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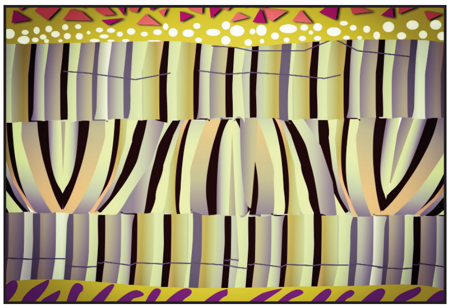

Igneous Rock Associations 15. The Columbia River Basalt Group: A Flood Basalt Province in the Pacific Northwest, USA

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SUMMARY

The middle Miocene Columbia River Basalt Group (CRBG) is the youngest, smallest, and best-preserved continental flood-basalt province on Earth. The CRBG covers ~ 210,000 km^2 of the Pacific Northwest, USA near the British Columbia border. CRBG consists of ~ 210,000 km^3 of basalt that began erupting ~ 16.7 Ma in the southern part of the province with younger eruptions progressively migrating northward; the last eruption occurred at ~ 5 Ma. The CRBG consists of seven formations. The Steens Basalt is the oldest but the next oldest, the Imnaha Basalt, began erupting near the end of the Steens volcanic episode. After a short hiatus at the end of the Imnaha Basalt, the Grande Ronde Basalt began to erupt. Both the Picture Gorge Basalt and Prineville Basalt erupted simultaneously with the Grande Ronde Basalt. The Steens, Imnaha, and Grande Ronde Basalts are the main phase of the eruptions representing ~ 94% of the CRBG volume. The Wanapum Basalt followed the Grande Ronde Basalt, which in turn was followed by the Saddle Mountains Basalt, the final phase of the eruptions. The formations, members and many flows of the CRBG can be identified by using a combination of major, minor and trace element compositions, lithology, magnetic polarity, and stratigraphic position. This allows the aerial extent and volume of the individual flows and groups of flows to be calculated and correlated with their respective dykes and vents. The eruption and emplacement rate of the flows has been controversial, with various lines of evidence suggesting that some flows erupted very rapidly and others probably erupted over much longer periods of time. The CRBG was probably derived from a mantle plume, although this conclusion is controversial. Compositions indicate the CRBG magmas underwent varying degrees of recharge, contamination, and fractionation prior to each eruption. Although the peak eruptions occurred during the middle Miocene Climatic Optimum, at present no significant extinction or environmental consequence has been correlated with the CRBG.

SOMMAIRE

Le Groupe de basaltes du fleuve Columbia (CRBG), du Miocène moyen, est la plus jeune, la plus petite et la mieux préservées des provinces de basaltes de plateau de la planète Terre. Le CRBG couvre une superficie d'environ 210 000 km^2 dans la portion nord-ouest des États-Unis du Pacifique près de la frontière avec la Colombie-Britannique. Le CRBG, c'est environ 210 000 km^3 de basaltes dont les premiers épanchements se sont produits il y a environ 16,7 Ma dans la portion sud de la province, les éruptions plus jeunes migrant progressivement vers le nord, la dernier s'étant produit il y a environ 5 Ma. Le CRBG est constitué de sept formations. La formation de basalte de Steens est le plus ancienne, mais la suivante, celle du basalte d'Imnaha est entrée en éruption près de la fin de l'épisode volcanique de Steens. Près une courte pause à la fin de l'épisode du basalte de la formation d'Imnaha, l'éruption du basalte de Grande Ronde a commencé. Et le basalte de Picture Gorge et le basalte de Prineville ont fait éruption en même temps que le basalte de Grande Ronde. Les basaltes de Steens, d'Imnaha, et de Grande Ronde forment la principale portion des éruptions avec environ 94 % du volume du CRBG. Le basalte de Wanapum a succédé au basalte de la Grande Ronde, puis ce fut le basalte de Saddle Mountains, la phase finale des éruptions. Les formations, les membres et le nombre de coulées du CRBG peuvent être définis par analyse de leur composition en éléments majeurs, mineurs et traces, leur lithologie, leur polarité magnétique, et leur position stratigraphique. Ce qui permet d'es-

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timer l'étendue et le volume de coulées individuelles, de groupes de coulées, et de les relier avec leur cheminée et dikes respectifs. Le taux des flux éruptifs ainsi que le leur mise en place ont été sujet à controverse étant donné que certaines indications suggèrent que certaines éruptions ont été très rapides alors que d'autres se seraient produites sur des périodes beaucoup plus longues. Le CRGB est probablement issus d'un panache mantellique, mais cela demeure controversé. Les compositions relevées indiquent que les magmas du CRBG ont subi à des degrés divers, des recharges, des contaminations et du fractionnement par cristallisation avant chaque éruption. Bien que les plus fortes éruptions se soient produites durant la période climatique optimum du Miocène moyen, jusqu'à présent, aucune extinction significative ou répercussion environnementale ont été mises en corrélation avec le CRBG.

INTRODUCTION

The Columbia River Flood Basalt Province (CRFBP) in the Pacific Northwest of the United States is the youngest and best-preserved continental large igneous province (LIP) on Earth. The Columbia River Basalt Group (CRBG) is a series of generally tholeiitic basalt to basaltic andesite with sparse alkali-olivine basalt that erupted between ~ 16.7–5.5 Ma (Jarboe et al. 2008; Barry et al. 2013) and cover more than 210,000 km^2 of Washington, Oregon, Idaho and Nevada (Fig. 1; Reidel et al. 2013a). They form part of a larger volcanic region that includes the Chilcotin Plateau Basalts of British Columbia, the contemporaneous silicic centres in northern Nevada, the basaltic and time-transgressive rhyolitic volcanic fields of the Snake River Plain and Yellowstone Plateau, and the High Lava Plains of central Oregon (Camp et al. 2003). Although the province is the smallest LIP on Earth, its location in the easily accessible Pacific Northwest has allowed the stratigraphy and structure to be refined by many decades of detailed fieldwork, combined with geochemical, geochronological, and paleomagnetic studies. Thus, the CRBG has become a model for the study of similar provinces worldwide.

This paper reviews the current status of the CRBG focusing on the stratigraphic framework, the areal extent and volume of the lava flows, their eruptive history, mode of lava flow emplacement, current thoughts on the petrogenesis of the basalt, and finally the impact of these lavas on the Miocene environment.

REGIONAL SETTING

The CRBG erupted in a back-arc setting between the Cascade volcanic arc and the Rocky Mountains (Fig. 1). The flood-basalt lavas cover basement rocks that record a long and complex geologic history beginning in the Proterozoic with the breakup of the supercontinent Rodinia, followed by the suturing of Mesozoic accreted terranes, and deposition and deformation of Paleogene and Neogene sedimentary and volcanic rocks. These basement structures became the template for geologic structures now superimposed on the basalt province (Reidel et al. 2013b).

Rocks older than the CRBG are exposed around the margins of the flood-basalt province and have been penetrated in deep boreholes in the Columbia Basin. In the southernmost part of the province, Mesozoic accreted terrane rocks and Paleogene and Neogene volcanic rocks are exposed in the footwalls of Basin-and-Range faults. To the northeast and east, the CRBG laps onto an assemblage of Proterozoic, lower Paleozoic and Jurassic rocks, and Cretaceous intrusions of the Idaho Batholith (Stoffel et al. 1991; Reidel et al. 2013b). Within and south of the Blue Mountains, the CRBG overlies Paleogene and Neogene volcanic rocks and related volcaniclastic rocks partly assigned to the Clarno and John Day formations. These, in turn, overlie northeast-trending belts of Permian to Cretaceous accreted terranes of intra arc- and volcanic arc-origin (Walker and MacLeod 1991; Schwartz et al. 2010; LaMaskin et al. 2011).

The Cascade volcanic arc forms the western margin of the CRFBP. CRBG flows were able to cross the Miocene Cascade volcanic arc through a major east-northeast-trending lowland structural gap, the Columbia Trans-arc Lowland (Fig.1; Beeson et al. 1979), where they spread across much of the northern Willamette Valley region, and through the Coast Range, eventually reaching the Pacific Ocean where they continued to advance onto the continental shelf (Beeson et al. 1979; Niem and Niem 1985).

The area covered by the CRBG is divided by the Blue Mountains into the Oregon Plateau and the Columbia Basin (Fig. 1) based on significant differences in the style of post-CRBG deformation. The Oregon Plateau contains four structural-tectonic regions: (1) the northern Basin and Range, (2) the High Lava Plains, (3) the Owyhee Plateau, and (4) the Oregon-Idaho graben. The Columbia Basin covers a broader region and consists mainly of the Yakima Fold Belt and the Palouse Slope.

STRATIGRAPHIC FRAMEWORK OF THE COLUMBIA RIVER BASALT GROUP

The CRBG (Figs. 2, 3, and 4) is a thick sequence of more than 350 mainly continental tholeiitic flood-basalt flows that were erupted over an 11 million year period (Swanson et al. 1979; Tolan et al. 1989; Jarboe et al. 2008; Barry et al. 2013) and have an estimated volume of about 210,000 km^3 (Fig. 2). The main eruptive phase of the basalt includes the Steens Basalt, the Imnaha Basalt and Grande Ronde Basalt when 94% of the basalt erupted in ~ 1 million years. The peak of CRBG eruptions occurred during Grande Ronde time, when ~ 74% of the flood-basalt volume was generated in only ~ 400,000 years or less (~ 16–15.6 Ma; Jarboe et al. 2008; Barry et al. 2010, 2013). The waning phase (~ 7%) includes the Wanapum Basalt and Saddle Mountains Basalt that erupted over 10 million years. The Picture Gorge and Prineville Basalts are much smaller in volume and were coeval with the Grande Ronde Basalt. The contribution of each of the seven formations is: Steens Basalt - ~ 15.2%; Imnaha Basalt - ~ 5.3%; Grande Ronde Basalt - ~ 72%; Picture Gorge Basalt - ~ 1.1%; Prineville Basalt - ~ 0.3%; Wanapum Basalt - ~ 5.8%; and Saddle Mountains Basalt - ~ 1.1%.

Volcanism began in the Oregon Plateau and quickly spread north to the Columbia Basin (Camp and Ross 2004). In the Oregon Plateau,

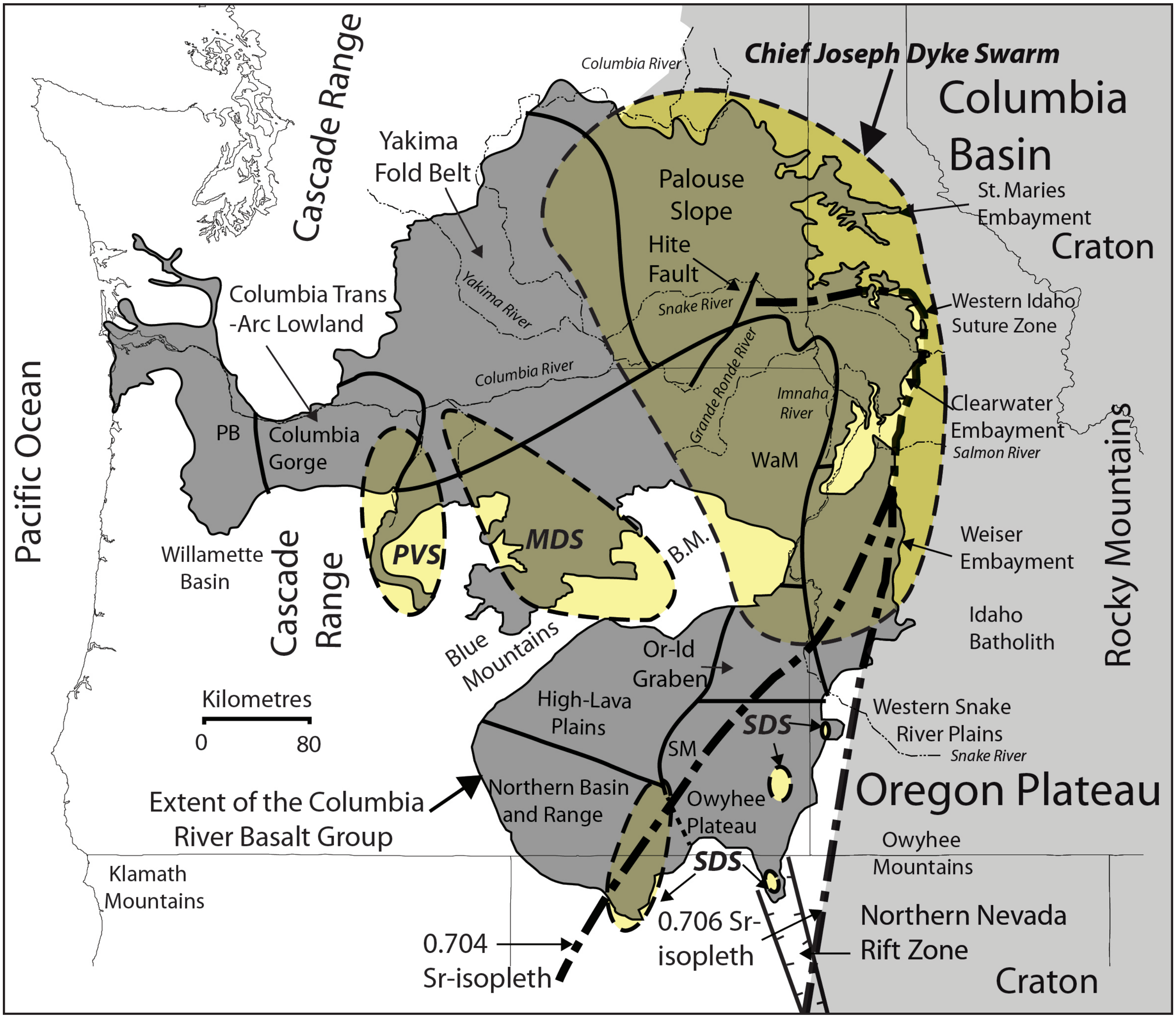

Figure 1. Location map of the Columbia River Flood Basalt Province. This figure shows the extent of the Columbia River Basalt Group. The Columbia Basin forms the northern portion of the province and is divided into the Yakima Fold Belt and Palouse Slope. The Oregon Plateau forms the southern portion of the province south of the Blue Mountains (B.M.) and is divided into the Oregon-Idaho graben (Or-Id Graben), the High-Lava Plains, the Owyhee Plateau, and the Northern Basin and Range. Geographic features include: Steens Mountain (SM), Steens Basalt dyke swarms (SDS), Monument (Picture Gorge) dyke swarm (MDS). Prineville Basalt source area (PVS), Wallowa Mountains (WaM), and Portland Basin (PB). The initial $^{87}Sr/^{86}Sr$ 0.704 and 0.706 isopleths are from Pierce and Morgan (2009). Basement rocks include the Precambrian craton of North America east of the 0.706 line, transitional crust with cratonic affinity between the 0.706 and 0.704 lines, and Paleozoic to Mesozoic accreted terranes west of the 0.704 line.

flood basalt eruptions were contemporaneous with rhyolitic volcanism at the western end of the Snake River Plain hotspot track and with a major period of crustal extension in northern Nevada that began at ca. 16–17 Ma (Camp et al. 2003). In the Columbia Basin, rapid subsidence along with folding and faulting of the basalt accompanied volcanism (Reidel et al. 1989b, 2013b).

The source for the lava flows was a series of generally north-trending linear fissure systems in eastern Washington, western Idaho, eastern Oregon, and northern Nevada (Figs. 1 and 4). Many basalt flows were of extraordinary size, commonly exceeding 1,000 km^3 in volume and traveling many hundreds of kilometres from their vent systems (Tolan et al. 1989; Reidel et al. 1989a; Reidel 1998, 2005; Reidel and Tolan 2013a).

Stratigraphy

CRBG studies began just prior to the turn of the twentieth century with the

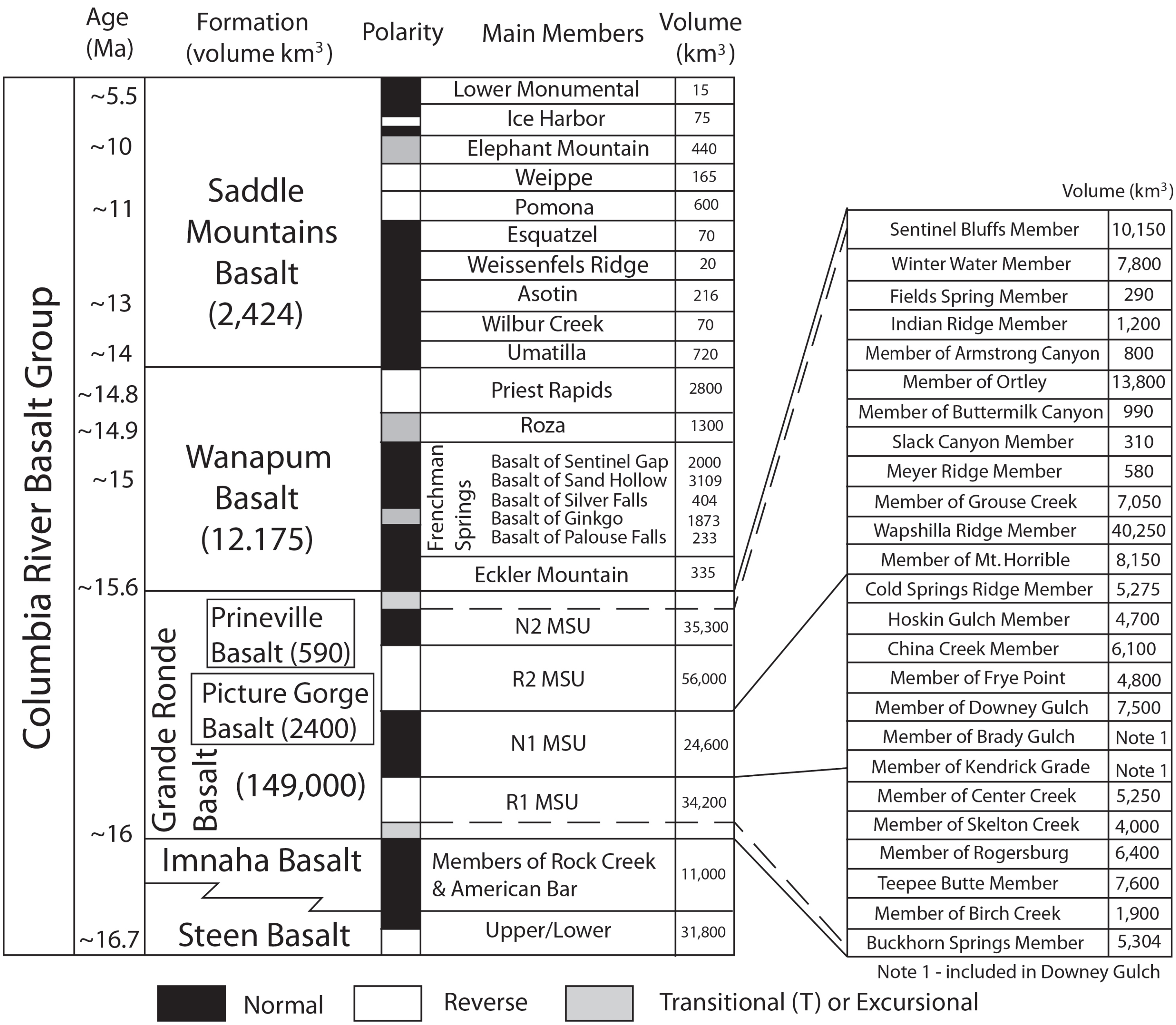

Figure 2. Generalized stratigraphy of the Columbia River Basalt Group showing the main stratigraphic units discussed in the text. Stratigraphy, volumes and polarities are from Reidel et al. (2013a), Reidel and Tolan (2013a), and Camp et al. (2013). Age dates are from Barry et al. (2010, 2013).

horseback reconnaissance studies of Russell (1893) and Smith (1901). Russell first described and named the basalt "the Columbia (River) Lavas" and Smith applied the name "Yakima Basalt" to what we now subdivide into the Grande Ronde, Wanapum, and Saddle Mountains Basalts. By the 1960s A.C. Waters (1961), J. Hoover Mackin (1961), and their students began looking at the basalts from a regional perspective. They further refined the stratigraphy, adapting the terms Lower Yakima Basalt, Middle Yakima Basalt, and Upper Yakima Basalt that were predecessors of the current formation names. Waters (1961), recognizing the importance of major-element chemical compositions of the basalts, started the current practice of using analyses for regional correlations and mapping.

The modern phase of CRBG research began with the work of D.A. Swanson and T.L. Wright and colleagues when they began an extensive mapping project which led to our current understanding of the stratigraphy (Swanson et al. 1979). A combination of lithology, paleomagnetic properties, and geochemical composition with regard to superposition have proved the most useful features to describe and characterize the stratigraphy (e.g. Swanson et al. 1979; Camp 1981; Reidel 1983, 1998, 2005; Beeson et al. 1985, 1989; Martin 1989; Reidel et al. 1989a; Wells et al. 1989; Hooper et al. 2007; Tolan et al. 2009). The current stratigraphic framework of the CRBG is discussed by Reidel et al. (2013a) and shown in Figure 2.

With completion of the basic

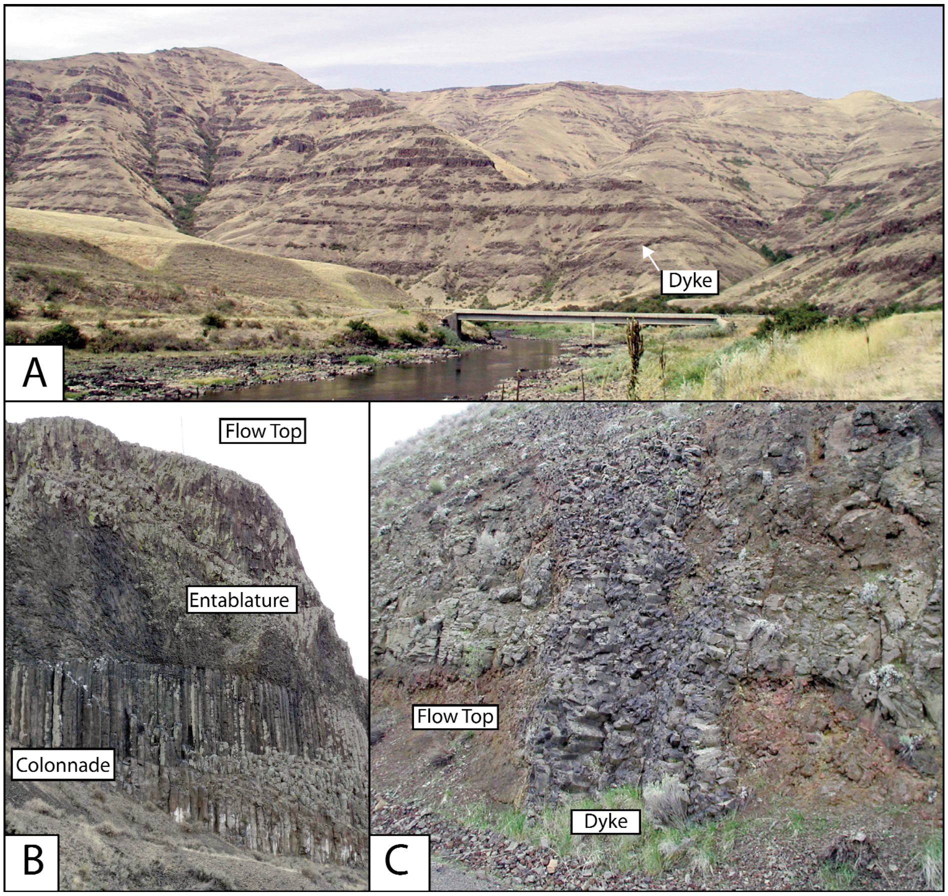

Figure 3. Photographs of the Columbia River Basalt Group (CRBG). A) Photograph showing the layered nature of the Grande Ronde Basalt in the Grande Ronde River valley. The thickness of basalt shown is 1000 m. B) Typical intraflow structures of a CRBG flow in Sentinel Gap, Washington. C) A dyke of the Roza Member, Wanapum Basalt near Lower Granite Dam on the Snake River.

framework of the basalts, investigations shifted to the emplacement processes of these huge flood basalt flows (e.g. Reidel and Fecht 1987; Martin 1989; Reidel and Tolan 1992; Reidel et al. 1994, 2013a; Self et al. 1996, 1997; Ho and Cashman 1997; Reidel 1998, 2005; Camp et al. 2013; Vye et al. 2013), and developing geochemical and petrogenetic models (e.g. Hooper and Hawkesworth 1993; Durand and Sen 2004; Ramos et al. 2005, 2013; Camp and Hanan 2008; Wolff et al. 2008; Wolff and Ramos 2013; Rodriguez and Sen 2013).

CRBG FLOW CHARACTERISTICS

The ability to map individual flows over large areas allowed geologists to recognize the regional characteristics of the flows, and to interpret their emplacement history and the paleoenvironment at the time of eruption. Rate and volume of lava erupted, lava composition and temperature, vent geometry, topography, and environmental conditions all play significant roles in the rheology, emplacement dynamics, and overall geometry of individual basalt lava flows or flow fields (Shaw and Swanson 1970; Beeson et al. 1989; Martin 1989, 1991; Reidel and Tolan 1992; Reidel et al. 1994; Hon et al. 1994; Self et al. 1996, 1997; Keszthelyi and Self 1998; Reidel 1998, 2005; Vye et al. 2013; Brown et al. 2014). This section summarizes typical characteristics of CRBG lava flows.

Flow Nomenclature

Many CRBG flows have features observed in recent eruptions (e.g. pahoehoe lobes), but some of the nomenclature applied to recent eruptions has proven difficult to adapt to flood basalts, primarily due to the scale difference (Self et al. 1996, 1997). Self et al. (1996) have attempted to resolve these differences by refining existing terms and introducing new ones for flood basalts. For example, they define a *lobe* as the smallest coherent package of lava, a *flow* as the product of a single outpouring of lava and a *flow field* as lava covering a large area that has many separate outpourings. The term lobe is easy to apply but problems still remain in recognizing what differentiates a lobe from a flow, and what constitutes a flow or flow field. For example, both the Pomona Member and Elephant Mountain Member are single flows at the source but more than 200 km down gradient, each member consists of two or more large, extensive flows, each with all the characteristics of major individual eruptions. Each flow has distinct contacts and historically they have been described as individual eruptions (e.g. Elephant Mountain flow and Ward Gap flow of the Elephant Mountain Member). Conversely, several individual eruptions constituting a flow field in the east have merged down gradient to produce a single flow (e.g. Asotin, Lapwai and Wilbur Creek merge to produce the Hunzinger flow; Hooper 1985; Reidel and Fecht 1987); Sillusi and Umatilla flows merge farther west to produce a single flow in the central Columbia Basin (Reidel 1998). Nevertheless, the definitions proposed by Self et al. (1996) provide a workable approach for describing most of these flood basalts and have been widely accepted.

Sheet and Compound Flows

Two basic end-member basalt-flow geometries are recognized for the CRBG - compound flows and sheet (simple) flows. A compound flow develops when a lava flow advances away from its vent in a series of distinct and separate lobes of flowing lava. Each lobe subsequently is covered by later lava lobes as the emplacement of lava continues. This results in the accumulation of elongated lobes of basalt with numerous, local, discontinuous, and relatively thin layers of basalt lava, which is typical of the earliest CRBG flows, the Steens Basalt (Camp et al. 2003). By contrast, a sheet flow results when high-volume eruptions allow the lava to advance away from the vent as a uniform, moving sheet or series of lobes that coalesce into a lava

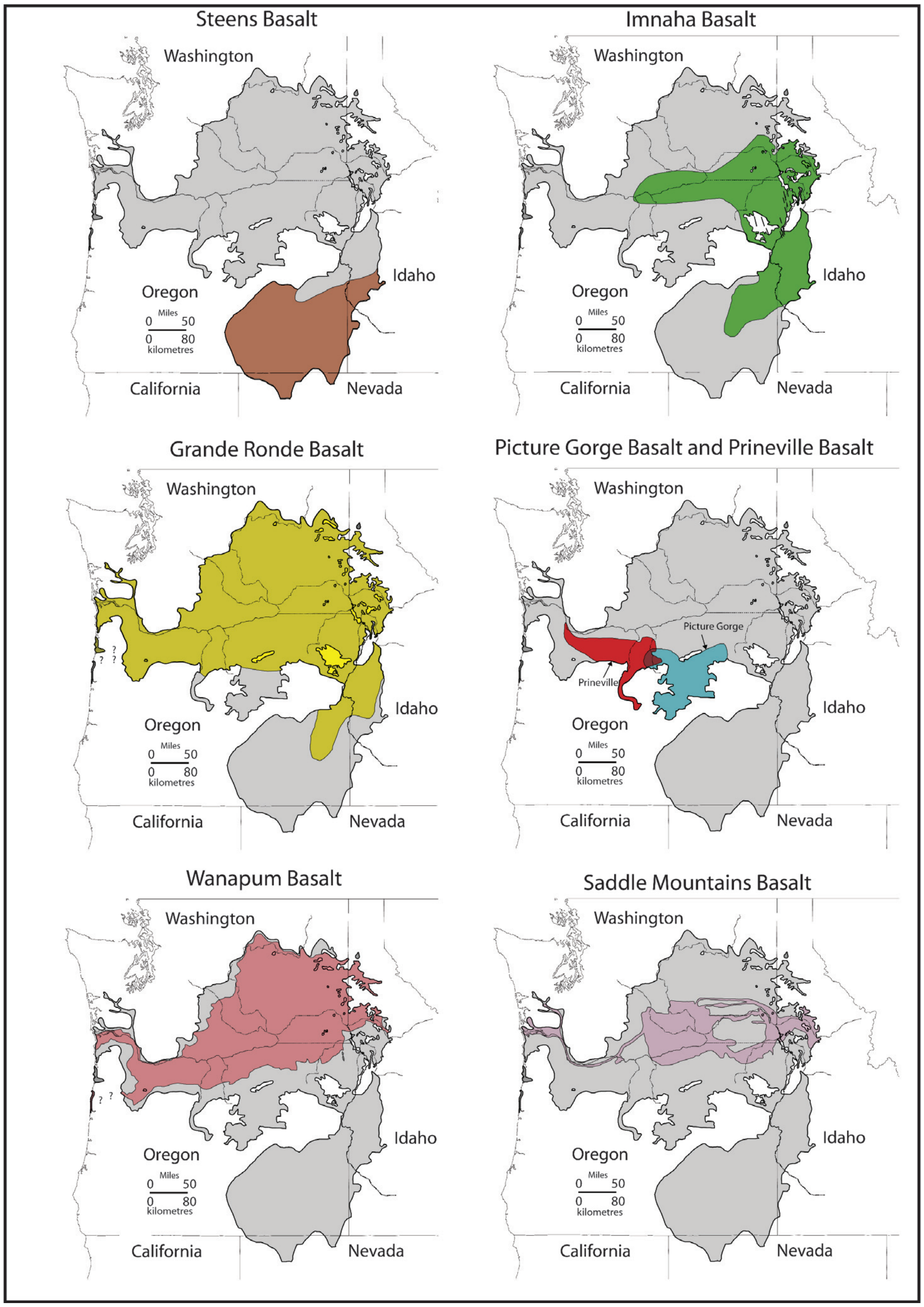

Figure 4. Extent of the seven formations of the Columbia River Basalt Group. Modified from Reidel et al. (2013a).

flow that, on the outside, appears to be just a single simple flow. Two examples are the 'Cohassett flow,' Sentinel Bluffs Member, Grande Ronde Basalt (Fig. 2; Reidel 2005) and the Palouse Falls flow, Frenchman Springs Member (Vye et al. 2013). Each successive sheet flow will create a layer, with the flow boundaries being delineated by distinct vesicular zones. However, these boundaries are not to be confused with single cooling units because they do not show evidence of a chilled contact but are clearly a continuous process. Although the great majority of the CRBG lavas are interpreted to have erupted as extensive sheet flows, the initial CRBG eruptions of Steens Basalt generated hundreds of thin (~ 1–5m-thick) lava lobes that interfinger and pinch out over short lateral distances but are chemically distinct (Camp et al. 2013). This resulted in the development of the Steens shield volcano.

Most CRBG formations contain many individual, large-volume flows (especially Grande Ronde Basalt) that display overall characteristics consistent with sheet flows (Swanson et al. 1979; Beeson et al. 1985, 1989a; Tolan et al. 1989; Reidel et al. 1989a, 1994; Beeson and Tolan 1990, 1996; Reidel and Tolan 1992; Self et al. 1996; Reidel 1998, 2005; Vye et al. 2013). However, these sheet flows typically exhibit complex features associated with compound flows at their flow margins or distal ends (Beeson et al. 1989; Reidel and Tolan 1992; Reidel et al. 1994; Beeson and Tolan 1996; Reidel 1998, 2005; Vye et al. 2013). Such 'atypical' quasi sheet/compound flow morphologies are more commonly found along the margins of the CRBG but can also be found in the basal CRBG units in the Willamette Valley (Beeson et al. 1989). These probably developed as the flow slowed and smaller 'break-outs' of lava formed.

Detailed studies of sheet flows have shown that they are actually a composite series of flow lobes inflating the initial sheet flow, as originally described by Hon et al. (1994) and Self et al. (1996). Excellent examples include the Roza Member (Thordarson and Self 1998; Brown et al. 2014), the Umatilla Member (Fig. 2; Reidel 1998), the Asotin-Wilbur Creek Members (Reidel and Fecht 1987), the Basalt of Palouse Falls (Vye et al. 2013), and the 'Cohassett flow' of the Sentinel Bluffs Member (Reidel 2005). The Cohassett flow was long thought of as a single, thick (100 m-thick) sheet flow (USDOE 1988). A detailed study of the flow by Reidel (2005) demonstrated that the Cohasset flow is a large, inflated sheet flow that formed as a series of sheet flows erupted from separate dykes (Fig. 5); each flow was able to sequentially invade the initial flow and inflate it. The result was a single sheet flow with a series of thin vesicular zones or vesicle sheets separating each injected flow lobe, where each lobe is recognized by its distinct chemistry. Where the flow is thickest in the centre of the Columbia Basin, the oldest lobes make up the top and bottom of the flow with progressively younger flow lobes toward the centre. Near the margins, however, one or more of the individual sheet flows may dominate (e.g. Fig. 5 C–C'). The Cohasset flow

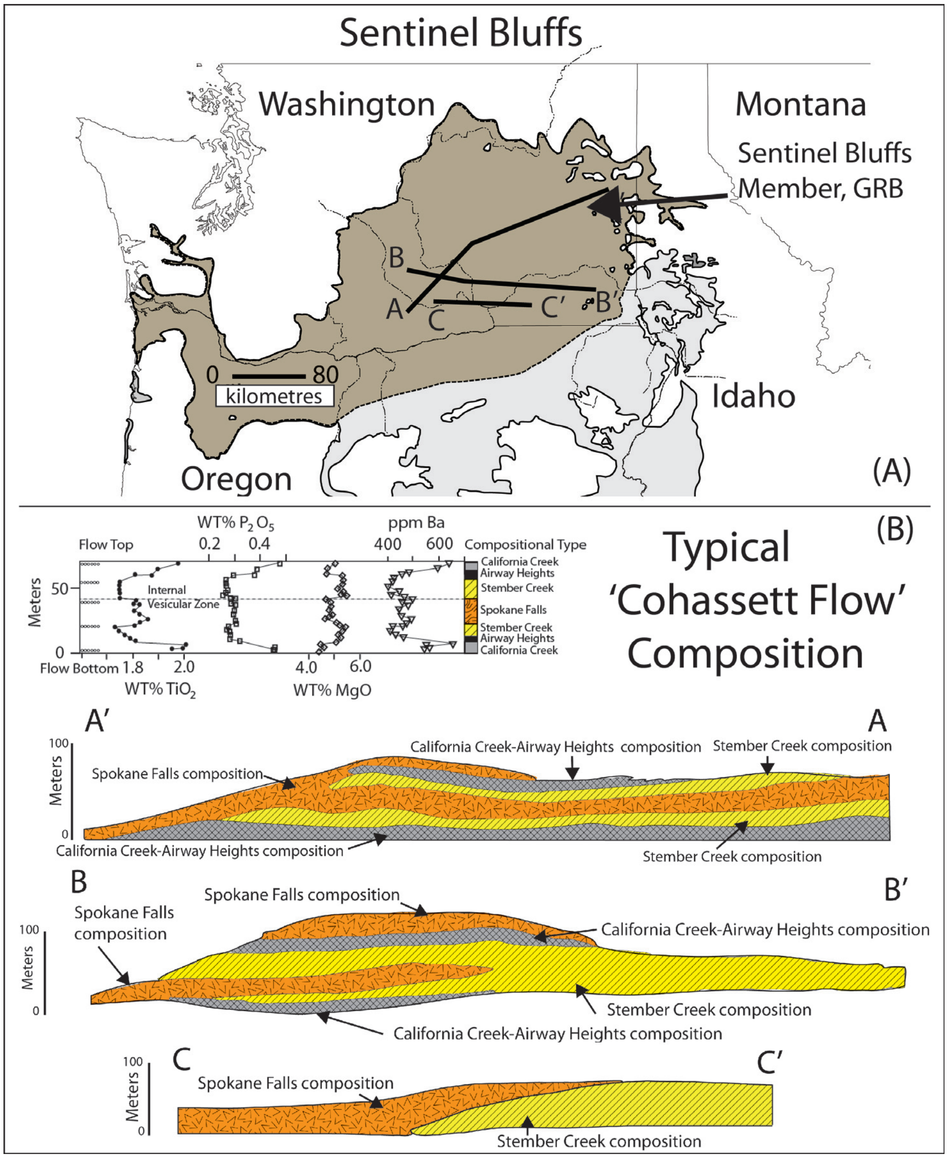

Figure 5. Extent of the Cohassett flow of the Sentinel Bluffs Member, Grande Ronde Basalt (GRB). Diagram shows the extent of the composite flow, compositions of the four individual flows that make up the composite flow (California Creek, Airway Heights, Stember Creek, and Spokane Falls), and cross sections through the flow that show the internal architecture of the composite flow. The cross sections are based on detailed analyses through the Cohassett flow along each section. See Reidel (2005) for details of the study.

differs from a compound flow in that there are no discontinuities or chilled zones between each injected layer.

Intracanyon Flows

A much less common mode of emplacement for CRBG flows is as intracanyon flows in locations where sheet flows were funneled through major river valleys (Swanson et al. 1979; Fecht et al. 1987; Reidel and Tolan 2013b). Such paleoriver canyons undoubtedly allowed some CRBG flows to travel significantly greater distances than they might have as sheet flows.

Intraflow Structures

Intraflow structures are defined as primary, internal features or stratified portions of basalt flows exhibiting grossly uniform macroscopic characteristics. These features originate during the emplacement and solidification of each flow and result from variations in cooling rates, degassing, thermal contraction, and interaction with the paleoenvironment during emplacement.

A CRBG flow typically has a flow top, a dense interior, and a flow bottom (Figs. 3 and 6). The contact between two individual basalt flows (i.e. a flow top and overlying basalt flow bottom) is referred to as an interflow zone which controls most of the groundwater in the Columbia Basin. Flows typically have internal joining referred to as colonnades and entablatures; entablatures reflect rapid quenching, top-down cooling, and colonnades reflect slow, bottom-up cooling (DeGraff and Aydin 1993). In addition to the basic physical structures, many flows have other internal features such as vesicle layers or cylinders, pillows where they encountered water, or brecciated flow tops or rafted flow tops (see Reidel et al. 2013a).

Lithology

The most important aspect of CRBG lithology is the presence or absence of plagioclase phenocrysts and/or olivine microphenocrysts (e.g. Swanson et al. 1979; Beeson et al. 1985; Reidel et al. 1989a). CRBG flows are typically aphyric to rarely phyric, with the major exception including the highly plagioclase-phyric flows of Steens Basalt, most Imnaha Basalt flows, and several Wanapum and Saddle Mountains Basalts flows. Wanapum flows with distinct lithology include the Dodge flows of the Eckler Mountain Member, several Frenchman Springs flows and the Roza Member. Although the Grande Ronde Basalt is typically described as aphyric, many of these flows can be recognized by the presence of plagioclase phenocrysts and microphenocrysts (Reidel et al. 1989a; Reidel and Tolan 2013a). The Pomona and Ice Harbor Members of the Saddle Mountains Basalt characteristically have plagioclase phenocrysts, and the Asotin Member commonly has a characteristic ophitic texture. However, a single flow can vary in coarseness and the relative abundance, sizes, and habits of the phenocrysts, leading to unfortunate misidentifications in the field.

Polarity

CRBG flows record many polarity reversals through the stratigraphic sequence (Fig. 2). Many CRBG flows possess distinctive paleomagnetic direc-

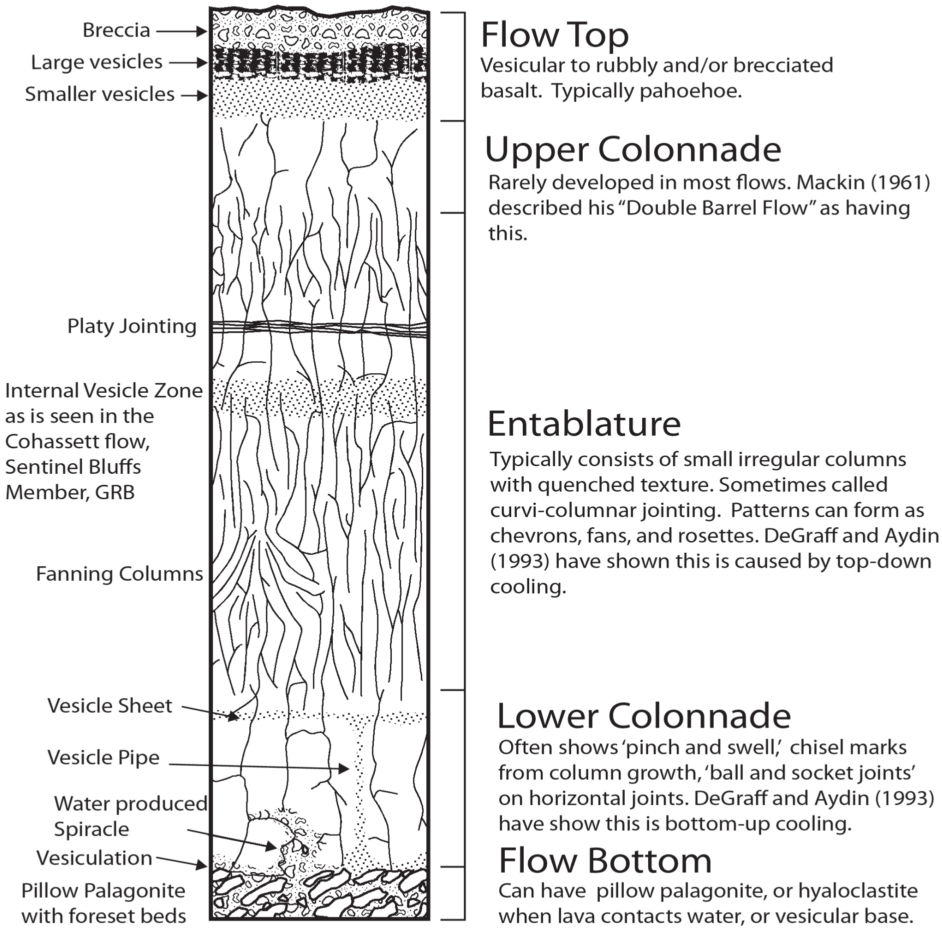

Figure 6. Diagram showing typical intraflow structure present in Columbia River Basalt Group lava flows. Modified from Swanson et al. (1979); Reidel et al. (2013a).

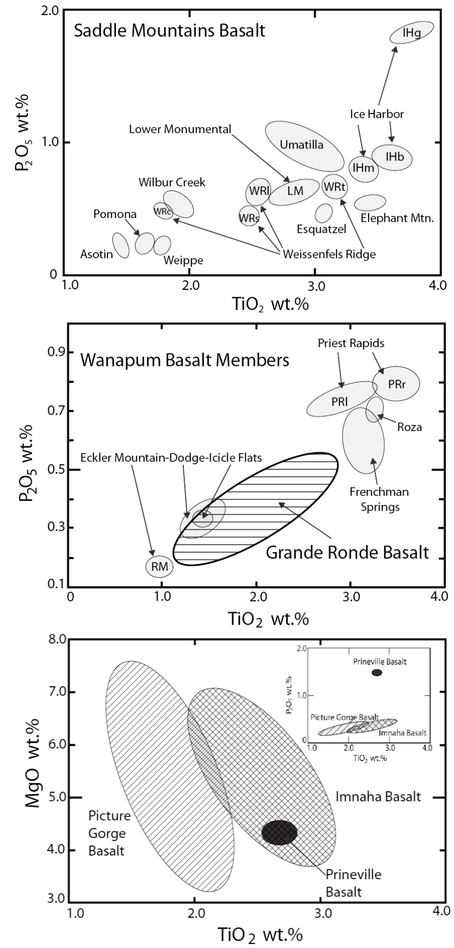

Figure 7. Variation diagrams showing compositions and differences of the seven Columbia River Basalt Group (CRBG) formations and selected members. Ranges of analyses are enclosed by lines. See Reidel et al. (2013a) and Reidel and Tolan (2013a) for a more complete listing of CRBG analyses.

tions (inclinations and declinations) that have proven to be extremely useful in helping to establish and correlate CRBG units. Polarities include normal and reverse polarities as well as excursional and transitional directions (e.g. Rietman 1966; Kienle 1971; Coe et al. 1978; Choiniere and Swanson 1979; Magill et al. 1982; Reidel et al. 1984; Beeson et al. 1985; USDOE 1988; Wells et al. 1989; Hagstrum et al. 2010). Some flows like the Roza even record a complete reversal in the magnetic field (Audunsson and Levi 1997) providing a constraint on the time it takes for a magnetic reversal to occur. Field determinations of the paleomagnetic polarity using a portable fluxgate magnetometer have proven to be an important criterion for identification and mapping flows, but these results must be viewed with caution. In many cases, the original remnant polarity is overprinted by a younger polarity field. Paleomagnetic laboratory analysis is often necessary and if the composition has undergone significant alteration, even laboratory analyses can be misleading.

Composition

By far, the composition of the lavas (Fig. 7) has proven to be one of the most important tools for recognizing and correlating flows, as well as understanding their origin. Over the last 40+ years the CRBG has been extensively analyzed for major and minor oxides, trace elements and isotopes and, with these data along with other field criteria, have been used to establish a regional-scale, mappable stratigraphy (e.g. Wright et al. 1973, 1989; Swanson et al. 1979; Reidel 1982, 1998, 2005; Beeson et al. 1985; Mangan et al. 1986; Reidel et al. 1989a, b; Wells et al. 1989, 2009; Hooper 2000; Hooper et al. 2007). The geochemical and isotopic data have also been invaluable for understanding the origin of CRBG magma (e.g. Wright et al. 1973, 1989; Reidel 1983; Hooper and Hawkesworth 1993; Durand and Sen 2004; Ramos et al. 2005, 2013; Camp and Hanan 2008; Wolff et al. 2008; Wolff and Ramos 2013; Rodriguez and Sen 2013). A major reason why a regional CRBG geochemical stratigraphy is possible is that many lava flows have a remarkable 'bulk' geochemical homogeneity despite their huge volumes and distances traveled. However, with more detailed work, the recognition of geochemical heterogeneities within CRBG flows, especially the Grande Ronde Basalt, now must be taken into consideration (e.g. Reidel and Fecht 1987; Reidel and Tolan 1992, 2013a; Reidel 1998, 2005).

COLUMBIA RIVER BASALT GROUP DYKES AND VENTS

Dykes

Initially, three dyke swarms were recognized as feeder systems for the CRBG (Waters 1961): the Monument, Grande Ronde, and Cornucopia. However, Taubeneck (1970) merged the northern Grande Ronde and southern Cornucopia swarms into a single giant swarm, the Chief Joseph swarm (Fig. 1). Beeson et al. (1985) and Reidel et al. (1989a; 2013a, b) extended the dyke swarm boundary to the north-central and northeastern margin of the CRBG based on the occurrence of several Wanapum Basalt dykes and the up-gradient northeastern extent of Wanapum and Grande Ronde Basalt flows that indicated their feeder dykes must also extend into this same region.

Chief Joseph dykes fed most of the CRBG flows. However, the Picture Gorge was fed by the Monument dyke swarm, and Prineville and Steens Basalts, were fed by separate swarms (Fig. 1). Steens Basalt dykes are exposed in the southern portion of the province, whereas Imnaha Basalt dykes occur north of the Steens Basalt dykes in the Chief Joseph dyke swarm. The full extent of Imnaha Basalt dykes is not known because many are buried by younger flows. In general, dykes of Grande Ronde and Wanapum Basalts are found throughout the Chief Joseph swarm whereas Saddle Mountains Basalt dykes and vents occur in the northern half of the Chief Joseph swarm. Several Wanapum dykes are the only dykes that show a geographic distribution with age. The dykes for the older Frenchman Springs Member tend to be near the western part of the swarm; Priest Rapids Member dykes, the youngest Wanapum Basalt, are nearer to the eastern margin of the swarm; and the vents and dykes for the Roza Member form a 175-kilometre long-system between the Frenchman Springs and Priest Rapids systems. The earliest Wanapum dykes, the Eckler Mountain Member, are in the central part of the swarm. The youngest CRBG dyke that fed the 5.5 Ma Lower Monumental flow has not been found but must be in the eastern part of the province based on flow outcrops.

CRBG dykes typically are long and narrow, and are 10 m or less in width. However, dykes can vary from a few cm (e.g. figure 7 in Reidel et al. 2013b) to many metres in width (Fig. 3) but they rarely exceed 25 m. Due to burial by younger flows, the lengths of older dykes typically are not known. Those that have been mapped, like the Roza Member dyke swarm, are well over 150 km in length but others like the 8.5-Ma Ice Harbor Member dykes are only ~ 60 km long. Based on the extent of some of the larger Grande Ronde Basalt flows, it is estimated that some dykes must be nearly 200 km in length.

The overall trend of the Chief Joseph dyke swarm in the eastern part of the province is ~ N10°W ± 10°, however, dykes west of the Hite fault (Fig. 1) have a more westerly trend (N30–50°W) due to basement control (Reidel et al. 2006, 2013b). The majority of dykes are vertical to within 30° of vertical; however, some Frenchman Springs dykes in the Blue Mountains have dips as low as 15° (75° from vertical) and are probably controlled by thrust faults.

Most of the Steens Basalt dykes occur in the vicinity of Steens Mountain in the Basin and Range of southern Oregon where they have a N20°E trend, which is an unusual direction for younger CRBG dykes. Camp et al. (2013) and Reidel et al. (2013b) attribute this atypical trend to magma rising along the northward continuation of the mid-Cretaceous Nevada shear zone.

The Monument dyke swarm of north-central Oregon in the Blue Mountains (Fig. 1), where dykes trend N30–35°W, was the exclusive source for the Picture Gorge Basalt (Bailey 1989). Several Picture Gorge flows interfinger with the Grande Ronde Basalt where the dykes extend into the southern Columbia Basin.

Prineville Basalt is the westernmost CRBG and also was erupting during Grande Ronde Basalt time, but no dykes have been definitively located. However, a dyke with a general N-S trend has been found in a remote part of the Deschutes River valley and is suspected of being a Prineville dyke because it is in the centre of the areal extent of the Prineville Basalt, and cuts the oldest Grande Ronde Basalt there.

CRBG dykes intruding older CRBG flows commonly have centimetre(s)-thick glassy margins (selvage zones), although multiple selvage zones indicating multiple injections are not uncommon. The compositions of some of the multiple selvage zones, however, typically do not have a counterpart in the erupted flows suggesting the magmas that fed them were of small volume and never erupted at the surface. Studies of dykes along their length, however, demonstrate heterogeneity of the magma chamber. Martin (1989) first recognized that the Roza Member dyke system erupted slightly different compositions along its length. He recognized at least 5 different compositions that fall into the Roza Member's compositional field. Another example of magma heterogeneity is the Cohassett flow of the Sentinel Bluffs Member, Grande Ronde Basalt; this flow is a composite flow consisting of four distinct compositions erupting nearly simultaneously from different locations along the length of the dyke system (Reidel 2005).

One of the few localities where CRBG dykes are exposed in basement rocks is in the Wallowa Mountains of NE Oregon where they intrude granodiorites (Taubeneck 1970). These dykes have chilled selvage zones against melted wallrock, and typically contain basement xenoliths (Grunder and Taubeneck 1997; Petcovic et al. 2001; Petcovic and Grunder 2003). In addition, several eruptions have used the same dyke conduit with the younger dykes cross-cutting the older ones.

CRBG dyke compositions typically are representative of the flows that they feed. The dyke compositions can be homogeneous across the width of the dyke, including the selvage zones, as in the Sillusi flow of the Umatilla Member (Reidel 1998). Others can have a mainly homogeneous composition but with selvage zones that have different (usually evolved) compositions, as in the Teepee Butte Member (Reidel and Tolan 1992). Still other dykes record a changing composition from margin to centre; the composition in the centre is that of the flow it fed (e.g. Reidel and Tolan 2013a; Fig. 5).

Vents

Most of the observed CRBG vents are for flows that were not covered by later eruptions. Since the initial work of Swanson et al. (1975, 1979), many vents have been located for Wanapum and Saddle Mountains Basalt flows. These vents have well-developed cones although most have undergone some erosion. One of the most extensively studied is the Roza Member, Wanapum Basalt (Swanson el al. 1979; Martin 1989) with a recent detailed study by Brown et al. (2014). Vents also have been recognized for Frenchman Springs flows (Swanson et al. 1975; Reidel et al. 1994; Thordarson and Self 1998; Martin et al. 2013). Tephra for the Basalt of Ginkgo has been found over 7 km downwind from the vent indicating a considerable height was obtained by the plume during the eruption (Reidel et al. 1994). Vents for the Ice Harbor Member (Swanson et al. 1975), Umatilla Member, Elephant Mountain Member, and Pomona Member of the Saddle Mountains Basalt have also been documented. These vents also indicate typical basaltic eruptions where lava fountaining is followed by the main eruption.

Vents for the Grande Ronde Basalt (GRB) are rare due to burial by younger flows but those found differ from younger vents in that they do not have a well-developed cone shape, perhaps because part of the cone was rafted away. One of the earliest exposed GRB vents, the Teepee Butte Member (Reidel and Tolan 1992), is about 1 kilometre in cross section and only 30 metres high, which is the approximate thickness of the flow near the vent. It is composed of deposits characteristic of Hawaiian-style volcanism. The vent is asymmetrical with the eastern rampart composed of intercalated pyroclastic deposits and thin pahoehoe flows. The western rampart is down-gradient and consists of shelly pahoehoe flows; vent deposits are interpreted to have been rafted away while the eastern rampart, which is downwind, is well preserved. Vent deposits indicate a complex history accompanied by lava fountaining, and deposition of tephra and spatter-fed flows. There are at least 4 distinct layers of remarkably pristine spatter, Pele's Tears, and bombs totaling over 20 metres thick. Magma withdrawal at the end of the eruption phase was followed by flow-back breccia and extensional faults in the spatter near the dyke margin. A lava pond formed after rampart collapse has an evolved composition compared to the flow.

CRBG EMPLACEMENT

The rate of emplacement for large-volume flood basalt has been debated for some time but estimates appear to be converging. Essentially, there are two end-member models – a fast emplacement and a slow emplacement but the times to emplace rather than the velocity have been the main numbers attached to the models. Historically, Shaw and Swanson (1970) proposed that flow emplacement was turbulent and that the flows moved across the landscape in weeks to months. However, using the analogy of inflated pahoehoe flows in Hawaii, Hon et al. (1994) and Self et al. (1996) proposed that individual CRBG flows were emplaced as large, inflated flow fields over many decades to centuries and, rather than as turbulent flows, they were erupted as fast-laminar flows (Ho and Cashman 1997).

Flow inflation is now recognized as a major process in the CRBG flows; it is especially important in sheet flows but also in compound flows. It begins as thin lobes of lava develop a chilled, visco-elastic skin, which then expands with continued injection of fluid lava (Hon et al. 1994). Thordarson and Self (1998) have described inflation lobes and other interflow structures belonging to the Roza Member (Fig. 2). Other examples of inflation include the Umatilla Member (Reidel 1998), Asotin-Wilbur Creek Members (Reidel and Fecht 1987), Sentinel Bluffs Member (Reidel 2005), and more recently the Basalt of Palouse Falls (Vye et al. 2013).

Although flow inflation now is recognized as an important mechanism for flood-basalt emplacement, interpretations of the eruption and emplacement rates cover a wide range. Slow emplacement requiring years to a few decades is supported by conductive cooling models determined for the Roza Member (Thordarson and Self 1998), and by thermal models (Keszthelyi and Self 1998). Compositional data preserved in lava flows and phenocrysts, however, are more consistent with eruption and emplacement over much shorter timescales of months to years (Reidel et al. 1994; Ho and Cashman 1997; Reidel 1998). Recent thermal models by Keszthelyi et al. (2006), however, incorporate aspects of both 'slow' and 'rapid' emplacement. They envision a 'typical' 1000 km^3 flood-basalt lava flow being emplaced as inflated sheet flows in under 6 years; however, they also propose that individual batches of lava can travel 100 to 300 km beneath an insulating crust from the vent to the flow front in no more than 10 days, a velocity similar to that proposed by Shaw and Swanson (1970).

Velocities for channelized CRBG flows follow historic Hawaiian lava flows closely. Reidel and Fecht (1987) and Reidel (1998) documented examples where two flows upon eruption, mixed together down gradient to form a single flow more than 200 km from the source; mixing occurred less than a metre from the surface suggesting short emplacement times based on cooling rates. For example, the Umatilla Member erupted in eastern Washington and flowed 240 km through the ancestral Salmon-Clearwater River channel to the Pasco Basin in the central Columbia Basin where it spread as a sheet flow (Fig. 8). Mixing between the first flow and a later flow of the Umatilla Member in the distal end conclusively shows that cooling and solidification of the first flow had barely begun when the second flow invaded and mixed with it. If one takes a Hawaiian channelized flow velocity of ~ 1 km/hr, the two flows of the Umatilla reach their final length in 10 days. If it were to take a month to reach the final length, then the velocity of the lava would be 0.33 km/hr, at the low end of typical Hawaiian channelized flows. Similar velocities and emplacement times are obtained for other channelized flows (e.g. Esquatzel Member, Asotin Member, Pomona Member, and Elephant Mountain Member). At the other end of the range, Vye et al. (2013) estimated that the small volume (233 km^3) Basalt of Palouse Falls, which traveled ~ 100 km and consists of two to four flows (Martin et al. 2013), took a minimum

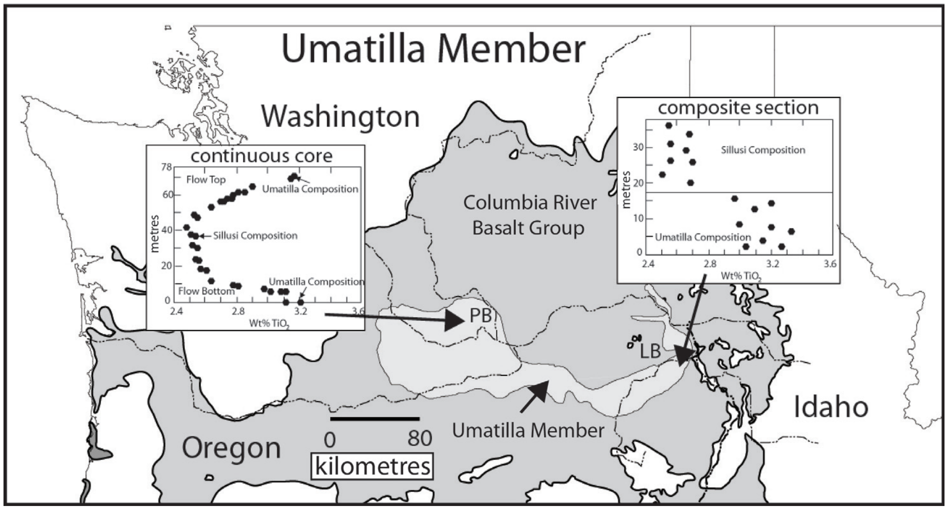

Figure 8. Diagram showing the extent of the Umatilla Member, Saddle Mountains Basalt and detailed vertical stratigraphic sections through the two flows, Basalt of Umatilla (oldest) and Basalt of Sillusi (youngest). In the Lewiston Basin (LB) there are two flows with distinct compositions but by the time the flows reached the Pasco Basin (PB), the older flow was invaded and mixed with the younger flow. See Reidel (1998) for details of the study.

of 19 years to emplace. This implies an average velocity that is much less than typical Hawaiian lavas.

Emplacement and emplacement rates for CRBG sheet flows are more difficult to estimate and, as pointed out by Vye et al. (2013), "*multi-layered lobes present a degree of complexity that make pathways and emplacement sequences more difficult to identify*" (p. 696, Vye at al. 2013). The composition of some flows allows the architecture to be resolved with a great deal of accuracy, however. For example, the previously discussed Cohasset flow consists of four nearly simultaneous eruptions along the length of the dyke system (Fig. 5). These eruptions combined to form one flow or cooling unit while preserving the main compositional integrity of each (Reidel 2005). Using the composition to define the various parts of the flow, an accurate picture of the architectural components of the flow can be resolved (Fig. 5, cross sections A–A', B–B' and C–C'). Applying this to the flow velocity, the greatest distance for each component to traverse to the place of inflation is about 300 km. At a velocity of 1 km/hr, a flow component could, in about 2 weeks, reach the central Columbia Basin where the flows inflate.

Emplacement Rates from Dyke-Wallrock Relations

Petcovic and Grunder (2003) analyzed wallrock melting reactions in a tonalite adjacent to the Maxwell Lake dyke in the Wallowa Mountains, a likely feeder to Wapshilla Ridge Member flows, the largest of all Grande Ronde Basalt members. The Wapshilla Ridge Member has an estimated volume of ~ 37,000 km^3 and a system of dykes estimated to extend over a length of 260 km (Reidel et al. 1989a; Reidel and Tolan 2013a).

A numerical model representing static conductions within a sustained basalt flow in the dyke for 3–4 years results in the melt zones observed in the dyke (Petcovic and Dufek 2005). Advective transport simulations matching field relations suggested that the initial basalt velocity in the dyke centre was ~ 10 m/s (~ 36 km/hr), but as basalt at the dyke margin solidified, constriction began slowing the velocity. After about 60 days, the model suggests that the magma in the dyke reached a sustained velocity of ~ 2 m/s (~ 7 km/hr) for the duration. Furthermore, the model suggests wallrock melting was initiated after ~ 1 year of flowing; the wallrock had dropped below its solidus temperature within ~ 2 years after flow ceased. Studies of phenocrysts erupted from CRBG magma chambers suggest that Grande Ronde Basalt flows can have very short residence times (approximately 4 yrs) prior to eruptions (Ramos et al. 2005, 2009, 2013) supporting Petcovic and Grunder's (2003) model.

PETROGENESIS

The origin of the CRBG has been an area of considerable debate for many years. Arguments include: a mantle-plume origin (e.g. Duncan 1982; Brandon and Goles 1988, 1995; Draper 1991; Hooper and Hawkesworth 1993; Geist and Richards 1993; Camp 1995, 2013; Dodson et al. 1997; Mege and Ernst 2001; Hooper et al. 2002, 2007; Camp et al. 2003; Camp and Ross 2004; Ramos et al. 2005; Camp and Hanan 2008; Wolff et al. 2008; Humphreys and Schmandt 2011; Wolff and Ramos 2013); simple melting of the upper mantle (Carlson and Hart 1987; Smith 1992; Christiansen et al. 2002; Hales et al. 2005; Tikoff et al. 2008; James et al. 2011; Liu and Stegman 2012; Long et al. 2012); back-arc extension resulting in the passive rise and adiabatic melting of the shallow mantle (Dickinson 1997; Sears et al. 2005; Tikoff et al. 2008), similar to that proposed for the Chilcotin Plateau Basalts of British Columbia (Bevier 1983); convective upwelling of upper mantle along the western edge of North America (King and Anderson 1998); lithospheric delamination (Hales et al. 2005); melting of buoyant peridotitic diapirs (Ivanov 2007); and upper mantle convection through or around the Farrallon-Juan de Fuca slab (e.g. James et al. 2011; Lui and Stegman 2012; Long et al. 2012).

The majority of workers support the plume origin based on field and petrochemical characteristics of the basalts (see references above). Tectonic investigations also are consistent with the plume model (e.g. Beeson and Moran 1979; Reidel 1984; Anderson 1987; Reidel et al. 1989a, 1994, 2013b; Price and Watkinson 1989; Beeson et al. 1989; Beeson and Tolan 1990; Blakely et al. 2011; Alloway et al. 2013; Anderson et al. 2013).

However, the nature and extent of the plume, and the petrogenetic processes in the magma are much debated. The location of the plume is one area of current debate. Wolff et al.

(2008) and Wolff and Ramos (2013) argue that the plume was centred near the western Snake River Plain, where the Oregon-Idaho graben and Chief Joseph dyke swarm converge; the magma moved north through a system of dykes similar to that suggested for the Mull complex in Scotland. Camp et al. (2003) and Camp and Ross (2004), however, argue that the plume originated in the Steens area and the plume head moved north over time reaching the northern part of the Chief Joseph dyke swarm.

Based on the tectonic history of the flood basalt province and the distribution of flows and dykes, Reidel et al. (2013b) concluded that the model of Camp et al. (2003) best fit the location of the plume and the manner in which the magma was delivered to the surface. Both the radiating dyke model and expanding plume-head model explain varying compositions erupting progressively northward. A plume head advancing outward from a central region, however, can explain the Picture Gorge Basalt and Prineville Basalt eruptions during the main phase of Grande Ronde Basalt more easily than radiating dykes. The Grande Ronde Basalt eruptions occurred during at least 4 magnetic reversals. The Picture Gorge Basalt, centred ~ 100 kms west of the Chief Joseph dyke swarm in the Blue Mountains, began erupting during the 'first' normal (N1) and ended during the 'second' reversal (R2 MSU; Fig. 2). The Prineville Basalt, centred 100 km west of the Picture Gorge Basalt, began during the 'second' reversal (R2) and ended in the last phase of the GRB, the N2. An advancing plume head envisioned by Camp and Ross (2004) could more easily explain the westward advance of younger eruptions during Grande Ronde Basalt time. As the plume head expanded, it would progressively encounter additional, diverse lithosphere that petrogenetic models incorporate. In addition, the expanding plume-head model can more easily explain some of the youngest Grande Ronde Basalt that erupted only at the northernmost end of the Chief Joseph dyke swarm.

Most petrogenetic models have concentrated on the main phase eruptions (i.e. Steens, Imnaha, Grande Ronde Basalt and Picture Gorge Basalt). The waning phase (i.e. Wanapum and Saddle Mountains Basalts) has been attributed to increasing crustal contamination of the residual melts (Hooper and Hawkesworth 2003; Wolff et al. 2008; Wolff and Ramos 2013) although not necessarily related to the plume (Wolff and Ramos 2013). However, the large size of some of the Saddle Mountains Basalt eruptions (e.g. Pomona and Elephant Mountain Members) suggests waning plume activity probably played a role in the final phase of the eruptions.

It is generally agreed that because of the similarity of trace elements and isotopes of the Imnaha Basalt (Imnaha component) to ocean island basalts and their high $^3He/^4He$ ratios (Hooper and Hawkesworth 1993; Wolff et al. 2008; Camp and Hanan 2008; Wolff and Ramos 2013), the Imnaha Basalt represents a plume-like component, the C2 component of Carlson et al. (1981). They argue that the plume-like component has subsequently been modified by crustal contamination, fractional crystallization and recharge. The nature and amounts of these components form the major disagreements between researchers and an in-depth discussion of this is beyond the scope of this paper.

Several researchers suggest the Steens, Imnaha and Picture Gorge Basalts were derived from a mixture of different sources including upwelling mantle (plume or no plume), depleted mantle, slab-derived fluids, and crust with some contaminant sources including a cratonic component as well as a general lithospheric component, including the Idaho batholith. However, all recent models recognize an 'Imnaha component' in all main phase eruptions including the Grande Ronde Basalt.

The Grande Ronde Basalt, the majority of the CRBG lavas, is mainly basaltic andesite that is compositionally more evolved and coherent than other CRBG formations. In addition, it has very limited isotopic variations and consistent trends in all major and minor elements (e.g. Carlson 1984; Wright et al. 1989; Hooper and Hawkesworth 1993; Hooper 2000; Camp and Hanan 2008; Wolff et al. 2008). The compositions show a strong clinopyroxene contribution that suggests the source of the basalt was a pyroxenite or peridotite (Wright et al. 1973; Reidel 1983; Takahashi et al. 1998; Camp and Hannan 2008). All current models agree that the Grande Ronde Basalt has undergone extensive contamination and fractional crystallization. The source of the contamination is a matter of debate, however. For example, Wolff and Ramos (2013) require a cratonic component, whereas Camp and Hanan (2008) incorporate a general lithospheric component. In summary, petrogenetic studies provide significant insight into the origin of the basalts but many areas of debate remain, indicating the need for more studies in this area.

ENVIRONMENTAL CONSEQUENCES OF THE ERUPTIONS

Flood basalts have long been linked to major extinctions in the geologic record (e.g. Morgan 1986; Rampino and Calderia 1992; Wignall 2001). The CRBG is one of the smallest flood basalt provinces but, as yet, has not been linked with any extinction event. However, the peak activity of the CRBG coincides with the middle Miocene Climatic Optimum (MCO) of 17–15 Ma, which was a period of global warmth (Foster et al. 2012) but has been attributed to events occurring in the Antarctic. Atmosphere CO_2 levels during the MCO were elevated compared to pre-industrial levels. At the low end, the estimated concentrations were 350–400 ppm (Foster et al. 2012), whereas You et al. (2009) estimated concentrations as high as 460–580 ppm. Atmospheric CO_2 pre- and post-MCO are estimated at between 200–260 ppm (Foster et al. 2012) similar to pre-industrial levels. You et al. (2009) estimate that during the MCO, the global mean surface temperature was ~ 3°C higher than present.

Thordarson and Self (1998) analyzed the ~ 14.9 Ma Roza Member, Wanapum Basalt for S, Cl, and F. The Roza Member was emplaced during the waning phase of the CRBG and is one of the smaller flow fields, representing only ~ 0.6% of the total volume of the CRBG. They estimated that over an approximated eruption time of 10 yrs, 12,500 megatons (Mt) of SO_2, 700 Mt HCl, and 1750 Mt HF were released directly to the atmosphere, not including ash; an additional 9600 Mt SO_2, 400 Mt HCl, and 1450 Mt HF were released from the vents. The lava itself is estimated to have released 2800 Mt SO_2, 305 Mt HCl, and 330 Mt HF alone. They suggested that these releases would have been sufficient to have caused a "*severe nuclear or volcanic winter*" (p. 71) with a sudden or short-lived surface cooling of 5–15°C lasting up to a decade or more.

With the peak of the CRBG occurring during the MCO, one would expect the main phase basalt to have released significantly more S, Cl and F as well as CO_2 than during the Roza eruptions, which was during the post-MCO cooling. Davis et al. (2013) have found that the Wapshilla Ridge Member of the Grande Ronde Basalt appeared to have released as much as 161 gigatons (Gt) of S, or nearly 3000 times that released from the 1815 Tambora event. They did not, however, estimate the amount of CO_2. Releases of CO_2 during the main phase of the CRBG eruptions (Steens, Imnaha and Grande Ronde) should have been substantial and could have easily caused warming related to the MCO in this author's opinion. This also suggests that during the peak of CRBG volcanism there were major releases of S, Cl and F. Böhme (2003), however, pointed out that only at the end of the MCO, between 14 and 13.5 Ma, which is past the peak of CRBG volcanism, was there a major regional extinction event of most thermophilic groups in Central Europe (Middle Miocene Extinction) with a drop in mean annual temperatures of ~ 7°C. Wignall (2001) indicates that the effects of S, Cl and F tend to operate over short time intervals of perhaps a decade. The effects of CO_2, however, have a much longer impact on global warming ranging from decades to 10^5 years but no estimates have been made for the CRBG CO_2 contributions. There is no reason to link the basalt and extinction events by cause and effect, but it is a curious coincidence that both the MCO occurred during the peak of the basalt eruptions and an extinction event occurred just after the peak of the CRBG eruptions.

One environmental consequence of the CRBG eruptions that is probable is that of disrupted weather patterns caused by the eruption of these large basalt flows. Devine et al. (1984) suggest that large fissure eruptions could create large atmospheric convection cells that could generate hurricane-force winds at the surface of the flow (Wignall 2001). The CRFBP is adjacent to the Pacific Ocean and, during the Miocene, the Cascade Range was active but not nearly the major rain-shadow to the Columbia Basin and British Columbia as it currently is. As these basalt flows erupted and spread across the Pacific Northwest, large convection cells rising from the lava flows would have drawn in considerable moisture and storms from the Pacific Ocean and, along with the orographic effect of the Rocky Mountains, could have caused major flooding across the region, perhaps major monsoonal rains accompanying the eruptions.

CONCLUSIONS

The Columbia River Flood Basalt Province is the youngest and best preserved flood basalt province on Earth. Its location and accessibility have allowed some of the most detailed stratigraphic, tectonic and petrogenetic studies to be performed and integrated, allowing a unique insight into the history and mechanisms of flood basalt origin and evolution, but many unanswered questions remain. The relationship between the basalt eruptions and the Miocene environment is poorly known and the role of volatiles and ash from the eruptions is still an open question. The plume model, although widely accepted, is still somewhat controversial and the nature of the magmatic processes that produced these lava flows is still being debated. Thus, the CRBG still remains an area for research in the future.

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