The western Hayfork terrane: Remnants of the Middle Jurassic arc in the Klamath Mountain province, California and Oregon

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ABSTRACT

Arc magmatism was widespread in the Cordillera of North America during Middle Jurassic time. The predominant representative of this arc magmatism in the Klamath Mountain province is the western Hayfork terrane (WHT). This terrane is primarily metasedimentary, consisting mainly of crystal-lithic arenite, argillitic sediments and lahar deposits, rare lavas, and sparse quartz-rich arenite. Because lavas are rare, petrologic study using bulk-rock compositions is restricted to analysis of cobbles in lahar deposits. Moreover, the WHT underwent greenschist-facies regional metamorphism with consequent modification of bulk-rock compositions. However, many of the sandstones preserve igneous clinopyroxene and calcic amphibole, which were phenocrysts in the original volcanic rocks. Major- and trace-element compositions of the magmatic pyroxene and amphibole permit reconstruction of the range of rock types eroded from the arc, specifically scant basalt, volcaniclastic sedimentary rocks, and rhyodacite. Eruptive temperatures reached ~1180 °C and may have been as low as ~800 °C on the basis of pyroxene and amphibole thermometry, with most eruptive temperatures >1000 °C.

On the basis of augite compositions, WHT magmatism is divided into two suites. One features high-Mg augite with high abundances of Cr and Sr, high Sr/Y and Nd/Yb values, and low Y and heavy rare-earth elements (REE). These compositions are typical of high-Mg andesite and dacite magmatic phases, particularly calcic pyroxene and plagioclase (e.g., Brandl et al., 2017). The other suite contains augite with lower Sr, Sr/Y, and Nd/Yb; these features are typical of normal calc-alkaline magmas. Augite from a coeval pluton emplaced inboard of the western Hayfork outcrop belt is similar to augite from the low-Sr group of WHT samples. In contrast, augite from the Ironside Mountain pluton, previously considered the plutonic equivalent of WHT sediments, is Fe-rich, with low Cr and Sr and relatively high Zr and REE. Previous suggestions that the Ironside Mountain pluton is correlative with the WHT are not supported by these data.

The magmatic diversity of the WHT is typical of the modern Aleutian and Cascade arcs, among others, and could reflect subduction of relatively young oceanic lithosphere or fragmentation of the subduction slab. Although we favor the former setting, present data cannot rule out the latter. The presence of scant quartz-rich sedimentary rocks within the predominantly volcanicogenic WHT is consistent with deposition as a sedimentary apron associated with a west-facing magmatic arc with late-stage input from cratonic sources. The results of this study indicate that detailed petrographic study of arc-derived sedimentary rocks, including major- and trace-element analysis of preserved magmatic phases, yields information about magmatic affinities, processes, and temperatures.

INTRODUCTION

In many convergent margin settings, the presence, timing, and nature of arc magmatism is readily determined on the basis of geochemical analysis of volcanic and plutonic rocks and U-Pb dating of accessory phases such as zircon. However, in some cases, neither volcanic nor plutonic rocks of the arc are preserved. One such case is the widespread Middle Jurassic arc activity in the North American Cordillera, in which some arc-related strata consist primarily of volcaniclastic rocks and volcanicogenic sedimentary rocks. Examples of such strata are components of the Fiddle Creek and Slate Creek complexes (Day and Bickford, 2004) and the Sailor Canyon Formation (Lewis and Girty, 2001) in the northern Sierra Nevada, the Ritter Range in the central Sierra Nevada (e.g., Sorensen et al., 1998), clastic sedimentary units on Cedros Island, Baja California (Busby-Spera, 1988), Jurassic units in the Palen Mountains of Arizona (Fackler-Adams et al., 1997), and the western Hayfork terrane in the Klamath Mountain province (KMP) of California and Oregon (Fig. 1), the subject of this study.

Detrital zircon dating has greatly advanced our understanding of age relationships and potential correlations of volcanic arc sediments. However, compositional data on zircon are generally insufficient to permit reconstruction of magma types and processes. Moreover, in sediments derived from primitive arcs, zircon is likely to be scant or absent. Instead, analytical studies aimed at understanding magma petrogenesis have utilized volcanic clasts (e.g., Savov et al., 2006), volcanic glass in tephra (e.g., Bryant et al., 2003), and glass inclusions in clinopyroxene and plagioclase (e.g., Brandl et al., 2017).

Until recently, chemical data on magmatic minerals preserved in volcanicogenic sediments constituted major-element compositions, and such studies mainly focused on determination of tectonic setting (e.g., Nisbet and Pearce, 1977; Garcia, 1978; Cawood, 1983, 1991; Fujioka and Saito, 1992) or exhumation rates (e.g., Jiang and Lee, 2017). However, the trace-element contents of some magmatic phases, particularly calcic pyroxene and amphibole, may record significant information about not just tectonic setting but also magma types and petrogenesis. Examples of such studies are Rossel et al. (2015), who used trace-element data on pyroxene to determine petrogenesis of altered Jurassic arc rocks in Chile, and Wurth (2019),...
Jurassic volcanic and plutonic arc rocks in California and adjacent states. After Irwin (2003), Wyld and Wright (2001), and Barton et al. (2011). The extent of the Sierra Nevada is shown by the dashed line. Figure 1. Generalized map indicating outcrop areas of Middle Jurassic arc, Klamath Mountains. The province-wide extent of the WHT (Fig. 2) indicates that it represents a significant component of arc magmatism in the KMP and is deserving of petrogenetic analysis. However, traditional methods are hampered by the fact that most of the unit is sandstone: samples of igneous rocks large enough to justify bulk analysis are found only as rare lavas and as clasts in lahar deposits. In contrast, many of the augite and amphibole grains in the sandstone preserve primary igneous compositions, which means that the major- and trace-element compositions and zoning patterns of these minerals provide information about the conditions of magmatism and the compositions of erupted material.

In what follows, we first describe the WHT and scant coeval plutons, investigate the differences and similarities of the mafic mineral assemblages, and further document the provenance of the unit as the sedimentary apron of a volcanic arc (Wright and Fahan, 1988). We then pursue the use of major- and trace-element compositions of augite and amphibole as indicators of provenance, but more importantly as indicators of the types and compositions of the arc magmas. We conclude that: (1) the majority of WHT magmas ranged from basaltic andesite to dacite; (2) many magmas had high-Mg affinities, whereas others were typical of common calc-alkaline magmas; and (3) the WHT was deposited in an arc environment, the magma compositions of which were similar to those in the modern Aleutian and Cascade arcs. Small coeval plutons display magmatic similarities to the WHT, but the slightly younger, batholith-scale Ironside Mountain pluton represents a distinctly different magmatic pulse.

**GEOLOGIC SETTING**

The KMP is divided into four broad lithotectonic belts (Fig. 2; Irwin, 1960, 1966), and each belt is subdivided into tectonostratigraphic terranes (e.g., Irwin, 1972; Blake et al., 1985; Wright, 1982). The WHT crops out in the so-called western Paleozoic and Triassic belt (wTrPz; Irwin, 1972), which consists primarily of Triassic and Jurassic terranes. In descending structural order, these units are Stuart Fork Formation (also called the Fort Jones terrane), North Fork terrane, eastern Hayfork terrane, western Hayfork terrane, and Rattlesnake Creek terrane (Fig. 2; Irwin, 1972; Wright, 1982; summarized in Snoke and Barnes, 2006). The wTrPz overlies rocks of the western Jurassic belt along a regional thrust, the Orleans fault (Fig. 2). The Rattlesnake Creek terrane was interpreted to be in faulted depositional contact beneath the WHT on the basis of sedimentary linkages at the base of the WHT (Wright and Fahan, 1988; Donato et al., 1996). The fault separating these two units, the Salt Creek fault (Fig. 2), is inferred to have minor displacement. The WHT is separated from the structurally higher eastern Hayfork terrane by the Wilson Point thrust (Wright and Fahan, 1988). Along-strike terrane relationships in the lower wTrPz and western Jurassic belt are shown in Figure 3.

The Rattlesnake Creek terrane consists of a basal ophiolitic mélangé overlain by two or more sequences of coherent strata that consist of metavolcanic and fine-grained metasedimentary rocks (Irwin, 1972; Wright, 1982; Donato et al., 1983, 1996; Gray, 1986; Donato, 1988; Wright and Wyld, 1994). The mélangé rocks range in age from Triassic to Early Jurassic (Irwin and Blome, 2004).
Figure 2. Geologic map of Klamath Mountain province after Irwin (1994) and Allen and Barnes (2006). Boxes indicate areas sampled. Pluton colors are related to individual age and compositional suites (Allen and Barnes, 2006). Numbers with named plutons indicate U-Pb (zircon) ages (Ma); see text for specific references. The contact at the base of the Cretaceous overlap sequence is depositional, and most contacts with plutons are intrusive—prominent exceptions are parts of the western Ironside Mountain batholith contact and eastern and western contacts of the Chetco Complex. Terrane-bounding contacts are faults. ttg—tonalite-trondjhemite-granodiorite; FS—Forks of Salmon pluton.
The coherent cover sequence of the Rattlesnake Creek terrane was described in detail by Gray (1985) and Wright and Wyld (1994). In the southern KMP, two distinct units were identified in the cover sequence: the lower Salt Creek assemblage of interlayered basaltic lavas, chert, argillite and epilastic rocks, and the upper Dubakella Mountain assemblage of porphyritic volcanic and volcanoclastic rocks (augite-phyric mafic–intermediate rocks that we consider similar to the Dubakella Mountain assemblage crop out along and west of the Klamath River area). The WHT is primarily a clastic sedimentary deposit with sparse lavas (Wright and Fahan, 1988; Donato, 1995a, 1995b; Donato et al., 1996; this work). The sedimentary rock types range from coarse-grained, variably conglomeratic arenite to feldspathic wacke, all of which are intercalated with fine-grained siliceous to carbonaceous argillite, scatchet layers, and rare, fine-grained ash deposits. Bedding varies in thickness from fine laminae (Supplemental Figs. S1A and S1B) to beds at least 50 cm thick and locally displays partial Bouma sequences. In outcrop, individual beds typically appear massive, in part because fine-scale features may have been obscured by metamorphism. In addition to the layered sedimentary rocks, diamicites are common. These deposits consist of pebble- to cobble-sized volcanic clasts in a sandy matrix (Supplemental Figs. S1C–S1E). Maximum clast dimensions are typically 20 cm, but a few reach 40 cm in length.

In some cases, the cobble-rich deposits occupy channels cut into bedded arenites (Donato et al., 1996), features typical of lahar deposits. Soft-sedimentary deformation includes small, rootless faults, pinch-and-swell structures, and flame structures. Decimeter-scale tectonic folds are sparsely present and variable dips on bedding suggest the presence of broad open folding (Supplemental Fig. S2). Some layers display weak tectonic lineation in the form of stretched mafic minerals.

In addition to these volcanogenic sediments, a distinctive, ~50-m-thick, feldspathic quartz arenite is exposed NW of the Denny complex (Fig. 2). At this locality, the quartz-rich arenite is contact
metamorphosed by the Ironside Mountain pluton. However, petrographic features indicate that the sandstone was medium grained, well sorted, and consisted mainly of quartz, K-feldspar, and plagioclase, in order of decreasing abundance. Although detrital zircon has yet to be extracted from this unit, it is an ideal candidate for future study of Middle Jurassic depositional systems in the Klamath Mountains.

The WHT stratigraphy varies considerably along strike. For example, Supplemental Figure S2 (footnote 1) illustrates a structural/stratigraphic section measured on an east-west transect south of Orioles Mountain (Fig. 2). This section is distinct from another, less complete east-west transect taken ~11 km to the south, in that the latter is richer in conglomeratic sands and lahar deposits and contains less argillite. Both sections are distinct from the Trinity River (near Pigeon Point pluton; Fig. 2) and Wildwood areas, where a mixed volcaniclastic + epiclastic + hemipelagic unit with local limestone breccia crops out (Wright and Fahan, 1988). Wright and Fahan (1988) also described a somewhat larger proportion of lavas in these areas.

The WHT was deposited between 177 and 168 Ma on the basis of K/Ar and 40Ar/39Ar ages on magmatic amphibole (Wright and Fahan, 1988; Hacker et al., 1995; Donato et al., 1996); ages that span Early to Middle Jurassic time. Three small plutons yielded U-Pb (zircon) ages that overlap WHT magmatism. The Forks of Salmon pluton is a small, dike-like body that intrudes the eastern Hayfork terrane (Fig. 2). It yielded a multi-crystal U-Pb (zircon) age of 174 Ma (Wright and Fahan, 1988). The Uncles Creek pluton also intrudes the eastern Hayfork terrane and is itself intruded by the ca. 158 Ma English Peak pluton (Barnes et al., 2016a; Ernst et al., 2016). The Uncles Peak pluton was dated to 172.3 ± 2.0 Ma (zircon; Ernst et al., 2016). In the northern part of the province, the Squaw Mountain pluton (174 Ma; Irwin and Wooden, 1999) intrudes the WHT (Fig. 2).

Western Hayfork magmatism ended with regional west-vergent (modern coordinates) thrusting, during which time chert-argillite melange and broken formation of the eastern Hayfork terrane were emplaced over the WHT along the Wilson Point thrust (Fig. 2; Wright, 1982; Sullivan, 2009). Exposure of WHT rocks in windows through the eastern Hayfork terrane in the Trinity River drainage (Pigeon Point, Fig. 2) indicates displacement on the Wilson Point thrust of at least 15 km.

Renewed magmatism quickly followed Wilson Point thrusting, as exemplified by emplacement of the 170–167 Ma (Lanphere et al., 1988; Wright and Fahan, 1988) Ironside Mountain batholith (Barnes et al., 2006). As defined by Barnes et al. (2006), this batholith includes the elongate Ironside Mountain pluton, which extends 72 km from 40°32’N latitude to 41°10’N and reaches 12 km width (Fig. 2), and two smaller, zoned, satellite bodies: the Denny intrusive complex and the West China Peak complex (Charlton, 1979; Fig. 2). Multi-crystal zircon U-Pb dating of the Ironside Mountain pluton and Denny intrusive complex yielded ages of 169–170 Ma and 168 Ma, respectively (Wright and Fahan, 1988). The Denny and West China Peak complexes intrude the eastern Hayfork terrane (Fig. 2) and the Ironside Mountain pluton intrudes Rattlesnake Creek, western Hayfork, and eastern Hayfork terranes (Barnes et al., 2006). That is, the Ironside Mountain pluton intrudes the Wilson Point thrust, thereby dating thrusting to older than ca. 170 Ma. Mankinen et al. (2013) interpreted the contact between the Ironside Mountain pluton and eastern Hayfork terrane to be the Wilson Point thrust on the basis of mapping published by Fraticelli et al. (2012). However, U.S. Geological Survey (USGS) mapping in the area of interest was completed prior to 1985 (Fraticelli et al., 2012) and thus did not take into account contact relations reported by Barnes et al. (2006). Nevertheless, on the basis of the older literature (e.g., Lanphere et al., 1988), some workers consider the Ironside Mountain pluton as the intrusive equivalent of the WHT. Therefore, as part of this research, we analyzed augite and amphibole from the Ironside Mountain and West China Peak plutons to permit direct comparison of these units.

PETROGRAPHY

Western Hayfork Terrane

Arenites in the WHT encompass widely variable proportions of volcanic rock fragments and individual grains (Fig. 4A) of plagioclase (to 2 cm long), augite (to 1.5 cm diameter; Fig. 4B), amphibole (to 0.5 cm in diameter; Fig. 4C), rare argillitic clasts, and extremely rare quartz. The majority of cobbles and volcanic sand grains display textures and mineral assemblages characteristic of basaltic andesite and andesite (Fig. 4D), with phenocrysts of plagioclase and augite ± brown to green-brown calcic amphibole. Dacitic clasts, with phenocrysts of plagioclase and amphibole ± augite are locally abundant (Fig. 4E). A few samples contain low-color-index clasts with plagioclase phenocrysts; these clasts are interpreted to be rhyodacite. Groundmass textures in the volcanic grains vary from plutonic to interstitial to granular. Although plagioclase is the most abundant phenocryst, augite phenocrysts are prominent because of their size. In thin section, unaltered augite is colorless to pale tan, and some grains display concentric color zoning, which is oscillatory in some samples. Other grains are unzoned. Hornblende grains are typically brown to reddish-brown but are green to pale green in clasts with low color index (Figs. 4C and 4E).

We did not undertake chemical analysis of plagioclase phenocrysts in this study because most grains were affected by low-grade metamorphism. Optical properties on the scant unaltered plagioclase grains indicate mainly intermediate compositions (~Ab50-An45). Wright and Fahan (1988) reported rare relic olivine in WHT samples. However, even though some of the analyzed cobbles have basaltic bulk compositions (see below), a single olivine grain was observed in this study, and calcite pseudomorphs (after olivine?) are rare. It is equally noteworthy that WHT samples lack orthopyroxene.

Fine-grained rocks interlayered with sandstones vary from massive to well laminated and were termed argillite in the field. Many of these argillitic rocks consist of fine-grained, angular plagioclase crystals in a very fine-grained, commonly granoblastic matrix, which suggests that the protoliths were sandy mudstones.

Regional greenschist-facies metamorphism resulted in partial to complete replacement of the igneous assemblage. Specifically, (1) plagioclase is commonly replaced by albite ± epidote ± calcite. (2) Augite is replaced by actinolitic amphibole ± chlorite. In many samples, pools of unaltered
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Figure 4. Petrographic features of western Hayfork terrane samples. (A) Full thin-section scan of typical crystal-lithic arenite. Some volcanic clasts are outlined in red. (B) Magmatic augite partly altered to actinolitic amphibole. (C) Fine-grained arenite with plagioclase and brown amphibole clasts. (D) Andesitic clast surrounded by fine-grained matrix and variably altered plagioclase grains. (E) Dacitic clast with flow-oriented plagioclase and green amphibole. Black spots in B and E are ink.

magmatic augite are common, as are nearly pristine grains (Fig. 4B). The distinction between magmatic augite and its alteration products is straightforward: magmatic augite is clear and colorless to pale tan, whereas alteration products range from pale-green, turgid pseudomorphs of actinolitic amphibole to intergrown mats of actinolite ± chlorite ± epidote. Moreover, magmatic augite is readily distinguished from amphibole on the basis of electron microprobe analysis (see below). (3) In contrast to augite, alteration of magmatic amphibole is rare and mainly expressed as thin, oxide-rich rims or beards of actinolitic amphibole at the ends of magmatic hornblende prisms.

In summary, the predominance of volcanic detritus in WHT arenite, the common occurrence of calcic amphibole, the intercalated argillite and ash deposits, the presence of lahar deposits, and the paucity of lavas, all indicate that the WHT was deposited in a submarine environment on the flanks of an active volcanic arc (cf. Marsaglia and Ingersoll, 1992; also Wright and Fahan, 1988; Donato et al., 1996). The presence of feldspathic quartz arenite in a presumed high stratigraphic level, and particularly the proportion of K-feldspar relative to plagioclase in this arenite, are consistent with terrigenous input near the end of WHT deposition (also Wright and Fahan, 1988).

Rattlesnake Creek Terrane Cover Sequence

Two augite-bearing samples from the northern coherent strata of the Rattlesnake Creek terrane were analyzed in this study, one from the Bolan Lake area and the other from the Somes Bar area (Figs. 2 and 3). Both are interpreted to be metamorphosed lavas. Bolan Lake sample KM-85B is basaltic, with augite and plagioclase phenocrysts as much as one mm long. Unaltered augite is oscillatory zoned but most is altered to actinolite. Plagioclase is altered to white mica. Sample 92KM6 is an ankaramite from the Somes Bar area and contains augite phenocrysts at least 4 mm in diameter, sericitized, flow-aligned plagioclase, augite ± plagioclase glomerocrysts, and pseudomorphs of serpentine ± epidote after olivine. Both
samples contain greenschist-facies assemblages of actinolite + albite ± epidote.

### Plutons Coeval with the WHT

The Forks of Salmon pluton (Fig. 2) consists primarily of medium-grained augite-amphibole gabbro with lesser amounts of amphibole-two-pyroxene gabbro and dikes of amphibole quartz diorite. Augite is typically rimmed and partly replaced by amphibole, and scant orthopyroxene is partly replaced by fibrous amphibole and chlorite. Olivian amphibole is prismatic to poikilitic and encloses augite, orthopyroxene, and plagioclase. Plagioclase (~An70–55) is normally zoned and locally displays deformation twinning. Accessory minerals are Fe-Ti oxides, apatite, and zircon ± titanite.

The Uncles Creek pluton is medium-grained, mafic quartz diorite to tonalite with hypidiomorphic granular intergrowths of plagioclase, amphibole, quartz, and biotite (Seyfert, 1965; Barnes et al., 2016a). The amphibole displays characteristic elongate prisms. Accessory minerals are apatite, zircon, and rare K-feldspar. Plagioclase is typically sericitized, and biotite is altered to chlorite and clinozoisite.

The Squaw Mountain pluton is biotite-amphibole quartz diorite, with blocky to elongate plagioclase, blue-green to olive-green amphibole, brown biotite, and interstitial to poikilitic quartz. Plagioclase displays saussuritized cores and weakly zoned mantles and rims. The amphibole varies from prismatic (crystals to 3 mm long) to subpoikilitic and contains inclusions of plagioclase, magnetite, ilmenite, apatite, and zircon. Pale, quartz-rich zones in amphibole indicate replacement of early-formed pyroxene. Brown biotite is mainly interstitial to poikilitic. Scant secondary minerals are chlorite, epidote, and pyrite.

### Younger Plutonic Rocks

The Ironside Mountain batholith was described in detail by Charlton (1979) and Barnes et al. (2006). The Ironside Mountain pluton ranges from diorite to quartz monzonite and scarce syenite. Although regular zoning patterns within the pluton are weak or absent, a crude gradation from mainly diorite in the west to quartz monzonite near the eastern contact was observed in the northern part of the pluton (Barnes et al., 2006). Most samples are hypidiomorphic granular, with euhedral to subhedral pyroxenes, lath-shaped to blocky plagioclase, anhedral biotite, and interstitial quartz. With increasing differentiation, alkali feldspar varies from interstitial to poikilitic to blocky, and amphibole, where present, varies from interstitial to prismatic. This pluton is distinct from nearly all other plutons in the province because in addition to augite and orthopyroxene, inverted pigeonite is common (Barnes et al., 2006). Plagioclase compositions are An$_{0.6}$–An$_{25}$ in more mafic rocks and An$_{15}$–An$_{25}$ in quartz-bearing rocks. Accessory phases are apatite, ilmenite, magnetite, zircon, and allanite.

Rocks of the Denny and West China Peak complexes are mainly medium- to coarse-grained gabbro to quartz diorite with smaller amounts of olivine pyroxenite. These rocks are generally richer in amphibole than those of the Ironside Mountain pluton and lack inverted pigeonite (Barnes et al., 2006).

### METHODS AND DATA SOURCES

Bulk-rock compositions (Fig. 5) are taken from the literature (Langhein et al., 1968; Hotz, 1971; Charlton, 1979; Barnes et al., 1995, 2006, 2016a; Wright and Wyld, 1994) with the exception of data on the Forks of Salmon pluton, data and analytical methods for which are given in Supplemental Data Table S6. Major-oxide compositions of augite and amphibole were determined by electron microprobe at the U.S. Geological Survey (Menlo Park), Southern Methodist University, the University of Wyoming, and the University of Oklahoma. Typical operating conditions were 15 kV accelerating voltage, 20nA sample current, and ~5µ diameter spot size. Calibrations used natural and synthetic standards. Trace-element abundances were determined in situ on polished thin sections by laser-ablation–inductively coupled plasma mass spectrometry (LA-ICPMS) at Texas Tech. The same sections analyzed for major-element compositions were used, along with additional sections prepared during this study. Ablation was done using a NewWave 213nm solid state laser, and the ablated material was analyzed on an Agilent 7500CS quadrupole mass spectrometer equipped with Pt cones. Nominal operating conditions were spot diameter 40 µm and laser pulse rate of 5 Hz. During the study, a dual-volume sample cell was installed. Analyses carried out in the older, single-volume cell used a fluence of 11–12 J/cm$^2$, whereas analyses carried out in the dual-volume cell used a nominal fluence of ~6 J/cm$^2$. For each analysis, 25 s of background (laser off) and 60 s of signal were recorded. The primary analytical standard for early analyses was National Institute of Standards and Technology (NIST) 612 glass (Gao et al., 2002), but after 2016, the U.S. Geological Survey glass standard GSD-1G (Jochum et al., 2011) was used. Standards were run after every 5–10 unknowns. Precision was determined by repeated analysis of basaltic glass BHVO-2G (Jochum et al., 2007). Long-term precision (RSD) ranges from 2.5%–12% and was <7% for most trace elements. After installation of the dual-volume cell, precision improved to 2.1%–9.2% and <6% for most trace elements. Accuracy as measured compared to basaltic glass BHVO-2G was better than 5% relative for Sc, Mn, Ni, Cu, Zn, Rb, Ce, Pr, and Ta and 10% for V, S, Nb, Ba, La, Nd, Sm, and Eu.

Ideally, locations of microprobe and LA-ICPMS analyses should coincide. However, because the great majority of microprobe data are “legacy” data (analyses made over a 25-year period), most spots analyzed by microprobe were not coincident with LA-ICPMS spot locations. In addition, the reader will notice that compositions of WHT augite display wide scatter in both major and trace elements (Figs. 6–9). This compositional scatter is related to the fact that the great majority of WHT samples are clastic rocks, such that each sample may contain mineral grains from several sources.

### RESULTS

#### Bulk-Rock Compositions

Analyzed igneous rocks from the WHT, Rattlesnake Creek terrane, and coeval plutons are magmas and range from calcic to alkalic in the
Figure 5. Bulk-rock compositions of igneous samples of the western Hayfork terrane (lavas and cobbles from lahar deposits), volcanic rocks from the cover sequence of the Rattlesnake Creek terrane, and plutons that may be related to western Hayfork magmatism. With the exception of samples from the Ironside Mountain pluton, nearly all samples are magnesian. The thick gray line outlines the field of average primitive arc basalts (Kelemen et al., 2014). The dashed line in A represents the field of high-silica adakite (Castillo, 2012). Data for Mount Shasta lavas from Grove et al. (2005), for Baja lavas from Saunders et al. (1987), and average Aleutian high-Mg andesite from Castillo (2008). RCT—Rattle Snake Creek terrane.
classification of Frost et al. (2001). In the case of the WHT, such rocks are volcanic clasts in lahar deposits. Rocks from the Ironside Mountain pluton are distinct in having low MgO contents (Fig. 5A) and among the highest FeO* contents (Fig. 5B) of all samples analyzed. Western Hayfork terrane and Rattlesnake Creek terrane cover sequence lavas range to high MgO and Cr contents (Figs. 5A and 5C), suggestive of primitive magma compositions. In contrast, all but four samples of the Ironside Mountain pluton contain less than 80 ppm Cr; these data were not plotted in Figure 5C for the sake of clarity. Strontium abundances range widely in WHT samples but show no correlation with SiO$_2$ (Fig. 5D). Most samples from the Rattlesnake Creek terrane cover sequence are poorer in Sr, generally <300 ppm (Fig. 5D).

In order to provide context for these data, we draw some comparisons with other arc magmas. In Figure 5, the gray-circled field represents the range of averages of primitive arc basalts (Mg# > 60) from 14 modern arcs (Kelemen et al., 2014). We also plotted the average composition of primitive andesite from the Aleutian arc (Kelemen et al., 2014), compositions of adakitic rocks from Baja California (Saunders et al., 1987; Castillo, 2008), and compositions of basaltic through dacitic rocks from Mount Shasta (Grove et al., 2005). High-MgO samples of the WHT are similar to average primitive arc basalts in terms of MgO, FeO*, Cr, and Sr contents. However, a subset of WHT samples is richer in Sr (>800 ppm; Fig. 5D) and slightly overlaps data from Mount Shasta.

These bulk-rock data indicate that the WHT arc consisted, in part, of primitive basalts and potentially of high-Mg andesitic-dacitic rocks. The data also call into question the supposed petrogenetic link between WHT and Ironside Mountain magmatism. However, use of bulk-rock data has limited value in understanding WHT magmatism and testing potential volcano-plutonic relationship for several reasons. First, the great majority of the WHT is sandstone, bulk-rock compositions of which reflect a mixed provenance. Second, there is the potential that post depositional alteration and metamorphism resulted in either depletion or enrichment in the alkalis, Sr, and CaO. For example, many western Hayfork samples contain calcite.
Figure 7. Amphibole compositions. Fields outline amphibole compositions in small plutons coeval with the western Hayfork terrane (WHT). (A) Classification of amphibole (Leake, 1997). Note that the highest Mg contents are in western Hayfork amphibole and the lowest in Ironside Mountain pluton amphibole. IMB—Ironside Mountain batholith. (B) Abundance of A-site cations versus Si (apfu—atoms per formula unit). (C) Calculated temperatures using Equation 5 of Putirka (2016) versus TiO\textsubscript{2} content. Amphibole from western Hayfork samples displays little correlation, whereas amphibole from plutonic rocks displays strong correlation of temperature with TiO\textsubscript{2} content. (D) Calculated temperatures versus MnO contents, illustrating the general increase in MnO with decreasing temperature.
veins and amygdules (Supplemental Fig. S1D [footnote 1]). Third, deuteric alteration of plutonic rocks may similarly mobilize the alkalis ± CaO and Sr. And fourth, at least some of the plutonic rocks are likely to be cumulate. This possibility is reflected in the broad scatter in Ironside Mountain pluton compositions, particularly at low SiO$_2$ contents (Fig. 5).

Isotopic data on the WHT and related plutons are sparse. A basaltic andesite cobble from the WHT (MMB-672D) yielded an initial $^{87}$Sr/$^{86}$Sr (175 Ma) value of 0.70314 (Barnes et al., 1990) and an $\epsilon_{Nd}$ value of 5.6 (Barnes et al., 1992). Three samples from the Forks of Salmon pluton display $^{87}$Sr/$^{86}$Sr (175 Ma) of 0.70346–0.70360, and a fourth sample has an initial ratio of 0.70417 (Masi et al., 1981; Supplemental Table S6 [footnote 2]). Locations and sample descriptions of these samples are in Supplemental Table S1. Isotopic data on the Ironside Mountain batholith (Masi et al., 1981; Barnes et al., 2006) indicate an average initial $^{87}$Sr/$^{86}$Sr of 0.70374 ± 0.00012 for the Ironside Mountain pluton (n = 12) and an average $\epsilon_{Nd}$ of 5.25 ± 0.12 (n = 3). One sample from the West China Peak pluton has initial $^{87}$Sr/$^{86}$Sr of 0.704410 and $\epsilon_{Nd}$ of 3.33 (Barnes et al., 2006).

### Clinopyroxene and Amphibole Major-Element Compositions

A feature common to all units under study is the presence of magmatic augite and/or amphibole. Recent studies (e.g., Putirka, 2008, 2016; Coint et al., 2013; Barnes et al., 2016b, 2017; Zhang et al., 2017) indicate that major- and trace-element abundances of these phases may be used to characterize and compare their magma compositions and evolution. In addition, analysis of unaltered magmatic...
minerals avoids the effects of hydrothermal and metamorphic alteration. Trace-element data presented in this and the following section indicate that in the WHT, augite compositions define two groups. One group features high Sr, Sr/Y, and normalized Nd/Yb, and the other displays lower values of these elements and ratios. The group characterized by high Sr and Sr/Y is, in a trace-element sense, similar to adakitic rocks; however, on the basis of bulk-rock data, many of these rocks are too low in SiO$_2$ to be considered adakite. Moreover, many contain amphibole, which is uncommon in adakite (Bindeman et al., 2005). We therefore choose to refer to these two groups as high-Sr and low-Sr, so as to avoid the descriptive and genetic connotations involved with the term adakite (Castillo, 2012; Kelemen et al., 2014).

### Clinopyroxene

The analyzed clinopyroxene grains range from augite to diopside (Fig. 6A; Supplemental Table S3 [footnote 2]). Clinopyroxene grains in WHT samples display a wide range of Mg# (molar Mg/(Mg + Fe$_{tot}$)), from 0.92 to 0.71. No distinction is evident between augite with high-Sr or low-Sr features. In contrast, Mg# of augite from the Ironside Mountain pluton is <0.7. These low values are distinct from Ironside Mountain satellite plutons (Denny and West China Peak), in which augite Mg#s range from 0.9 to 0.7 (Fig. 6A).

The TiO$_2$ contents of augite generally increase with decreasing Mg# (Fig. 6B). The exception is the Ironside Mountain pluton in which, on a sample-by-sample basis, TiO$_2$ decreases slightly with decreasing Mg#. This anticorrelation of TiO$_2$ and Mg# (except for the Ironside Mountain pluton) indicates that Ti abundances may be used as a crude differentiation index when dealing with trace-element variation in augite.

### Amphibole

Magmatic amphibole in all units is calcic, but ranges widely in composition depending on alkali
and Ti contents (Fig. 7; Supplemental Table S4 [footnote 2]). The highest values of Mg/(Mg+Fe++) are displayed by tschermakitic amphibole from the WHT, and these analyses partly overlap compositions of amphibole from the Forks of Salmon pluton (Fig. 7A). The WHT amphibole also contains the highest A-site alkali contents, with the highest values among amphibole from high-Sr samples (Fig. 7B). The A-site occupancy of amphibole from the Forks of Salmon pluton overlaps WHT amphibole values. As with augite compositions, amphibole from the Ironside Mountain pluton is distinct in having significantly higher Fe contents (Fig. 7A) and higher Si contents for a given value of A-site occupancy (Fig. 7B). Amphibole from the Ironside satellite plutons is distinct in having Mg/(Mg+Fe++) lower than WHT amphibole and higher than Ironside Mountain pluton amphibole (Fig. 7A).

Trace-Element Compositions

Clinopyroxene

Chromium contents vary significantly among augite from the Rattlesnake Creek terrane cover sequence and WHT (Fig. 8A; Supplemental Table S5 [footnote 2]), with the Sr-rich augite displaying the highest Cr contents. In samples where trace-element zoning profiles were measured, it was not uncommon for Cr abundances to vary irregularly from core to rim. For example, in 92OMB-151A, grain 1 (Supplemental Table S5) displays core and rim Cr contents of ~2300 ppm but a mantle zone with >5000 ppm Cr. In sample 92OMB-148, many augite grains display colorless cores with as much as 7700 ppm Cr that are sharply bounded by pale-brown rims whose Cr contents are typically <100 ppm. Moreover, pale-brown zones typically have higher Ti and Zr contents than the colorless zones. The Cr contents of the augite in the Forks of Salmon pluton are very low, with all values <10 ppm. Augite from the Ironside Mountain pluton contains less than 340 ppm Cr, and most samples contain less than 200 ppm Cr.

Although Ni was not analyzed in all samples, it shows similar patterns, with low abundances in augite from the Ironside Mountain and Forks of Salmon plutons and higher abundances in augite from the WHT and Rattlesnake Creek terrane cover sequence (Fig. 8B). Abundances of both Cr and Ni display decreasing values with increasing Ti, except in the Ironside Mountain pluton, where Ni contents decrease with decreasing Ti. These trends are consistent with variation of TiO2 with Mg/(Mg+Fe+), (Fig. 6B) and indicate that increasing Ti is a measure of magma differentiation in all units except the Ironside Mountain pluton. This variability is not evident in bulk-rock compositions—an indication that mineral compositions provide information about magma variability that may be obscured in bulk-rock data, particularly considering most bulk-rock samples are sandstone. Chromium abundances in augite from Aleutian adakitic and basaltic lavas (Fig. 8A) overlap those of WHT augite (Fig. 8A).

Vanadium abundances increase with increasing Ti in all units (Fig. 8C). Except for the Ironside Mountain pluton, this correlation indicates that V behaved incompatibly. In contrast, in the Ironside Mountain pluton, V was compatible during augite crystallization, indicating the effects of Fe-Ti oxide fractionation in that pluton (Barnes et al., 2006).

Concentrations of Zr increase with increasing Ti except in Ironside Mountain pluton, in which Zr contents increase as Ti decreases (Fig. 8D). The high Zr abundances in Ironside Mountain pluton augite are distinct from all other augite data from the Klamath province (Coint et al., 2013; Weiss, 2014; Berry, 2015), most of which display Zr abundances <50 ppm. These high Zr abundances in Ironside Mountain augite are consistent with the relatively high bulk-rock Zr contents of the pluton (Barnes et al., 2006).

Strontium abundances in augite from the WHT and Rattlesnake Creek terrane cover sequence (~20–150 ppm) display little or no correlation with Ti (Fig. 8E). We chose the range 40–150 ppm to characterize the high-Sr group and 20–60 ppm to characterize the low-Sr group (see Fig. 8E). Augite from the Rattlesnake Creek terrane cover unit overlaps these groups, but most samples have Sr abundances similar to those of the low-Sr group (Fig. 8E). Augite from the Ironside Mountain and Forks of Salmon plutons contains <40 ppm Sr. These low abundances are also characteristic of other Jurassic suites in the KMP, such as the Wooley Creek batholith (Coint et al., 2013) and Chetco complex (Weiss, 2014).

The uncommonly high Sr contents of WHT augite are reflected in Sr/Y ratios, which range from 1 to 6 in the low-Sr group and from 2 to 20 in the high-Sr group (Fig. 8F). In both groups, the Sr/Y ratio decreases with increasing Ti. Augite from the Forks of Salmon and Ironside Mountain plutons displays low and very low Sr/Y values, respectively, whereas augite from Rattlesnake Creek terrane cover sequence is similar to augite in the low-Sr group. Augite from Aleutian adakitic rocks is also uncommonly rich in Sr, and many samples display high Sr/Y values (Figs. 8E and 8F).

Total rare-earth element (REE) abundances display positive correlations with Ti except for Ironside Mountain pluton (Fig. 9A). In general, the abundances of individual REE are also correlated with Ti, as is shown for Yb in Figure 9B, with the lowest values from the low-Sr group. Augite from the WHT and Rattlesnake Creek terrane cover sequence also display distinctive rare-earth element patterns (Figs. 10A, 10B, and 10E). These patterns are characterized by a prominent maximum at Nd and Sm and negligible to small negative Eu anomalies. Augite from the Forks of Salmon pluton (Fig. 10D) displays REE patterns with a maximum normalized abundance at Sm, small negative Eu anomalies, and shallower heavy REE slopes. Augite from the Ironside Mountain pluton is distinct from all other units in having deep Eu anomalies and relatively shallow slopes (Fig. 10C). Among all samples, the steepest slopes, illustrated in Figures 9C–9E via the normalized Nd/Yb ratio, are in the high-Sr group. Samples from the low-Sr group typically display lower slopes.

Most augite from Aleutian adakite has lower REE abundances than augite in the low-Sr group (Fig. 10F) and generally lower Nd/Yb ratios (Fig. 9C). Augite from Aleutian basalts displays still lower light REE abundances and therefore the lowest Nd/Yb ratios. The Sr abundances in the Aleutian basalitic augite are among the lowest identified in this study and are similar to the lowest Sr samples from the low-Sr group (Figs. 8E and 9E).
In detail, the REE patterns of WHT augite reveal significant ranges in abundance as well as more subtle variations in REE pattern. For example, in low-Sr group sample KM-7C (Fig. 10E), some individual augite grains display normal zoning (i.e., increasing REE abundance from core to rim), but other grains lack zoning, and some are reversely zoned. Variation in abundance is expected, because the majority of WHT samples are sandstones, which means that individual augite grains are unlikely to be genetically related to others in the sample. However, high-Sr sample MMB-672D (Fig. 10B) is a cobble from a lahar deposit, yet contains normally zoned and reversely zoned augite, which displays a large range of REE abundances, even within individual crystals. These data suggest that sample MMB-672D is a hybrid, with augite from at least two distinct magmas.

**Amphibole**

Trace-element compositions of amphibole span a wide range of Ti contents (Figs. 7C and 11A). In amphibole from the plutonic rocks, Ti is well correlated with calculated temperature (cf. Putirka, 2016 and see below); however, Ti in WHT amphibole is uncorrelated with temperature (Fig. 7C). A proxy for T, and potentially for differentiation, is Mn abundance, which increases with differentiation and, generally, as T decreases (Fig. 7D). Therefore, increasing Mn contents in Figure 11 are considered to provide a crude differentiation index.

Strontium abundances range from ~485 to <10 ppm (Fig. 11D). A distinction may be made between high-Sr and low-Sr amphibole (Fig. 11D) although there is overlap. Nevertheless, samples that contain both augite and amphibole may be consistently classified as either high- or low-Sr. The
Sr contents in amphibole from other arc-related calc-alkaline plutons are commonly less than 120 ppm (Coint et al., 2013; Barnes et al., 2016b, 2017). Thus, Sr contents in WHT amphibole are higher than is typical of arc amphibole. Although Sr contents decrease with increasing Mn, Y abundances generally increase with increasing Mn (Fig. 11E). This combination of decreasing Sr and increasing Y thus leads to a prominent decrease in Sr/Y with increasing Mn (Fig. 11F).

As with augite, the Cr contents in WHT amphibole reach values as high as ~1300 ppm among the high-Sr group, but are lower in the low-Sr group (Fig. 11B). Zirconium contents in WHT amphibole increase with increasing Mn, suggesting that Zr behaved incompatibly during amphibole crystallization. In the remaining plutonic samples, Zr concentrations are not correlated with Mn content.

Representative REE patterns for amphibole (Fig. 12) resemble those of augite in that amphibole from high-Sr samples displays a maximum in the light REE, steep heavy REE slopes, and small to negligible Eu anomalies. Many amphibole grains with low-Sr affinities contain lower REE contents and display a wider range of REE abundances (Figs. 12E and 12F). The REE patterns of amphibole from the Forks of Salmon pluton are similar to those in amphibole from low-Sr sample KM-38 (Fig. 12F).

**Magmatic Temperature and Pressure**

Crystallization temperatures for augite and amphibole were estimated using the algorithms of Putirka (2008, 2016, respectively; Supplemental Table S2 [footnote 2]). Crystallization temperatures of augite from lavas in the Rattlesnake Creek terrane cover sequence and in clasts in the WHT were calculated using two thermometers based on augite-bulk-rock data (Equations 33 and 34, Putirka, 2008) and a clinopyroxene-only thermometer (Equation 32d). In general, the clinopyroxene-only thermometer yields the highest T estimates. Some sand grains contain both augite and amphibole. The sand grains are too small to analyze for bulk composition; therefore, the chemical composition of amphibole was used to calculate the composition...
of melt in equilibrium with the amphibole (Zhang et al., 2017), and potentially with coexisting augite. This calculated melt composition was then used in Putirka’s (2008) Equations 33 and 34. Inasmuch as melt calculated from amphibole compositions is likely to be more evolved than the melt originally in equilibrium with augite, these temperatures are considered to be minima.

Augite from the Rattlesnake Creek terrane cover sequence yielded augite–bulk-rock temperatures in the range 1095–1133 °C and clinopyroxene-only temperature estimates from 1157 to 1166 °C. Augite from the WHT yielded augite–bulk-rock temperatures in the range 1078–1177 °C and augite-only temperatures from 1160 to 1180 °C. Temperature estimates in which calculated melt compositions (from amphibole) were used ranged from 982 to 1038 °C. Average temperatures estimated from amphibole compositions range from 863 to 981 °C. Among the three samples with coexisting augite and amphibole, estimated T decreases from the highest values using clinopyroxene-only thermometry to augite–melt thermometry, to amphibole thermometry, as expected in H₂O-bearing mafic to intermediate magmas. Moreover, values of amphibole stability as high as 981 °C suggest relatively H₂O-rich compositions in at least some of the WHT magmas (e.g., Grove et al., 2005; Nandedkar et al., 2014).

Augite compositions may also be used to estimate pressure of crystallization (Putirka, 2008). We used two augite-melt barometers and an augite-only barometer that takes into account H₂O content of the melt (Equations 30, 31, and 32C respectively; Putirka, 2008). In the augite-melt barometer, melt compositions were assumed to be bulk-rock compositions for augite from analyzed cobbles or melt compositions estimated on the basis of amphibole compositions in sand grains with coexisting augite and amphibole. All of the augite–“melt” pressure estimates used 4 wt% H₂O in the melt, which is sufficient for amphibole stability but typically less than abundances necessary for fluid saturation. Use of this H₂O content resulted in pressure estimates from 470 ± 250–670 ± 90 MPa (Equation 30), 620 ± 170–1050 ± 100 MPa (Equation 31), and 550 ± 190–880 ± 160 MPa (Equation 32C). The uncertainties listed are one standard deviation on individual mineral
analyzes and do not take into account the large uncertainties of the fitted Equations (360, 290, and 150 MPa for Equations 30, 31, and 32c, respectively).

Equation 31 yields pressure estimates as high as 1050 MPa, which is within the stability field of garnet (e.g., Ulmer et al., 2018). In contrast, Equations 30 and 32c return pressure estimates ≤470 and ≤880 MPa, suggestive of crystallization in mid-to lower-crustal magma reservoirs. If this range of estimated pressures is correct, then the experiments of Nandedkar et al. (2014) and Ulmer et al. (2018) are applicable. The WHT rocks are characterized by a virtual lack of olivine phenocrysts, even in the least evolved cobbles, so that the predominant mafic phase at high T was augite (~1175–1180 °C), with amphibole crystallizing at T as low as high as ~980 °C. Orthopyroxene is lacking, either in cobbles or as detrital grains. This sequence of crystallization is similar to that determined in 700 MPa experiments for H2O-undersaturated conditions (Nandedkar et al., 2014), except that the Nandedkar (2018) experiments produced minor proportions of orthopyroxene at the same T as amphibole appearance (~1010 °C). In these experiments, the proportion of orthopyroxene was routinely small compared to amphibole. We therefore suggest that slight differences between WHT parental magmas and the starting composition used by Nandedkar et al. (2014) may explain the lack of orthopyroxene in WHT samples.

In summary, the data indicate augite crystallization at temperatures as high as 1180 °C in WHT magmas. In some magmas, amphibole began to crystallize near 1025 °C (Fig. 7C), whereas in others, amphibole crystallized to T as low as ~800 °C. If minimum amphibole temperatures reflect eruption temperatures, then many WHT magmas erupted in the ~800–975 °C range. The wide range of P estimates, along with the large uncertainties associated with them, serve mainly to suggest that many WHT magmas were stored in mid- to deep-crustal reservoirs. The high-T stability of amphibole indicates that the magmas contained sufficient H2O to stabilize amphibole (>3 wt% and probably as much as 6 wt%). Moreover, the absence of orthopyroxene indicates that melt compositions were too CaO-rich to stabilize orthopyroxene.

### Melt Compositions

Mineral-melt Fe-Mg exchange equations were used to estimate the Mg# of melts from which augite and amphibole crystallized (Putirka, 2008, 2016). For augite, the Fe-Mg Kd value of 0.28 ± 0.08 (Putirka, 2008) yields estimates of melt Mg# as high as 0.77 to as low as 0.39 (Fig. 6B). For amphibole, the melt Mg# values estimated using Fe-Mg Kd of 0.27 ± 0.11 (Putirka, 2016) are in a narrower range of 0.77–0.64, which is in agreement with the high end of Mg# estimates from augite compositions.

Arc-related melts with Mg# > 0.70 are generally considered to be primitive, in the sense that they could be in equilibrium with mantle olivine. Therefore, several WHT samples and two samples from satellite plutons of the Ironside Mountain batholith could be mantle derived (Fig. 6B), and this conclusion is consistent with the high Cr and Ni concentrations in WHT augite, the Ti contents of which are less than 2000 ppm (Figs. 8A and 8B). In addition, the overall increase in TiO2 with decreasing calculated Mg#(melt) (Fig. 6B), along with increasing V and Zr, indicates that Fe-Ti oxides and zircon were not important fractionating phases in WHT magmas, in accord with the absence of Fe-Ti oxide phenocrysts and zircon in WHT samples.

Melt abundances of Sr and Y were also calculated using mineral/melt partition coefficients (d). As with all such calculations, d values are functions of melt composition and polymerization, temperature, and co-precipitating phases. Inasmuch as WHT magmas spanned a range from basaltic to dacitic, we calculated Sr abundances and Sr/Y ratios using d values for basalt (Norman et al., 2005) and dacite (Severs et al., 2009). Calculations using d values from Norman et al. (2005; d Sr = 0.058, d Y = 0.46) yield maximum Sr concentrations of ~2500 ppm and Sr/Y values as high as 160 in melts associated with augite from the high-Sr group. Use of d values from Severs et al. (2009, d Sr = 0.10, d Y = 0.95) result in maximum Sr(melt) concentrations of ~1500 ppm and Sr/Y values as high as 190. Results of this latter calculation are shown as the right-hand y-axis values in Figures 8E and 8F and in Figure 13A. It is noteworthy that among the high-Sr group, increasing Sr/Y is correlated with increasing Cr contents.

Figure 13. Calculated values of Sr/Y versus Y (A) and La/Yb versus Yb (B) of melt in equilibrium with augite using partition coefficients from Severs et al. (2009).

We also used d values from Norman et al. (2005) and Severs et al. (2009) to calculate REE patterns of melts in equilibrium with augite compositions. The two sets of d values result in similar REE pattern shapes, with relatively steep slopes among high-Sr samples and shallower slopes among
These same high-Mg magmas were characterized as adakite or adakitic (e.g., Saunders et al., 1987; Grove et al., 2005; Castillo, 2012; Kelemen et al., 2014; Yogodzinski et al., 2015).

Yogodzinski and Kelemen (1998) published trace-element compositions of augite in basaltic and high-Mg andesitic (adakitic) rocks from the Adak Island area of the Aleutian arc. When compared to augite from Aleutian lavas, Ti abundances in WHT augite are similar, although WHT augite ranges to higher Ti contents (Fig. 8). Abundances of Cr, Zr, and Sr in Aleutian adakitic augite overlap those of the high-Sr group, whereas augite from Aleutian basaltics is similar to augite of the low-Sr group (Fig. 8A, 8D, and 8E). The same relationship is evident in Sr/Y and La/Yb ratios (Fig. 13). In contrast, REE abundances in augite from Aleutian adakite are typically lower than in augite of the high-Sr group, particularly the light and middle REE (Fig. 10). The REE patterns of some samples of low-Sr augite overlap those of augite from Aleutian basaltics, although many low-Sr group augite grains display higher light and middle REE contents (Fig. 10E).

The trace-element features considered characteristic of adakitic magmas, and commonly of high-Mg andesite and related magmas—low Y and HREE, high Sr, Sr/Y, and Nd/Yb—are considered to be typical of residual garnet. The question of where and how garnet fractionates has led to a variety of tectonic and petrogenetic models. Among these models are (1) partial melting of eclogitic oceanic crust in the subducting slab, yielding adakitic melts (Defant and Drummond, 1990); (2) partial melting of garnet-bearing rocks (eclogite) in the slab, after which the produced melt metasomatizes peridotite in the mantle wedge (e.g., Kay, 1978; Martin et al., 2005) resulting in subsequent mantle wedge melts with trace-element signatures of residual garnet; (3) partial melting of deep-seated, garnet-bearing mafic crustal rocks (e.g., Stevenson et al., 2005; Qian and Hermann, 2013; Hastie et al., 2015); (4) fractional crystallization with residual garnet and/or amphibole (Macpherson et al., 2008; Xu et al., 2015); and (5) more complicated versions of (2) with formation of mantle-wedge pyroxenite, and siliceous melts thereof, which then rise diapirically through the wedge, pond in the upper mantle, and variably erupt and/or mix with basaltic magmas produced in the hottest zones of the mantle wedge (Yogodzinski et al., 2015). Many studies of high-Mg andesite and adakite petrogenesis call on disruption of the subducting slab, for example slab tears, which expose subducted lithosphere to higher-T conditions due to rising asthenospheric mantle (e.g., Falloon et al., 2008; Ayabe et al., 2012; Castillo, 2012).

High values of Mg# in augite from several WHT samples, and the resulting high Mg# calculated for melt compositions (Fig. 6), suggest that some WHT magmas were primitive. That is, they formed by partial melting of mantle peridotite with minor subsequent differentiation. This interpretation is consistent with the high Cr and Ni contents observed in the most primitive (lowest Ti) augite (Fig. 8). Another characteristic of the magma source is the Zr/Hf ratio, which may be estimated from augite compositions. The calculated Zr/Hf value of all WHT melts is 40.7 ± 5.4 using mineral/melt partition coefficients from Norman et al. (2005) and 37.9 ± 5.0 using partition coefficients from Severs et al. (2009). Both averages are, within uncertainty, near the range of mid-ocean ridge basalt (MORB)–source mantle (McDonough and Sun, 1995). It is noteworthy that most of the features cited above describe both high-Sr and low-Sr groups. It is only in the somewhat higher Cr contents of the high-Sr group where the groups differ slightly.

The paucity of olivine in the WHT, including samples with high-Mg augite, further suggests that basaltic bulk compositions were subordinate to andesitic and more evolved magmas. It is possible to calculate melt compositions in equilibrium with calcic amphibole using equations derived by Zhang et al. (2017). Inasmuch as this approach may only be used with amphibole-bearing samples, it probably underestimates the proportion of mafic magmas. Nevertheless, the total array of melt compositions is consistent with petrographic inferences on the range of magma types (basalt to rhyodacite), and apparent clustering of compositions from 55 to 65 wt% (Fig. 15) suggests that basaltic andesite and andesite were most abundant.

Increases in Zr, V, and REE abundances with increasing Ti in augite (Figs. 8 and 9) additionally suggest that primary WHT magmas underwent...
Figure 14. Examples of melt rare-earth element (REE) patterns calculated using clinopyroxene partition coefficients from Severs et al. (2009).
The data strongly indicate that magma mixing was a common process during WHT magmatism. These data include non-systematic zoning in individual crystals, including abrupt compositional changes associated with color zoning, rim-ward increases in Cr in some samples, and irregular core-rim zoning of REE (Fig. 10), despite the general correlation of REE with Ti. These features are found in individual crystals in augites, as well as in phenocrysts in cobbles (e.g., sample MMB-672D). The data indicate that some compositional variation within WHT minerals resulted from magma mixing of evolved (higher Ti, Y, REE, lower Mg#) magmas with less evolved, potentially primitive (lower Ti, Y, REE, higher Mg#) magmas, where “primitive” can mean either basaltic or high-Mg andesitic magmas. Additional support for this idea comes from the fact that most high Sr/Y analyses are from augite cores, although a number of high Sr/Y values are rim compositions (Supplemental Table S5 [footnote 2]).

In summary, a simplistic model of WHT magmatism involves (1) generation of high-Mg andesitic magmas along with somewhat less basaltic magma; (2) fractionation of both magma types in crustal reservoirs; and (3) mixing of primitive magmas with fractionated magmas. Because the high-Sr and low-Sr groups can be distinguished in many trace-element diagrams (Figs. 8 and 9), we suggest that primitive magmas generally mixed with differentiated magmas in the same magma group; that is, primitive high-Sr magma with evolved high-Sr magma, etc.

We tentatively interpret the geochemical features of primitive high-Sr group magmas (high Mg#, Cr, and Ni) as mantle-derived. This interpretation is consistent with petrogenetic models in which partial melting of subducted eclogitic lithosphere yields felsic magmas that rise into and hybridize with peridotite in the mantle wedge, followed by partial melting of the hybrid peridotite (e.g., Kay, 1978; Martin et al., 2005; Yogodzinski et al., 2015). Genesis of the low-Sr group magma is less clear-cut but is consistent with partial melting of non-hybridized mantle peridotite to produce primary basaltic magmas (e.g., Yogodzinski et al., 2015).

**Tectonic Setting**

Magma compositions of the WHT, as deciphered from augite and amphibole data, are similar to those of the High Cascade and Aleutian arcs (and others) in the sense that both high-Mg, high-Sr andesitic magmas and more typical arc basaltic magmas are present, and that these magmas may undergo differentiation and mixing in crustal magma chambers (e.g., Smith and Leeman, 1993; Grove et al., 2002, 2003, 2005; Kelemen et al., 2014; Yogodzinski et al., 2015; Sas et al., 2017). Compared to the High Cascade arc, the sedimentary record of the WHT, and particularly the paucity of olivine (Wright and Fahlan, 1988; this work), suggest that basaltic magmas were less abundant in the WHT and that differentiated amphibole-bearing dacitic and rhyodacitic magmas were more abundant.

As discussed above, generation of high-Mg andesite with adakitic trace-element features is explained by some workers as a result of subduction of young, hot lithosphere, whereas others suggest that slab failure and/or disruption of the slab allows for rise of hot asthenosphere, giving rise to slab melting. Obviously, information about the structure of subducting lithosphere beneath the KMP during Middle Jurassic time has been lost. However, it is reasonable to conclude that the WHT deposits were related to a west-facing arc (Fig. 16A). This interpretation is, in part, based on the presence of quartz- and K-feldspar-rich arenite in stratigraphically high parts of the WHT. These strata require a provenance capable of supplying quartz-rich sediment, presumably the North American craton. If the WHT were associated with west-dipping subduction, such sediments would have been consumed in the trench. In addition, we postulate that the WHT magmas resulted from subduction of a young slab, because augite characteristic of high-Mg magmas occurs in all areas studied—along at least 150 km of strike length of the WHT. This feature is suggestive of an area-wide source of high-Mg magmas rather than a slab tear, which would be expected to affect somewhat shorter strike lengths in the arc (e.g., Rosenbaum et al., 2008).

**Relationship between WHT Magmas and Middle Jurassic Plutons**

Previous workers (Lanphere et al., 1968; Hotz, 1971) correlated WHT magmatism with the Ironside Mountain batholith, and particularly with the Ironside Mountain pluton. However, both bulk-rock (Fig. 5) and augite (Figs. 6–9) data indicate that Ironside Mountain magmas bear no geochemical or petrologic similarity to WHT magmas. This dissimilarity is consistent with the fact that the Ironside Mountain pluton postdates deposition and thrusting of the WHT (Fig. 16B).

Augite in the Forks of Salmon pluton is similar to augite from the low-Sr group; so it is permissible that this pluton is the intrusive equivalent of the WHT. If this is the case, then it is important to note that the Forks of Salmon pluton intrudes the eastern Hayfork terrane, which was emplaced over the WHT along the west-vergent Wilson Point...
thrust. If the Forks of Salmon pluton is related to the WHT arc, and considering that the Rattlesnake Creek terrane is the depositional basement of WHT sediments, it is logical that during WHT magmatism, the Rattlesnake Creek terrane was juxtaposed against the eastern Hayfork terrane (Fig. 16A). In addition, it is possible that arc volcanoes responsible for WHT sedimentary rocks were constructed above the eastern Hayfork terrane (Fig. 16A). If this were the case, then the arc axis would have been thrust, along with its host eastern Hayfork terrane, beneath the inboard North Fork terrane (Fig. 2) at the same time the eastern Hayfork terrane was thrust over the now-exposed WHT (Fig. 16B).

An alternative explanation for the lack of an arc axis is the presence of the axis to the west, in an outboard position. In this scenario, the arc was migrating (northward?) along the Cordilleran margin, making the WHT a backarc deposit laid down on the already-accreted Rattlesnake Creek terrane. In this case, a potential source of WHT sands would be the Talkeetna-Bonanza arc (e.g., Hillhouse and Coe, 1994; DeBari et al., 1999; Clift et al., 2005; Wurth, 2019).

■ CONCLUSIONS

The western Hayfork terrane consists primarily of metasedimentary rocks associated with Middle Jurassic arc magmatism in the Klamath Mountain province. Crystal-lithic arenites are intercalated with argillitic sediments, lahar deposits, and rare lavas. Greenschist-facies regional metamorphism resulted in actinolite ± chlorite ± epidote + albite assemblages, but many samples preserve igneous clinopyroxene and calcic amphibole, which were phenocrysts in the original volcanic rocks. Major- and trace-element compositions of the magmatic pyroxene and amphibole indicate that WHT magmas ranged from scant basalt, volumetrically dominant basaltic andesite and andesite, and smaller but significant amounts of dacite and rhyodacite. Pyroxene and amphibole thermometry indicate eruptive temperatures as high as ~1180 °C and as low as ~800 °C, with most pyroxene temperatures >1000 °C.

Approximately half of the analyzed samples are characterized by Mg-rich augite, the trace-element abundances and ratios (e.g., high Cr, Sr, Sr/Y, Nd/Yb; low Y, and heavy REE) of which are typical of high-Mg andesite and dacite suites in which garnet is a residual mineral. The remaining samples have lower Sr, Sr/Y, and Nd/Yb—features typical of normal calc-alkaline magmas. Augite from the inboard Forks of Salmon pluton is similar to augite of the low-Sr group of WHT samples. These data are consistent with development of the WHT as a west-facing magmatic arc associated

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Figure 16. Schematic diagrams of western Hayfork terrane (WHT) deposition and relationships to subsequent magmatism (after Harper and Wright, 1984). (A) Deposition of WHT arc. In this interpretation, the arc axis is inferred to lie inboard of present exposures. In this model, the Rattlesnake Creek and eastern Hayfork terranes were juxtaposed at this time, allowing construction of the main arc on the eastern Hayfork terrane and deposition of WHT sediments on both terranes. This model is non-unique but is consistent with WHT-aged plutons that intrude the eastern Hayfork terrane (Forks of Salmon and Uncles Creek plutons) and the WHT (Squaw Mountain pluton). (B) Contractual deformation at ca. 170 Ma telescoped the WHT and its Rattlesnake Creek terrane basement against the eastern Hayfork terrane (eHT) along the Wilson Point thrust. At the same time, the eastern Hayfork terrane was juxtaposed under the inboard North Fork terrane (NFT). Therefore, if the model illustrated in panel A is correct, the arc axis was truncated by thrusting. Regional contraction was followed by development of the Ironside Mountain batholith, which intrudes Rattlesnake Creek, western Hayfork, and eastern Hayfork terranes. The basal metasedimentary unit in yellow is inferred on the basis of isotope data (Allen and Barnes, 2006).
with subduction of relatively young oceanic lithosphere. Partial melts of eclogitic rocks in the slab rose into the mantle wedge and metasomatized wedge peridotite. Subsequently, melting of the metasomatized mantle gave rise to high-Mg magmas with the garnet signature (high-Sr group), whereas partial melting of non-metasomatized mantle resulted in magmas with typical calc-alkaline trace-element signatures (low-Sr group). The location of the arc axis is unknown. If it was to the east, it was underthrust beneath older terranes during Siskiyou orogeny, and exposed WHT rocks represent the forearc. If it was to the west, it is possible that the WHT is a backarc assemblage associated with a northward-migrating arc, such as the Talkeetna-Bonanza arc.

Finally, our results demonstrate the utility of detailed major- and trace-element analysis of detrital magmatic phases as a means to better understand ancient arc magmatism. Augite and hornblende grains that survived regional low-grade metamorphism provide information about magmatic affinities, processes, and temperatures.

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