**of paleodrainage systems. These processes and their associated erosional and structural features also influenced the nature of late Neogene sedimentation during and after the Columbia River Basalt Group eruptions. In this paper, we describe and revise the stratigraphic framework of the province, provide current estimates on the areal extent and volume of the flows, and summarize their physical features and compositional characteristics.**

## INTRODUCTION

The Columbia River flood basalt province is typical of other continental-based large igneous provinces where voluminous flows of basaltic lava erupt onto continental crust, resulting in the rapid accumulation and great thickness of lava covering from ~$10^5$ to >$10^6$ km$^2$ (Jerram and Widdowson, 2005). The Columbia River Basalt Group erupted between ca. 16.7 Ma and 5.5 Ma (Barry et al., this volume) and inundated more than 210,000 km$^2$ of the Pacific Northwest (Fig. 1). It is the youngest, smallest, and best-preserved continental flood basalt province on Earth, with a well-developed stratigraphy that makes it a model for the study of similar provinces worldwide.

The flood basalt stratigraphy has been refined by years of detailed field work, combined with geochemical, geochronological, and paleomagnetic studies. In this paper, we describe and revise the stratigraphic framework of the province, present new estimates on the areal extent of the lava flows and their volume, describe the common regional aspects of the stratigraphy and flow characteristics, and provide a summary of the eruptive history and mode of lava flow emplacement.

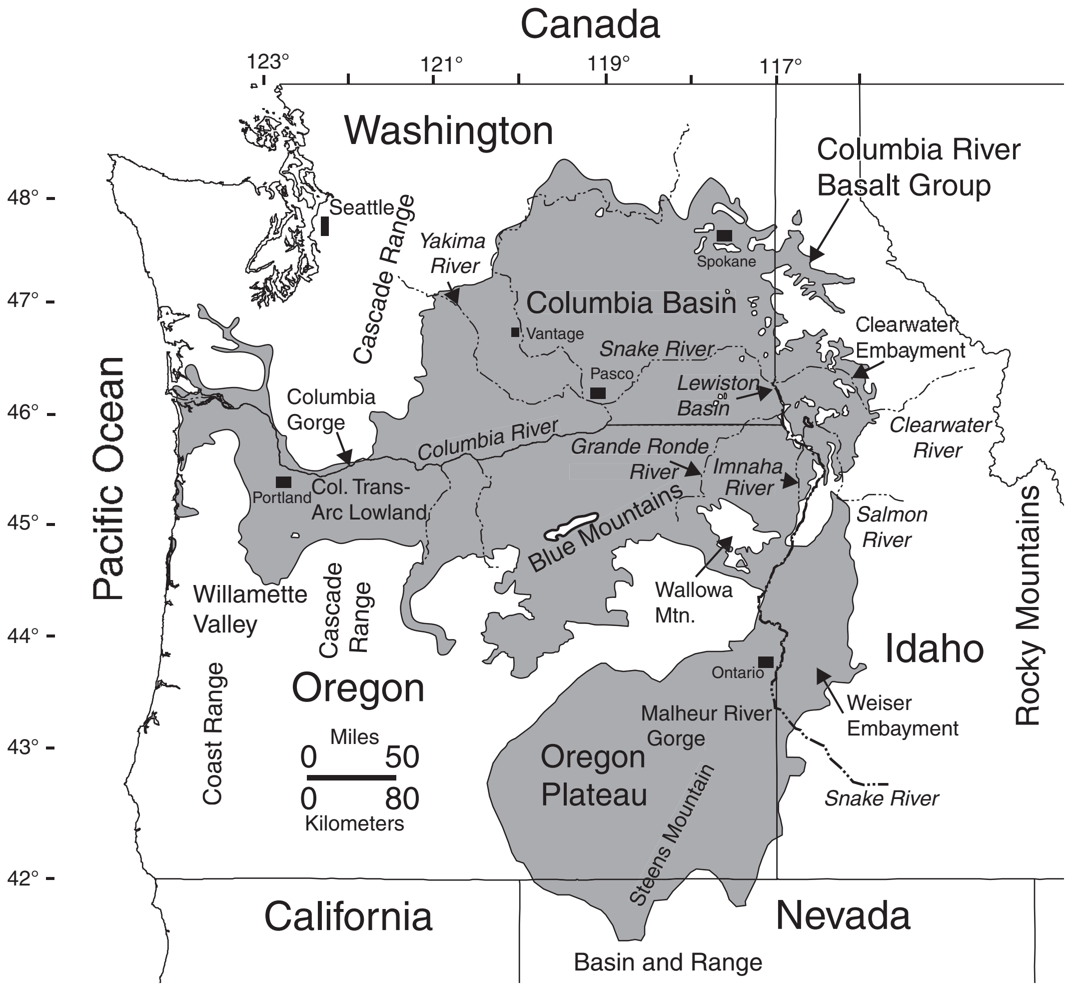

Figure 1. Map showing the Columbia River flood basalt province, areal extent of the Columbia River Basalt Group, and features discussed in text. Shaded area is extent of Columbia River Basalt Group.

## REGIONAL SETTING

The Columbia River flood basalt province covers most of eastern Washington and Oregon, western Idaho, and part of northern Nevada in the Pacific Northwest of North America (Fig. 1). The basaltic lavas of the Columbia River Basalt Group erupted in a backarc setting between the Cascade volcanic arc and the Rocky Mountains. The initial eruptions began in the southern Oregon Plateau near the northern limit of Basin and Range extension but quickly spread north. The flood basalts then inundated the Columbia Basin, flowing westward through the Cascade arc, Willamette Valley, and Coast Range, and finally into the offshore Miocene forearc basins. The greatest thickness, more than 4 km, occurs near the center of the Columbia Basin (Reidel et al., 1989b; Reidel et al., this volume, Chapter 5).

Rocks older than the Columbia River Basalt Group 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, they are exposed in the footwalls of Basin and Range faults. To the northeast and east, the Columbia River Basalt Group laps onto a cratonic assemblage of Proterozoic and Lower Paleozoic rocks, and Jurassic and Cretaceous intrusions of the Idaho Batholith (Stoffel et al., 1991; see Reidel et al., this volume, Chapter 5). Within and south of the Blue Mountains (Fig. 1), the Columbia River Basalt Group overlies Lower to Middle Tertiary volcanic rocks and related volcaniclastic rocks partly assigned to the Clarno and John Day Formations, which in turn overlie northeast-trending belts of Cretaceous to Permian 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 Columbia River flood basalt province. Flood basalt flows of the Columbia River Basalt Group were able to cross the Miocene Cascade volcanic arc through an east-northeast–trending lowland gap (Columbia Trans-Arc Lowland; Beeson et al., 1979), where they spread across much of the northern Willamette Valley region, and through the Coast Range (Fig. 1), eventually reaching the Pacific Ocean, where they continued to advance onto the continental shelf (Beeson et al., 1979; Niem and Niem, 1985).

In eastern Oregon, the Columbia River Basalt Group is partly overlain by a more diverse assemblage of tholeiitic, silicic, calc-alkaline, and mildly alkaline volcanic rocks that are best preserved in the La Grande, Baker, and Oregon-Idaho grabens (Cummings et al., 2000; Hooper et al., 2002; Ferns et al., 2010; Ferns and McClaughry, this volume). The most extensive of these volcanic rocks include the ca. 14.2–10.3 Ma Owyhee Basalt and Keeney Sequence in the south (Cummings et al., 2000) and the ca. 13.8–12 Ma Powder River volcanics in the north (Ferns et al., 2010). These rocks appear to lie along a 300-km-long vent system that is superimposed along southernmost part of the Columbia River Basalt Group vent axis (Ferns and McClaughry, this volume). However, in contrast to the environment of mantle upwelling that generated tholeiitic flood basalt volcanism of the Columbia River Basalt Group, these younger calc-alkaline lavas appear to be associated with a later period of crustal stretching (Hooper et al., 2007).

## STRATIGRAPHIC FRAMEWORK OF THE COLUMBIA RIVER BASALT GROUP

The Columbia River Basalt Group (Fig. 2) is a thick sequence of more than 350 continental tholeiitic flood basalt flows that were erupted over an 11 m.y. period from about ca. 16.7 Ma to 5.5 Ma (Swanson et al., 1979b; Tolan et al., 1989; Barry et al., this volume). These flood basalt flows cover an area over 210,000 km$^2$ in Washington, Oregon, western Idaho, and northernmost Nevada (Fig. 1) and have an estimated volume of ~210,000 km$^3$ (Table 1). This volume includes the Steens Basalt in southeast Oregon, which now is included in the Columbia River Basalt Group (Camp et al., this volume). The source for most of the flows was a series of generally north-northwest–trending linear fissure systems located in eastern Washington, eastern Oregon, and western Idaho, although ~7% of the Columbia River Basalt Group volume also includes the first erupted flows from north-northeast–trending dikes located in southeastern Oregon (Fig. 3).

Whereas the entire eruptive period of the Columbia River Basalt Group spans ~11 m.y., ~93% of the flood basalt volume erupted in ~1.1 m.y. (ca. 16.7–15.6 Ma) (Fig. 2). We refer to these uninterrupted eruptions as the main eruptive phase, which generated the Steens, Imnaha, Grande Ronde, Prineville, and Picture Gorge Basalts. The peak of Columbia River Basalt Group eruptions occurred during Grande Ronde time, when ~72% of the flood basalt volume was generated in only ~400,000 yr

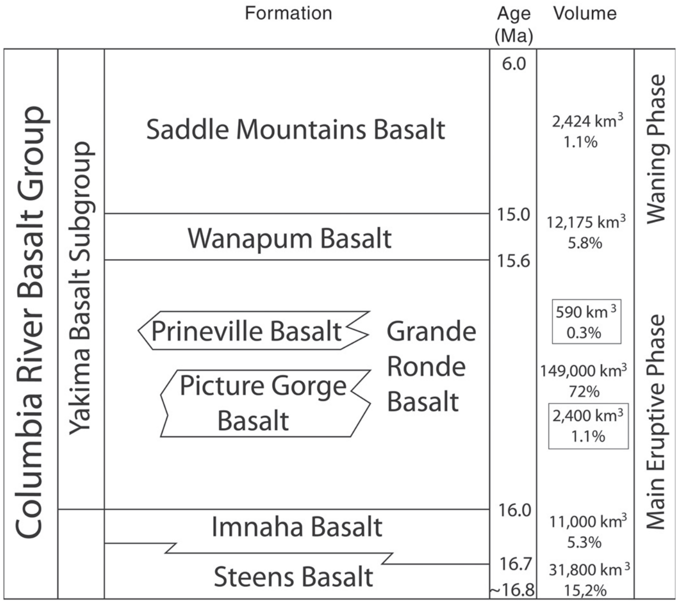

Figure 2. Major subdivisions of the Columbia River Basalt Group. This illustration shows the nomenclature to formation level. Figures 7 and 8 show the correlation of members and flows.

TABLE 1. AREAL EXTENT, VOLUME, AND NUMBER OF COLUMBIA RIVER BASALT GROUP FLOWS (*Continued*)

| Unit | Areal extent ($km^2$) | Volume ($km^3$) | Volume (%) | Estimated number of flows | Average volume/flow ($km^3$) | Isotopic age (Ma) from Barry et al. (this volume) and Tolan et al. (1989) |
|---|---|---|---|---|---|---|
| Roza Member | 40,350 | 1300 | 0.6 | 5 | 260 | 14.98 |
| Frenchman Springs Member* | 76,200 | 7600 | 3.7 | As many as 23 | 330 | 15.0 |
| Basalt of Sentinel Gap | 49,125 | 2000 | 1.0 | 1–3 | 666–2000 | |
| Basalt of Sand Hollow | 65,200 | 3109 | 1.5 | 1–6 | 518–3109 | |
| Basalt of Silver Falls | 15,650 | 404 | 0.2 | 1–4 | 101–404 | |
| Basalt of Ginkgo | 46,140 | 1873 | 0.9 | 1–6 | 312–1873 | |
| Basalt of Palouse Falls | 10,495 | 233 | 0.11 | 1–4 | 58–233 | |
| Basalt of Weiser | 2130 | 140 | 0.07 | 28 | 5 | |
| Lookingglass Member | ND | ND | ND | 1 | – | |
| Basalt of Cuddy Mountain | 70 | 1 | >0.001 | 2 | – | |
| Eckler Mountain | 9300<br>(6090) | 335<br>(170) | 0.16 | 5–6 | 56–67 | |
| Basalt of Dodge | 1200 | ~300 | 0.14 | 5 | – | |
| Basalt of Robinette Mountain | ~1000 | ~35 | | 1 | – | |
| Basalt of Icicle Flat | 520 | 11 | 0.005 | 1 | – | |
| Prineville Basalt | 11,440 | 590 | 0.3 | 8 | 74 | |
| Picture Gorge Basalt | 10,680 | 2400 | 1.1 | 61 | 40 | 15.2–16.4 |
| Grande Ronde Basalt | 151,600 | 149,000 | 72 | ~110 | 1355 | 15.6–16.0 |
| Imnaha Basalt | 60,200 | 11,000 | 5.3 | 26 | 423 | 16.0–16.7 |
| Steens Basalt | 53,000 | 31,800 | 15.2 | ~130 lobes[†] | | 16.6–16.8 |
| Total Columbia River Basalt Group | 210,000 | 210,000 | – | ~350[§] | ~600 | 16.8–6.2 |

*Frenchman Springs data from Martin et al. (this volume).

[†] This number is the maximum in vertical section. It is difficult to make an accurate calculation on the total number of flow lobes spread across the outcrop area, but it is certainly in the range of several hundred.

[§] Because the total number of Steens flow lobes is difficult to calculate and would bias the Columbia River Basalt Group total, they are not included in this calculation.

(ca. 16–15.6 Ma; Barry et al., 2010, this volume). During the main eruptive phase and into Wanapum time, many flows that erupted were of extraordinary size, commonly exceeding 1000 $km^3$ in volume and traveling many hundreds of kilometers from their vent systems (Tolan et al., 1989; Reidel et al., 1989a; Reidel, 1998, 2005; Reidel and Tolan, this volume, Chapter 5).

## Stratigraphy

The historical development of the Columbia River Basalt Group nomenclature up to 1989 has been discussed by Tolan et al. (1989). In this paper, we address revisions in stratigraphic relationships and nomenclature since the publication of Geological Society of America (GSA) Special Paper 239 (Reidel and Hooper, 1989). However, we would be remiss if we did not acknowledge the pioneering studies of Mackin (1961), Waters (1961), Bond (1963), Grolier and Bingham (1971, 1978), Swanson et al. (1979a, 1979b, 1980, 1981), and Beeson and Moran (1979), who developed the basic Columbia River Basalt Group stratigraphic framework that could be correlated and mapped over large areas.

Since 1989, a significant amount of Columbia River Basalt Group research has been directed into refining the stratigraphy, investigating the emplacement processes of these huge flood basalt flows (e.g., Reidel and Fecht, 1987; Reidel and Tolan, 1992; Reidel et al., 1994; Ho and Cashman, 1997; Self et al., 1996, 1997; Reidel, 1998, 2005), developing geochemical and petrogenetic models (e.g., Hooper and Hawkesworth, 1993;

Figure 3. Dike swarms of the Columbia River flood basalt province. The interpreted extent of the dike swarms is based on surface exposures of dikes and vents, known extent of flows, and geophysical signatures of dikes.

Camp and Hanan, 2008; Wolff et al., 2008), and understanding the hydrogeology of the Columbia River Basalt Group (see Tolan et al., 2009a; Burns et al., 2011).

## Stratigraphic Nomenclature and Revisions to the Columbia River Basalt Group

The basic stratigraphic framework of the Columbia River Basalt Group was established by Swanson et al. (1979a), and refined in Tolan et al. (1989) and related papers published in GSA Special Paper 239 (Reidel and Hooper, 1989). Whereas the framework of the Columbia River Basalt Group nomenclature has remained largely unchanged over the past 20 yr, there have been several significant changes to the stratigraphic detail. In this paper, we provide updated information on the areal extent and volume of the flows and summarize the knowledge gained and the ideas that have developed since 1989. In addition, we discuss changes to the stratigraphic nomenclature and the rationale for establishing those changes.

The current geographic distribution for the Columbia River Basalt Group formations is shown in Figure 4, and the individual lithostratigraphic units comprising the Wanapum Basalt and Saddle Mountains Basalt are shown in Figure 5. Progressive change in the volume of basalt through time is shown in Figure 6. In companion papers, Camp et al. (this volume) delineate the distribution for lithostratigraphic and magnetostratigraphic units of the Steens Basalt, and Reidel and Tolan (this volume, Chapter 5) delineate the distribution for lithostratigraphic units of the Grande Ronde Basalt. The Imnaha Basalt has not been subdivided on a stratigraphic basis; however, several compositional types have been recognized but are not stratigraphically controlled (Hooper and Hawkesworth, 1993). No changes to the Prineville Basalt have been made, nor has the Picture Gorge Basalt been revised since Bailey (1989).

### *Revision to Columbia River Basalt Group Formations*

Since the publication of Swanson et al. (1979a), workers have strived to follow the Stratigraphic Code of North America (Anonymous, 2005), which states in Article 7 (p. 1561): "The name of a formal geologic unit is compound. For most categories, the name of the unit should consist of a geographic name combined with an appropriate rank (e.g., Wasatch Formation) or descriptive term (e.g., Viola Limestone)"; and (2) more specifically for formations in Article 30d (p. 1576), "A formation name consists of a geographic name followed by a lithic designation or by the word Formation."

Following the original Columbia River Basalt Group nomenclature formalization by Swanson et al. (1979a), all Columbia River Basalt Group formations will be formally named using the geographic designator followed by "Basalt," as in Grande Ronde Basalt, rather than Grande Ronde Formation, because this designator is more descriptive than the generic term "Formation."

Hooper and Hawkesworth (1993) suggested the addition of the term "Clarkston Basalt" to the nomenclature as a subgroup to designate the main pulse of Columbia River Basalt Group eruptions. Their new subgroup included all formations except the Saddle Mountains Basalt, which they designated as a separate subgroup, therefore abandoning its formal status as a formation originally established in Swanson et al. (1979a). Although we have no objection to designating subgroups in the Columbia River Basalt Group, because Swanson et al. (1979a) established the Yakima Basalt Subgroup, we do not incorporate the informal nomenclature of Hooper and Hawkesworth (1993) based on the following reasons. First, the Saddle Mountains Basalt as a formation is well established in the literature, and changing it to a subgroup could add much confusion to the literature. Second, the name Clarkston is already a formal geographic designator in the stratigraphic nomenclature, and its duplication is forbidden by the stratigraphic code. Third, since there is only one formation that is not included in the Clarkston subgroup of Hooper and Hawkesworth (1993) (the Saddle Mountains Basalt), its stratigraphic significance is diminished. Although this is not forbidden by the code, we argue that the present use of "Saddle Mountains Basalt" as a formation conveys a more appropriate descriptor and that the original usage of Swanson et al. (1979a) is more appropriate. Fourth, although Hooper and Hawkesworth (1993) suggested that Saddle Mountains Basalt be raised to subgroup status, it only contains ~1% of the total Columbia River Basalt Group and incorporates no formations, thus making it unclear whether the former members of the Saddle Mountains Basalt should be considered as new formations or remain as members without being incorporated in

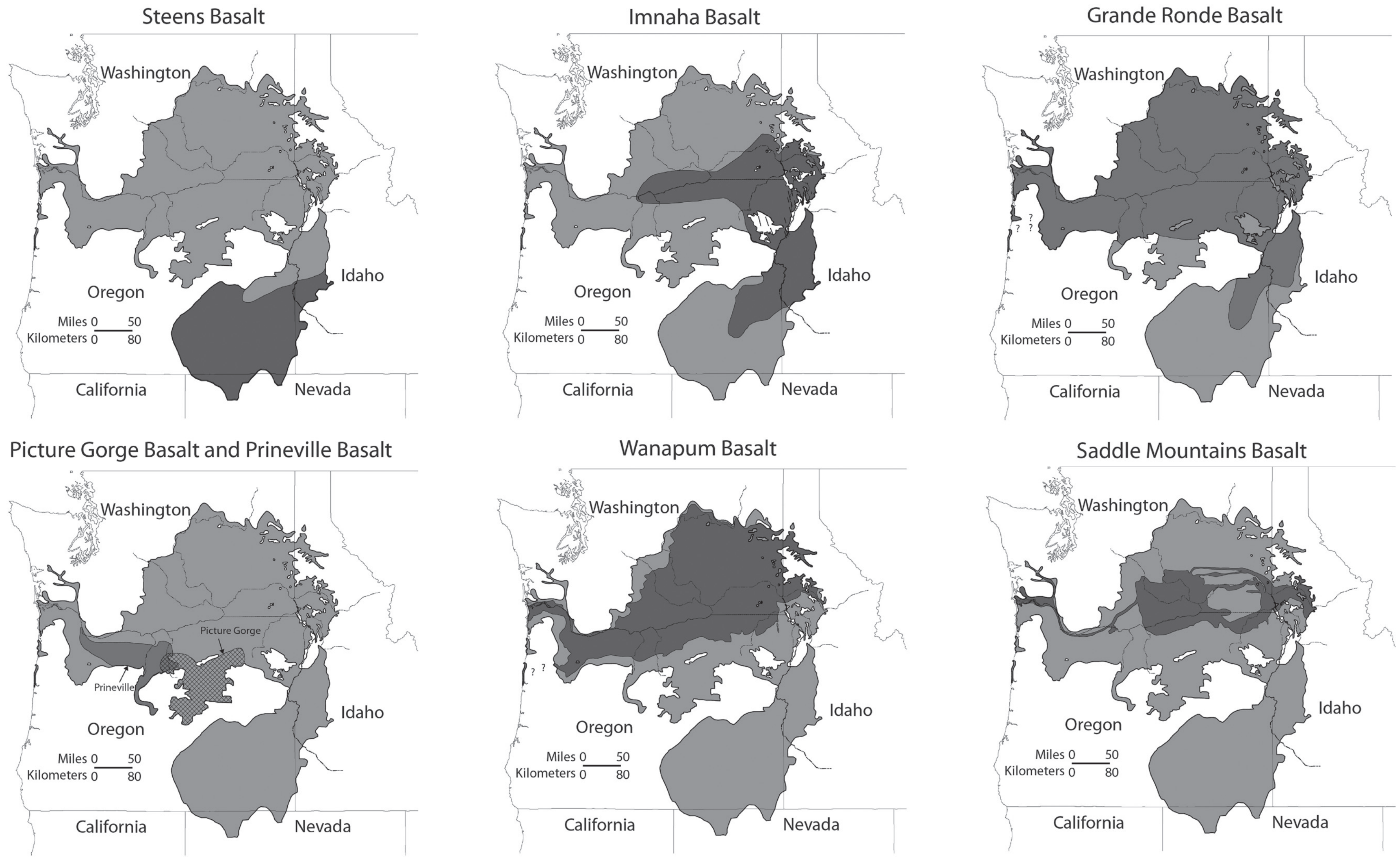

Figure 4. Areal extent of the seven formations comprising the Columbia River Basalt Group. Steens data are from Camp et al. (this volume) and Grande Ronde Basalt data are from Reidel and Tolan (this volume, Chapter 5).

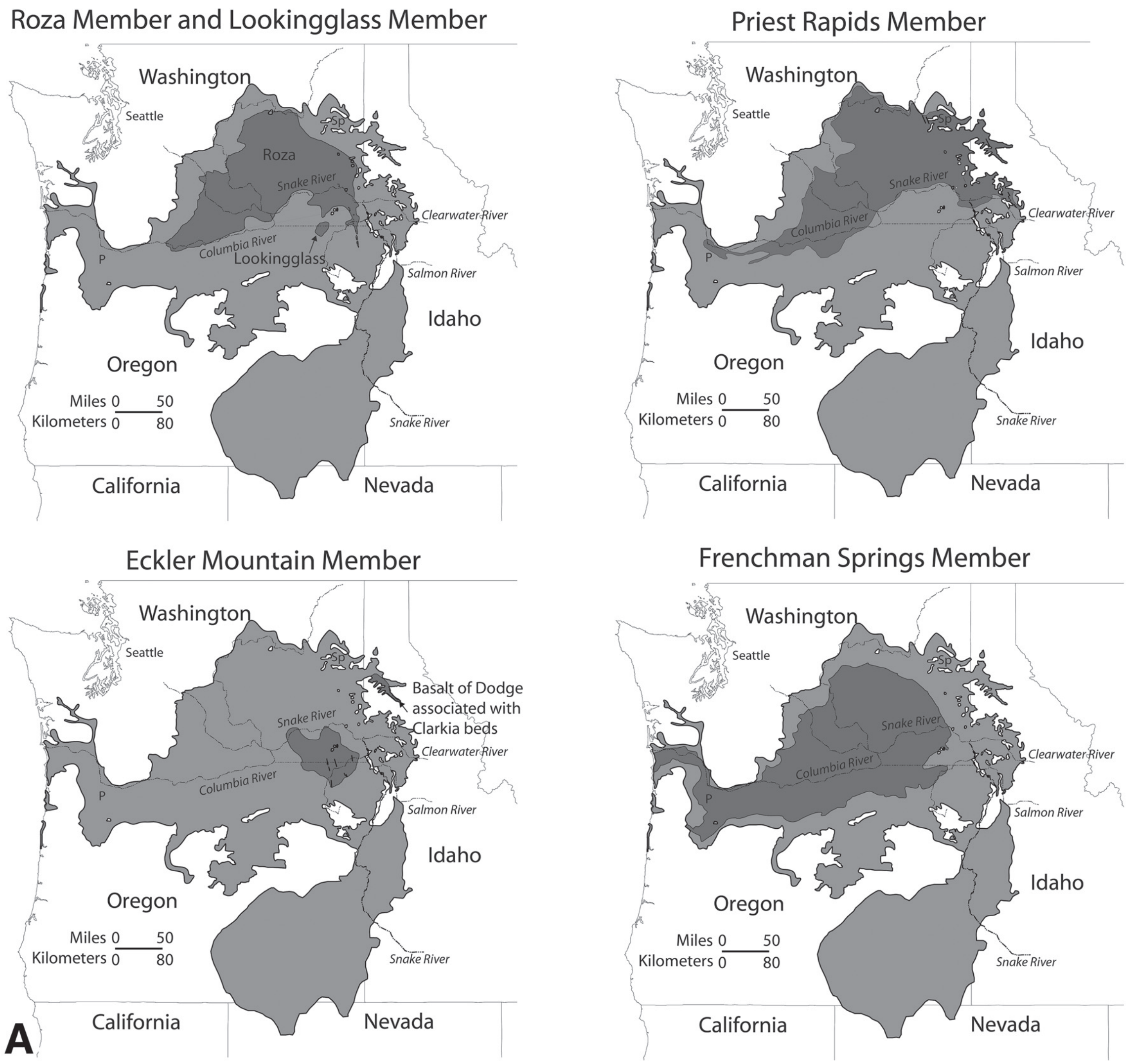

Figure 5 (*Continued on following pages*). Areal distribution of the main members and flows of the Columbia River Basalt Group. (A) Eckler Mountain, Frenchman Springs, Lookingglass, Roza, and Priest Rapids Members of the Wanapum Basalt; (B) Basalt of Rosalia, Priest Rapids Member, Wanapum Basalt; Umatilla, Wilbur Creek, and Asotin Members, Saddle Mountains Basalt; (C) Esquatzel, Pomona, Grangeville, Buford, and Elephant Mountain Members, Saddle Mountains Basalt; (D) Feary Creek, Swamp Creek, Weissenfels Ridge, Craigmont, Weippe, Ice Harbor, Lower Monumental Members, Saddle Mountains Basalt; basalts of Cuddy Mountain, Weiser, Icicle Flat, and Walla Walla. P—Portland.

a particular formation. We see much confusion and little value in formalizing such drastic changes in the Columbia River Basalt Group nomenclature, particularly when the existing stratigraphy is well established in the geological literature. Thus, we do not include the Clarkston Basalt subgroup in the formal stratigraphy established here.

Swanson et al. (1979a) formalized five formations: the Imnaha Basalt, the Grande Ronde Basalt, the Picture Gorge Basalt, the Wanapum Basalt, and the Saddle Mountains Basalt. In this volume, we invoke two changes at the formation level. Following Camp et al. (2003) and Camp et al. (this volume), we adopt their addition of the Steens Basalt as the sixth Columbia River Basalt Group formation. Documentation for this designation is provided by Camp and Ross (2004), Hooper et al. (2007), and Camp et al. (this volume).

The second change in formation status is to the Prineville Basalt, which, like the Picture Gorge Basalt, interfingers with the Grande Ronde Basalt. Anderson (1980), Smith (1988), Goles (1986), and Tolan et al. (1989) suggested that the Prineville Basalt be excluded from the Grande Ronde Basalt and be assigned as a separate formation within the Columbia River Basalt Group following the current treatment of the Picture Gorge Basalt. In this volume, we adopt their recommendation and assign the Prineville Basalt as the seventh formation.

One final consideration for the lithostratigraphic terminology was a suggestion by Bailey (1989) to reclassify the formational

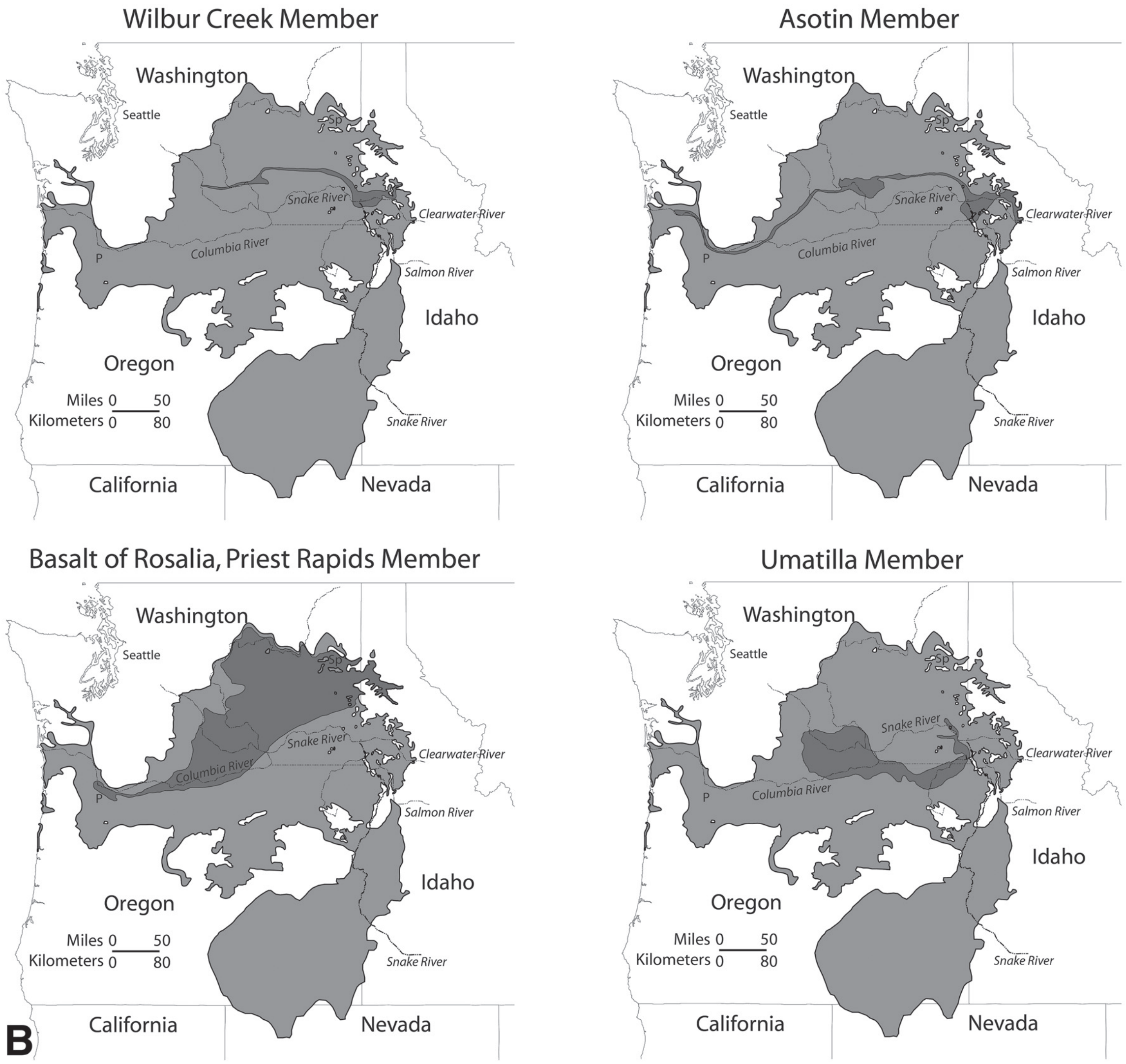

Figure 5 (*Continued*).

status of the Picture Gorge Basalt by upgrading it to subgroup status, and by extension, subdividing its constituent flows into three new formations: the Twickenham, Monument Mountain, and Dayville Basalts. Although the lateral continuity of these three units appears to be well defined, their extent is on a much smaller scale than the remaining Columbia River Basalt Group Formations, and the flows contained in each are similarly less extensive and not as well defined as the formal basalt members that comprise the other Columbia River Basalt Group formations. For these reasons, we prefer to retain the formational status of the Picture Gorge Basalt as originally defined by Swanson et al. (1979a).

### *Revisions to Columbia River Basalt Group Members*

The newly defined Steens Basalt contains two informal members (Camp et al., this volume). No changes or additions involving members or flows have been made to the Imnaha Basalt, Prineville Basalt, or Picture Gorge Basalt (Bailey, 1989) since 1989. However, some changes have been made to the Grande Ronde Basalt (Reidel and Tolan, this volume, Chapter 5), Wanapum Basalt (Martin et al., this volume; Hooper et al., 1995), and Saddle Mountains Basalt.

### *Steens Basalt*

The Steens Basalt contains two regionally extensive and stratigraphically coherent chemical groups: a lower group of flows that are tholeiitic, chemically homogeneous, and typically more primitive, and a heterogeneous and typically more-evolved upper group of flows composed of tholeiitic basalt, alkaline basalt, and basaltic trachyandesite. Camp et al. (this volume) retained the terminology of Camp et al. (2003) to define these groups as informal members of the Steens Basalt.

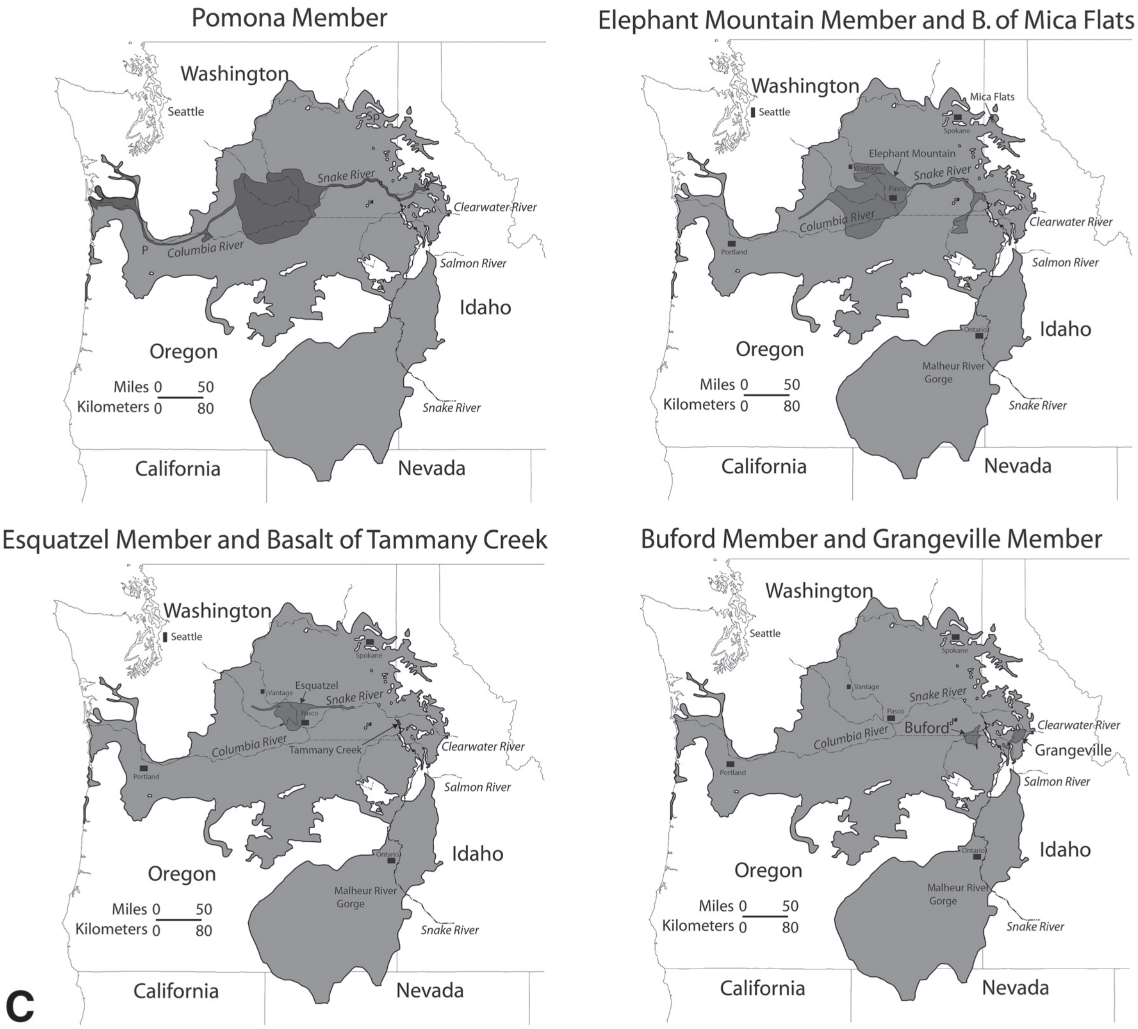

Figure 5 (*Continued*).

### *Grande Ronde Basalt*

Reidel et al. (1989a) recognized 17 informal members in the Grande Ronde Basalt. Since then, several members have been formalized in the literature. Reidel and Tolan (this volume, Chapter 5) have revised the previous nomenclature to include new units, and formalize new members. Many of their informal units do not fit the criteria for well-defined members, so they remain informal. In addition, Reidel and Tolan (this volume, Chapter 5) provide estimates of the areal extent and volume of both formal and informal members.

### *Wanapum Basalt*

The Roza and Priest Rapids members have not changed, so no revisions have been made; however, Martin et al. (this volume) revise the Frenchman Springs Member by reducing the original six units defined by Beeson et al. (1985) to five. The basalt of Lyons Ferry has been eliminated because it is now considered as part of the basalt of Sentinel Gap. Martin et al. (this volume) also provide new estimates of the areal extent and volume of the Frenchman Springs flows, their dike systems, and their physical volcanology.

Swanson et al. (1979a) originally designated the Eckler Mountain Member as the oldest member of the Wanapum Basalt, which included the basalt of Robinette Mountain, basalt of Dodge, basalt of Schumaker Creek, and later the basalt of Lookingglass (Hooper and Swanson, 1990). Hooper et al. (1995) refined these stratigraphic relationships and suggested that the basalt of Schumaker Creek be upgraded to a new member because it lies above the Frenchman Springs Member. In this paper, we adopt the suggestion of Hooper et al. (1995) to formalize the Schumaker Creek Member, but we reject their suggestion that the Eckler Mountain Member be raised to formation status and that the basalt of Lookingglass be made a separate member. The Eckler Mountain flows still best fit the original designation of Swanson et al. (1979a) as a single member because they are very small-volume flows that cannot be mapped over a great distance.

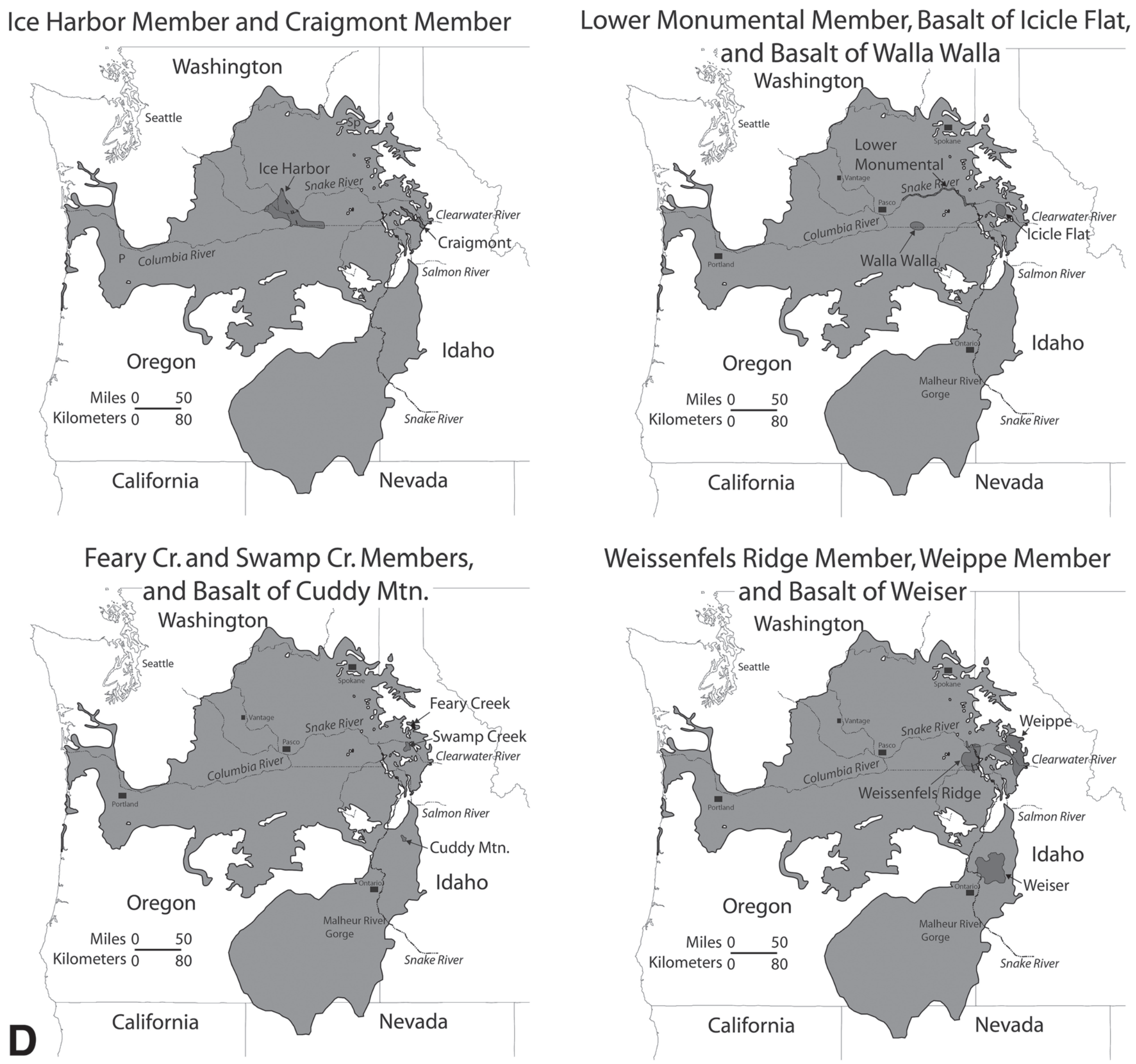

Figure 5 (*Continued*).

### *Saddle Mountains Basalt*

Several members of Saddle Mountains Basalt originally defined by Swanson et al. (1979a) no longer reflect current stratigraphic knowledge. However, the nomenclature for these units are so entrenched in the literature that we are hesitant to formally revise their stratigraphic definition. We find it necessary, however, to summarize the complex field relationships of these units that make traditional stratigraphic designations problematic. These complexities are now mainly recognized in the Umatilla, Wilbur Creek, and Asotin Members, as revealed in detailed field and geochemical studies.

As the oldest member of the Saddle Mountains Basalt, the Umatilla Member marks the beginning of the waning period of Columbia River Basalt volcanism (Fig. 2). It was first recognized by Laval (1956), who described two flows—the younger Sillusi flow and the older Umatilla flow, both of which erupted in the eastern part of the Columbia Basin. Reidel (2005) studied these flows in detail and used their distribution and physical and compositional characteristics to show that they erupted separately but flowed westward, intermingling and partly mixing to form a single flow in the central Columbia Basin. Sillusi chemistry is preserved in the center of the flow, between layers of Umatilla chemistry at the top and bottom, with a complete gradation between the two. We see no reason to change the Umatilla Member designation, but we now recognize that the two flows described by Laval (1956) erupted separately but very rapidly (approximately months; Reidel, 2005) and flowed 200 km westward, where the younger flow (Sillusi) physically invaded and intermingled with the older (Umatilla) flow, forming a single, quasi–sheet-compound flow that retains the chemical signatures of both constituent lava types. Mixing of two separate lava flows at the surface has an historic analogue in the A.D. 1256 eruption of the Madinah flow in western Saudi Arabia (Camp et al., 1987).