that collected the data in Table 5. Information about numbered vineyards is presented in Table 2.

topographic features such as the Olympic-Wallowa lineament whereas the synclines generally form basins that are covered by younger sediments (Fig. 7). The Red Mountain and Goose Hill anticlines form the northern and southern geological boundaries of the Red Mountain AVA. Most of the vineyards are underlain by the intervening syncline, which has been called both the Goose Gap syncline and the Benton City syncline (Reidel and Fecht, 1994). According to Reidel and Fecht (1994) the southern limb of the Red Mountain anticline is steeper than the northern limb and like many such structures in the Yakima Fold Belt, may have local reverse faults (West *et al.*, 1996). Such faulting, as illustrated in the upper part of Figure 7, may explain the great differences in yield between otherwise similar water wells in the Red Mountain area.

Glacial Sediments

Except on ridgetops above about 400 m in elevation and where incised by modern drainage, the basalt in the Red Mountain area is everywhere overlain by unconsolidated sediments (labeled as Qht in Fig. 5) that were deposited by the series of glacial outburst floods related to the drainage of glacial Lake Missoula, described above. As the peak of Red Mountain is 430 m and the mean slackwater elevation of Lake Lewis, which temporarily filled the Pasco Basin (Fig. 2), is estimated at about 390 m, it is likely that the floodwater torrent surrounded Red Mountain, forming a very strong back-eddy behind (to the south of) Red Mountain as illustrated in Figure 8. The paleohydrology of this back-eddy resulted in extreme heterogeneity of the sediments that were deposited to the south of Red Mountain and that make up the deeper soil levels of the vineyards within the Red Mountain AVA.

Perhaps the most noticeable sedimentary features are the glacial erratics, large boulders that were carried by icebergs from the broken ice dam. These icebergs must have ranged up to 10s and perhaps 100s of metres in size, as the boulders that were dropped when these icebergs grounded, melted and deposited their entrained load, range up to several metres in size (Fig. 9A, B). Erratics are particularly prevalent along the high water strand of the slackwaters (Fig. 9A), but also are distributed throughout the Red Mountain AVA as illustrated in Figure 8D and evidenced by the rows, walls, and boxes of boulders (Fig. 9C) removed from the vineyards during initial planting and subsequent ploughing. Most of the boulders are granitic and metamorphic rock types that are not found within several hundred kilometres of Red Mountain, but which are abundant in the Rocky Mountain source region of the flood waters and the impounding glaciers. Figure 9B shows one such boulder that is about 3 m in diameter and consists of gleaming white marble with layers of brown garnet skarn, rock types that do not occur in outcrop anywhere in Central Washington.

Although the largest boulders could not have been carried directly by the flood waters, the peak velocity and discharge of the floods, estimated at 200 m/sec and 2 x 10^7 m^3/sec, respectively, (O'Connor and Baker, 1992) were sufficient to carry large amounts of relatively coarse sediment that was subsequently deposited when the water slowed near obstructions, as would be the case in the eddies behind Red Mountain (illustrated in Fig. 8D). This resulted in lenses of coarse gravels (Fig. 9D, F) in the generally finer grained silt and sand deposited by the ponded slackwater of Lake Lewis (Fig. 2).

In addition to the multiple pulses of floodwater that resulted in complex interbeds of gravel, sand, and silt, periodic eruption of Cascade volcanoes to the West

Table 2 Vineyards in the Red Mountain appellation[1]

Map no.	Name	Acres	Grapes	First Planted	Owner
1	Artz Vinneyard	20	8 cs, 5 m, 4 sb, 1 cf, 1 s, 1 c	1995	Fred Artz
2	Belle Ville	31	15 cs, 5 sy, 3 cf	1997	Pete Hedges
3	Blackwood Canyon	80	25 cs, 20 c, 15 m, 10 s, 5 sy, 2 n, 1 ca, 1 t, 1 cf	1984	Mike Moore
4	Cadence Vineyards	11	4 cf, 3 cs, 1 pv	2003	Ben Smith & Gaye L. McNutt
5	Ciel du Cheval	95	25 cs, 15 m, 14 sy, 9 cf, 7 sg, 5 ri, 5 ro, 4 v, 4 pv, 3 cb, 2 g, 2n, 1 co	1976	Jim Holmes
6	Grand Ciel Vineyard	9	7 cs, 2 sy	2001	Jim Holmes, Delille LLC
7	Golitzen Vineyard	17	17 cs	2001	Jim Holmes, Alex & Jeanette Golitzen
8	Hedges Cellars	36	18 m, 16 cs, 1 cf, 1 pv, 1 so	1990	Pete Hedges
9	Kiona Vineyards	70	28 cs, 15 l, 8 m, 5 cb, 4 c, 3 cf, 3 sg, 3 ri	1975	John and Ann Williams
10	Klipsun Vineyard	120	60 cs, 30 m, 13 sb, 9 s, 6 sy, 1 n	1984	Patricia & David Gelles
11	Tapteil	25	16 cs, 8 m, 2 cf	1985	Larry Pearson
12	Sand Hill (RMV)	40	24 cs, 13 m, 2 cf, 1 pg	1989	John Dingethal
13	Seth Ryan	7	2 cs, 2 m, 2 cf, 1 c	1996	Ron and Jo Brodzinski
14	Shaw Vineyard	12	7 cs, 4 m, 1 cf	1998	Ed and Eve Shaw
15	Terra Blanca	80	20 cs, 20 sy, 15 m, 5 c, 1 ma, 1 pv	1993	Keith Pilgrim
16	Williams	21	12 sy, 5 g, 3 sg	1978	Scott Williams

Grape abbreviations: ca = Carmenere, cf = Cabernet Franc, cs = Cabernet Sauvignon, c = Chardonnay, cb = Chenin Blanc, co = Counoise, g = Gewurtztraminer, l = lemberger, ma = malbec, m = Merlot, n = Nebbiolo, pg = Pinot Gris, pn = Pinot Noir, pv = Petite Verdot, ri = Riesling, ro = Roussane s = Semillon, sb = Sauvignon Blanc, sg = Sangiovese, so = Souzao, sy = Syrah, t = Tannat, v = Viognier

[1] Data from Jim Holmes and individual vineyard owners, written communication, 2002. Vineyard locations are shown in Figure 4.

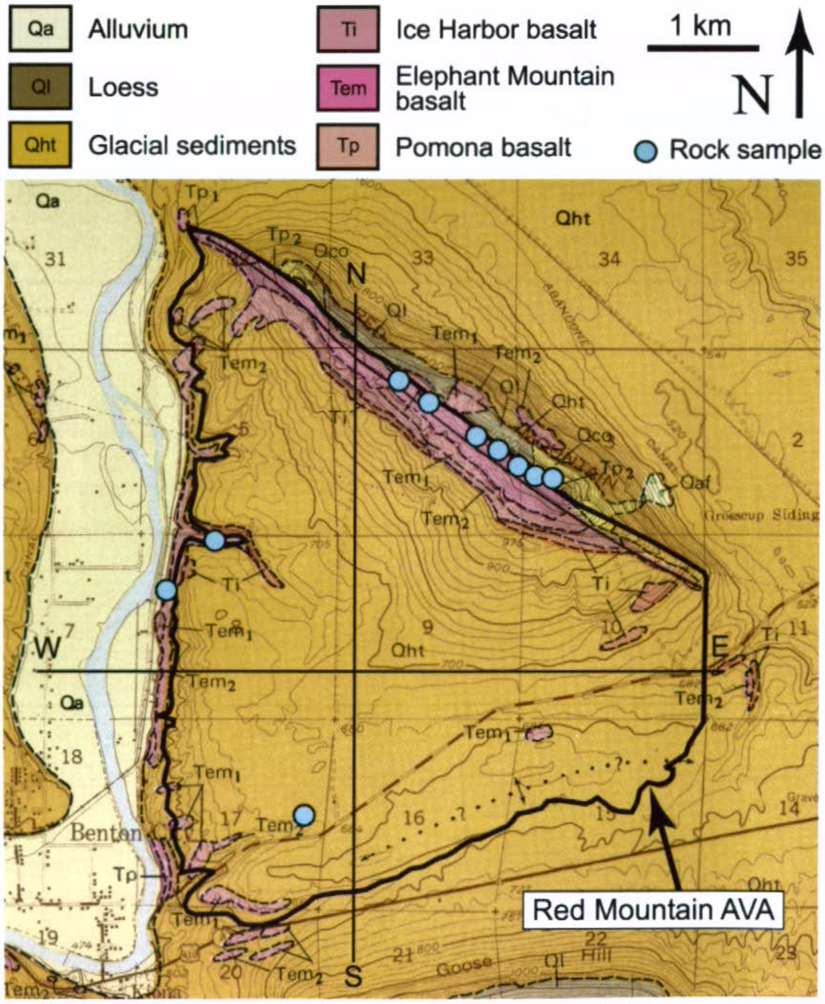

Figure 5 Geology of the Red Mountain AVA showing location of analyzed rocks (Table 3) and location of N–S and E–W cross-sections of Figure 7 (modified from Reidel and Fecht, 1994).

added a component of volcanic ash to the sediment mixture. Ash layers, such as Mt. St. Helens ash "S" (13,000 ^{14}C yr.; Mullineaux, 1996) are preserved in some roadcut and vineyard exposures (Fig. 9E). Although volumetrically minor, such ash layers provide evidence of periods of quiescence between flood pulses, necessary for the preservation of the delicate ash horizon.

WIND-BLOWN SEDIMENTS

Even though it is not shown generally on the geological map of the Red Mountain AVA (Fig. 5), loess or dune sand is everywhere present as a thin mantle ranging in thickness from decimetres to several metres on top of the slackwater sediments. As described above, the loess and the dunes were created by southwesterly winds that eroded slackwater and other glacial sediments and redeposited them into the present blanket of loess that covers much of the Columbia Plateau (Busacca, 1991). Buried soils in older loess at nearby sites not inundated by the floods indicate that deposition was intermittent during the Quaternary. The generally arid climatic conditions that continue to the present day resulted in limited chemical weathering and leaching, causing formation of calcic and petrocalcic soil horizons (Busacca, 1991; Soil Survey Staff, 1999).

CALCIUM CARBONATE CONTENT

Although as much as 90% of incoming precipitation is returned to the atmosphere

Table 3 Chemical composition of representative Red Mountain rocks[1]

Sample no.	RM-1	RM-9	RM-11	RM-2	RM-3	RM-4	RM-5
Unit	Elephant Mtn	Elephant Mtn	Elephant Mtn	Pomona	Pomona	Pomona	Pomona
Type	Basalt	Basalt	Basalt	Basalt	Basalt	Basalt	Basalt
Location	RM top	Artz-BC gully	Demoss Rd.	50m W RM	100m W RM	150m W RM	200m W RM
SiO_2	51.47	51.17	51.50	52.48	52.29	52.53	52.78
Al_2O_3	13.23	13.00	12.89	15.34	14.98	15.22	15.27
TiO_2	3.69	3.62	3.55	1.65	1.68	1.72	1.72
FeO(t)	14.13	14.53	14.79	9.32	10.37	9.90	9.94
MnO	0.20	0.21	0.20	0.17	0.18	0.17	0.17
CaO	8.71	8.96	8.64	11.31	11.01	11.28	11.12
MgO	4.06	4.36	4.26	6.55	6.22	5.91	5.68
K_2O	1.42	1.30	1.16	0.59	0.66	0.59	0.66
Na_2O	2.51	2.32	2.47	2.36	2.38	2.44	2.43
P_2O_5	0.58	0.53	0.54	0.24	0.24	0.24	0.24
Ni	11	13	14	37	47	60	47
Cr	33	36	33	118	102	109	107
Sc	46	33	37	35	37	39	37
V	426	426	432	264	279	293	273
Ba	531	480	476	941	568	828	339
Rb	29	26	28	10	11	9	9
Sr	238	242	230	262	254	253	246
Zr	256	244	253	127	135	140	140
Y	50	49	51	29	29	30	31
Nb	26	24	24	12	13	14	13
Ga	26	25	22	20	18	20	17
Cu	7	7	5	28	36	43	40
Zn	147	142	142	81	82	88	93
Pb	12	3	11	6	5	4	0
La	39	31	31	41	3	9	13
Ce	73	61	82	28	23	40	47
Th	8	0	4	3	2	2	0

Sample no.	RM-6	RM-7	RM-8	Average	Average	Average	RM-10
Unit	Pomona	Pomona	Pomona	Ice	Elephant		Scooteney
Type	Basalt	Basalt	Basalt	Harbor	Mtn	Pomona	Caliche
Location	300m W RM	400m W RM	500m W RM	Basalt[2]	Basalt[2]	Basalt[2]	Quarry
SiO_2	52.29	52.29	52.81	47.98	51.68	52.19	38.48
Al_2O_3	14.81	14.89	15.05	11.70	13.16	14.76	4.82
TiO_2	1.70	1.60	1.67	3.78	3.54	1.64	0.41
FeO(t)	10.50	10.42	9.80	17.24	14.17	10.38	2.27
MnO	0.17	0.17	0.17	0.28	0.21	0.18	0.03
CaO	10.99	10.97	10.97	8.91	8.79	10.78	49.19
MgO	6.34	6.46	6.31	4.23	4.08	6.88	3.25
K_2O	0.68	0.69	0.58	1.31	1.24	0.57	0.56
Na_2O	2.29	2.30	2.40	2.71	2.58	2.39	0.73
P_2O_5	0.24	0.22	0.24	1.85	0.55	0.23	0.24
							28.29*
Ni	45	44	36	7	10	43	0
Cr	107	107	105	33	30	106	23
Sc	39	33	33	41	35	37	0
V	284	265	276	214	408	272	56
Ba	368	264	430	838	552	191	297
Rb	11	11	13	25	31	13	19
Sr	239	234	237	240	243	231	427
Zr	138	131	143	467	242	130	166
Y	31	30	30	108	50	31	15
Nb	13	12	12	55	28	13	7
Ga	23	20	20	26	23	19	9
Cu	38	32	30	6	18	50	10
Zn	87	87	88	223	154	88	20
Pb	0	0	1	9	6	7	4
La	37	17	26	72	26	9	21
Ce	7	47	28	160	72	43	27
Th	0	0	0	5	6	2	0

* Loss on Ignition

[1] Analyses by XRF and ICPMS in the Geoanalytical Lab at Washington State University.

[2] Averages for Ice Harbor, Elephant Mountain, and Pomona members from Hooper (2000).

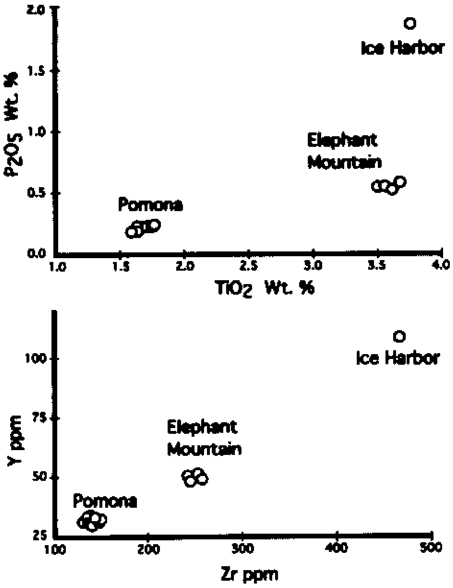

Figure 6 Compositional discrimination diagrams for Columbia River basalts using a) P_2O_5 versus TiO_2 and b) Y versus Zr. Data from Table 3 and Hooper (2000).

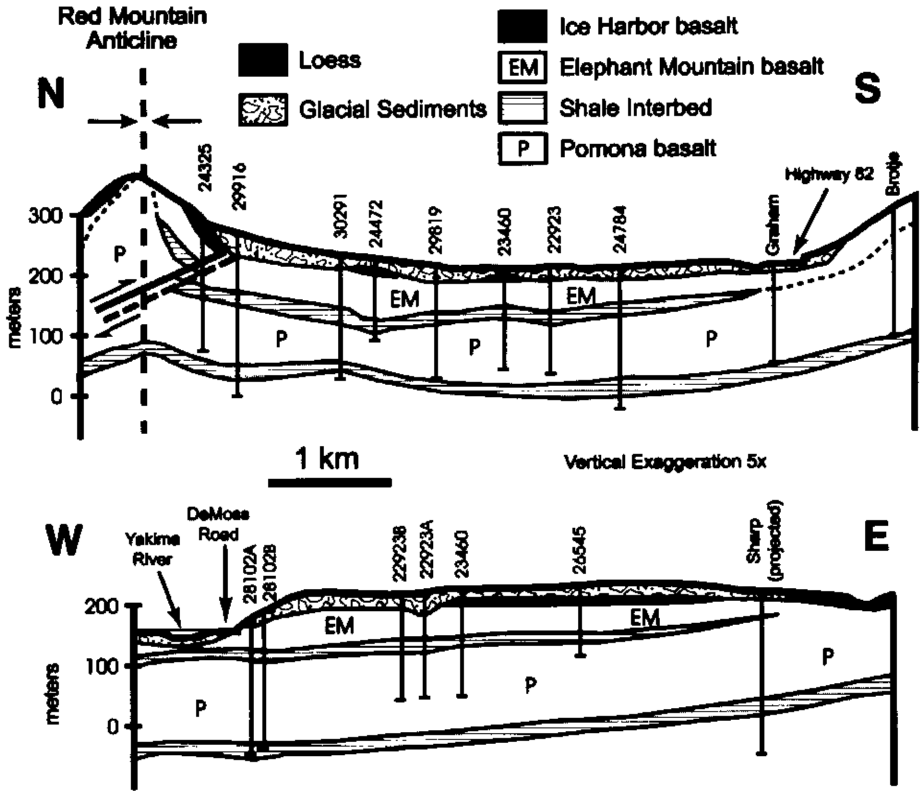

Figure 7 Geological cross-sections through the Red Mountain area (vertical exaggeration 5:1). Well log data courtesy of Lorne Jacobsen, written communication, 2001. Location of cross-sections is illustrated in Figure 5.

as evapotranspiration, the coarse gravel lenses intercept and channel the infiltration of precipitation descending through overlying loess and dune materials. Thus, shallow gravel lenses can contain significant calcium carbonate. An analysis of one such petrocalcic horizon (RM-10, Table 3) shows that it contains up to 50% CaO, an order of magnitude more calcium than average soil and rock values (Tables 3, 4). Although limestone is absent in the Red Mountain AVA, other than as erratic boulders, the calcite-cemented gravel lenses form significant reservoirs of calcium carbonate that can affect vineyard performance. For example, calcium is known to inhibit vine uptake of such essential nutrients as nitrogen and potassium (Winkler *et al.*, 1974; Ribéreau-Gayon *et al.*, 2000). Also, Fe is particularly affected if water pools on calcic layers in the root zone (Sara Spayd, written communication, 2002). Some Red Mountain wineries such as Terra Blanca, Spanish for white earth, point to these calcic layers as an important and sometimes negative part of the local terroir.

RED MOUNTAIN SOILS

The layered stratigraphy of bedrock basalt and overlying glacial floodwater and eolian sediments forms the substrate for soil development in the Red Mountain AVA. Given the heterogeneity of these sediments, it is not surprising that there are a number of different soils in the Red Mountain AVA (Fig. 10), and that these soils perform very differently under grape production.

A common theme to the soils of the benched area of Red Mountain is that they formed in eolian materials (loess or dune) over slackwater sediments from giant glacial outburst floods (Meinert and Busacca, 2000). Yet within this landscape, no fewer than eight different soil series have been mapped, and these can have very different textures (Table 4) and profile morphology (Fig. 11): Hezel (Xeric Torriorthents), Quincy (Xeric Torripsamments), and Finley, Scooteney, Prosser, Starbuck, Kiona, and Warden (all Xeric Haplocambids; Soil Survey Staff, 1999). Vineyards are planted on most of these, with development planned for the remainder.

All but two of the principal soils are classified as Aridisols in soil taxonomy (formative word Arid; Soil Survey Staff, 1999) based primarily on an aridic soil moisture regime. The two soils that formed in dune materials (Hezel and Quincy) are Entisols (formative word Recent) because the shifting sands lack most soil profile features. In sharp contrast to the Aridisols and Entisols of the appellation, soils on the floodplain of the Yakima River less than one kilometre outside the appellation and planted to *Vinifera* are Mollisols of the Pasco series (Fig. 11; Cumulic Endoaquolls), which are wet soils with very dark, thick, humus-enriched topsoils. These soils have a permanent water table whose height in the soil profile fluctuates seasonally with stages of the Yakima River. The generally high water table results in carbonates to the surface and uncontrolled access to water during the growing season.

Large areas of the benchlands of the Red Mountain appellation are underlain by the Warden series soils, formed in about 50 cm of loess or mixed loess and eolian sand over stratified flood sediments (Fig. 11), whereas adjacent areas, even within the same vineyard, are underlain by the Hezel series soils (Fig. 14b), which formed in a cover of about 50 cm of dune sand over sandy stratified flood sediments. In contrast, areas of Scooteney soils grade downward from an eolian sandy loam or loam at the surface to a fluvial unit of very cobbly sandy loam at

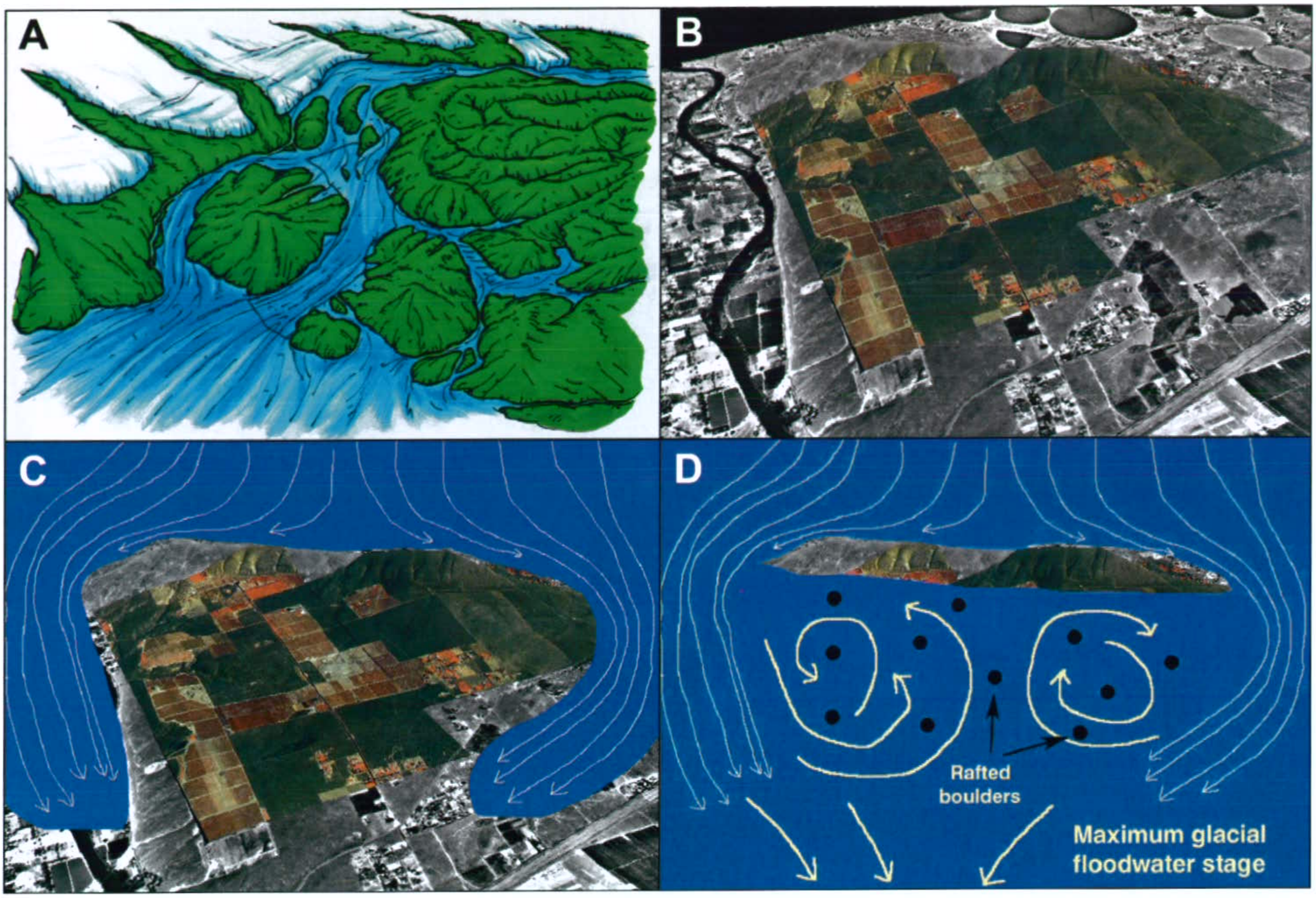

Figure 8 Cartoon illustrating the sequence of events during flooding caused by the catastrophic draining of glacial Lake Missoula. A) Artist's rendition of outburst flooding caused by failure of a glacial ice dam. Note torrent of water rushing around isolated hills analogous to Red Mountain. Modified from Molenaar (1988). B) 3-D perspective view of Red Mountain area with color infrared imagery draped over black and white ortho aerial photograph. Note that in infrared images, green vegetation such as leafy vineyards are red whereas arid range lands are dark green. Images courtesy of Francis Pierce, Center for Precision Agricultural Systems, WSU-IAREC. C) Approach of floodwaters with flowlines around Red Mountain. Even though standing water, as evidenced by the strandline of ice-deposited erratics, did not cover Red Mountain, it is possible that the initial flood surge may have overtopped the peak creating a temporary but rather large standing wave. D) Maximum flood stage as evidenced by the strandline of ice-deposited erratics, and schematic location of boulders deposited by melting of rafts of ice. See Figure 9A, B, C for examples of such ice-rafted boulders.

150 cm. All three of these soils can be tens of metres thick above hard basalt bedrock. A variant of Scooteney series soils, which was not recognized in the previous soil survey (Rasmussen, 1971), was found in our field reconnaissance to have a strongly lime-silica cemented duripan in flood gravel at depths of 50 cm to 100 cm. Thus vineyards in the Red Mountain AVA have soils that range from loess to dune sand to gravel to slackwater sediments in the lower part of the vine rooting zone.

Still other areas in this same landscape are underlain by Prosser and Starbuck series soils (Fig. 11), with bedrock at less than 40 cm to 80 cm depth. Small areas have Quincy soils that formed in dune sand more than 150 cm deep. Soils of the Kiona series (Fig. 11) that occupy the steep south face of Red Mountain (with slopes up to 60 percent) have formed in slope colluvium of fractured basalt mixed with loess and are cobbly loams to more than 150 cm. It appears that no vineyards have yet been planted on areas of Kiona soils.

The majority of the soils in the Red Mountain appellation are thicker than several metres (Fig. 7). The most important vineyard soils formed as the result of two end-member eolian processes, dune saltation and loess suspension. Dominantly sandy dune materials accumulated over either flood gravels or stratified flood slackwater sediments (*e.g.,* Hezel series, Fig. 11) in some places on Red Mountain, whereas dominantly silty loess materials have accumulated over flood materials in other places (*e.g.,* Warden series, Fig. 11). This is evident in the high total sand content of a Hezel sample (75.9%, CC-3, Table 4) versus the lower total sand content of a Warden sample (19.6%, BV-3, Table 4). However, mixing of variable amounts of saltated sand and suspended silt occurred in most of the sampled soils, leading to highly variable soil textures. In general, the soils are more sandy in the surface layer and more silty at 1 m depth (Table 4), suggesting that loess deposition dominated early in the post-flood history of Red Mountain and that dune sands have more recently covered or

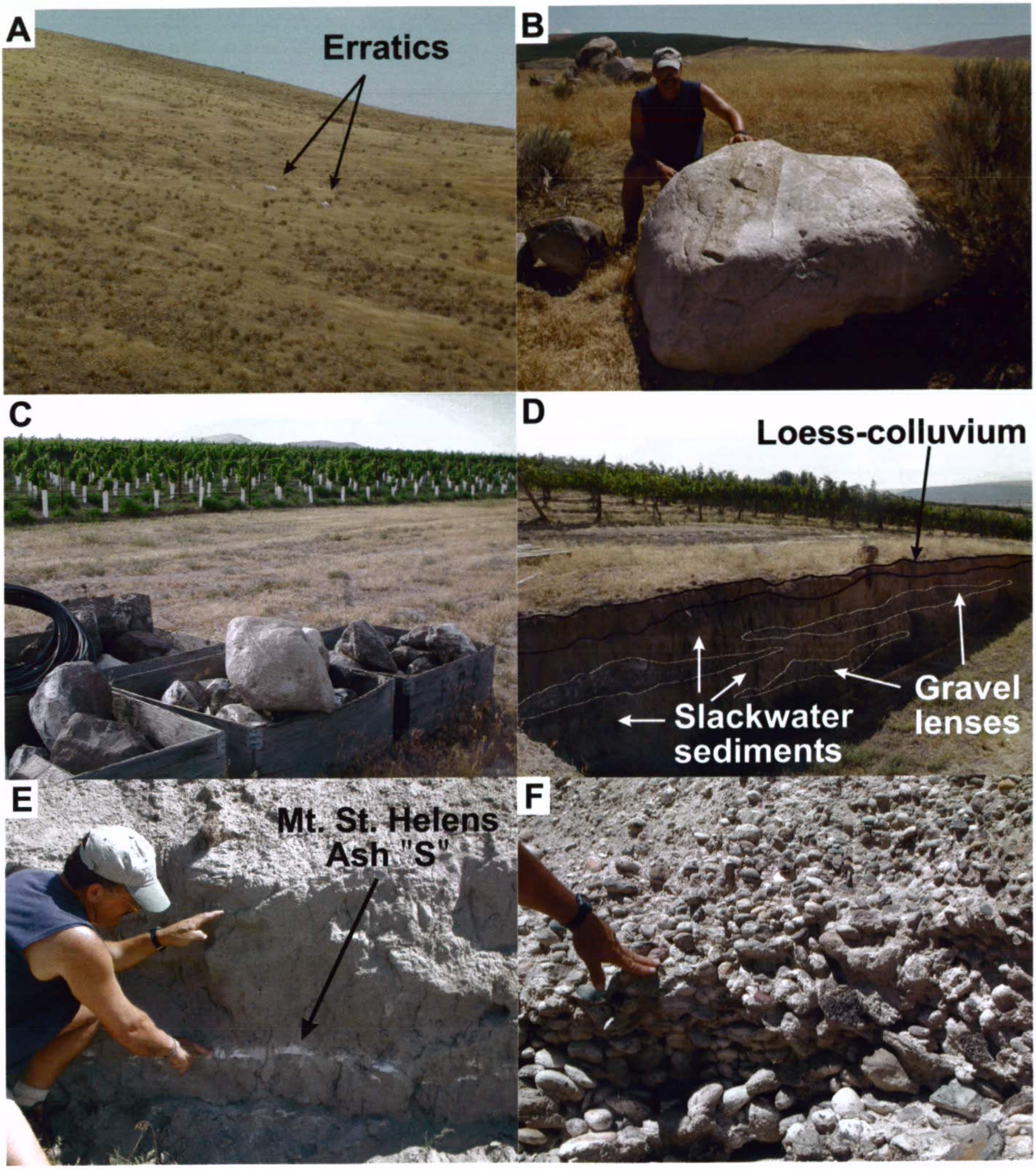

Figure 9 Photographs of vineyard features in the Red Mountain area. A) South side of Red Mountain about 100 m below the peak showing location of ice-rafted boulders. For scale, sagebrush is about 1 m high. B) Example of an ice-rafted boulder. The polished and rounded stone is gleaming white marble with layers of brown garnet skarn. C) Glacial erratic boulders gleaned from the Kiona vineyard are collected in wooden boxes (grape picking bins). D) Cut bank in Tapteil vineyard exposing 3–4 m cross-section of Quaternary loess, slackwater deposits, gravel lenses, and loess-colluvium. Gravel in lenses is similar in size to that in photo F. E) 2–4 cm white band of Mt. St. Helens "S" ash in Quaternary slackwater and channel deposits exposed in roadcut on south side of Red Mountain AVA. F) Lime-cemented gravels of the Scooteney soil association.

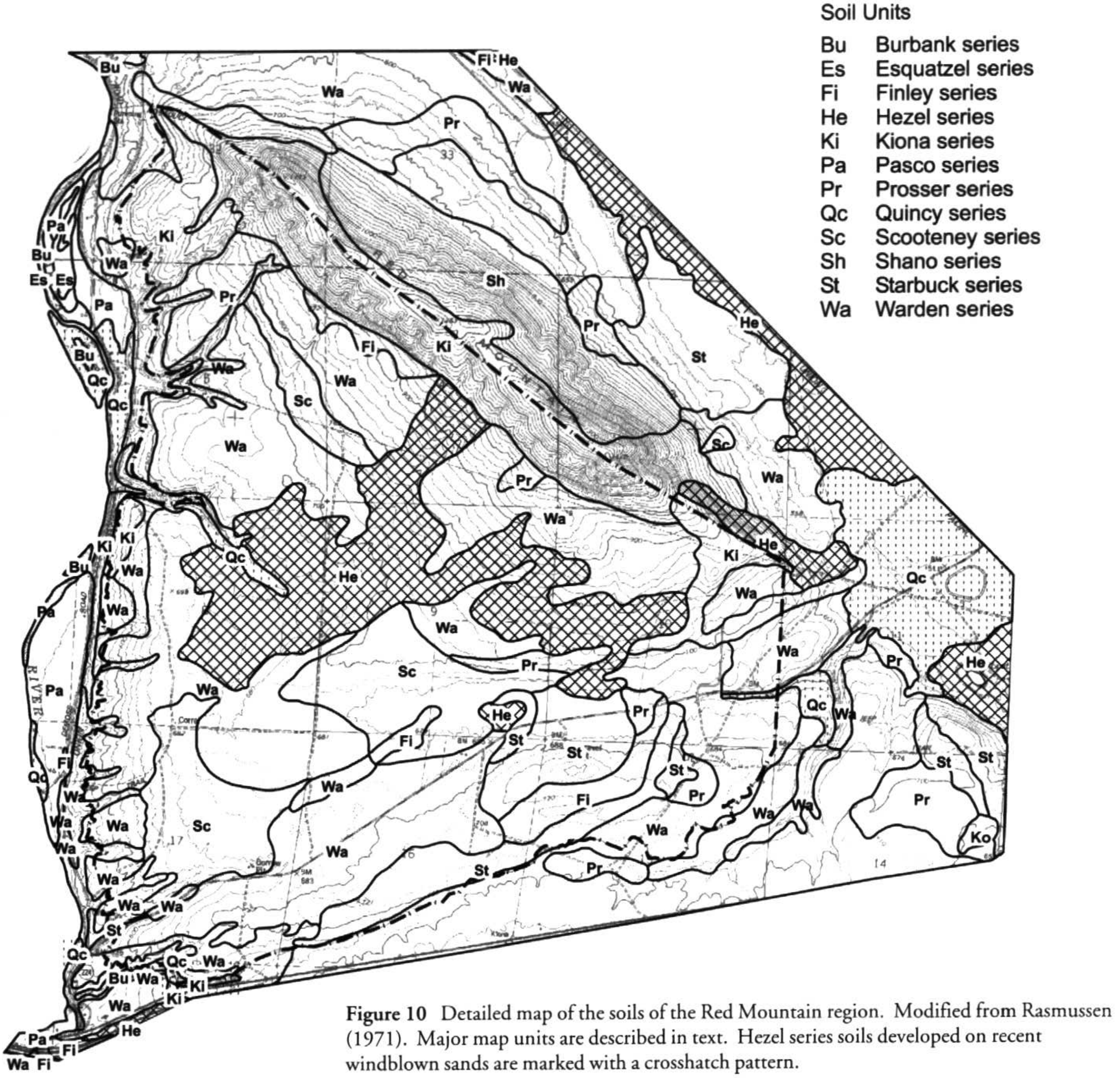

Figure 10 Detailed map of the soils of the Red Mountain region. Modified from Rasmussen (1971). Major map units are described in text. Hezel series soils developed on recent windblown sands are marked with a crosshatch pattern.

influenced most of the soils. With such marked variation in texture within and among soil profiles at Red Mountain, the volumetric water content at field capacity ranges from 7% for soils like the Hezel at the Ciel du Cheval vineyard to as high as 24% for soils like the Warden at the Belle Ville vineyard.

X-ray fluorescence and inductively coupled plasma mass spectrometry (ICPMS) total elemental analyses of selected soil samples from Red Mountain (Table 4) show that these soils have a remarkably uniform composition, ranging from 61 to 67% SiO_2, 12 to 14% Al_2O_3, and 6 to 8% FeO. The most variable element is calcium, ranging from about 4 to 8%. This is explained by the presence of variable amounts of pedogenic lime coatings in the samples. The major-element composition of the soils appears to be partly related to clay content; that is, soils with higher clay contents tend to have higher SiO_2 contents.

Soil profiles like the Scooteney hardpan variant strongly restrict rooting depth, whereas Scooteney, Warden, and Hezel pose only moderate restrictions on rooting depth. We have observed a vineyard just outside the appellation that is partly planted on the Starbuck soil (Fig. 11) that is less than 50 cm to bedrock. Vines in this soil show stunted development and severe late-season water stress compared to vines on deeper soils in the same vineyard.

Virtually all of the soils have free lime both at the surface and at one-metre depth (Table 4), which is a reflection both of the very low rainfall for leaching and the continual addition of carbonate-bearing dust to these soils. All of the soils have pH values of about 8 at the surface, reflecting a pH control by free calcium carbonate. Interestingly, all of the samples from a depth

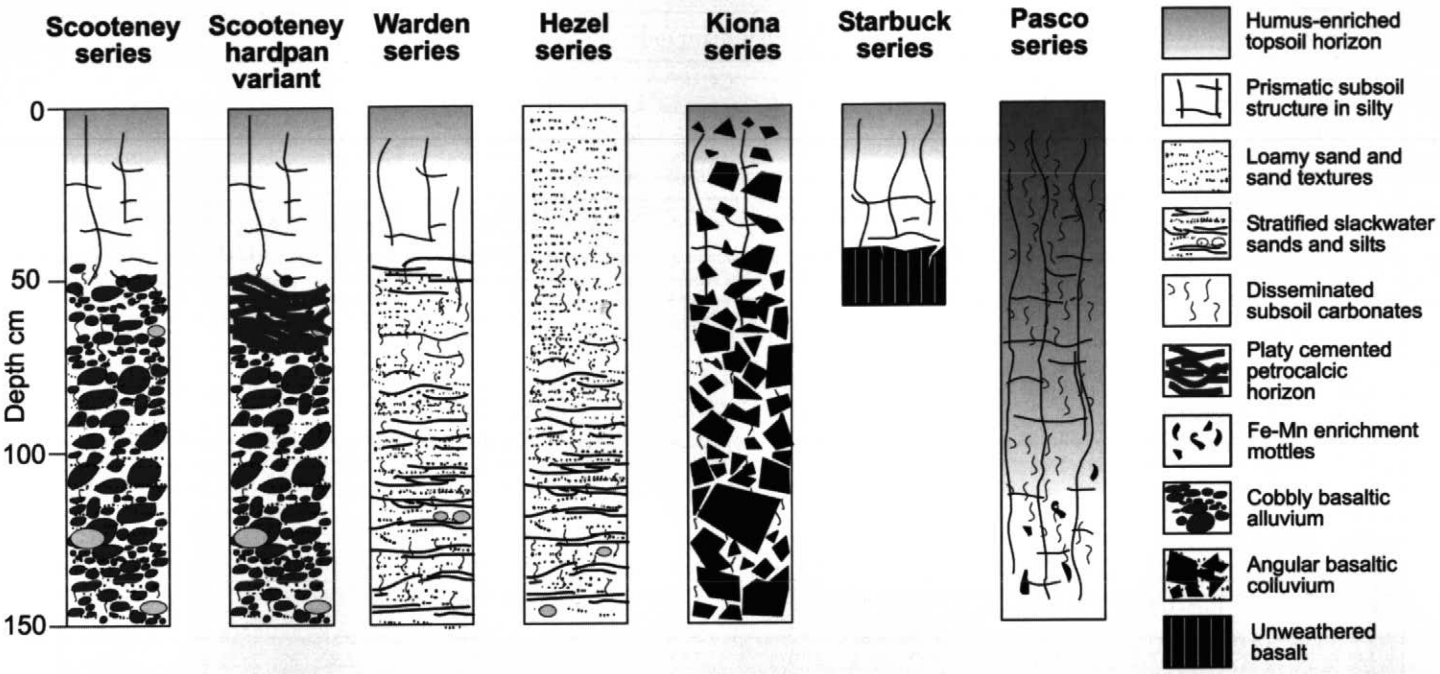

Figure 11 Representative soil profiles of the main soil series in the Red Mountain area. Degree of shading of the topsoil horizons is proportional to the content of humified organic matter. The irregular lines in the prismatic subsoil pattern represent the pattern of soil structure that develops in these silty soil horizons.

of one metre have pH values from 8.5 to 8.8, suggesting that these soils contain moderate amounts of exchangeable sodium. No evidence for a true sodic soil condition has been observed in the vineyards, however.

Vineyards planted on the wide range of soils that occur within the bounds of the AVA have large differences in water-holding capacity, infiltration, and potentially runoff. All of the soils share a strong soil-moisture deficit during the growing season, which allows growers to control water uptake by the grape vines and thus, one determinant of vine vigour. Some of the Scooteney hardpan variant soils may have a risk of shallow saturation and waterlogging under irrigation whereas others nearby are susceptible to drought.

RED MOUNTAIN CLIMATE

Red Mountain is one of the warmer vineyard sites in Washington State with 3409 degree days (50°F) recorded in 1998 and an average of 3016 degree days for the years of record (Table 5). For comparison, the Napa Valley in California and the Barossa Valley in Australia average 3280 and 3090 degree days, respectively [see the broader discussion by Meinert and Busacca (2000) of climatic measures in Washington and by Gladstones (1992, 2001) of general climatic measures relative to viticulture]. Red Mountain also may be the driest viticultural area in Washington State, with an average annual precipitation of 17.8 cm and a low in 1999 of 8.4 cm (Table 5). Comparison of monthly temperatures and precipitation (Fig. 12) shows that the lowest precipitation coincides with the highest temperatures, and because of the low water-holding capacity of the soil and low water table, this creates a moisture deficit that requires irrigation in all vineyards. With the high evapotranspiration rates in such conditions, drip irrigation is the dominant method of supplying supplemental water.

Red Mountain, at the eastern end of the Yakima Valley, is exposed to fairly steady westerly winds, averaging 6.8 km/hr, with relatively little monthly variation (5.5–7.9 km/hr). Strong winds (>24 km/hr) mostly occur in the spring, with only three months (March–May) having on average 10 or more daylight hours of winds >24 km/hr. During the prime ripening season of July–October there are only 4 daylight hours total with winds >24 km/hr (Table 5).

Another variable of critical importance in ripening of grapes is sunlight exposure (see Fig. 2 in Gladstones, 1992) which at Red Mountain averages 1229 kW/m^2 from April to October (Table 5). Both the heat summation (degree days) and the total sunlight exposure are nearly identical for vineyards in Red Mountain and Napa Valley, California even though Red Mountain is about 1000 km farther north (Gladstones, 1992). However, there are many other variables that distinguish between these regions, such as number of frost-free days and diurnal temperature range.

When standing in Red Mountain vineyards on a typical summer day, another aspect of the mesoclimate can be observed. Generally, because of regional air circulation patterns, there is a high pressure zone over Red Mountain that results in clear skies directly overhead even when partial cloud cover may obstruct areas only 10 km away (Fred Artz, personal communication, 2002). These clear skies over Red Mountain can have a negative aspect during the cooler months, as both frost damage and winter kill can be a problem in some years (Jim Holmes, personal communication, 2001). Winter temperatures drop below −10°C in most years and −27.6°C was recorded in 1996 (Table 5), a year of devastating winter kill in many Pacific Northwest vineyards.

VINEYARDS AND WINES OF THE RED MOUNTAIN AVA

The Red Mountain AVA is not only Washington's newest AVA (approved in 2001), but many of the plantings are

Table 4 Composition and grain size of representative Red Mountain soils[1]

Sample #	CC-3	CC-4	CC-5	CC-6	CC-8	CC-9	CC-10	CC-1	CC-2	CC-7
Vineyard	Ciel Cheval	Ciel Cheval	Ciel Cheval	Ciel Cheval	Ciel Cheval	Ciel Cheval	Ciel Cheval	Ciel Cheval	Ciel Cheval	Ciel Cheval
Soil type	Hezel	Hezel	Hezel	Hezel	Warden	Warden	Warden	Scooteney	Scooteney	Scooteney
Depth	Surface	1 m	Surface	1 m	Surface	1 m	Surface	Surface	1 m	Surface
Grape type	Cab Sauv	Cab Sauv	Cab Sauv	Cab Sauv	Cab Sauv	Cab Sauv	Syrah	Merlot	Merlot	Cab Sauv
SiO_2	66.40	64.40	66.65	65.53	66.68	64.98	66.23	66.10	64.98	66.28
Al_2O_3	13.22	13.44	13.49	13.22	13.83	13.52	13.89	13.17	13.19	13.87
TiO_2	1.37	1.49	1.36	1.35	1.25	1.21	1.33	1.36	1.42	1.35
FeO(t)	6.98	7.09	6.77	6.69	6.84	6.81	7.16	6.93	7.34	6.95
MnO	0.12	0.13	0.12	0.12	0.12	0.12	0.12	0.12	0.13	0.12
CaO	4.62	6.03	4.31	5.72	4.00	6.16	4.00	5.00	5.61	4.12
MgO	2.35	2.71	2.29	2.51	2.23	2.54	2.30	2.54	2.55	2.28
K_2O	1.99	1.83	1.95	1.80	2.09	1.99	2.06	2.00	1.80	2.07
Na_2O	2.51	2.42	2.61	2.63	2.55	2.24	2.47	2.32	2.52	2.51
P_2O_5	0.26	0.28	0.25	0.25	0.24	0.24	0.25	0.27	0.27	0.25
LOI	3.58	3.88	3.17	3.91	3.89	5.44	4.82	4.01	3.19	4.22
Ni	18	24	22	22	20	23	21	19	19	22
Cr	47	55	51	51	41	40	48	47	45	53
Sc	17	19	23	19	22	15	18	16	16	20
V	183	210	184	190	156	161	155	182	199	172
Ba	647	651	653	677	651	659	659	627	655	657
Rb	63	62	61	58	69	74	70	68	60	67
Sr	355	354	359	393	330	317	319	337	390	336
Zr	245	262	245	250	252	223	271	262	250	263
Y	31	33	32	32	35	34	35	32	31	35
Nb	15	17	16	16	16	16	16	13	14	17
Ga	14	16	20	14	16	17	17	17	15	15
Cu	6	9	4	4	6	7	7	10	8	9
Zn	84	84	73	73	86	80	83	82	84	80
Pb	14	13	17	17	21	19	25	19	14	19
La	29	22	55	32	32	27	31	26	45	28
Ce	55	70	62	81	63	52	56	66	51	86
Th	10	13	12	11	11	9	7	8	12	11
very coarse sand	1.0	2.4	1.2	1.3	0.6	0.2	1.7	n.d.	0.9	n.d.
coarse sand	2.5	1.8	2.4	2.2	1.3	0.5	2.1	n.d.	1.5	n.d.
medium sand	3.9	2.6	3.7	3.3	2.0	0.5	2.8	n.d.	2.0	n.d.
fine sand	1.3	0.1	0.1	1.4	7.0	0.1	0.4	n.d.	0.1	n.d.
very fine sand	67.2	43.9	65.0	69.2	46.2	30.3	56.2	n.d.	68.5	n.d.
% total sand	75.9	50.9	72.4	77.4	57.1	31.7	63.2	n.d.	73.0	n.d.
coarse silt	8.7	36.0	8.5	15.6	17.9	47.2	16.5	n.d.	20.8	n.d.
fine silt	4.1	11.4	5.1	4.5	10.1	18.4	7.7	n.d.	5.1	n.d.
% total silt	12.8	47.4	13.7	20.0	28.0	65.6	24.2	n.d.	25.9	n.d.
% total clay	11.3	1.8	13.9	2.6	14.9	2.7	12.6	n.d.	1.1	n.d.
total	100.0	100.0	100.0	100.0	100.0	100.0	100.0	n.d.	100.0	n.d.
pH 1:1	8.2	8.5	8.0	8.7	8.2	8.5	8.2	8.4	8.8	8.1
$CaCO_3$	0.7	3.0	2.7	3.3	0.4	4.8	0.4	1.1	2.2	0.4
$MgCO_3$	0.38	0.21	0.12	0.22	0.15	0.21	0.59	0.19	0.20	0.13

[1] All samples sieved to exclude >2mm fraction. Major and trace elements analyses by XRF and ICPMS in the Geoanalytical Lab at Washington State University. Grain size, pH, carbonate, and nirtogen analyses by Department of Crop and Soil Sciences at Washinton State University

relatively young, making up only about 30% of the AVA's potential acreage in cultivation. Irrigated vineyards form a striking contrast to the natural xerophytic (drought tolerant) vegetation, including species of *Artemisia*, *Purshia*, and *Crysothamnus* (Fig. 13A). While most of the older vineyards are planted in N–S rows, some of the younger plantings have a N10°E orientation (Fig. 13B) to maximize sun exposure (60% morning, 40% afternoon) at this latitude (46°20') and provide greater shading of fruit on the west side of the canopy in the later afternoon (Jim Holmes, personal communication, 2001).

Although the Red Mountain AVA is bounded on the west by the Yakima River (Fig. 13C), none of this water is used directly for irrigation within the Red Mountain AVA. Rather, all irrigation water in the Red Mountain AVA comes from wells that typically are about 200 m deep in order to tap intraflow aquifers (Fig. 7). Static water level is about 100 m below the surface in most of these wells, except for those closest to the Yakima River on the western margin of the Red Mountain AVA. Because of this hydrological regime, the rooting zone of all Red Mountain vineyards is well above the water table and most available soil moisture comes from drip irrigation augmented by stored soil moisture from winter rainfall and by relatively rare rainshowers during the growing season (about 5 cm total from April to October; Table 5).

As previously described, the soils and bedrock geometry of the Red Mountain AVA are well suited for vineyard production and differ in several respects from those in areas immediately surrounding the AVA. For example, the soils in vineyards such as Klipsun (Fig. 13D) within the Red Mountain AVA are quite different from those in vineyards that are only a few hundred metres outside the AVA, such as on

Table 4 Continued

Sample #	CC-11	CC-12	CC-13	K-1	BV-1	BV-2	BV-3	O-1	O-2
Vineyard	Ciel Cheval	Ciel Cheval	Ciel Cheval	Klipsun	Belle Ville	Belle Ville	Belle Ville	Oakwood	Oakwood
Soil type	Scooteney	Scooteney	Scooteney	Scooteney	Warden	Warden	Warden	Pasco	Pasco
Depth	1 m	Surface	1 m	Surface	Surface	Surface	1 m	Surface	1 m
Grape type	Syrah	Syrah	Syrah	Cab Sauv	Sagebrush	Syrah	Syrah	Riesling	Riesling
SiO_2	65.20	66.91	63.67	67.31	66.94	64.05	65.72	66.39	67.02
Al_2O_3	13.40	13.60	12.88	14.12	13.71	13.18	13.52	13.91	14.39
TiO_2	1.43	1.26	1.31	1.15	1.29	1.36	1.23	1.37	1.13
FeO(t)	7.73	6.74	7.14	6.38	6.69	7.21	6.87	6.65	5.93
MnO	0.13	0.12	0.12	0.11	0.12	0.12	0.12	0.12	0.11
CaO	4.99	4.10	7.80	3.84	4.07	7.06	5.39	4.16	4.05
MgO	2.59	2.31	2.60	2.04	2.15	2.46	2.57	2.25	2.17
K_2O	1.82	2.06	1.84	2.00	1.95	1.90	1.93	1.88	1.94
Na_2O	2.29	2.48	2.21	2.64	2.67	2.20	2.23	2.81	2.85
P_2O_5	0.25	0.24	0.24	0.21	0.22	0.26	0.22	0.26	0.23
LOI	4.18	3.79	6.12	3.72	2.78	5.79	4.79	4.10	2.93
Ni	25	22	20	29	21	20	23	29	32
Cr	45	50	46	61	44	43	49	97	81
Sc	24	19	17	18	21	16	19	16	18
V	173	152	170	134	170	171	168	161	136
Ba	635	623	626	643	639	645	682	619	643
Rb	68	68	65	67	63	69	72	59	62
Sr	314	335	333	331	354	321	308	341	330
Zr	288	272	286	285	256	283	321	262	216
Y	37	34	36	31	32	36	37	32	29
Nb	18	16	16	16	16	18	18	15	13
Ga	17	17	18	17	13	15	18	18	19
Cu	11	8	11	9	3	11	9	7	10
Zn	79	78	76	82	74	81	77	84	75
Pb	23	21	26	23	20	22	23	22	20
La	29	29	48	35	55	24	32	55	19
Ce	63	61	72	99	64	69	69	82	47
Th	9	10	14	11	11	11	13	10	8
very coarse sand	2.4	0.5	1.2	2.5	3.8	1.8	0.2	1.8	2.2
coarse sand	2.2	1.2	1.4	3.1	4.6	2.2	0.3	2.8	2.7
medium sand	0.9	2.4	1.9	3.2	4.6	1.9	0.2	4.0	3.5
fine sand	0.1	1.0	0.1	6.8	0.1	0.1	0.0	12.4	0.3
very fine sand	29.9	51.0	34.6	34.8	61.2	34.9	18.8	41.3	53.5
% total sand	35.5	56.1	39.1	50.4	69.9	40.9	19.6	66.6	62.2
coarse silt	48.2	20.9	39.6	23.2	18.7	40.8	64.9	18.1	22.2
fine silt	15.2	9.2	17.0	10.5	5.9	15.2	13.8	8.1	9.3
% total silt	63.4	30.1	56.6	33.7	24.6	56.0	78.7	26.2	31.5
% total clay	1.1	13.8	4.2	15.9	5.5	3.1	1.7	7.2	6.3
total	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
pH 1:1	8.7	8.4	8.6	8.7	7.9	8.7	8.8	7.8	8.6
$CaCO_3$	2.0	0.5	7.8	0.6	0.3	6.5	3.9	0.3	0.4
$MgCO_3$	0.14	0.10	0.18	0.11	0.09	0.23	0.27	0.08	0.12

a high basalt knob to the Southwest (Fig. 13E) or on the Yakima River floodplain to the West (Fig. 13F).

The pictured vineyard (Fig. 13F) on the Yakima River flood plain is about 100 m west of the Red Mountain AVA boundary and about 200 m from the Klipsun vineyard (Fig. 13D). The rich Mollisol soils (Table 4, Fig. 11) and abundant water (even without supplemental irrigation) in the flood plain of the Yakima River result in more vigourous vegetative growth of both grape vines and ground cover relative to the nearby Red Mountain vineyards, as illustrated in photos taken on the same day of the growing season (compare Fig. 13D and 13F).

About 700 m southwest of the Red Mountain AVA there is a vineyard planted on a basalt hill that has less than a metre of loess and Quaternary glacial sediments on top of the basalt to form soils. The vine roots have penetrated into the basalt and the free drainage of the fractured basalt and thin sediment cover results in a rapid loss of soil moisture. In contrast to the vineyards on the Yakima River floodplain that have perhaps an overabundance of moisture and plant vigour, the shallow soils on this basalt knob hold little water, even after irrigation, and the resulting moisture deficit can result in reduced plant vigour (Fig. 13E).

Although the above examples illustrate differences between Red Mountain and surrounding areas, there also are important differences within the Red Mountain AVA. As previously discussed, there are variations in soil types, thickness and homogeneity of Quaternary glacial sediments, and depth to bedrock among Red Mountain vineyards (Figs. 5, 7, 10, 11, 14).

For example, Ciel du Cheval (Fig. 14B) lies in the geographic center of the Red Mountain AVA (Fig. 4) and is one

Table 5 Red Mountain 1995–2001 climate data (Red Mountain PAWS*, Lat. 46°20', Long. 119°40', Elev. 194 m)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Mean max. temp. °C	5.3	8.8	14.2	18.8	23.3	27.5	32.9	32.5	27.1	18.0	10.2	4.4	18.6
Mean avg. temp. °C	1.5	3.7	7.8	11.6	15.9	19.8	24.2	23.4	18.3	10.7	5.5	1.0	11.9
Mean min. temp. °C	-2.1	-1.0	1.3	3.6	7.4	10.7	14.3	13.8	9.8	3.6	1.0	-2.3	5.0
Precipitation (cm)	2.4	2.1	1.8	0.8	1.2	0.7	0.8	0.1	0.7	1.8	3.4	2.0	17.8
Snowfall (cm)	10.9	4.3	0.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.8	6.4	23.1
Mean wind speed (kph)	7.6	7.9	7.5	7.2	7.4	7.2	6.1	5.7	5.5	5.7	6.9	7.2	6.8
Daylight hrs wind >24 kph	2	8	11	12	10	5	1	3	0	0	0	2	54
Solar radiation (kW/m²)	38	63	112	161	195	222	216	201	142	93	44	28	1514
Mean 9 am temp. °C	0.4	2.5	6.9	11.6	16.3	20.1	24.0	23.2	18.1	10.4	4.6	0.3	11.5
Mean 9 am relative humidity	86	81	69	55	49	45	41	44	53	67	85	86	63
Mean 2 pm temp. °C	4.2	7.6	12.8	17.3	21.6	25.8	30.8	30.7	25.7	16.9	9.0	3.2	17.1
Mean 2 pm relative humidity	71	60	45	36	33	28	24	24	31	42	68	75	45
Degree days (50°F)	2	8	26	161	320	529	772	700	389	91	16	2	3016

	1995	1996	1997	1998	1999	2000	2001	Mean
Maximum air temperature °C	40.1	41.5	39.4	42.7	39.5	39.8	40.2	40.4
Minimum air temperature °C	-17.0	-27.6	-13.3	-16.8	-8.2	-10.5	-6.6	-14.3
Precipitation (cm)		24.8	19.4	22.9	8.4	19.3	11.8	17.8
Degree days (50°F)		2836	3039	3409	2786	2920	3106	3016

* Data from Washington State University Public Agricultural Weather System (PAWS)
http://frost.prosser.wsu.edu/ Courtesy of Francis Pierce, Center for Precision Agricultural Systems, WSU-IAREC

of the older vineyards, first planted in 1976. The Ciel du Cheval vineyard has a relatively low slope (Fig. 4), with homogeneous air drainage and mesoclimate. Thus, most climatic variables are approximately constant throughout the vineyard. In contrast, there are three different soil units present in the vineyard (Fig. 14B) that cut across the N–S rows of vines. The three soil units are Hezel, Scooteney, and Warden. As previously discussed, these differ in texture and composition. The Ciel du Cheval vineyard has been owned and managed by a single person, Jim Holmes, for nine years and thus has a consistency of management style that should allow for examination of viticultural and enological variations as a reflection of soil type. Initial results of grape analyses suggest that there are differences that may correlate with soil types and an ongoing study of wine sensory analysis over a three-year period has been designed to test whether different soil types can be correlated with statistically significant wine flavor profiles (Sara Spayd, written communication, 2002). This will be reported in a future publication. Such sensory differences have been correlated previously with a number of terroir variables (*e.g.*, Douglas *et al.*, 2001).

In contrast to Ciel du Cheval, the Belle Ville vineyard is relatively young, first planted in 1997. It is the northeasternmost vineyard in the Red Mountain AVA (Fig. 4), is underlain entirely by Warden series soils, and lies on a moderate slope that was extensively graded to smooth the original topography (Steve Lessard, personal communication, 2001). Expressions of topography and drainage are readily visible in Figure 14C, an orthogonal infrared image taken in August, 2001. The variations visible in the image correspond to zones of vine stress that cut across rows of a single cultivar and management regime and therefore are unlikely to result from differences in canopy management, irrigation, or other viticultural practice (Steve Lessard, personal communication, 2001). It is hypothesized that grading of the Warden series soils may have disrupted the natural drainage patterns, grain size distribution, or lime content that vary systematically with depth in the other non-graded vineyards (Table 4). All of these factors may be interrelated, making it difficult to pinpoint a single variable that may be most responsible for differences in vineyard vigour. Previous studies have correlated the onset of black leaf and other problems in Washington State to within vineyard variations of soil moisture, drainage, and grading (Ahmedullah and Dow, 1982; Silbernagel *et al.*, 1998). Whatever the cause of the observed vine stress in the Belle Ville vineyard, the apparent correlation with topography and drainage patterns suggests that environmental variation can have at least as significant an effect as can viticultural practices in vineyard performance.

DISCUSSION

The vineyards in the Red Mountain AVA share a common history of soils developed on eolian materials (loess or dune) over variable sediments that derive from giant glacial outburst floods, which in turn overlie basalts of the Columbia River Group. Variations in soil type within the appellation or even within individual vineyards, such as Ciel du Cheval, are significant but pale in comparison to that of vineyards just outside of the appellation such as on adjacent basalt knobs (Fig. 14E) or on the Yakima River floodplain (Fig. 14F). This illustrates the importance of terroir in defining a sense of place, that with appropriate vinification can lead to a distinct wine style. The Red

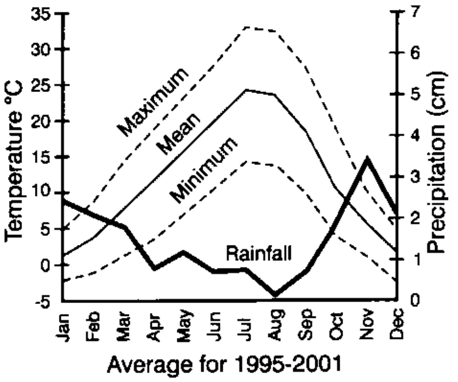

Figure 12 Graph of monthly maximum, mean, and minimum temperatures in contrast to precipitation for the Red Mountain area. Data from Table 5.

Figure 13 Photographs of vineyard features in the Red Mountain area. A) View looking northeast from the Klipsun vineyard (#10) across the Hedges Cellars (#8) and Bell Ville (#2) vineyards towards Red Mountain. B) Newly planted vines of the Golitzen vineyard (#7) have a northeasterly trend relative to the older N–S plantings of the Sand Hill (#12) and Hedges Cellars (#8) vineyards. C) View from Artz Vineyard (#1) northwest across the Yakima River towards Rattlesnake Mountain. D) View from Klipsun vineyard (#10) south towards Goose Hill. E) Vineyard planted on very shallow (<1 m, locally <10 cm) soils on top of basalt knob approximately 700 m southwest of Red Mountain AVA illustrating difference in plant vigour relative to Klipsun vineyard (#10). F) Vineyard planted on Yakima River floodplain approximately 100 m west of Red Mountain AVA illustrating difference in vine and ground cover vigour relative to Klipsun vineyard (#10). Photos D and F taken on the same day.

Mountain wine style has been described by wine critics as powerful and intense (Antrim, 2002). Some terroir elements that contribute to this wine style include high heat summation, intense growing-season solar energy from nearly cloud-free skies, very low annual precipitation, and large growing-season soil-moisture deficits.

The numerous awards won by wines made from the Red Mountain appellation suggest that this grape-growing region is indeed becoming recognized. For example, in the past two years wines made from Red Mountain grapes have received nine scores of 94 or above out of 100 in independent blind tastings by national wine publications (Jim Holmes, written communication, 2002). In addition, the Andrew Will Merlot made from grapes from the Ciel Du Cheval Vineyard was named the best merlot in the United States by Food and Wine Magazine in 2000 (Anon., 2000) and by Wine & Spirits Magazine in 2002 (Teague, 2002). Finally, the Klipsun vineyard of Red Mountain was recognized in 2002 as one of the top 25 vineyards in the world by Wine & Spirits Magazine (Antrim, 2002).

Comparisons with other appellations in Washington State (*e.g.*, Meinert and Busacca, 2000), North America, and other wine regions in the world show some common threads and also some important differences. As noted at the onset of this paper, more than 90% of Washington vineyards are located in areas affected by glacial outburst floods. In the Red Mountain area, these flood sediments were mostly deposited from the swirling back-eddies behind Red Mountain and include numerous lenses of relatively coarse gravel. In the Walla Walla area, the flood sediments are generally finer grained as a result of their deposition from ponded floodwaters behind Wallula Gap, although there are some zones of coarse gravels in modern river channels (Fig. 9C, D, E; Meinert and Busacca, 2000). Even with these differences in grain size, however, both Red Mountain and Walla Walla have in common a mantle of loess and more recent wind-blown sands over the glacial flood sediments.

The common glacial history of most Washington vineyards is offset by differences in a variety of climate measures. Red Mountain is near the extremes for Washington State in terms of high heat summation (growing-degree days) and low precipitation. For example, most of the Yakima Valley has 200 to 400 fewer growing-degree days than Red Mountain, and Walla Walla has more than twice the precipitation on average (Meinert and Busacca, 2000). Like many Washington appellations, Red Mountain is susceptible to both spring frosts and winter kill. According to the optimum climatic criteria for winegrape growing identified by Gladstones (1992, 2001), Red Mountain is near the top in growing-degree days, growing-season solar radiation, mean temperature, and rainfall. However, Red Mountain is outside of the optimum ranges identified by Gladstones for relative humidity, high maximum temperature, and temperature variability index (roughly the daily variation between highest and lowest temperatures), although the very high-quality wines that have been produced from Red Mountain grapes suggest that the subtle interactions of climatic factors are not completely understood.

With the clear evidence of glacial influence on Washington state vineyards, it seems appropriate to examine how other viticultural regions have been affected by glaciation. Although the complex sedimentary patterns caused by the glacial outburst flooding in the back-eddy of Red Mountain may be unique among world vineyards, many other wine-producing areas of the world also have links to Pleistocene glaciation. This is primarily due to two factors: worldwide lowering of sea level during maximum glaciation, and the locally abundant clastic sediments produced by alpine and continental glaciers.

At the glacial maximum, sea level was lowered by about 130 m relative to today, exposing many coastal areas to increased erosion and changing sedimentation patterns, such as wind-blown loess and sand dunes from the newly exposed coastal shelves. Many viticultural areas within 100 km of the ocean have been so affected. Concurrent with this sea level drawdown was an increased sediment load in both rivers and valley glaciers fed by mountain ranges that intercepted moisture-laden maritime air and consequently built up extensive icefields.

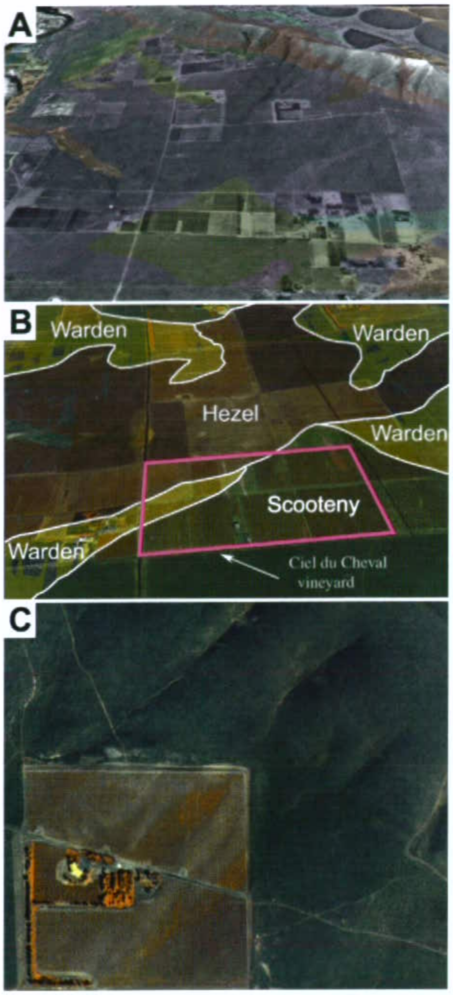

Figure 14 Soil and vegetation patterns for vineyards in the Red Mountain AVA. A) 3-D perspective view of Red Mountain area with soil series draped over black and white ortho aerial photograph. Data from Rasmussen (1971). B) Close-up of 14A showing soil series patterns within individual vineyards. In the Ciel du Cheval vineyard (#5) some vine rows cross three different soil types, providing an opportunity to study the effect of different soil characteristics on grape vine performance with little or no change in climate or viticultural practice. C) Aerial color infrared imagery showing differences in plant vigour relative to topography and soil distribution in the Belle Ville vineyard (#2). Note that in infrared images, green vegetation such as leafy vineyards is red whereas arid range lands are dark green. Images courtesy of Francis Pierce, Center for Precision Agricultural Systems, WSU-IAREC.

A prime example of this is the Graves-Médoc region of Bordeaux, France (Wilson, 1998). Outwash gravels from alpine glaciation in the Pyrenees along the French-Spanish border and the Massif Central in central France overloaded the Garonne and Dordogne rivers leading to the Gironde Estuary, which itself had been enlarged and deepened in response to the lowering of sea level. Each period of glaciation produced its own series of gravel outwash floodplains along the rivers. Of the four glacial stages identified by Wilson (1998), the Günz stage produced the gravel mounds that are synonymous with the best (First Growth) vineyards (Wilson, 1998). Wineries such as Chateaux Lafite-Rothschild, Haut-Brion, Latour, and Mouton-Rothschild are well known to wine-lovers throughout the world, and each of these wineries and their estate vineyards are located on gravel mounds (the geographical name 'Graves' means gravel in French) formed during a Pleistocene glacial maximum. Wilson (1998, his Table 5.1) provided an extended analysis of the various glacial and interglacial epochs of the Bordeaux region along with correlations to archeological timelines that predate settlement of North America by tens of thousands of years, such as the prehistoric cave art of Les Eyzies, Lascaux, and Pech Merle. Even without the common terroir connection to Washington State this makes for fascinating reading!

Less well known are the gravel outwash plains of the South Island of New Zealand. These were fed by the extensive alpine glaciation of the Southern Alps mountain range that transects the island. These gravels form the substrate for many of the vineyards in the Marlborough area of New Zealand, and some of the wineries of this region focus on the coarse gravels, such as the Rapaura Series, for their best vineyards (http://www.stoneleigh.co.nz/). Another area in New Zealand, Gimblett Gravels, is perhaps the first viticultural region in the world to specifically define itself on the basis of the gravel. Legally, wines from this appellation have to consist of at least 95% grapes grown on the Gimblett Gravels, specifically the Omahu Gravels (http://www.gimblettgravels.com/index.htm). These gravels are somewhat different from those in the Marlborough area in that they have been extensively reworked by present and paleoflows of the Ngaruroro River. Within the Gimblett Gravels are lenses of sand, silt, and clay at various depths. These lenses contain up to 20% silt and 9% clay. In general, the gravels are free draining with little water-holding capacity, mostly between 9 and 20% soil moisture (http://www.gimblettgravels.com/terroir.htm). These features are similar to those documented for the gravels of Bordeaux, France (Figure 6.3 of Wilson, 1998) and some of the soil and gravel lenses of Red Mountain, Washington (Table 4, Fig. 9D, F).

Even though some vineyards in Washington State, Bordeaux, and New Zealand share elements of a common Pleistocene glacial history, there still are large differences in climate, viticultural, and oenological practices that make these areas distinct. The present study does not aim to minimize these other factors or the importance of human ingenuity in making great wine from great vineyards (Moran, 2001), but seeks to illustrate the importance of understanding the physical environment as one essential element of terroir. From both an oenological and geological perspective, the terroir of Red Mountain is truly excellent.

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