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Origin and Evolution of the Sierra Nevada and Walker Lane themed issue

Petrologic, tectonic, and metallogenic evolution of the Ancestral Cascades magmatic arc, Washington, Oregon, and northern California

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ABSTRACT

Present-day High Cascades arc magmatism was preceded by ~40 m.y. of nearly cospatial magmatism represented by the ancestral Cascades arc in Washington, Oregon, and northernmost California (United States). Time-space-composition relations for the ancestral Cascades arc have been synthesized from a recent compilation of more than 4000 geochemical analyses and associated age data. Neither the composition nor distribution of ancestral Cascades magmatism was uniform along the length of the ancestral arc through time. Initial (~40 to 36 Ma) ancestral Cascades magmatism (mostly basalt and basaltic andesite) was focused at the north end of the arc between the present-day locations of Mount Rainier and the Columbia River. From 35 to 18 Ma, initial basaltic andesite and andesite magmatism evolved to include dacite and rhyolite; magmatic activity became more voluminous and extended along most of the arc. Between 17 and 8 Ma, magmatism was focused along the part of the arc coincident with the northern two-thirds of Oregon and returned to more mafic compositions. Subsequent ancestral Cascades magmatism was dominated by basaltic andesite to basalt prior to the post–4 Ma onset of High Cascades magmatism. Transitional tholeiitic to calc-alkaline compositions dominated early (before 40 to ca. 25 Ma) ancestral Cascades eruptive products, whereas the majority of the younger arc rocks have a calc-alkaline affinity. Tholeiitic compositions characteristic of the oldest ancestral arc magmas suggest development associated with thin, immature crust and slab window processes, whereas the younger, calc-alkaline magmas suggest interaction with thicker, more evolved crust and more conventional subduction-related magmatic processes. Presumed changes in subducted slab dip through time also correlate with fundamental magma composition variation. The predominance of mafic compositions during latest ancestral arc magmatism and throughout the history of modern High Cascades magmatism probably reflects extensional tectonics that dominated during these periods of arc magmatism.

Mineral deposits associated with ancestral Cascades arc rocks are uncommon; most are small and low grade relative to those found in other continental magmatic arcs. The small size, low grade, and dearth of deposits, especially in the southern two-thirds of the ancestral arc, probably reflect many factors, the most important of which may be the prevalence of extensional tectonics within this arc domain during this magmatic episode. Progressive clockwise rotation of the forearc block west of the evolving Oregon part of the ancestral Cascades magmatism produced an extensional regime that did not foster significant mineral deposit formation. In contrast, the Washington arc domain developed in a transpressional to mildly compressive regime that was more conducive to magmatic processes and hydrothermal fluid channeling critical to deposit formation. Small, low-grade porphyry copper deposits in the northern third of the ancestral Cascades arc segment also may be a consequence of more mature continental crust, including a Mesozoic component, beneath Washington north of Mount St. Helens.

INTRODUCTION

The importance of Cenozoic arc magmatism to the geologic evolution of western North America is widely recognized and has been extensively studied. Traditionally, Cenozoic volcanic rocks of the Cascade Range in Oregon have been split into two physiographic provinces, the High Cascades and the Western Cascades (Fig. 1) (Callaghan, 1933; Thayer, 1937; Peck et al., 1964). Active volcanoes of the modern Cascade magmatic arc form the High Cascades, including the prominent north-south chain of stratovolcanoes that extends from Mount Garibaldi (British Columbia) in the north to Lassen Peak (California) in the south (Hildreth, 2007). Most of these essentially undissected constructional landforms along the crest of the Cascade Range consist of rocks erupted after 4 Ma. High Cascades rocks in Oregon are underlain by a broad, deeply dissected volcanic terrace, preserved in the Western Cascades, that represents older arc magmatism that spanned nearly 40 m.y. These Western Cascades arc rocks in Oregon plus Tertiary volcanic rocks that underlie modern arc rocks northward into central Washington and southward into northernmost California constitute the northern (southern Washington–Oregon–northern California) segment of the ancestral Cascades arc. The southern segment (Busby et al., 2008; Cousins et al., 2008; du Bray et al., 2009) extends southeast, through northeast California, along the California-Nevada border, and to its terminus in western Nevada at ~lat 37°N. Volcanic rocks of the northern segment of the ancestral Cascades arc (hereafter the ancestral arc) represent renewed steep subduction beneath the Pacific Northwest following a period (Late Cretaceous to Eocene) of relatively low angle subduction that deflected magmatism eastward, resulting in development of widely distributed magmatism, including that associated with the Eocene Challis volcanic field and the Eocene Clarno and Oligocene John Day Formations, well inboard of the western continental margin (Lipman et al., 1971; Dickinson and Snyder, 1978; Duncan and Kulm, 1989; Christiansen and Yeats, 1992).

Thayer (1937) and Peck et al. (1964) attempted regional correlation of the ancestral arc volcanic rocks in the Western Cascades and developed stratigraphic nomenclature (Coleston, Little Butte, and Sardine Formations) to synthesize their observations. However, continental magmatic arc environments produce coalescing and overlapping volcanic centers; their intimately
West Cascades arc magmatism

intermingled deposits have neither significant lateral continuity nor consistency. The conceptual framework of a continental arc presented by Smith (1993, Fig. 3 therein) illustrates the lack of stratigraphic coherency characteristic of these deposits. In contrast, syntheses of geochemical data along and across continental magmatic arc segments (Hildreth and Moorbath, 1988; Feeley, 1993) demonstrate systematic interrelationships between arc magmatism, tectonics, and metallogeny. Although many local studies have been conducted, volcanic rocks of the ancestral arc have not been as thoroughly studied as the modern arc, nor has any synthesis of existing data been undertaken since the interpretive compilations of Mc Birney (1978), White and Mc Birney (1978), Priest (1990), and Hammond (1998). With those investigations as a foundation, the geochemical compilation in du Bray et al. (2006), which includes analyses of more than 4000 samples, provides a comprehensive framework for evaluation of ancestral arc magmatism. Using these data, we establish the time-space-composition evolution of ancestral arc magmatism during its ~40 m.y. history. The scope of the data compilation allows development of geochemical characteristics for comparison to those of the modern Cascades arc as well as arcs elsewhere in the world. These data also provide the context for investigating why the number, size, and grade of magmatic-hydrothermal mineral deposits associated with the ancestral arc are insignificant relative to numerous, diverse, large, high-grade deposits associated with the archetypal Andean magmatic arc analog (e.g., Sillitoe and Perelló, 2005).

METHODS

Our interpretation of ancestral arc geochemical evolution is based on the data compilation in du Bray et al. (2006), which contains geochemical, geochronologic, and lithologic data, estimates of data quality, and miscellaneous background data for more than 4100 samples representative of the ca. 45–4 Ma time period. A

Figure 1. Shaded relief, digital elevation map of the Pacific Northwest (USA) showing approximate distribution of ancestral and modern Cascades arc rocks (compiled from Wagner and Saucedo, 1987; Smith, 1993; and Sherrod and Smith, 2000). Locations of principal Holocene to Pleistocene stratovolcanoes (names in italics) of the modern arc are shown for reference. Approximate outline of the Siletzia terrane is from Wells et al. (1998).
few new analyses, especially for trace elements, were added to the working version of the database used for this interpretation (Supplemental Table 1). Major oxide data were recalculated to 100%, volatile free, and the database contents were processed to replace all censored data (e.g., greater or less than analytical limits, or not detected) with blank cells. Remaining data were progressively filtered relative to parameters designed to identify altered and/or mineralized samples and inaccurate analyses. Samples with any of the following characteristics were removed from the interpreted data set: total volatile content >4%, SiO$_2$ >78%, Al$_2$O$_3$ >22%, FeO* >15%, MnO >0.6%, CaO >15%, Na$_2$O <1% or >6.5%, K$_2$O <0.15% or >6.0%, Na$_2$O/K$_2$O >11 or <0.5, P$_2$O$_5$ >1%, Ag >2 ppm, Cu >200 ppm, Mo >5 ppm, Pb >25 ppm, Zn >120 ppm, and Au >0.01 ppm. In addition, analyses with total volatile content >0 and initial analytical total >102 or <98 were removed, as were samples with total volatile content unknown and initial analytical total >101.5 or <97.5. These thresholds were established by considering typical igneous rock compositions and by reference to the tails of frequency distributions presented in du Bray et al. (2006). Final filtering involved visual inspection of major oxide variation diagrams for the remaining data. Rare samples with unusual abundances (well beyond data arrays formed by the majority of samples and probably indicative of otherwise undetected alteration) were identified and removed from the interpreted database. After filtering, more than 3400 samples remained.

Using radiometric and geologic age data presented in du Bray et al. (2006), a best age estimate was made for more than 3200 samples. Best ages for samples with specified age ranges were defined as the midpoint of the range. Accordingly, ages were assigned to more than 3200 samples. The database was then sorted by age and each sample assigned to one of the time intervals defined by Smith (1993) and Sherrod and Smith (2000). To facilitate comparison of ancestral and modern Cascade arc geochemistry, a representative set of more than 1000 analyses (Supplemental Table 2) was extracted from the GEOROC (2010) database. Selected analyses represent the major High Cascades volcanic edifices between Mount Baker in the north and Mount Shasta in the south. All analyses for samples of these volcanoes with major oxide analyses, analytical totals between 98 and 102, and total volatile contents <3% are included in the representative set. Analyses of high alumina olivine tholeiites and samples from rear-arc volcanic fields identified by Hildreth (2007) were excluded from the representative set.

**GEOLOGIC BACKGROUND**

**Geologic Constituents of the Ancestral Cascades Arc**

Constituents of the ancestral Cascades arc have not heretofore been clearly established. In particular, rocks that are unequivocally part of the arc, as opposed to those that clearly predate or postdate the arc, in either forearc or backarc settings, have not been identified. We used the following observations and parameters to delineate rocks of the ancestral arc (see also du Bray et al., 2006).

**Eastern and Western Boundaries**

In Oregon and northernmost California, the ancestral arc is composed only of Tertiary volcanic rocks exposed west of the present Cascade Range crest. Volcanic rocks east of the Cascade crest, including the Clarno and John Day Formations (Christiansen and Yeats, 1992, Figs. 17 and 20 therein), are considered to represent magmatism related to the Challis volcanic field, backarc magmatism, or Basin and Range province magmatism. In southern Washington, some constituents of the ancestral arc extend beneath stratovolcanoes of the modern arc and east of the Cascade crest. In Oregon and Washington, volcanic rocks west of the Puget-Willamette Lowland probably do not reflect subduction-related magmatism and are not ancestral arc constituents. More likely, these Oregon Coast Range rocks are products of forearc or mid-ocean ridge magmatism, or volcanism associated with oblique rifting along the continental margin (Duncan and Kulm, 1989; Christiansen and Yeats, 1992; Evarts and Swanson, 1994; Oxford, 2006).

**Northern Boundary**

The north end of the ancestral arc is particularly poorly defined. Vance et al. (1987), Duncan and Kulm (1989), and Christiansen and Yeats (1992) variously depicted the ancestral arc as terminating north of Mount Rainier. Exposure levels appear significantly deeper north of Mount Rainier, where middle Tertiary volcanic rocks are rare and plutonic rocks are abundant. Whether large plutonic masses, such as the Oligocene–Miocene Snoqualmie batholith north of Mount Rainier, are part of the ancestral arc is not well established. In accord with the dearth of demonstrably arc-like volcanic rocks north of Mount Rainier, we did not include plutonic rocks north of Mount Rainier in this study. These plutonic rocks, as suggested by Evarts and Swanson (1994), appear to be the products of magmatic activity for which a plate tectonic context is poorly developed and likely are not associated with ancestral arc magmatism.

**Southern Boundary**

Ancestral arc rocks of its northern segment extend across the Oregon-California border to just north of Mount Shasta, where they become volumetrically insignificant and the segment ends. The distribution of other potentially arc-related rocks is deflected east to near the California-Nevada border, where the southern segment of the ancestral arc begins (du Bray et al., 2009; Colgan et al., 2011).

**Age Constraints**

Volcanism associated with the ancestral arc may have begun as early as 45 Ma and may be as young as 4 Ma. At 45 Ma, particularly in central Washington, differentiating volcanic rocks that are demonstrably associated with the onset of arc magmatism from those that represent magmatism associated with other tectonic regimes is difficult, but 45 Ma is in accord with most estimates for the onset of ancestral arc magmatism. Similarly, in many parts of the Cascade Range, no clear discontinuity between magmatism associated with the ancestral and High Cascades arcs has been identified. Consequently, establishing a definitive age for the transition from ancestral to modern arc magmatism is somewhat subjective, especially given quasi-continuous late Cenozoic magmatism in this region. Callaghan (1933) suggested that a pronounced unconformity separates High Cascades from ancestral arc rocks, but such an unconformity is not a ubiquitous or synchronous feature along the length of the arc.

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1Supplemental Table 1. PDF file of geochemical data for northern segment ancestral arc samples. If you are viewing the PDF of this paper or reading it offline, please visit http://dx.doi.org/10.1130/GES00669.51 or the full-text article on www.gsapubs.org to view Supplemental Table 1.

2Supplemental Table 2. PDF file of Representative High Cascades data extracted from GEOROC, 2010. If you are viewing the PDF of this paper or reading it offline, please visit http://dx.doi.org/10.1130/GES00669.52 or the full-text article on www.gsapubs.org to view Supplemental Table 2.
The onset of High Cascades volcanism has been variably given as between 10 and 2 Ma. Duncan and Kulm (1989) suggested that the boundary between ancestral and High Cascades volcanism is not well defined in many places. Although Smith (1993) and Sherrod and Smith (2000) suggested that some ancestral arc magmatism is as young as 2 Ma and constructed their rock age groupings accordingly, local geologic relations and other criteria suggest that only Pacific Northwest volcanic rocks older than ca. 4 Ma can be ascribed with certainty to ancestral arc magmatism. Accordingly, we adopted 4 Ma as an approximate minimum age for ancestral arc magmatism.

**Ancestral Arc Versus Modern Arc**

Undated, undissected volcanic rocks that retain primary constructional morphology are considered to be part of the High Cascades magmatic arc (Hildreth, 2007).

**Columbia River Basalt**

Middle to Late Miocene mafic volcanic rocks of the voluminous Columbia River Basalt are widely considered to reflect mantle plume processes (Camp and Hanan, 2008) and consequently are unrelated to ancestral arc magmatism.

**Temporal Evolution of the Ancestral Cascades Arc**

Numerous studies, including those of Lux (1982) and Duncan and Kulm (1989), addressed the onset and periodicity of ancestral arc magmatism and suggested its initiation ca. 42 Ma, when current tectonic plate relations and motions developed (Table 1). Christiansen and Yeats (1992) suggested that arc magmatism began between 43 and 37 Ma, and Evarts and Swanson (1994) confirmed its onset ca. 42 Ma, as represented by rocks of the Northcraft and Tukwillia Formations in central Washington. McBriney et al. (1974) first suggested that eruptive volumes within the ancestral arc varied considerably with time. Verplanck and Duncan (1987) and Duncan and Kulm (1989) confirmed the essential continuity of arc magmatism through time, but identified episodic periods with greater rates of ancestral arc magmatism; their work related magma volume variations to rates of plate convergence and obliquity. An overall decrease of magma erupted between the onset of subduction and initiation of High Cascades volcanism is widely recognized (McBriney et al., 1974; Verplanck and Duncan, 1987; Duncan and Kulm, 1989). Verplanck and Duncan (1987) associated the systematic decrease in arc productivity with a fivefold decrease in convergence rate, as corroborated by Priest (1990). In recognition of the punctuated character of ancestral arc magmatism, geologic compilations for this region correlate particular time intervals with defined map units and geologic discontinuities related to magmatic output variations. In particular, Smith (1993) and Sherrod and Smith (2000, p. 5) defined compilation units that “...are based on a mixture of traditional chronostratigraphic units and the more or less instantaneous geologic events...” and serve as the temporal foundation of our analysis. Time intervals identified by Smith (1993) and Sherrod and Smith (2000) are (1) 45–36 Ma: 45 Ma approximates the onset of arc-related volcanism in the Cascades; (2) 35–26 Ma: 35 Ma corresponds to the time of well-established ancestral arc volcanism; (3) 25–18 Ma: several significant ancestral arc pyroclastic flow sequences were erupted between 25 and 23 Ma, which approximates the Oligocene-Miocene boundary; (4) 17–7 Ma: between 17 and 15 Ma extensive mafic magma was erupted in northern and central Oregon, but otherwise magmatism during this interval was relatively limited; (5) 7–2 Ma: 7 Ma is the age of widespread mafic volcanism following an interval of limited magmatism; this period was in turn followed by the inception of modern High Cascades magmatism between 4 and 2 Ma.

Different minimum ages of ancestral arc magmatism, 2 Ma for the geologic compilation (Smith, 1993; Sherrod and Smith, 2000) and 4 Ma for the geochemical compilation (du Bray et al., 2006), are unlikely to adversely affect our synthesis.

Available geochronologic data for the ancestral arc compiled in du Bray et al. (2006) also suggest that magmatic output rates varied through time (Table 1). The character of the ancestral Cascades rocks (interfering deposits erupted from contiguous volcanic centers of diverse age), erosion and preservation issues, and dense rain forest and Quaternary deposits that mantle these rocks preclude direct estimates of erupted volume versus time. Consequently, given a relatively large number of age determinations, we assumed that the results of geochronologic investigations were representative of volume-time relations and constructed an age-frequency histogram (Fig. 2) as a proxy for relative volume-time relations. Ancestral arc volcanic rock ages suggest relatively minor magmatism at the onset of volcanism. Subsequently, magma output volume increased, attaining a maximum ca. 25 Ma (as indicated by considering both volcanic and plutonic age determinations) before decreasing systematically through the duration of ancestral arc magmatism. One would expect the age distribution for the ancestral arc plutons, constructed using representative ages for each pluton, to be symmetric to that of co-genetic volcanic rocks. However, the two distributions are distinctly asymmetric, probably due to some combination of (1) volcanic rocks in some time intervals having been disproportionately sampled and analyzed, (2) incomplete sampling in areas where both extrusive and intrusive rocks are exposed, and (3) erosion insufficient to expose intrusive rocks. Progressively smaller numbers of plutons with decreas-

### TABLE 1. GENERALIZED CHARACTERISTICS OF THE ANCESTRAL CASCADES ARC, WASHINGTON, OREGON, AND NORTHERNMOST CALIFORNIA

<table>
<thead>
<tr>
<th>Time period (Ma)</th>
<th>Distribution</th>
<th>Relative volume</th>
<th>Dominant compositions</th>
<th>Dominant magma series</th>
<th>Tectonic setting</th>
<th>Pluton abundance</th>
<th>Mineral deposits</th>
</tr>
</thead>
<tbody>
<tr>
<td>45–36</td>
<td>Mostly southwest Washington</td>
<td>Small</td>
<td>Basalt, basaltic andesite, andesite</td>
<td>Tholeiitic to calc-alkaline</td>
<td>Subduction, compression</td>
<td>Rare</td>
<td>Rare Cu breccia pipe deposits</td>
</tr>
<tr>
<td>35–26</td>
<td>Entire arc, except Mount Hood area</td>
<td>Moderate</td>
<td>Basalt, basaltic andesite, andesite</td>
<td>Tholeiitic to calc-alkaline</td>
<td>Subduction, compression</td>
<td>Sparse</td>
<td>Rare Cu breccia pipe deposits</td>
</tr>
<tr>
<td>25–18</td>
<td>Entire arc, except Mount Hood area and northern California; slight eastward axis shift</td>
<td>Large</td>
<td>Basaltic andesite, andesite, dacite, rhyolite</td>
<td>Tholeiitic to calc-alkaline</td>
<td>Subduction, compression</td>
<td>Common</td>
<td>Common porphyry Cu and related deposits; rare epithermal Au-Ag deposits</td>
</tr>
<tr>
<td>17–8</td>
<td>Oregon arc segment</td>
<td>Small</td>
<td>Basaltic andesite, andesite</td>
<td>Calc-alkaline</td>
<td>Subduction, compression</td>
<td>Rare</td>
<td>Rare porphyry Cu and related deposits</td>
</tr>
<tr>
<td>7–4</td>
<td>Oregon–northern California arc segment; additional eastward axis shift</td>
<td>Moderate</td>
<td>Basaltic andesite</td>
<td>Calc-alkaline</td>
<td>Subduction, compression</td>
<td>None</td>
<td>Rare porphyry Cu-Mo deposits</td>
</tr>
</tbody>
</table>
ing age is partly a result of the diminished time available for younger plutons to be uplifted and exposed by erosion.

Magma output rate variations versus time were also evaluated using the surface area of volcanic rocks as a proxy for volumes erupted during each of the five ancestral arc time intervals (Fig. 2). The results of this approach are influenced by erosion and preservation issues, but no more so than erupted volumes computed directly from mapped geologic distributions. Using the maps of Smith (1993), Sherrod and Smith (2000), and Smith (2002, written commun.), we calculated the area (Table 2) covered by basalt (and basaltic andesite), andesite, dacite, and rhyolite erupted during each of the five time intervals. Areas of plutonic rock could not be effectively incorporated into this analysis because these maps include all intrusive rocks in a single Tertiary age map unit. The calculated area analysis yields magma output rate versus time relations similar to those deduced from the frequency distribution of geochronology results. In particular, both approaches indicate minimal volumes erupted at the onset of arc magmatism, and a significant increase in erupted volume by 25–18 Ma. The calculated area of magma erupted during the 17–8 Ma time interval is dramatically lower, whereas the frequency distribution of geochronology results suggests that volcanism peaks between 17 and 8 Ma before declining during waning ancestral arc magmatism. The calculated area of ancestral arc magmatism appears to conclude with a dramatic increase during the 7–2 Ma time interval. Given that calculated area is a more direct evaluation of erupted volume than the frequency distribution of geochronology results, varying ancestral arc magma output rates are probably best indicated by the calculated area data. High apparent erupted volumes during the 17–8 Ma time interval suggested by the frequency distribution of geochronology results may reflect sampling bias. The apparent dramatic increase in output volume during the 7–2 Ma time interval is at least partially a consequence of these being the youngest and therefore least eroded and best preserved of the ancestral arc rocks. Our volume-age observations, especially those derived from the calculated areas of erupted ancestral arc rocks, concur with and those of Mc Birney et al. (1974), Verplanck and Duncan (1987), and Duncan and Kulm (1989).

### Spatial Distribution of Ancestral Cascades Arc Magmatism Through Time

Previous investigations have suggested that only certain arc segments were productive at the initiation of ancestral arc magmatism. The compilations of Smith (1993) and Sherrod and Smith (2000) were used to construct a series of time interval geologic maps of the ancestral arc (Fig. 3). Compositions and areal distribution of subduction-related igneous rocks throughout the ancestral arc, as portrayed on these maps, reveal the following generalizations concerning the temporal evolution of ancestral arc magmatism.

The earliest (45–36 Ma) ancestral arc magmatism was strongly focused in the area west of Mount St. Helens and Mount Rainier, and to a lesser extent in the area northeast of Mount Rainier (Fig. 3A). No plutonic rocks of this age are known and most eruptive products are basalt, basaltic andesite, and andesite (Table 2). A minor volume of basalt and andesite also was erupted in the central Oregon arc segment.

Between 35 and 26 Ma, magmatism continued in the area between Mount St. Helens and Mount Rainier and extended southward into northern California; essentially the full length of the arc was active to some extent. An apparent magmatic gap extends south from the Columbia River, past Mount Hood to ~ lat 44.5°N. Basalt, basaltic andesite, and andesite continued to be volumetrically dominant, though small volumes of dacite and rhyolite were also erupted. Several small intrusions were emplaced in southern Washington and northern Oregon.

Between 25 and 18 Ma, arc magmatism continued unabated in southern Washington, shifted slightly eastward throughout central Oregon, and the southern extent migrated slightly north into southern Oregon. The apparent magmatic gap south of the Columbia River persisted. Intrusive rocks were a major component of arc magmatism for the first time, although varying exposure levels may skew this observation. Basalt and basaltic andesite became rare, as compositions, dominated by andesite (Table 2), evolved to include significant dacite and minor rhyolite.

### Table 2. Area Covered by Ancestral Arc Volcanic Rock of the Indicated Composition as a Function of Age

<table>
<thead>
<tr>
<th>Age group (Ma)</th>
<th>Basalt and basaltic andesite (km²)</th>
<th>Andesite (km²)</th>
<th>Dacite (km²)</th>
<th>Rhyolite (km²)</th>
<th>Total area (km²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>45–36</td>
<td>1903</td>
<td>1174</td>
<td>0</td>
<td>89</td>
<td>3116</td>
</tr>
<tr>
<td>35–26</td>
<td>3004</td>
<td>2038</td>
<td>385</td>
<td>235</td>
<td>5662</td>
</tr>
<tr>
<td>25–18</td>
<td>1072</td>
<td>4851</td>
<td>1398</td>
<td>177</td>
<td>7498</td>
</tr>
<tr>
<td>17–8</td>
<td>530</td>
<td>3257</td>
<td>73</td>
<td>0</td>
<td>3860</td>
</tr>
<tr>
<td>7–2</td>
<td>4890</td>
<td>1471</td>
<td>310</td>
<td>38</td>
<td>6749</td>
</tr>
<tr>
<td>Total</td>
<td>11439</td>
<td>12791</td>
<td>2166</td>
<td>539</td>
<td>28925</td>
</tr>
</tbody>
</table>

**Note:** Areas computed from the digital geologic map data of Smith (1993), Sherrod and Smith (2000), and J.G. Smith (2002, written commun.).
Between 17 and 8 Ma, the volume of arc magmatism decreased dramatically. In particular, eruptive activity essentially ceased in southern Washington and was supplanted by the emplacement of many, mostly small, shallow intrusions. The southern extent of arc magmatism shifted farther north, and the magmatic gap near the Columbia River characteristic of all previous time segments was filled by voluminous andesite, the dominant eruptive product of this period.

Between 7 and 2 Ma, arc magmatism continued to be absent in southern Washington, was narrowly confined to the east flank of the arc in Oregon (where the erupted volume decreased significantly), and expanded dramatically to the south into southern Oregon and northern California. A small magmatic gap developed just north of present-day Crater Lake, between lat 43°N and 43.5°N. Again, basalt, basaltic andesite, and andesite dominated the erupted rocks, though small volumes of dacite and rhyolite were also erupted.

These maps, as well as the spatial distribution of samples representative of each time interval (Fig. 3F), identify distinctive time-space characteristics pertinent to the entire arc. First, arc width varies systematically through time. In particular, 45–18 Ma volcanic rocks define a relatively wide, diffuse arc. In contrast, between 17 and 2 Ma, volcanic rocks define a much narrower, more tightly focused arc. Progressive arc narrowing with time may indicate a transition from a subduction regime (relatively low convergence rate) that favored within-arc exten-

Figure 3 (on this and following five pages). Geologic maps showing the distribution and composition of ancestral Cascades arc rocks. Dashed red is the approximate outline of the Siletzia terrane from Wells et al. (1998). Pale blue and tan areas show the distribution of High Cascades rocks and Columbia River Basalt, respectively; these distributions are portrayed to delineate the maximum extent to which ancestral Cascades rocks might be concealed by these younger volcanic rocks. Because the ages of most small intrusive masses are unknown, each time interval shows the distribution of all intrusive rocks; the 45–36 Ma time interval map does not show the distribution of intrusive rocks because exposed intrusions older than ca. 36 Ma are rare. (A) 45–36 Ma. (B) 35–26 Ma. (C) 25–18 Ma. (D) 17–8 Ma. (E) 7–2 Ma. (F) Distribution and age of samples included in geochemical compilation (du Bray et al., 2006).
sion to one (relatively high convergence rate) in which transarc compression became dominant (Verplanck and Duncan, 1987). In addition, throughout ancestral arc evolution, the locus of magmatism shifted progressively eastward, culminating with the onset of modern High Cascades volcanism along the present range crest. The distribution of various rock types portrayed on these maps, as well as on those of Smith (1993) and Sherrod and Smith (2000), suggests that through much of its evolution the ancestral Cascades arc was dominated by large, composite stratovolcanoes and shield volcanoes that erupted primarily mafic to intermediate magma.

GEOCHEMICAL RESULTS

Major Oxide Data

Major oxide characteristics of ancestral arc rocks are consistent with their genesis in a continental margin arc setting. Relative to standard metrics (in cited sources), most ancestral arc rocks are subalkaline (Irvine and Baragar, 1971), metaluminous (Shand, 1951), calcic to calc-alkaline, and magnesian (Frost et al., 2001). However, both calc-alkaline and tholeiitic rocks (Miyashiro, 1974) are well represented in the ancestral arc. Abundances of SiO₂ in ancestral arc rocks range continuously from ~47 to 77 wt%. Concentrations of TiO₂, FeO*, MnO, CaO, and P₂O₅ decrease linearly and systematically with increasing SiO₂. Abundances of Al₂O₃ increase in samples with 47 to ~55 wt% SiO₂ and then systematically decrease with increasing SiO₂. Abundances of MgO decrease in a systematic though curvilinear fashion with increasing SiO₂ to produce a concave-up data array. Abundances of Na₂O increase in samples with 47 to ~60 wt% SiO₂ and then become essentially invariant. Abundances of K₂O increase with increasing SiO₂ content, forming a subtly concave-up data array that is transitional from low-K to medium-K compositions (Gill, 1981) at low SiO₂ abundances and from medium-K to high-K compositions in samples with more than 65 wt% SiO₂. Ancestral arc intrusive rock major oxide compositions resemble those of their 25–18 Ma extrusive equivalents with the important exception that most of the plutonic rocks have greater SiO₂ abundances (>~60 wt% SiO₂). Elevated SiO₂ abundances among the plutonic rocks could reflect fractionation (which likely affects the geochemistry of magmas represented by the plutonic rocks to a greater extent than that of ancestral arc eruptive rocks) during emplacement and residence in shallow reservoirs. It is important to note that, as described below, ancestral arc rock compositions exhibit considerable temporal variation.
Essentially all ancestral arc rocks are subalkaline and span continuously the basalt to rhyolite composition range (Fig. 4); very rare samples with alkaline compositions probably represent residual altered samples or rock units with atypical compositions and limited distribution. Total alkali-silica relations clearly depict compositional variation of ancestral arc rocks with time (Le Bas et al., 1986). Samples from the 45–36 and 35–26 Ma age groups are primarily basaltic andesite, but many are basalt or andesite; both age groups, especially the 35–26 Ma age group, include minor dacite or rhyolite. Samples of the 25–18 Ma age group have somewhat more evolved compositions distributed approximately uniformly between basaltic andesite and rhyolite, but also include minor basalt. In contrast, most samples of the 17–8 Ma age group are basaltic andesite or andesite, though some samples are dacite, rhyolite, or basalt. The trend toward more primitive compositions continues with the 7–4 Ma age group, in which samples are dominantly basaltic andesite or basalt but include some andesite or dacite. Relative to all other ancestral arc rocks, 7–4 Ma age group samples have slightly elevated total alkali contents at any particular SiO₂ content, especially among those composed of basalt to andesite. Ancestral arc plutonic rocks and their 25–18 Ma extrusive equivalents have indistinguishable alkali versus silica compositions.

Relative abundances of FeO* and MgO in the ancestral arc rocks (Fig. 5) indicate compositions approximately equally divided between those that are either tholeiitic or calc-alkaline relative to the metric of Miyashiro (1974); application of the criterion of Frost et al. (2001) suggests that as much as 20% of these arc rocks are ferroan (approximately equivalent to tholeiitic compositions), whereas the remainder are magnesian. Most samples of the 45–36, 35–26, and 25–18 Ma age groups are relatively primitive, iron enriched, and tholeitic, whereas the majority of samples from the 17–8 and 7–4 Ma age group are more evolved, magnesium enriched, and calc-alkaline. These relations are confirmed by relative abundances of K₂O + Na₂O, FeO*, and MgO (AFM; Fig. 1 in the Supplemental Figure File). The majority of pre–25 Ma ances-
Central arc rocks plot in the tholeiitic field of Irvine and Baragar (1971).

Frost et al. (2001) refined compositional relations based on relative abundances of K$_2$O, Na$_2$O, CaO, and SiO$_2$ and established revised nomenclature for the balance between the alka-
lies and calcium (Fig. 6). Ancestral arc rock compositions define a data array that is calcic (transitional to calc-alkalic) for samples with 45–65 wt% SiO$_2$ and calc-alkalic (transitional to calcic) for samples with 65–77 wt% SiO$_2$. These relations vary significantly in a temporal con-
text; most samples in the 45–36 and 35–26 Ma age groups are calcic, whereas those in the 25–18 Ma age group vary from calcic to calc-alkalic with increasing silica, and samples of the 17–8 and 7–4 Ma age groups have compositions that are transitional from calcic to calc-alkalic through the entire range of silica content. Many samples from the 25–18 and 17–8 Ma age groups have Na$_2$O + K$_2$O-CaO values that are distinctly higher than those of the 45–36 and 35–26 Ma age groups at any particular silica content between ~50 and 55 wt% SiO$_2$. With the exception of the very few ancestral arc plutonic rocks that have low SiO$_2$ abundances, the alkali versus calcium balance in these intrusive rocks is indistinguishable from that of their 25–18 Ma extrusive equivalents.

Relative abundances of the Na$_2$O, K$_2$O, CaO, and Al$_2$O$_3$ are often evaluated with reference to the alumina saturation index [ASI: molar Al$_2$O$_3$/(Na$_2$O + K$_2$O + CaO)] and agpaitic index [AI: molar Al$_2$O$_3$/(Na$_2$O + K$_2$O)]. Most ancestral arc rocks are metaluminous, though some are weakly peraluminous, and none are peralka-
line (Fig. 2 in the Supplemental Figure File; see footnote 3). ASI and AI values for ancestral arc rocks display limited time-dependent variation. Compositions of some 45–36 Ma age group samples are shifted to low ASI and high AI val-
ues relative to samples of the other age groups. ASI and AI values for samples of the other age groups are essentially indistinguishable, but extend to higher and lower ASI and AI values, respectively, than those for 45–36 Ma age group samples. Ancestral arc plutonic rocks are indis-
tinguishable from their 25–18 Ma extrusive equivalents. Given the common association of rare metal (especially Sn, W, and Mo) depos-
its, with moderately to strongly peraluminous rocks, the very small number of ancestral arc rocks with ASI > 1.1 indicates very low prob-
ability for associated deposits of this type.

Major oxide variation diagrams for ancestral arc rocks define two distinctive assemblages (Fig. 7). Samples of the older assemblage, composed of the 45–36, 35–26, and 25–18 Ma age groups, have major oxide abundance arrays that are diffuse relative to SiO$_2$ content. Within the
older assemblage, most samples contain between 47 and 60 wt% SiO$_2$ (basalt, basaltic andesite, and andesite), whereas samples of the 25–18 Ma age group form a continuous composition array spanning the 50–77 wt% SiO$_2$ range. Relative to the younger assemblage, which includes the 17–8 and 7–4 Ma age groups, older assemblage samples contain higher TiO$_2$, FeO*, MnO, and CaO abundances and lower Al$_2$O$_3$, MgO, Na$_2$O, and K$_2$O abundances at any given SiO$_2$ abundance. Within the younger assemblage, abundances of Al$_2$O$_3$, TiO$_2$, FeO*, MnO, MgO, and K$_2$O, at any particular SiO$_2$ content, are indistinguishable for the two age groups. However, at any particular SiO$_2$ content, abundances of CaO are subtly higher and abundances of Na$_2$O and P$_2$O$_5$ are slightly lower in 25–18 Ma age group samples relative to the other age groups. Abundances of all major oxides in plutonic rocks of the ancestral arc are indistinguishable, at any given SiO$_2$ content, from those of their 25–18 Ma extrusive equivalents. Ancestral arc rocks of the 7–4 Ma age group with 50–55 wt% SiO$_2$ have distinctly elevated potassium contents.

Major oxide compositions of volcanic rocks in the ancestral and modern arcs are remarkably similar (Fig. 7). In particular, compositions of the youngest ancestral arc rocks, those of the 17–8 and 7–4 Ma age groups, are indistinguishable from those of the modern arc. Just as major oxide compositions of the older and younger ancestral arc assemblages (described herein) are somewhat distinct, older assemblage rocks contain, on average, higher TiO$_2$, MnO, FeO*, and slightly higher CaO abundances and lower MgO and slightly lower Na$_2$O abundances, at any given SiO$_2$ abundance, relative to the modern arc rocks. Cousins et al. (2008) also noted that major oxide compositions of volcanic rocks in the southern ancestral and modern Cascade arc segments are similar, but suggested that southern ancestral arc rocks are slightly more alkaline than their modern arc counterparts. In contrast, northern ancestral and modern arc segment rocks have essentially indistinguishable alkalinity, although many older ancestral arc assemblage basalts and basaltic andesites are slightly less alkaline than the modern arc rocks (Fig. 4).

**Trace Element Data**

Ancestral arc rocks have high large ion lithophile element (LILE) abundances and low high field strength element (HFSE) abundances similar to those of other convergent margin, broadly calc-alkaline igneous rocks, such as those in the Andean, Kamchatka, and Central American arcs (GEOROC, 2010). Abundances of Ba and Rb in these rocks increase monotonically with
increasing silica content, befitting their incompatible behavior (Hanson, 1980). Zirconium abundances increase as silica contents increase from 47 to ~65 wt% and decrease in rocks with >65 wt% SiO₂. Strontium abundances increase slightly between 47 and ~55 wt% SiO₂ (most notably among 45–36 and 35–26 Ma age group samples) and progressively decrease with increasing silica. Lanthanum, Ce, Y, and Nb abundances display no consistent covariation with changing silica contents. At any given SiO₂ content, Ba and Sr abundances in the 17–8 and 7–4 Ma age groups are distinctly elevated relative to those of the 45–36 Ma age group; these relations, best developed relative to Sr abundances, are also evident for the 35–26 and 25–18 age groups. Samples of the 45–36 Ma age group with between 47 and ~60 wt% SiO₂ have slightly elevated Nb abundances relative to other ancestral arc rocks. Between 50 and 60 wt% SiO₂, most samples of the 17–8 and 7–4 Ma age groups contain subtly elevated Ce abundances relative to other ancestral arc rocks.

Rare earth element (REE) data for ancestral arc rocks are very limited and dominated by analyses of volumetrically minor intrusive rocks; data for the volcanic and plutonic rocks were synthesized and interpreted separately. Only 11 of ~100 volcanic rock REE analyses are for samples composed of either basalt or rhyolite; these samples were not included in the synthesis and interpretation of ancestral arc REE data. Of the group of samples whose REE systematics were studied, most samples are composed of basaltic andesite or andesite, but the group includes a few samples of dacite. REE data for each of the age groups are subtly distinct; this is best illustrated by age group REE plots as well as average REE patterns for each age group (Fig. 8). Available REE data for the ancestral arc rocks are typical of intermediate composition, calc-alkaline continental margin magmatic arc igneous rocks (e.g., Gill, 1981; Cameron and Cameron, 1985; Wark, 1991; Feeley and Davidson, 1994). REE patterns for each of the ancestral arc age groups have negative slopes and small negative europium anomalies (Fig. 8); light (L) REE pattern segments are slightly more steeply sloping than heavy (H) REE segments. Within age group REE patterns, as well as average age group REE patterns, are essentially parallel but total REE abundances decrease systematically from oldest to youngest among the age groups. In addition, each progressively younger age group has relatively lower HREE abundances; HREE pattern segments fan slightly downward. Progressively younger ancestral arc REE patterns are increasingly similar to those of the modern arc rocks. REE patterns for intrusive rocks of the 25–18 and
17–8 Ma age groups are distinctly clockwise rotated, LREE enriched and HREE depleted, relative to their same age extrusive equivalents. Transition metal abundances, including those of Co, Cr, Ni, Sc, and V, in ancestral arc rocks display remarkably coherent geochemical behavior and decrease systematically with increasing silica content. Basaltic andesite samples of the 17–8 and 7–4 Ma age groups contain consistently and distinctly elevated abundances of Co, Cr, and Ni and slightly low V abundances relative to other similar composition ancestral arc rocks. Transition metal abundances in the ancestral arc plutonic rocks are indistinguishable from those of their 25–18 Ma extrusive equivalents.

Ore metal abundances, including those of Cu, Mo, Pb, Zn, and Ag, in unmineralized ancestral arc rocks, with the exceptions noted as follows, are comparable to their global average abundances in basalt and granite. Copper abundances in a significant proportion of basalt and basaltic andesite samples of the 45–36 and 35–26 Ma age groups are as much as double the abundances typical of basalt, 20 times greater than those characteristic of granite, and are distinctly elevated relative to abundances in other ancestral arc rocks. These elevated Cu abundances suggest that Cu remained in the crystallizing magmas, and was not concentrated in magmatic-hydrothermal fluids, thereby hindering formation of porphyry copper deposits in rocks of these age groups. Slightly elevated Zn abundances characterize basalt and basaltic andesite of ancestral arc rocks older than 18 Ma.

Trace element abundances in volcanic rocks of the ancestral and modern arcs are essentially indistinguishable (Figs. 8–13). As is true for ancestral and modern arc rock major oxide compositions, trace element abundances of the older (45–26 Ma) ancestral arc assemblage are slightly distinct relative to modern arc compositions. Whereas trace element abundances of younger assemblage (25–4 Ma) ancestral arc rocks are entirely indistinguishable from those of the modern arc, older assemblage rocks have slightly elevated Rb abundances (relative to K2O and Sr contents) (Fig. 9), lower absolute Sr abundances (Fig. 10), lower Ba/Nb at any given SiO2 (Fig. 12), and lower K/Rb at any given Rb abundance (Fig. 13) than modern arc rocks. Cousens et al. (2008) demonstrated that southern segment ancestral arc rocks have elevated LILE and LREE abundances relative to southern segment modern Cascade arc rocks. In contrast, northern segment ancestral and modern arc rocks have essentially indistinguishable LILE and LREE abundances.

DISCUSSION

Petrogenetic Implications of Major Oxide Data

One of the most striking features of ancestral arc major oxide abundances is the absence of compositional gaps between ~47 and 77 wt% SiO2. Major oxide abundance arrays are almost universally diffuse at low SiO2 abundances and converge to more well-defined arrays at higher SiO2 contents (Fig. 7). The concave-down array depicted by Al2O3 data, especially among 45–26 Ma samples, likely reflects the onset of plagioclase crystallization and/or fractionation at ~55–57 wt% SiO2. Increases in K2O and Na2O abundances with increasing silica content probably reflect their concentration in residual liquids that became more evolved by fraction-
The inflection in the Na₂O data array at ~60 wt% SiO₂ probably results from sodium-bearing plagioclase becoming a significant fractionating phase. The essentially linear decrease in P₂O₅ abundances in samples with >~60 wt% SiO₂ probably reflects apatite fractionation. Because of their antithetic geochemical behavior, abundances of K₂O and MgO were selected to highlight the geochemical evolution of ancestral arc rocks through time (Fig. 14). The trends, best defined by the highest abundances at any particular time (and confirmed by mean values for each time interval), are diffuse but likely meaningful. K₂O abundances are lowest at the beginning of ancestral arc magmatism, increase to a peak between 20 and 25 Ma, and then decrease with decreasing age (Fig. 14A). Correspondingly, abundances of MgO are relatively elevated at the onset of ancestral arc magmatism, decrease systematically to minimum values ca. 20 Ma, and then increase with decreasing age (Fig. 14B). Early ancestral arc magmatism is geochemically primitive (includes a significant mantle component) and is probably little contaminated or fractionated. As the ancestral arc became better established, mantle components may have become less dominant, crustal contamination of magma ascending through increasingly thick and hybridized crust became more important, and reservoirs may have become sufficiently long lived to allow fractionation, resulting in more evolved compositions. The trend reversal ca. 20 Ma suggests significant changes in subduction and associated magma generation dynamics that caused magmas to revert to increasingly primitive compositions. Other major oxide and trace element abundances define similar temporal-composition relations.

Ancestral arc magmatism was spatially associated with two distinct crustal blocks. The western, forearc block is composed largely of early Tertiary accreted basaltic seamounts that constitute the Siletzia terrane (Fig. 3; Wells et al., 1998), whereas the eastern (non-Siletzia) block is composed of the western edge of the North American plate, which was evolving in an extensional regime due to oblique subduction (Wells et al., 1998). To evaluate whether magmas erupted through these two crustal blocks have distinct compositions, the database in du Bray et al. (2006) was sorted to produce subsets of samples geospatially coincident with each of the two blocks. Samples west of long 122°W and north of lat 43°N were assigned to the Siletzia terrane subset and all others were assigned to the North American (non-Siletzia) terrane subset. North American block samples have distinctly higher mean SiO₂ and K₂O contents, whereas Siletzia block samples have distinctly elevated mean TiO₂, FeO*, MgO, and CaO abundances. Consequently, North American block samples have compositions that are generally more evolved than those of the Siletzia block samples. Whether this is a simple function of across-arc geochemical variations related to the thickness of continental crust above the zone of magma genesis, as described by Feeley (1993) for the Andean arc, or truly represents the geochemical imprint of Siletzia crust on ancestral arc magmas is indeterminate. However, observed Siletzia versus North American geochemical distinctions are not uniform through time, which suggests that temporally nonsystematic imposition of Siletzia compositional characteristics on ancestral arc magmas is the most likely cause of the observed geospatially linked compositional distinctions.
Petrogenetic Implications of Trace Element Data

Hildreth and Moorbath (1988) suggested that MASH (melting, assimilation, storage, and homogenization) processes are responsible for most geochemical variation among magmatic arc rocks. Abundances of Ba, La, Ce, Rb, Sr, Y, Zr, and Nb in ancestral arc rocks suggest that MASH processes also systematically influenced compositional dynamics within the ancestral arc. The progressive decrease in Zr abundances in rocks with >65% SiO$_2$ probably reflects the onset of zircon crystallization and fractionation. Relative abundances of K, Rb, and Sr suggest minimal magma evolution among ancestral Cascade arc magmatic systems (Fig. 9). During magma evolution, K is enriched relative to Sr, and ultimately, Rb is enriched relative to K, both largely as a function of feldspar, principally plagioclase, fractionation (Hanson, 1980). Mantle source compositions, as well as potential contributions from partial melting of the subducted slab, also influence relative abun-
dances of K, Rb, and Sr. Ancestral arc rocks are Sr enriched (relative to K and Rb), which indicates minimal plagioclase-mediated magma evolution. Samples of the 45–36 Ma age group are the most consistently Sr enriched of any age group (Fig. 9). In contrast, samples of the 35–26 and 25–18 Ma age groups define a continuous, diverse array of relatively Sr-rich to Sr-poor compositions; these rocks depict a broad range of compositional evolution produced by varying amounts of plagioclase fractionation. Compositions of 17–8 Ma age group samples define a somewhat restricted, more Sr-enriched array. The trend to a restricted compositional array and increasing relative Sr enrichment continues among samples of the 7–4 Ma age group (Fig. 9). Relative to major oxide compositions, trace element abundances of ancestral arc rocks indicate an initial period dominated by primitive compositions, followed by more evolved compositions, and a subsequent return to more primitive compositions prior to the onset of High Cascades magmatism. Although a few ancestral arc plutonic rocks contain highly elevated relative Sr abundances, the relative abundances of Sr, K, and Rb in these rocks are mostly indistinguishable from those of their 25–18 Ma extrusive equivalents.

Many of the ancestral arc rocks have Sr-enriched compositions considerably greater than those typical of the Andean arc (Hildreth and Moorbath, 1988; du Bray et al., 1995). In mafic rocks of the 45–36 Ma age group, Sr abundances (Fig. 10) increase with increasing silica content (suggestive of incompatible behavior), whereas mafic rocks of the 35–26 and 25–18 Ma age groups have relatively constant Sr abundances. In contrast, Sr abundances decrease in ancestral arc rocks with >60% SiO₂; this suggests plagioclase crystallization and fractionation. Cousens et al. (2008) suggested that LILE enrichment (including Sr) of southern

Figure 7 (on this and following three pages). Variation diagrams showing abundances of major oxides (wt%) in ancestral Cascades arc rocks. Field boundaries on K₂O versus SiO₂ diagram are from Le Maitre (1989); high K-shoshonitic dividing line is from Ewart (1982). Dashed line delineates the composition field of modern arc (MA) rocks of the High Cascades (data from GEOROC, 2010).
segment ancestral arc rocks reflects a significant lithospheric mantle contribution to the petrogenesis of these rocks. Alternatively, Putirka and Busby (2007) suggested that LILE enrichments in mafic southern segment ancestral arc rocks resulted from small-degree melting of enriched mantle. Each of these processes may also have influenced LILE characteristics of northern segment ancestral arc rock LILE abundances.

Absolute Sr abundances (Fig. 10) also vary systematically through time among mafic, weakly fractionated ancestral arc rocks (those that contain 50%–60% SiO2). Plagioclase, the principal residence of Sr (Hanson, 1980), is a stable phase in mantle compositions at pressures <10–20 kbar (Green, 1982) and therefore does not contribute Sr to shallow (35–70 km), subduction-related partial melts beneath thin continental margin crust. In contrast, at higher pressures beneath thicker crust, plagioclase is unstable and Sr is preferentially partitioned into silicate liquid during partial melting. Mafic rocks of the 45–36 and 35–26 Ma age groups contain distinctly low Sr abundances at any given SiO2 content relative to rocks of the 25–18, 17–8, and 7–4 Ma age groups. Accordingly, plagioclase must have been stable and not involved in magma genesis during early ancestral arc magmatism. In contrast, Sr was strongly partitioned to silicate liquids produced by higher pressure partial melting during subsequent arc magmatism. Hildreth and Moorbath (1988) noted that Sr-enriched arc magmas are produced beneath thick continental crust at elevated pressures. Analogously, ancestral arc magmas with the highest Sr abundances indicate melting at relatively elevated pressures beneath thickened continental margin crust and are also consistent with enhanced magma contamination by crustal components through time.

Relative abundances of Rb and Y + Nb in ancestral arc samples are mostly coincident with the volcanic arc field defined on the tectonic setting discriminant diagram (Fig. 11) of Pearce et al. (1984). Relative abundances of Y + Nb among samples of the various age groups and their associated plutonic rocks are essentially indistinguishable. However, relative
abundances of Rb for samples of the various age groups are distinct, and may reflect variable lithospheric mantle contributions (Cousens et al., 2008), different degrees of partial melting (Putirka and Busby, 2007), and the relative abundances of mafic versus intermediate composition rocks. Rubidium abundances for samples of the 45–36 and 35–26 Ma age groups are distinctly low, relative to those for the 25–18 Ma age group, and confirm their geochemically primitive character. Rubidium abundances in some 35–26 Ma age group samples are moderately elevated. Most 25–18 Ma age group samples (rocks that correspond to the principal period of porphyry copper deposit formation in the ancestral arc) define a compositionally distinct, Rb-enriched cluster relative to other ancestral arc rocks; a subpopulation of plutonic rocks of this age forms a distinctly Rb-enriched cluster. Samples of the 17–8 and 7–4 Ma age groups revert to less Rb-enriched compositions that are essentially indistinguishable from those of the 45–36 and 35–26 Ma age groups. On average, Y + Nb abundances for the two youngest age groups are slightly lower than for other ancestral arc rocks. Uncommon samples having within-plate compositions probably reflect somewhat more hybridized magmas, likely those resulting from increased contamination by assimilation of continental crust beneath the ancestral arc. The percentage of samples within each of the age groups with elevated Y and Nb abundances appears to be essentially age independent. Rubidium abundances of ancestral arc plutonic rocks are higher than their 25–18 Ma extrusive equivalents and are higher than those for all other ancestral arc rocks.

Relative abundances of Ba and Nb in ancestral arc rocks are transitional between those characteristic of mid-oceanic ridge basalt (MORB) and arc magmas (Fig. 12). Gill (1981) suggested that magmatic-arc orogenic andesite has Ba/Nb ≥ 15. Hawkesworth et al. (1995), Pearce and Peate (1995), Cousens et al. (2008), and Schmidt et al. (2008) associated elevated Ba/Nb with the addition of subducted slab components to magmas generated during slab dehydration and fluid-flux–induced partial melting.
of the mantle wedge. Most of the ancestral arc 45–36 Ma age group samples have Ba/Nb <15, akin to MORB compositions. Samples of the 35–26 Ma age group define a temporal progression to less MORB-like, more arc-like Ba/Nb ratios. Most 35–26 Ma age group samples have Ba/Nb >15, as do almost all samples of the younger 3 age groups. Elevated Ba/Nb for samples of the three youngest age groups are essentially indistinguishable. Immediately prior to the onset of High Cascades magmatism, Ba/Nb appears to decrease slightly again. Ancestral arc intrusive rocks have much greater Ba/Nb than their 25–18 Ma extrusive equivalents; this may, in part, reflect increasing Ba incompatibility with progressive magma evolution.

Negative, primitive mantle-normalized Nb-Ta anomalies (Figs. 3 and 4 in the Supplemental Figure File; see footnote 3), considered diagnostic of subduction-related, arc magmatic rocks (Wood et al., 1979; Gill, 1981; Pearce et al., 1984), are variably developed in most samples of ancestral arc rocks. In particular, samples of all but the 45–36 Ma age group rocks have strong negative anomalies. The absence of significant negative Nb-Ta anomalies in the oldest ancestral arc rocks is consistent with their MORB-like chemical affinity or, as suggested by Leeman et al. (2005), a little-contaminated asthenospheric mantle source.

Ancestral arc extrusive rock age group REE patterns (Fig. 8) are nearly parallel, gently negatively sloping (La/Yb = 4.7–7.6), and have small to nonexistent negative Eu anomalies (Eu/Eu* = 0.84–1.02). Higher overall REE abundances in the older ancestral arc rocks are consistent with REE incompatible behavior and progressive source region REE depletion by successive partial melting events. Heavy REE abundances of the 7–4 Ma age group are noticeably depleted, consistent with source region garnet retention, likely a consequence of deeper melting in a regime dominated by more mature, thicker crust. Similarly, Putirka and Busby (2007) and Cousens et al. (2008) discussed the impact of garnet-bearing residues, especially beneath thickened, mature crust, on REE budgets in southern segment ancestral arc rocks.
Figure 8. Chondrite-normalized rare earth element (REE) diagrams for samples of the ancestral Cascades arc, by age group and averaged by age group. Chondrite abundances are from Anders and Ebihara (1982). Shaded gray field depicts the REE abundances in ~400 modern Cascades arc samples (data from GEOROC, 2010).
Average pluton REE patterns for the 25–18 Ma (the principal period of porphyry copper deposit formation in the ancestral arc) and 17–8 Ma age groups are more steeply negatively sloping (systematically lower HREE abundances), possibly related to amphibole fractionation (Davidson et al., 2007), than patterns for coeval extrusive rocks. Like extrusive rocks of the ancestral arc, the older intrusive rocks have systematically elevated REE contents relative to the younger intrusive rocks. The 25–18 Ma age group REE pattern has the most well-developed negative Eu anomaly (Eu/Eu* = 0.74) of any ancestral arc subset, suggesting that these rocks underwent moderate plagioclase fractionation.

Trace element abundances of ancestral arc samples also correlate with the crustal block with which they are associated. Samples from the western part of the arc, spatially coincident with the Siletzia terrane, have higher Sr and transition metal (Ni, Sc, Co, and Cr) abundances than those associated with the eastern, non-Siletzia block. In contrast, abundances of Y, Th, and the LILEs, including Rb, Ba, and Cs, are distinctly elevated in samples from the eastern block. These systematic trace element variations are in accord with respective compositions of their likely crustal contaminants. However, whether these variations are truly manifestations of arc magma–host crust interaction or simply reflect systematic across arc (Feeley, 1993) compositional variations is unknown.

Cousens et al. (2008) suggested that LILE and LREE enrichment characteristic of southern segment ancestral relative to modern arc rocks indicates a dominant lithospheric mantle component in the petrogenesis of these rocks. Eruption of southern segment ancestral arc magmas involved lithospheric mantle and subducted slab components that had been dramatically affected by prior generation of the Triassic–Cretaceous Sierra Nevada batholith. The absence of well-developed LILE and LREE enrichment in northern segment ancestral arc rocks suggests lesser lithospheric mantle contributions in their genesis. In addition, southern segment ancestral arc magmas transited thick continental crust and were likely variably contaminated by assimilation of Sierra Nevada batholith components, just as some Andean magmas were contaminated by assimilation of similar crustal components (Feeley and Davidson, 1994). In contrast, crust overlying the northern segment ancestral arc was relatively thin and compositionally primitive. Consequently, the distinctive tectonic setting and petrogenetic processes responsible for southern segment ancestral arc rock LILE and LREE enrichment likely were much less important to petrogenesis of their northern segment counterparts.

Figure 9. Ternary variation diagram showing the relative proportions of Rb, K, and Sr in samples of ancestral Cascades arc rocks. Dashed line delineates the composition field of modern arc (MA) rocks of the High Cascades (data from GEOROC, 2010).
Immediately prior to the onset of ancestral arc magmatism, the Pacific Northwest was the locus of Challis magmatic belt igneous activity (Christiansen and Yeats, 1992). During Challis belt magmatism, subduction-related magmatism in this part of western North America was localized well inboard of the Middle Eocene–present-day arc (Madsen et al., 2006). Between 50 and 45 Ma, the oceanic Siletzia terrane, largely composed of basaltic seamounts, was accreted along the Washington-Oregon coastline almost simultaneously with a significant change in Pacific plate trajectory (Duncan, 1982; Wells et al., 1998). Accretion of Siletzia was also accompanied by a significant westward jump of the subduction zone in this area (Duncan and Kulm, 1989; Madsen et al., 2006). These events marked the end of Challis magmatic belt activity and the beginning of ancestral arc magmatism ca. 42 Ma.

Between ca. 45 and 40 Ma the Farallon-Resurrection and Kula-Farallon spreading ridges sequentially intersected the North American trench, and slab windows associated with these intersections slowly propagated northward into southern Washington. Madsen et al. (2006) suggested that geochemically distinct, mafic tholeiitic rocks preserved in the forearc Oregon-Washington Coast Range basalt province are the result of slab window magmatism. Although Madsen et al. (2006) suggested that subduction of these ridge segments did not affect ancestral arc magmatism, the unusually voluminous outpouring of compositionally distinct tholeiitic basalt in southern Washington between ca. 45 and 26 Ma seems a logical consequence of slab window processes and is in accord with the character of slab window magmatism described by Thorkelson (1996). Cole and Stewart (2009) suggested that magmas associated with slab window volcanism have TiO₂ >1.5%, Ba/Ta <270, and Th/Yb of 0.2–1.5. Almost half of the ancestral arc 45–36 and 35–26 Ma age group samples have TiO₂ >1.5%. Although Th and Ta data for these rocks are scarce (du Bray et al., 2006), most available Ba/Ta and Th/Yb data are consistent with a slab window association (assuming that Nb/Ta ≈ 15, average Ba/Ta for the 45–36 Ma age group is 220).

Wells (1990) and Wells et al. (1998, Fig. 4 therein) suggested significant clockwise rotation of the Cascadia forearc block west of the ancestral arc since Eocene time. The proposed forearc rotation suggests a significant role for tectonics in ancestral arc petrologic and metallogenic evolution. Clockwise rotation of the Cascadia forearc, a consequence of the Cascadia block being pinned at its north end by the Canadian Coast Mountains buttress and northwest translation of the Sierra Nevada block from the south, resulted in profoundly different stress regimes along the length of the ancestral arc: the southern Washington arc segment evolved in a compressional regime, whereas the Oregon segment developed in an increasingly extensional regime southward.

Previous studies suggested that crustal thickness beneath the ancestral arc varied systematically through time. Evarts et al. (1987) suggested that at the onset of ancestral arc magmatism the crust beneath the arc was thin (~30 km) and mafic (possibly oceanic), but thickened progressively to the present-day thickness of 45–50 km. Priest (1990) suggested, and the data in du Bray et al. (2006) support the inference, that the active arc narrowed and migrated eastward through time.
Arc narrowing probably reflects progressive steepening of the subduction zone through time at the critical depth where slab dehydration flux melting initiates, whereas the eastward shift of the arc axis suggests that overall, the dip of the subducted slab shallowed during that time, thereby deflecting the locus of magma genesis eastward (see Priest, 1990, Fig. 15 therein). Some of the eastward shift is probably related to westward rotation of the arc frontal block (Wells, 1990); however, because this rotation does not explain the observed arc narrowing, only some eastward migration of magmatism is likely a manifestation of westward forearc block rotation.

Geochemical characteristics of many arc rock assemblages are diagnostic of crustal thickness and the tectonic regime prevailing during arc evolution. Hildreth and Moorbath (1988) demonstrated that modern Andean magmatic arc volcanoes of the central Chile segment located above the thickest continental crust have the highest Ce/Yb, probably as a consequence of (HREE rich) garnet stabilization in the higher pressure regime associated with thicker crust. Similarly, Ce/Yb values of ancestral arc rocks are low among samples of the 45–36 Ma and 35–26 Ma age groups (average 19 and 15, respectively) relative to values for samples of the 25–18, 17–8, and 7–4 Ma age groups (average 26, 22, and 25, respectively). Elevated Sr abundances in the younger, unfractated ancestral arc rocks are also consistent with increasing crustal thickness through time.

K/Rb is principally controlled by source composition, degree of partial melting, and assimilation-related contamination (by crustal components) during MASH processes. The highly incompatible behavior of Rb (Hanson, 1980) causes K/Rb values at any given Rb abundance to reflect only varying amounts of contamination, because Rb abundance is fixed by source composition and degree of partial melting. Consequently, at any given Rb abundance, rocks with the highest K/Rb are the most contaminated, likely a consequence of having transited relatively thicker crust (Feeley, 1993). Initially low K/Rb values (average 437) for older assemblage ancestral arc rocks with 10–20 ppm Rb (Fig. 13) are consistent with minimal contamination by the relatively primitive, thin column of continental crust likely to have prevailed beneath the ancestral arc at the time. Higher K/Rb values (average 636) for younger assemblage rocks with 10–20 ppm Rb suggest that these rocks were significantly more contaminated by crustal components, which may reflect their having transited continental crust thickened and hybridized by ongoing subduction-related magmatism.

Major oxide ancestral arc rock compositions that became generally less primitive through time (Figs. 7 and 14) are also consistent with enhanced crustal contamination plausibly related to relatively greater crustal thickness. Similar relations between crustal thickness and compositional variation among subduction-related magmas have been widely documented (Miyashiro, 1974; Gill, 1981; Leeman, 1983; Hildreth and Moorbath, 1988) and, as described
by Evarts and Swanson (1994, p. 2H-6), probably relate to the fact that “the base of the crust acts as a density filter that controls the depth at which basalt derived from the mantle wedge stagnates and fractionates.” Accordingly, thin crust fosters the transit and eruption of diverse magmas, including higher-density mafic magmas, whereas thicker crust allows transit of only more evolved, lower-density magmas. In addition, the state of stress in the crust beneath the arc contributes to compositional systematics. Extensional regimes and associated structural conduits promote relatively rapid crustal transit of more mafic, less contaminated magma, whereas compressional settings inhibit crustal transit, causing magma to stagnate, foster enhanced contamination by crustal host rocks, and fractionate. Compositional variation

Figure 12. Variation diagram showing Ba/Nb versus SiO₂ in samples of ancestral Cascades arc rocks. Dashed line at Ba/Nb = 15 (Gill, 1981) separates mid-oceanic ridge basalt (MORB) compositions (below line) from those characteristic of magmatic arc andesite. Dashed line delineates the composition field of modern arc (MA) rocks of the High Cascades (data from GEOROC, 2010).
observed within ancestral arc rocks likely represents a combination of these processes.

Previous investigations of ancestral arc rocks noted the unusual, tholeiitic character of the arc’s early eruptive products. Evarts and Swanson (1994) suggested that tholeiitic magmatism ended abruptly ca. 18 Ma; data compiled in du Bray et al. (2006) are consistent with these conclusions (Fig. 5), and demonstrate that early, volumetrically dominant eruptions of tholeiitic rock were concentrated in southern Washington (Figs. 3A, 3F). Miyashiro (1974) and White and Mc Birney (1978) suggested that transitions from tholeiitic to calc-alkaline compositions are principally related to crustal thickness. The change within the evolving ancestral arc from dominantly tholeiitic to calc-alkaline magmatism is consistent with crustal maturation and thickening that promoted magma generation at greater depths with time and caused compositions to evolve accordingly. The return to more iron-enriched compositions among some samples of the two youngest age groups may also be a consequence of slab dip reduction and genesis in a thinner crustal environment. In addition, White and Mc Birney (1978) noted that time-composition relations among ancestral arc magmas are consistent with progressive depletion of a relatively homogeneous mantle source; they demonstrated that REE abundances, especially HREEs, are lower in progressively younger ancestral Cascade arc rocks, whereas the limited isotopic data show that their radiogenic isotopic compositions are essentially invariant. Abundances of strongly incompatible elements such as Rb also reflect source-depth relations. Initially, Rb abundances increased as a consequence of crustal thickening (through 25–18 Ma), but decreased in samples of the 17–8 and 7–4 Ma age groups, possibly as a consequence of prior source-region Rb depletion (Fig. 13). Ancestral arc rocks may depict melting that progressively depleted hyperfusible, incompatible element components from a mineralogically invariant mantle source. Relatively lower HREE abundances among progressively younger ancestral arc rocks may also relate to increased garnet stability (Green, 1982) associated with progressive crustal thickening and a higher pressure melting environment. HREE-enriched garnet melting was inhibited by prevailing high pressure associated with enhanced crustal maturity and thickness that caused magmas produced in progressively higher pressure environments to have lower HREE abundances.

**Metallogeny of the Ancestral Cascades Arc**

Continental magmatic arcs overlying active subduction zones are some of the most fertile areas for the formation of metallic mineral deposits, as epitomized by porphyry copper and epithermal gold-silver deposits in the Andean arc in South America (e.g., Sillitoe, 1972, 1987, 2008, 2010; Richards, 2003; Sillitoe and Hedenquist, 2003; Seedoff et al., 2005; Sillitoe and Perelló, 2005; Cooke et al., 2005; Simmons et al., 2005). Although numerous deposits and prospects genetically related to magmatic activity are arrayed along the length of the ancestral Cascades arc (Fig. 15), the number, grades, and sizes of known deposits, especially of epithermal deposits, are atypical relative to those associated with many magmatic arcs (Long et al., 1998, 2000; Sillitoe, 2008), and only deposits related to porphyry copper systems are of sufficient size and grade to be of potential economic importance (Table 3). In contrast, the southern part of the ancestral Cascade arc in eastern California and western Nevada contains numerous epithermal gold-silver deposits and large areas of hydrothermally altered rock that may be the upper parts of porphyry copper systems (Wallace, 1979; John, 2001; Vikre and Henry, 2011).
Figure 14. Variation diagrams showing compositional variation among samples of the ancestral Cascades arc in a temporal context. Black triangles at the age midpoint of each age group indicate age group mean compositions. (A) K\textsubscript{2}O. (B) MgO.
Figure 15. Map showing the distribution of mineral deposits and occurrences associated with ancestral Cascades arc magmatism; numbered deposits correspond to those in Table 3. Dashed red line is the approximate outline of the Siletzia terrane (from Wells et al., 1998). Dashed black lines delineate areas in which multiple samples have adakitic compositions. Mineral deposits and occurrences are modified from the U.S. Geological Survey Mineral Resources Data System database (http://tin.er.usgs.gov/mrds/find-mrds.php).
<table>
<thead>
<tr>
<th>Identifying Number (see Fig. 15)</th>
<th>Name</th>
<th>District</th>
<th>Location (lat °N, long °W)</th>
<th>Deposit type</th>
<th>Host rock</th>
<th>Mineral deposit age (Ma)</th>
<th>Resources and/or Production (short tons)</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>1A</td>
<td>Glacier Peak</td>
<td>Sampson</td>
<td>48.20, 120.98</td>
<td>Porphyry Cu-Mo</td>
<td>Cloudy Pass batholith</td>
<td>22</td>
<td>1700 Mt at 0.334% Cu and 0.015% MoS₂</td>
<td>Grant, 1982; Lasmanis, 1995</td>
</tr>
<tr>
<td>1B</td>
<td>Fortress Mountain</td>
<td>Sampson</td>
<td>48.18, 120.94</td>
<td>Porphyry Cu-Mo</td>
<td>Cloudy Pass batholith</td>
<td>22</td>
<td>46.6 Mt at 0.319% Cu and 0.071% MoS₂</td>
<td>Grant, 1982; Lasmanis, 1995</td>
</tr>
<tr>
<td>2</td>
<td>Sunrise (Vesper Peak)</td>
<td>Sultan</td>
<td>48.01, 121.50</td>
<td>Cu-breccia pipe</td>
<td>Vesper Peak stock</td>
<td>32.7</td>
<td>28.2</td>
<td>Lasmanis, 1995</td>
</tr>
<tr>
<td>3</td>
<td>Middle Fork (includes):</td>
<td>Snoqualmie</td>
<td>47.52, 121.34</td>
<td>Cu-breccia pipe</td>
<td>Snoqualmie Batholith</td>
<td>25</td>
<td>0.23 Mt at 0.9% Cu</td>
<td>Lasmanis, 1995</td>
</tr>
<tr>
<td>3A</td>
<td>Clipper</td>
<td>Snoqualmie</td>
<td>47.53, 121.33</td>
<td>Cu-breccia pipe</td>
<td>Snoqualmie Batholith</td>
<td>25</td>
<td>1.8 Mt at 0.7-0.9% Cu</td>
<td>Lasmanis, 1995</td>
</tr>
<tr>
<td>3B</td>
<td>Three Brothers</td>
<td>Snoqualmie</td>
<td>47.50, 121.36</td>
<td>Cu-breccia pipe</td>
<td>Snoqualmie Batholith</td>
<td>25</td>
<td>2.3 Mt at 0.65% Cu</td>
<td>Lasmanis, 1995</td>
</tr>
<tr>
<td>3C</td>
<td>Condor</td>
<td>Snoqualmie</td>
<td>47.50, 121.36</td>
<td>Porphyry Cu-Mo</td>
<td>Snoqualmie Batholith</td>
<td>25</td>
<td>90.7 Mt at 0.4% Cu and 0.02% MoS₂</td>
<td>Lasmanis, 1995</td>
</tr>
<tr>
<td>3D</td>
<td>Hemlock-Porter</td>
<td>Snoqualmie</td>
<td>47.56, 121.24</td>
<td>Porphyry Cu-Mo</td>
<td>Snoqualmie Batholith</td>
<td>25</td>
<td>0.8 Mt at 1.1% Cu</td>
<td>Lasmanis, 1995</td>
</tr>
<tr>
<td>4</td>
<td>Dutch Miller</td>
<td>Snoqualmie</td>
<td>47.57, 121.55</td>
<td>Cu-breccia pipe</td>
<td>Snoqualmie Batholith</td>
<td>25</td>
<td>780 Mt at 0.41% Cu and 0.013% MoS₂</td>
<td>Lasmanis, 1995; Smithson et al., 2003</td>
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<tr>
<td>5</td>
<td>Quartz Creek</td>
<td>Taylor River</td>
<td>47.51, 121.71</td>
<td>Cu-breccia pipe</td>
<td>Snoqualmie Batholith</td>
<td>25</td>
<td>0.8 Mt at 1.1% Cu</td>
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</tr>
<tr>
<td>6</td>
<td>Mount Si</td>
<td>none</td>
<td>47.69, 121.65</td>
<td>Porphyry Cu-Mo</td>
<td>Snoqualmie Batholith</td>
<td>Low 40s</td>
<td>37</td>
<td>McCulla, 1986; John et al., 2003; Blakely et al., 2007</td>
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<td>7</td>
<td>Matt</td>
<td>Silver Creek</td>
<td>47.94, 121.41</td>
<td>Porphyry Cu</td>
<td>Quartz diorite</td>
<td>18</td>
<td>17.3</td>
<td>Small Cu production</td>
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<tr>
<td>8</td>
<td>Una</td>
<td>Miller River</td>
<td>47.66, 121.41</td>
<td>Cu-breccia pipe</td>
<td>Snoqualmie Batholith</td>
<td>25</td>
<td>5.6 Mt at 1.2% Cu, 0.058% MoS₂, and 8.6 g/t Ag</td>
<td>McCulla, 1986; John et al., 2003; Blakely et al., 2007</td>
</tr>
<tr>
<td>9</td>
<td>White River</td>
<td>none</td>
<td>47.15, 121.82</td>
<td>Silica lithocap with high sulfidation epithermal Au-Ag and underlying porphyry Cu-Mo</td>
<td>Fife's Peak Formation</td>
<td>21-20</td>
<td>19</td>
<td>Substantial silica production</td>
</tr>
<tr>
<td>10</td>
<td>Mineral Creek</td>
<td>none</td>
<td>46.66, 122.10</td>
<td>Porphyry Cu-Mo</td>
<td>Spirit Lake pluton</td>
<td>20</td>
<td>523 Mt at 0.36% Cu, 0.01% MoS₂, 0.24 g/t Au, and 1.58 g/t Ag</td>
<td>Johnson et al., 1983; Herdick et al., 1995; Lasmanis, 1995; Smyth et al., 2003</td>
</tr>
<tr>
<td>11</td>
<td>Margaret (Earl Group) (includes Last Hope and Polar Star breccia pipes)</td>
<td>St. Helens</td>
<td>46.35, 122.11</td>
<td>Porphyry Cu-Mo</td>
<td>Spirit Lake pluton</td>
<td>21</td>
<td>16.6-17.3</td>
<td>Small Cu production</td>
</tr>
<tr>
<td>12</td>
<td>Black Jack–Miners Queen</td>
<td>Washougal</td>
<td>45.77, 122.20</td>
<td>Porphyry Cu-Au</td>
<td>Silver Star pluton</td>
<td>19.6</td>
<td>19</td>
<td>Small Cu production</td>
</tr>
<tr>
<td>13A</td>
<td>Santiam Copper</td>
<td>North Santiam</td>
<td>44.85, 122.23</td>
<td>Porphyry Cu</td>
<td>Quartz diorite–andesite</td>
<td>13</td>
<td>2.6 Mt at 1.2% Cu, 0.058% MoS₂, and 8.6 g/t Ag</td>
<td>Callaghan and Buddington, 1938; Power, 1985; Pollock and Cummings, 1986; Summers, 1990; Stone, 1994</td>
</tr>
<tr>
<td>13B</td>
<td>Bornite</td>
<td>North Santiam</td>
<td>44.65, 122.19</td>
<td>Cu-breccia pipe</td>
<td>Andesite</td>
<td>11 to 10</td>
<td>2.8 Mt at 2.44% Cu</td>
<td>Callaghan and Buddington, 1938; Power, 1985; Summers, 1990</td>
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<td>14</td>
<td>Bohemia</td>
<td>Bohemia</td>
<td>43.58, 122.65</td>
<td>Intermediate sulfidation epithermal–polymetallic vein</td>
<td>Champion stock</td>
<td>23.5</td>
<td>~23</td>
<td>Substantial silica production</td>
</tr>
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<td>Quartz Mountain</td>
<td>none</td>
<td>43.16, 122.67</td>
<td>Silica lithocap</td>
<td>Porphyritic dacite</td>
<td>21.6</td>
<td>1102 pdf</td>
<td>Ramp, 1960; Geitgey, 1990; R.J. Fleck, 2005, written commun.</td>
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</tbody>
</table>
Figure 16. Variation diagram showing Sr/Y versus SiO₂ in samples of the northern part of the Fifes Peak Formation (host to the White River porphyry deposit) and Spirit Lake pluton (host to the Margaret porphyry deposit) in the ancestral Cascades arc. Lines at Sr/Y = 20 and SiO₂ ≥ 56% (Richards and Kerrich, 2007) define the field of adakitic compositions.

Worldwide, porphyry copper deposits predominantly form from magmatic fluids released during shallow emplacement and crystallization of oxidized, hydrous, sulfur-bearing magmas in arcs constructed above active subduction zones at convergent plate margins (Richards, 2003). Genetically related base and precious metal skarn, carbonate replacement, sediment hosted, and high- and intermediate-sulfidation epithermal deposits commonly form peripheral to and above the porphyry copper deposits. Unaltered magmatic rocks in arcs that contain porphyry copper deposits are mostly calc-alkaline and metaluminous, and most porphyry copper systems are associated with moderately evolved granitic rocks (as shown by moderate silica contents and high K/Rb and Rb/Sr). These rocks are enriched in LILEs and fluid-mobile elements (e.g., Cs, Rb, Ba, U, K, Pb, and Sr), relatively depleted in Nb, Ta, P, and Ti compared to primitive mantle, and most are depleted in Mn and Th. The mineralizing stocks are oxidized (high whole-rock values of Fe₂O₃/FeO) magnetite-series rocks, and most contain magnetite and titanite. Most mineralized intrusions have highly fractionated REE patterns (commonly with HREE and Y depletions relative to barren intrusions), high La/Yb (40–60), high Sr/Y (mostly >20), and chondrite-normalized REE patterns that have small negative or positive Eu anomalies. Numerous authors have noted that many of the minor element, REE, and radiogenic isotopic compositional features of porphyry copper–related igneous rocks are similar to those of adakites (Richards and Kerrich, 2007; Ayuso and John, 2010), magmatic arc rocks with unusual geochemical compositions whose genesis may involve subducted slab melting (Kay, 1978; Defant and Drummond, 1990). Geochemical characteristics of adakites include SiO₂ ≥ 56%, Sr/Y ≥ 20, Y ≤ 18 ppm, Cr ≥ 30 ppm, Ni ≥ 20 ppm, and La/Yb > 20 (Richards and Kerrich, 2007).

Only ~120 of the ~3400 samples in the ancestral arc database, including representatives of each age group, have SiO₂ ≥ 56%, Sr/Y ≥ 20, Y ≤ 18 ppm, Cr ≥ 30 ppm, Ni ≥ 20 ppm, and La/Yb > 20 (Richards and Kerrich, 2007). Consequently, the vast majority of magmatic activity associated with the ancestral arc is not adakitic. Richards and Kerrich (2007) suggested that the spatial and genetic association between porphyry copper deposits and adakites is neither robust nor useful with regard to locating prospective igneous rocks. Similarly, in the Pacific Northwest, the spatial coincidence of adakitic ancestral arc rocks and known mineralized systems is limited (Fig. 15). In addition, most samples of the Fifes Peak Formation (host to the White River porphyry deposit; Table 3) and the Spirit Lake pluton (host to the Margaret porphyry deposit; Table 3) are not adakitic (Fig. 16), further corroborating the lack of a relationship between adakites and porphyry copper deposits in the ancestral arc. Adakitic rocks form several geographic clusters (Fig. 15) along the length of the ancestral arc, suggesting that they have some other but unknown genetic significance.

In the ancestral Cascades arc, most porphyry copper systems (and most known metallic mineral deposits) are located north of the Columbia River, especially in northern Washington, where an association with well-defined arc magmatism is uncertain. Most dated porphyry copper deposits and related Cu-rich breccia pipe and polymetallic vein deposits in Washington are hosted by large plutons and batholiths younger than ca. 22 Ma (Table 3), although the ages of several deposits are poorly known. Epithermal Au-Ag deposits are especially uncommon in the ancestral arc. However, large subhorizontal zones of rock altered to quartz-rich advanced argillic assemblages (residual quartz alteration) form lithocaps mined locally for silica (White River, Washington, and Quartz Mountain and Abbott Butte, Oregon); those at White River contain subeconomic-grade high-sulfidation–type Au mineralization (Fig. 15).

The scarcity, low grades, and small tonnages of porphyry copper and related deposits in the ancestral Cascade arc relative to many other subduction-related magmatic arcs may be the result of several factors. These include: (1) magma source, (2) magma composition, including volatile (especially H₂O) contents, sulfur abundances, and magmatic oxidation state, (3) crustal composition and thickness, (4) tectonic setting prevailing during magma genesis and emplacement, and (5) presence or absence of unusual episodes of subduction (Sillitoe and Perelló, 2005), including periods of flat or shallow subduction induced by subduction of buoyant oceanic ridges, plateaus, or seamount chains, periods of subduction-zone erosion, or episodes of plate reorganization. Some combination of these factors probably limited the distribution and size of porphyry copper systems in the ancestral arc. It is important that the weakly mineralized character of the ancestral arc cannot universally be related to exposure level because volcanic and intrusive rocks of the ancestral arc depict a broad array of exposure levels, especially in southern Washington. In Oregon, exhumation of the plutonic rocks is not as complete; this may contribute to the character of mineral deposits associated with that part of the ancestral arc.

Fluxes of water-rich magmatic fluids are critical to porphyry–related hydrothermal ore deposit formation; low abundances could inhibit mineralizing processes. Phenocrystic amphibole, ubiquitous in many ancestral and...
modern Cascades arc rocks, indicates that their host rocks contained >4 wt% H₂O (Rutherford and Hill, 1993). Consequently, many ancestral and modern Cascades arc magmas arrived at their emplacement loci containing volatile contents conducive to mineralizing processes. Tourmaline-rich breccias are a common and distinctive feature of weakly mineralized ancestral Cascades systems (Mason et al., 1977; Summers, 1990; Cummings et al., 1990; Lasmanis, 1995). Given that boron is principally derived from slab devolatilization (Leeman, 1996), the presence of tourmaline (a principal mineralogic residence of boron) in ancestral Cascades arc systems implies that slab-derived volatiles were involved in ancestral Cascades arc magmatism. Consequently, neither lack of volatiles, in general, nor slab-derived constituents, in particular, are likely responsible for the inconsequential nature of mineral deposits associated with the ancestral Cascades arc.

As previously discussed, the southern Washington–Oregon and northern Washington parts of the ancestral arc evolved in distinctly different tectonic regimes. The southern part of the ancestral arc developed in an extensional environment (Wells, 1990; Wells et al., 1998) above primitive, oceanic crust (Siletzia), whereas the northern part developed in a compressive transpressional setting above crust that was thickened by early and focused slab window to transpressional setting above crust that was thickened by early and focused slab window magmatism (Madsen et al., 2006). Consequently, mineralizing processes responsible for the genesis and character of ancestral arc-related mineral deposits may have been influenced by the prevailing tectonic regime, as well as the character of the crust beneath the arc.

Tosdal and Richards (2001) and Richards (2003) emphasized the importance of a mildly compressive to transpressional environment in focusing and constraining arc magmas and associated exsolved hydrothermal fluids responsible for the genesis of porphyry copper and related mineral deposits. In particular, porphyry copper deposits seem to be preferentially sited along compressional parts of magmatic arc segments in small extensional stepover zones between arc-parallel strike-slip faults. The White River deposit in southern Washington (Table 3) is located in just such a stepover zone (Blakely et al., 2007). Accordingly, the extensional regime that prevailed along the southern Washington–Oregon part of the ancestral arc during much of its evolution (Wells, 1990; Wells et al., 1998) appears to have fostered the diffuse, sporadic, unfocused mineralization characteristic of this arc domain. In contrast, the transpressional to compressional regime that prevailed in the ancestral arc from Mount St. Helens northward appears to have constrained and focused hydrothermal fluids, resulting in larger, higher-grade mineral deposits.

In a detailed study of the Miocene Tatoosh intrusive suite (du Bray et al., 2011), a very weakly mineralized ancestral arc magmatic system on the south flank of Mount Rainier, several factors were identified that may have inhibited formation of magmatic-hydrothermal mineral deposits including porphyry copper deposits, despite evidence that these rocks were pervasively affected by weak hydrothermal systems. The study (du Bray et al., 2011) noted (1) that magmatic sulfide minerals and altered rocks containing sulfide minerals are scarce, suggesting relatively low magmatic sulfur abundances and/or sulfur loss during cooling and degassing, (2) an absence of magmatic anhydrite and titane, sparse magnetite, and abundant ilmenite, suggesting a low to moderate magmatic oxidation state, (3) scarce fractures and low vein density, suggesting low permeability insufficient to foster hydrothermal fluid convection, (4) relatively minor groundmass and/or porphyry texture development, suggesting late H₂O-rich vapor saturation and/or exsolution, and (5) fluid inclusions lacking daughter chalcopyrite and/or sulfur loss during cooling and degassing.

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Tosdal and Richards (2001) and Richards (2003) emphasized the importance of a mildly compressive to transpressional environment in focusing and constraining arc magmas and associated exsolved hydrothermal fluids responsible for the genesis of porphyry copper and related mineral deposits. In particular, porphyry copper deposits seem to be preferentially sited along compressional parts of magmatic arc segments in small extensional stepover zones between arc-parallel strike-slip faults. The White River deposit in southern Washington (Table 3) is located in just such a stepover zone (Blakely et al., 2007). Accordingly, the extensional regime that prevailed along the southern Washington–Oregon part of the ancestral arc during much of its evolution (Wells, 1990; Wells et al., 1998) appears to have fostered the diffuse, sporadic, unfocused mineralization characteristic of this arc domain. In contrast, the transpressional to compressional regime that prevailed in the ancestral arc from Mount St. Helens northward appears to have constrained and focused hydrothermal fluids, resulting in larger, higher-grade mineral deposits.

In a detailed study of the Miocene Tatoosh intrusive suite (du Bray et al., 2011), a very weakly mineralized ancestral arc magmatic system on the south flank of Mount Rainier, several factors were identified that may have inhibited formation of magmatic-hydrothermal mineral deposits including porphyry copper deposits, despite evidence that these rocks were pervasively affected by weak hydrothermal systems. The study (du Bray et al., 2011) noted (1) that magmatic sulfide minerals and altered rocks containing sulfide minerals are scarce, suggesting relatively low magmatic sulfur abundances and/or sulfur loss during cooling and degassing, (2) an absence of magmatic anhydrite and titane, sparse magnetite, and abundant ilmenite, suggesting a low to moderate magmatic oxidation state, (3) scarce fractures and low vein density, suggesting low permeability insufficient to foster hydrothermal fluid convection, (4) relatively minor groundmass and/or porphyry texture development, suggesting late H₂O-rich vapor saturation and/or exsolution, and (5) fluid inclusions lacking daughter chalcopyrite minerals and whole-rock copper contents that remained high throughout crystallization, suggesting partitioning of Cu into crystallizing magmas instead of magmatic-hydrothermal fluids (Bodnar, 1995). Relatively reduced, sulfur-poor magma that became H₂O-rich vapor saturated relatively late during its crystallization did not develop strong hydrothermal systems capable of forming porphyry copper deposits in the Tatoosh plutons. The limited number, size, and grade of metallic mineral deposits associated with the ancestral arc may also be related to some of these factors.

Although distinct crustal lithologies in the ancestral arc domain that includes Oregon and southern Washington versus that including only northern Washington correlate with the size and grade of associated mineral deposits, cause-and-effect relations relevant to this correlation are less clear; mineralization intensity probably reflects a combination of factors. In the northern Washington domain, compressional tectonics and thicker, lower density crust along the western edge of the North American plate may have inhibited volcanism and promoted deeper MASH zone processes. In this environment, extensive interaction with the crust resulted in more silicic and K-rich magmas and more abundant plutons characteristic of this region. Magma generated along the southern Washington–Oregon arc domain that interacted with mafic Siletzia crust seems to have been influenced by conditions (including redox state, metal partitioning, and volatile content) that hindered generation of magmatic-hydrothermal fluids capable of well-developed mineralizing events. In contrast, magma that interacted with compositionally distinct crust associated with the northern Washington ancestral arc domain generated hydrothermal fluids that sustained somewhat more significant mineralizing systems. However, none of these rocks is as strongly mineralized as many segments of the Andean and other subduction-related magmatic arcs. Crust having the appropriate composition, in a moderately transpressional regime, appears to be critical to focusing arc magmatism and hydrothermal fluids into shallow crustal reservoirs, as well as creating and localizing vertically interconnected zones of extensional faulting along which mineralizing fluids can be channelized. The relative absence of these features likely contributed to the small, low-grade character of mineral deposits associated with the ancestral arc, particularly in its southern half.

Work by Richards (2009) suggests that with ongoing subduction, subcontinental lithospheric mantle above convergent margins can become a fertile source of Cu, Au, and other metals. Metals may become enriched in these mantle materials because they can include an oxidized and hydrous residue that contains residual sulfide minerals enriched in base and precious metals. Fertile arc magma sources of this type can develop only when relatively barren asthenospheric mantle does not interact with metal-enriched lithospheric mantle. Steeply inclined subduction promotes asthenospheric mantle wedge incursion beneath active arcs (Gvirtzman and Nur, 1999), whereas shallow subduction precludes this type of mantle hybridization and might promote lithospheric mantle metal enrichment. Neogene subduction along much of the highly mineralized Andean arc was relatively shallow. In contrast, the relative narrowness of the middle Tertiary ancestral Cascades arc suggests steeper subduction. Consequently, the relative dearth, low grade, and small size of mineral deposits associated with the ancestral Cascades arc might also reflect more steeply inclined subduction than that beneath more intensely mineralized arcs.

CONCLUSIONS

Cenozoic arc magmatism in the Pacific Northwest includes both modern and ancestral components. The ancestral arc was active for more than 40 m.y. and the associated rocks exhibit systematic time-space-compositional variations. Initial (pre-40 Ma to 35 Ma), dominantly tholeiitic basaltic and basaltic andesite magmatism was strongly focused in southern...
Washington. Between ca. 35 and 26 Ma, basaltic and basaltic andesite continued to be volcanometrically dominant, although some andesite and dacite were also erupted. During this period, magmatic activity spanned essentially the full length of the northern segment of the ancestral Cascades arc. From 25 to 18 Ma, andesitic arc magmatism, involving minor basalt, basaltic andesite, dacite and rhyolite, continued in southern Washington, shifted eastward in central Oregon, and the southern arc terminated shifted north into southern Oregon. Starting ca. 25 Ma, magma compositions changed from tholeiitic to calc-alkaline. The volume of arc magma, dominantly andesitic, decreased dramatically between 17 and 8 Ma as activity receded farther northward into central Oregon and essentially ceased in southern Washington. Southern Washington continued to be amagmatic between 7 and 2 Ma, whereas magmatic activity, dominated by basalt and basaltic andesite and lesser andesite and including minor dacite, extended southward again into northern California and the arc narrowed in Oregon.

Variation of ancestral arc magma geochemistry through time principally reflects subduction-related processes, crustal maturity and thickness, and subducted plate dip. Tholeiitic compositions of the early ancestral arc magmas in southern Washington reflect spreading center subduction and associated slab window magmatism. Trace element abundances, particularly low Sr abundances and elevated HREE abundances, are in accord with partial melts generated in relatively lower pressure environments in which plagioclase was stable and garnet unstable. Subsequently, as the crust matured and thickened, calc-alkaline compositions became dominant; partial melts were generated beneath thickened crust at higher pressures in which plagioclase was unstable and garnet stable, resulting in relatively higher Sr abundances and lower HREE abundances. In the final period of ancestral arc magmatism, immediately prior to the onset of modern High Cascades magmatism, compositions became more iron rich again, in accord with decreased dip on the subducted slab. Throughout its history the ancestral arc narrowed and shifted progressively eastward, reflecting progressively steeper subduction zone dip in the partial melting zone but overall shallowing of the dip on the subducted slab.

The number, size, and grade of most mineral deposits associated with the ancestral arc are small relative to the Andean arc analog; it is likely that many factors contributed to these relatively weak mineralizing systems. Most important, the Oregon arc segment evolved in an extensional regime not conducive to mineral deposition. In contrast, the southern Washington arc segment evolved in a transpressional to compressional tectonic setting more favorable to deposit formation. The relatively greater abundance, size, and grade of deposits in southern Washington appear to reflect the more favorable structural environment and also may reflect thicker, more silicic crust than that underlain by mafic, accreted Siletzia crust in the southern part of the ancestral arc.

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