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The Castle Rock and Ironside Mountain Calderas, Eastern Oregon, USA: Adjacent Venting Sites of Two Dinner Creek Tuff Units—The Most Widespread Tuffs Associated with Columbia River Flood Basalt Volcanism

Matthew Cruz
Portland State University

Martin J. Streck
Portland State University, streckm@pdx.edu

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The Castle Rock and Ironside Mountain calderas, eastern Oregon, USA: Adjacent venting sites of two Dinner Creek Tuff units—the most widespread tuffs associated with Columbia River flood basalt volcanism

Matthew Cruz and Martin J. Streck[†]
Department of Geology, Portland State University, Portland, Oregon 97201-5221, USA

ABSTRACT

The Dinner Creek Tuff is an important unit of mid-Miocene rhyolite volcanism contemporaneous to flood basalts of the Columbia River magmatic province. Field mapping along with analytical data of tuff samples identify two calderas, the Castle Rock and Ironside Mountain calderas, as the venting sites of two widespread ignimbrites of the Dinner Creek Tuff. Both calderas lie within the area of the proposed general storage sites of main-phase Columbia River Basalt magmas. The Castle Rock caldera formed during the eruption of the 16.16 Ma Dinner Creek Tuff unit 1. The northwestern boundary of the caldera is roughly defined by the juxtaposition of over 300 m of densely welded rheomorphic intra-caldera tuff and tuffaceous mega-breccia deposits against Mesozoic Weathersby Formation shale and pre-Miocene Ring Butte trachybasalt lavas. Following caldera collapse, fluvial and lacustrine volcaniclastic sediments were deposited on the caldera floor, and outflow tuffs of the Dinner Creek Tuff units 2 and 4 were deposited into the caldera. Aphyric basaltic andesite and icelandite (Fe-rich andesite), which correlate stratigraphically to upper Grande Ronde Basalt lavas, intrude the caldera floor deposits, and lavas are interbedded with sediments and Dinner Creek Tuff unit 4.

The Ironside Mountain caldera formed during eruption of the 15.6 Ma Dinner Creek Tuff unit 2, which lies ~15 km north of the Castle Rock caldera. The caldera is an 11 × 6 km depression wherein over 900 m of intra-caldera, rheomorphic, and partially welded tuff are bound by Weathersby Formation shale and Tureman Ranch granodiorite. Post-caldera collapse, basaltic andesite and icelandite dikes and sills that are also stratigraphically correlative to upper Grande Ronde Basalt lavas intruded into the tuff, mostly along the margins of the caldera, which altered much of the tuff.

Mafic lavas within the study area that closely pre- and post-date Dinner Creek Tuff units were correlated with regional units of the Columbia River Basalt Group. Porphyritic and aphyric mafic lava flows underlying Dinner Creek Tuff unit 1 at Castle Rock are correlated with Picture Gorge Basalt and Grande Ronde Basalt. Aphyric basaltic andesite and icelandite that intrude into and overlie the Dinner Creek Tuff units 1 and 2 are westward extensions of fractionated tholeiitic magmas as seen in late-stage Grande Ronde Basalt units such as the Hunter Creek Basalt. Finally, porphyritic basalt lava flows that overlie the Hunter Creek Basalt and volcaniclastic sediments at the Castle Rock caldera are correlative with the 13.5 Ma Tim's Peak Basalt. At Castle Rock, pre-caldera Columbia River Basalt Group lavas appear to lap onto a mid-Miocene topographic high that stretches northward and westward for tens of kilometers based on stratigraphic data, and it may be related to regional uplift at initial impingement of the mantle upwelling to produce the Columbia River Basalt Group.

The Castle Rock and Ironside Mountain calderas exemplify bimodal volcanism of the Columbia River magmatic province. Eruption of rhyolites is closely pre- and post-dated by the eruption of local and regional tholeiitic lavas belonging to the Columbia River Basalt Group. The local eruption of evolved tholeiitic lavas likely concealed calderas, but these lavas also illustrate the close proximity of mafic and rhyolitic magmas at depth at these rhyolite centers. Consequently, the stratigraphy of both the Castle Rock and Ironside Mountain calderas somewhat differs from that of rhyolite calderas dominated by silicic and calc-alkaline intermediate pre- and post-caldera volcanism.

INTRODUCTION

Ignimbrites of the mid-Miocene Dinner Creek Tuff of eastern Oregon, USA, are the most widespread silicic volcanic units of the mid-Miocene rhyolite flare-up that is associated with the nearly contemporaneous main-phase members of the Columbia River Basalt Group (Webb et al., 2018). Eruption of the Columbia River Basalt Group tholeiitic lavas is thought to have begun in southeastern Oregon and migrated northwards into northeastern Oregon and southeast Washington (Fig. 1) (Wolff and Ramos, 2013), although this has been recently called into question (Cahoon et al., 2020). Centers of silicic volcanism seemingly parallel this northward migrating trend, beginning with the High Rock and McDermitt caldera complexes in northern Nevada and southeastern Oregon, respectively, and migrating northwards to the Lake Owyhee Volcanic Field (Marcy, 2014; Streck et al., 2015; Coble and Mahood, 2012; Benson and Mahood, 2016; Benson et al., 2017; Henry et al., 2017), although new age data from undated centers and the redating of centers with prior age information in eastern Oregon have also called the northward migration of silicic centers into question (Streck et al., 2017; Webb et al., 2018) (Fig. 1). Flood basalt lava flows, Basin and Range faulting, and erosion have obscured many of these silicic volcanic centers, and disagreements remain as to their exact boundaries (e.g., Coble and Mahood, 2012; Benson and Mahood, 2016). Hence, detailed field investigations are critical and provide the needed base data.

The Dinner Creek Tuff was first described in the 1960s and 1970s and was originally restricted to the Castle Rock and Malheur River Gorge area, with a maximum aerial distribution of ~2000 km^2 (Fig. 1; Kittleman et al., 1965; Haddock, 1967; Woods, 1976). Field work in the following decades expanded the area of the tuff, grouped it into the Lake Owyhee Volcanic Field along with

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Martin J. Streck http://orcid.org/0000-0003-3329-6568
[†]Corresponding author: streckm@pdx.edu.

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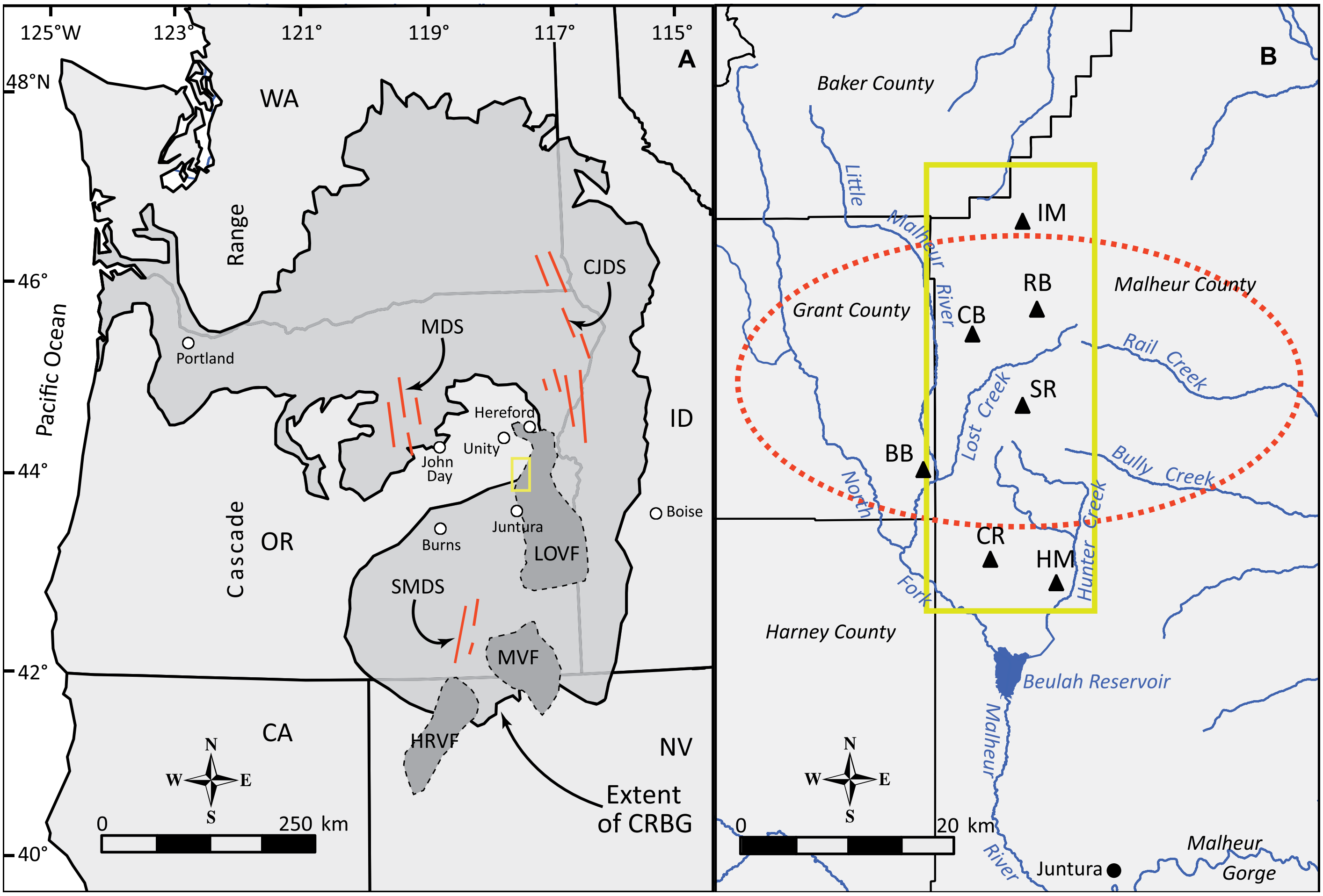

Figure 1. (A) Map of the Pacific Northwest shows the extent of Columbia River Basalt Group (CRBG) lava flows and source dikes (SMDS—Steens Mountain Dike Swarm; MDS—Monument Dike Swarm; CJDS—Chief Joseph Dike Swarm). Contemporaneous silicic volcanic fields are also shown (HRVF—High Rock Volcanic Field; MVF—McDermitt Volcanic Field; LOVF—Lake Owyhee Volcanic Field). Extent of study area is defined by yellow rectangle shown in Figures 1A–1B. Figure was modified from figure 1 of Ferns and McClaughry (2013). (B) Close-up view of study area shows major streams and topographic high points (CR—Castle Rock; HM—Hunter Mountain; IM—Ironside Mountain; BB—Black Butte; SR—Sheepshead Rock; CB—Clevenger Butte; RB—Ring Butte). The red dotted oval is the Dinner Creek Tuff Eruptive Center as defined by Streck et al. (2015).

several other regionally extensive rhyolitic tuffs, lava flows, and domes, and postulated a source caldera near Castle Rock without providing any field evidence (Brooks et al., 1979; Rytuba et al., 1989; Rytuba and Vander Meulen, 1991; Ferns et al., 1993; Evans and Binger, 1997). The only actual published field work that existed to support this interpretation was based on the M.S. thesis work by Woods (1976), who interpreted the prominent physiographic feature of Castle Rock and other nearby outcrops of Dinner Creek Tuff as dikes that served as sources of the tuff. More recently, Streck et al. (2015) analyzed tuff samples from outcrops across eastern Oregon and included some that were previously identified as Dinner Creek Tuff and others that were identified as different tuffs (Mascall Ignimbrite, tuff of Paradise Valley, and tuff of Bully Creek). This study concluded that the Dinner Creek Tuff consists of four ignimbrites, discussed below as Dinner Creek Tuff units 1–4, which vary in age, subtly in major/trace element geochemistry, and in the main feldspar phenocryst phase. Streck et al. (2015) expanded the aerial distribution to >32,000 km^2 and, based on the distribution of the tuff outcrops, identified a general source area in Malheur County, southeastern Oregon, between Castle Rock and Ironside Mountain that they called the Dinner Creek Tuff Eruptive Center (Fig. 1B).

Identifying the location of eruptive sources of ignimbrites of the Dinner Creek Tuff plays a key role in our understanding of the timing and distribution of the silicic component of the bimodal Columbia River magmatic province. This paper summarizes field work within a 35 × 14 km area of the proposed source area of the Dinner Creek Tuff, between Castle Rock in the south and Ironside Mountain in the north, to delimit the exact source of the ignimbrites. Data from tuff samples were used to identify individual Dinner Creek Tuff units within the study area and, in conjunction with field mapping data, to identify their respective eruptive centers. Analytical data from lava samples of the stratigraphy of the area were used to correlate lavas with regional mafic units and Columbia River Basalt Group members to better understand the temporal relation of the Dinner Creek Tuff Eruptive Center with flood basalt volcanism. Finally, the size of the Dinner Creek Tuff Eruptive Center and its temporal and spatial relation to the Columbia River Basalt Group and other silicic volcanic centers are considered.

METHODS

Samples were collected from tuff outcrops across the study area. Major and trace element geochemical data, feldspar phenocryst data, and lithological characteristics were used to identify individual Dinner Creek Tuff units. Major and trace element data were also acquired for mafic lavas that pre- and post-date the Dinner Creek Tuff to correlate the lava flows with regional volcanic units. The locations of the samples were recorded using a global positioning system (GPS) unit.

Major and trace element data from 52 samples were acquired by X-ray fluorescence spectroscopy (XRF) and inductively coupled plasma–mass spectrometry (ICP-MS) at the GeoAnalytical Lab at Washington State University (WSU), Pullman, Washington, USA. Sample preparation followed the standard procedures of the lab (Hooper et al., 1993; Knaack et al., 1994; Johnson et al., 1999).

Fifteen tuff samples were selected for feldspar analysis in the Zeiss Sigma scanning electron microscope (SEM) at Portland State University, Portland, Oregon, USA. The samples were selected to discriminate among individual units of the Dinner Creek Tuff. Analysis was done after feldspar separation and mounting in an epoxy plug with five samples per plug and six to 11 crystals per sample. Analysis within the SEM was done in high vacuum mode. The accelerating voltage was set to 15 KeV, the aperture was set to 60 μm, and working distance was set to 8.5 mm. Prior to sample analysis, the beam was calibrated on copper tape and set to high current mode to improve analysis. Editing of the data involved checking elements by oxide wt% and removing anomalous and poor measurements. Plagioclase spectra with oxide wt% totals below 90 were discarded.

REGIONAL GEOLOGY AND PRIOR WORK

Here we provide a review of the regional geology of eastern Oregon and prior work in the area of this study. Both are needed to place our mapping results into a regional geological framework and disciplinary context.

The basement of eastern Oregon consists of accreted island arcs, oceanic crust, and accretionary prism sediments of the Blue Mountains Province (Figs. 2A and 3). These terranes were accreted, from east to west, to the North American continent from the Late Permian to the Late Jurassic (Dickinson, 1979; Walker, 1989; Ave Lalemant, 1995; Dickinson, 2008; LaMaskin et al., 2011). A marine fore-arc basin formed in the Late Triassic, known as the Izee Basin, in which sandstones, siltstones, shale, and minor limestone were deposited unconformably atop oceanic crust and an accretionary prism into the mid-Jurassic (Dorsey and LaMaskin, 2008; LaMaskin et al., 2011; Ware, 2013). The eastern portion of these sediments is known as the Weathersby Formation, and it crops out in the central part of the study area. Northeast-trending folds are common in the Weathersby Formation due to the northwest/southeast convergence of the Blue Mountain terranes, which continued into Late Jurassic time (Lowry, 1968; Ave Lallemant, 1995; Ware, 2013). Plutons intruded into the Blue Mountain Province during the Late Jurassic and Early Cretaceous, usually along suture zones between the individual terranes (Walker, 1986, 1989; Ware, 2013). One such pluton, the Tureman Ranch biotite–hornblende tonalite, crops out along the southern flanks of Ironside Mountain. It is an oval, 6 × 3 km mass that was intruded into the surrounding Weathersby Formation along vertical to near vertical contacts (Lowry, 1968; Thayer and Brown, 1973). Minor stocks and dikes cut across the Weathersby For-

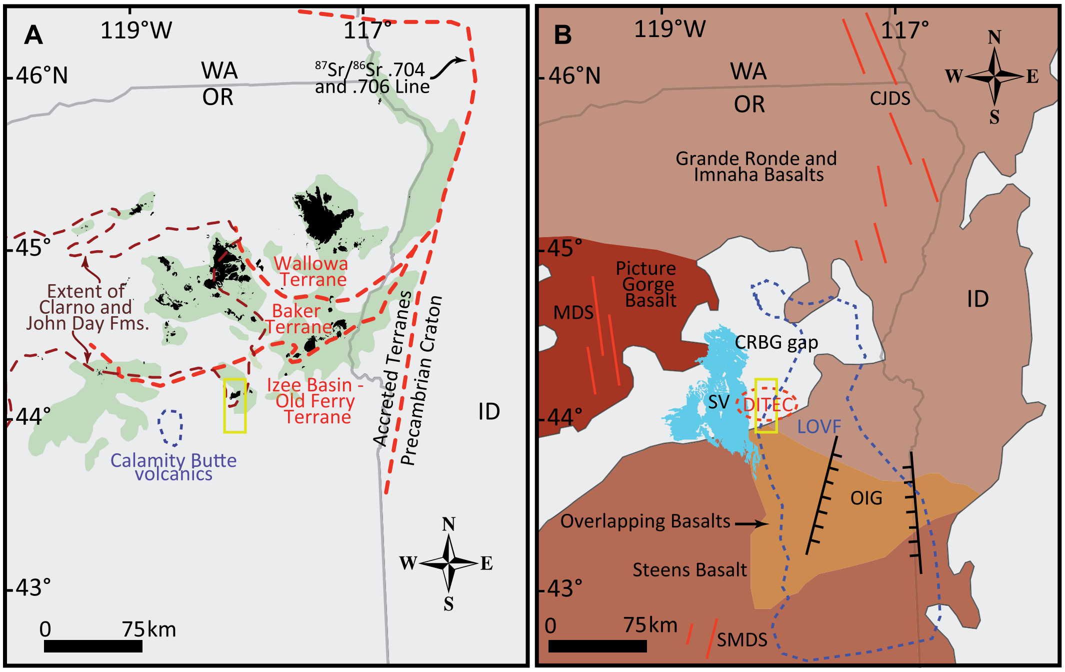

Figure 2. (A) Map of eastern Oregon shows outcrops of sedimentary and metamorphic Paleozoic to Mesozoic Blue Mountain Terranes (green) (Dorsey and LaMaskin, 2007; McClaughry et al., 2009). Terrane boundaries are shown as red dotted lines. The ^{87}Sr/^{86}Sr 0.704 and 0.706 line is interpreted to be the boundary between accreted terranes to the west and Precambrian North American continental crust to the east (Armstrong et al., 1977). Black shaded areas are Jurassic to Cretaceous plutons. Brown dashed line is aerial extent of Eocene Clarno Formation and Oligocene John Day Formation lava flows and tuffs (McClaughry et al., 2009). Blue dotted line is approximate extent of recently mapped late Oligocene to early Miocene calc-alkaline lavas in the vicinity of Calamity Butte (Isom and Streck, 2016; Cruz and Streck, 2017; Dvorak and Streck, 2018). (B) The same map shows mid-Miocene (17–15 Ma) Columbia River Basalt Group (CRBG) lava flows and source dikes (SMDS—Steens Mountain Dike Swarm; CJDS—Chief Joseph Dike Swarm; MDS—Monument Dike Swarm), the silicic Lake Owyhee Volcanic Field (blue dashed line labeled LOVF), the Dinner Creek Tuff Eruptive Center (red dashed oval labeled DITEC), the Strawberry Volcanics (blue, labeled SV), and the Oregon-Idaho graben (OIG) (Cummings et al., 2000; Coble and Mahood, 2012; Steiner, 2015; and Streck et al., 2015). WA—Washington; OR—Oregon, ID—Idaho.

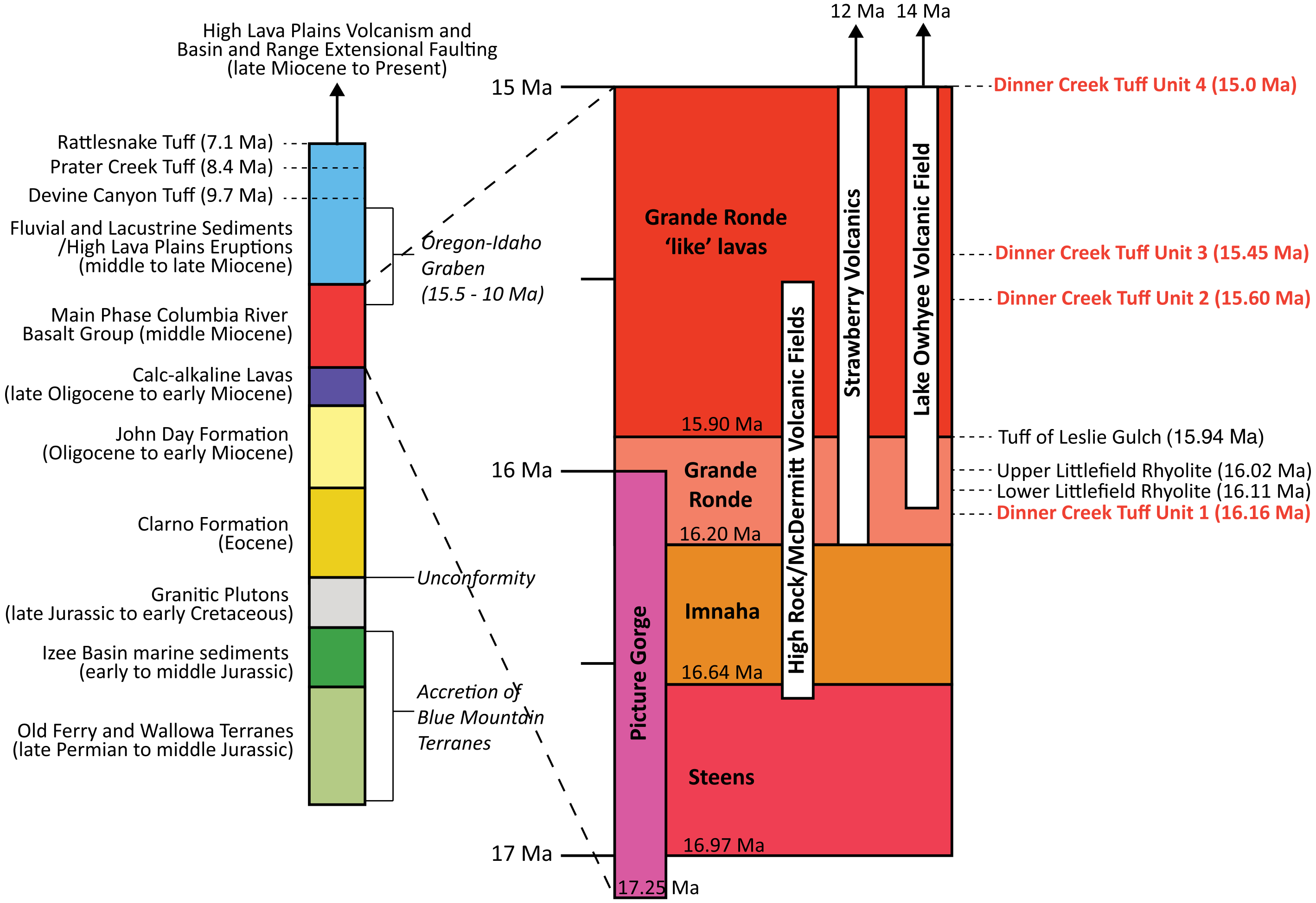

Figure 3. Stratigraphic column of regional units. All ages are derived from the $^{40}Ar/^{39}Ar$ method. Right column and Columbia River Basalt Group age dates from Cahoon et al. (2020). Age dates for Dinner Creek Tuff Units from Streck et al. (2015). Littlefield Rhyolite age dates from Webb et al. (2018). Tuff of Leslie Gulch age date from Benson and Mahood, (2016). Oregon-Idaho Graben age range from Cummings et al. (2000). Age dates for Devine Canyon, Prater Creek, and Rattlesnake Tuffs from Jordan et al. (2004).

mation northwest of the main mass. Based on U-Pb data, the pluton was intruded at ca. 129 Ma (Brown and Thayer, 1966; Ware, 2013).

An unconformity separates the Mesozoic bedrock from overlying Cenozoic calc-alkaline to tholeiitic volcanic rocks. In central Oregon, Eocene arc volcanism is recorded in the Clarno Formation and Oligocene to early Miocene bimodal volcanism in the John Day Formation (Figs. 2A and 3) (Swanson, 1969; McKee, 1970; Enlows and Parker, 1972; Rogers and Novitsky-Evans, 1977; Manchester, 1981; Robinson et al., 1984; Retallack et al., 1999; McClaughry et al., 2009). Lowry (1968) called lava flows in the center of the study area the Ring Butte andesite (Ring Butte lava flows in Fig. 4) and correlated them with the Clarno Formation based on petrography. Likewise, Brown and Thayer (1966) correlated porphyritic andesitic lava flows along the Little Malheur River (Little Malheur River Andesite in Fig. 4) in the very northwestern part of the study area with the Clarno Formation based on petrography. Neither of these units have been definitively shown to be part of the Clarno Formation via isotopic age or geochemical data, and no other occurrences of the Clarno Formation are known this far east. These older lava flows in the study area could be correlative with other late Oligocene to early Miocene (24–19 Ma, $^{40}Ar/^{39}Ar$ ages), calc-alkaline volcanic rocks that occur in patchy outcrops across eastern Oregon and are rarely exposed beneath the more voluminous mid-Miocene tholeiitic flood basalts (Camp et al., 2003; Isom and Streck, 2016; Cruz and Streck, 2017; Dvorak and Streck, 2018).

Lavas of the mid-Miocene Columbia River Basalt Group cover much of eastern Oregon, and main-phase activity can be divided into four formations based on compositional, stratigraphic, and age data: the 16.97–16.5 Ma Steens Basalt, the 16.64–16.47 Ma Imnaha Basalt, the 17.25–16.15 Ma Picture Gorge Basalt, and the 16.5–15.9 Ma Grande Ronde Basalt (Figs. 2B and 3; Wolff and Ramos, 2013; Moore et al., 2018; Kasbohm and Schoene, 2018; Cahoon et al., 2020). The Steens Basalt erupted from dikes south of the study area at Steens Mountain, the Imnaha and Grande Ronde Basalts erupted from the Chief Joseph Dike Swarm east and northeast of the study area, and the Picture Gorge Basalt erupted from the Monument Dike Swarm northwest of the study area (Fig. 2B; Hooper, 1997; Hooper et al., 2002; Camp and Ross, 2004; Camp and Hanan, 2008; Wolff and Ramos, 2013; Coble and Mahood, 2012; Reidel et al., 2013). None of these main-phase Columbia River Basalt Group units have previously been recognized in the study area, although the three members of the basalt of Malheur Gorge, exposed 20 km southeast of the study area in the Malheur Gorge, have been correlated with the main-phase Columbia River Basalt Group units, namely the Lower Pole Creek member with the

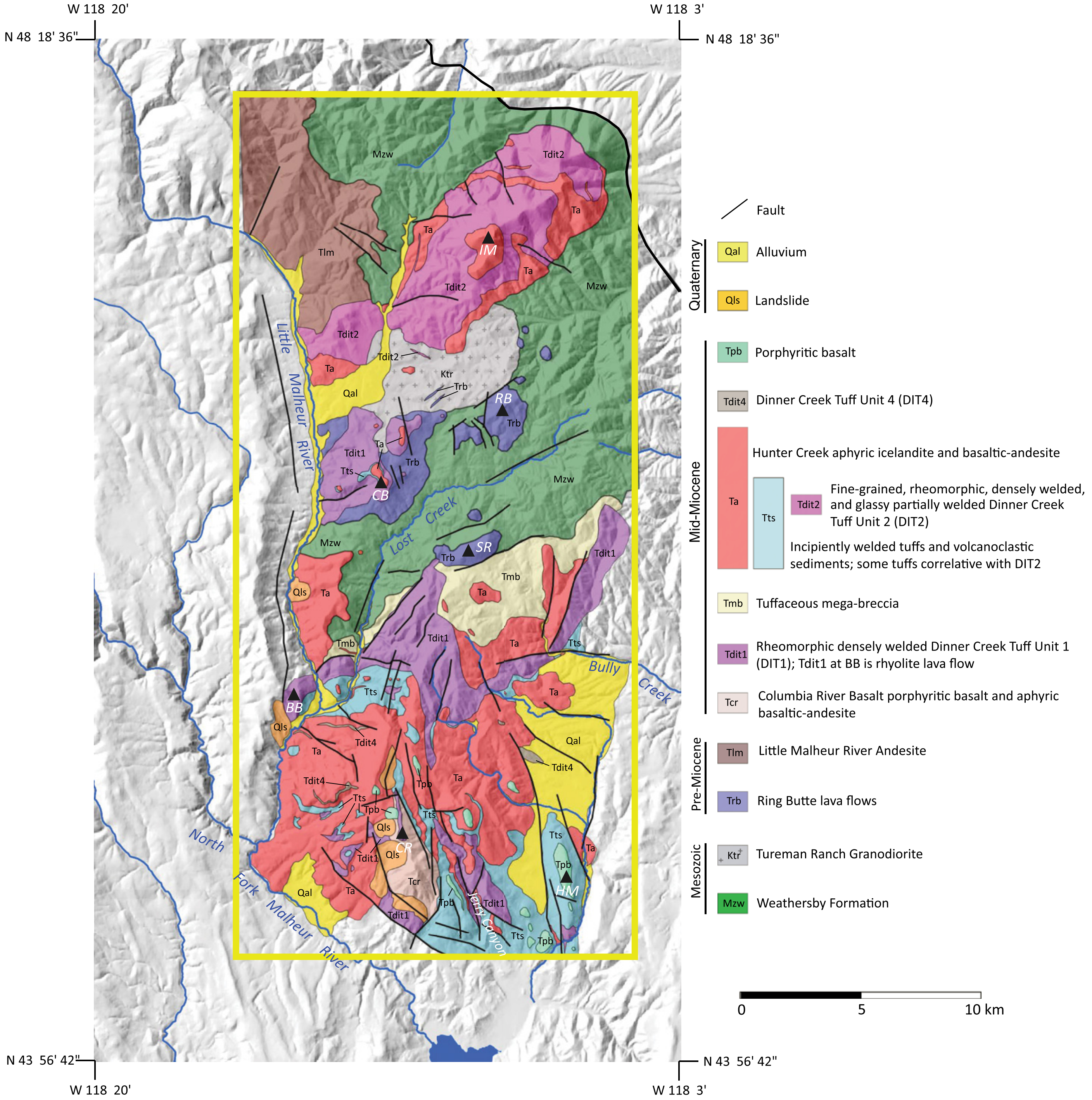

Figure 4. Geologic map of the study area (yellow rectangle) shows geologic units. Geographic points are shown as black triangles with labels. CR—Castle Rock; IM—Ironside Mountain; RB—Ring Butte; CB—Clevenger's Butte; BB—Black Butte; SR—Sheepshead Rock; HM—Hunter Mountain.

Steens Basalt, the Upper Pole Creek member with the Imnaha Basalt, and the Birch Creek and Hunter Creek member with the Grande Ronde Basalt (Evans, 1990; Ferns et al., 1993; Hooper et al., 2002; Camp et al., 2003; Ferns and McClaughry, 2013). Haddock (1967) and Woods (1976) correlated the >600 m of tholeiitic lava flows that underlie the Dinner Creek Tuff at Castle Rock with the basalt of Malheur Gorge based on petrography. The Hunter Creek Basalt is defined as a regionally extensive aphyric icelanditic basaltic andesite to andesitic lava that overlies the Dinner Creek Tuff in the greater area of this study mainly to the southeast; based on geochemical data, it is the youngest unit that has been correlated with the Columbia River Basalt Group and specifically the upper Grande Ronde Basalt. Samples of this unit have yielded ^{40}Ar/^{39}Ar ages ranging from 16.1 Ma to 15 Ma (Lees, 1994; Evans and Binger, 1997; Cummings et al., 2000), but recently it was more tightly

TABLE 1. DISTINGUISHING CHARACTERISTICS OF DINNER CREEK TUFF (DIT) UNITS 1–4 AS DEFINED IN STRECK ET AL. (2015)

Dinner Creek Tuff	Ar/Ar age (Ma)	Feldspar phase	SiO_2 (wt%)	CaO (wt%)	Zr (ppm)	Nb (ppm)	Sr (ppm)
Unit 1 (DIT1)	16.16	$\sim An_{10}$ plagioclase	>75	0.3–1	400–500	>20	<60
Unit 2 (DIT2)	15.6	$\sim An_{20}$ plagioclase	70–74	1–2.5	300–400	10–22	70–120
Unit 3 (DIT3)	15.45	Anorthoclase	70–74	0.5–2	300–400	15–24	50–100
Unit 4 (DIT4)	15	Anorthoclase	<70	2.5–3.5	250–300	10–15	250–300

constrained by Webb et al. (2018) to range in age from 16.1 Ma to 16.05 Ma. Webb et al. (2018) also showed that it is not a single lava flow but rather a series of lavas that range in composition from $\sim$55–63 wt% SiO_2 and overlie Dinner Creek Tuff unit 1. This study will reemphasize this aspect and use the designation Hunter Creek Basalt for tholeiitic to icelanditic lavas that are younger than those of Dinner Creek Tuff unit 1. Another extensive mid-Miocene volcanic unit in the surrounding region is the Strawberry Volcanics (Figs. 2B and 3; Robyn, 1977; Steiner and Streck, 2013). Thayer and Brown (1973) and Woods (1976) correlated several aphyric lava flows and tuffs at Ironside Mountain and the western flanks of Castle Rock with this volcanic field, which crops out mostly to the west (Robyn, 1977), and which we do not support (see below). ^{40}Ar/^{39}Ar age dates for the Strawberry Volcanics vary from 16.2 Ma to 12 Ma, and the unit is believed to have formed via open-system processes of Columbia River Basalt Group magmas with Blue Mountain terrane crust (Steiner, 2015; Steiner and Streck, 2018).

Silicic tuffs and lavas erupted contemporaneously with the Columbia River Basalt Group from areas near the Oregon-Nevada border in the south to areas around Unity in the north (Fig. 1; e.g., Coble and Mahood, 2012; Webb et al., 2018). The southern caldera complexes (High Rock and McDermitt) were active at the end of the Steens Basalt phase (ca. 16.5 Ma), while most volcanic centers of the Lake Owyhee Volcanic Field were active concurrently with the Grande Ronde Basalt phase and slightly thereafter from 16.3 Ma to 15.5 Ma (Streck et al., 2015; Benson and Mahood, 2016; Henry et al., 2017; Streck et al., 2017; Webb et al., 2018), although some centers were active as early as the High Rock and McDermitt caldera complexes (Streck et al., 2017). The Dinner Creek Tuff is the largest of the silicic volcanic units in the Lake Owyhee Volcanic Field and covers $\sim$32,000 km^2 of eastern Oregon (Hanna, 2018), which makes it the most widespread tuff of the rhyolite flare-up related to Columbia River Basalt Group magmatism. Previous, relatively localized studies around the town of Juntura (Fig. 1) described the tuff as a single, densely welded, and sometimes rheomorphic ignimbrite (Haddock, 1967; Woods, 1976). More recent geochemical analysis and ^{40}Ar/^{39}Ar age dating of samples across the entire distribution area revealed that the Dinner Creek Tuff consists of four individual compositionally closely related ignimbrites: the 16.16 Ma Dinner Creek Tuff unit 1 (DIT1), the 15.6 Ma Dinner Creek Tuff unit 2 (DIT2), the 15.46 Ma Dinner Creek Tuff unit 3 (DIT3), and the 15 Ma Dinner Creek Tuff unit 4 (DIT4) (Streck et al., 2015). The units vary in major element concentrations, with a decrease in wt% SiO_2 and alkalis from the rhyolitic DIT1 to DIT3 to the dacitic DIT4. Conversely, wt% FeO, MgO, Al_2O_5, P_2O_5, and CaO generally increase from DIT1 to DIT4. Concentrations of the trace elements Zr, Nb, and Y and rare earth elements (REEs) decrease from DIT1 to DIT4 while Sr increases. The units also differ in the main type of feldspar phenocrysts, with An_{10} plagioclase in DIT1, An_{20} plagioclase being prevalent in DIT2, and anorthoclase occurring in DIT3 and DIT4. All Dinner Creek Tuff units are low in phenocryst and lithic fragment content ($<$5%). Table 1 summarizes some of the differences between the units as defined in Streck et al. (2015).

Haddock (1967) and Woods (1976) considered a north-south–trending outcrop of Dinner Creek Tuff on the summit of Castle Rock as the dike from which the tuff erupted, although later researchers disputed this and believed a caldera was the source of the tuff (Rytuba and Vander Meulen, 1991; Camp et al., 2003; Streck et al., 2015). Our research confirms the presence of two such calderas, which are discussed further in this paper.

The Dinner Creek Tuff units and the Hunter Creek Basalt are the final eruptive units related to the main-phase Columbia River Basalt Group in the study area and surrounding region. Subsequently, extensional faulting was occurring, which formed the Oregon-Idaho graben east of the study area (Cummings et al., 2000; Ferns and McClaughry, 2013). Mid- to late Miocene lavas, volcaniclastic sediments, and tuffs overlie the Columbia River Basalt Group units in the southern part of the study area and beyond and are associated with this extensional period. The 13.5 Ma Tim's Peak Basalt is interbedded with these sediments in the southern part of the study area and overlies the Hunter Creek Basalt in the Malheur Gorge, which is southeast of the study area (Lees, 1994; Johnson et al., 1998; Evans and Binger, 1997; Camp et al., 2003). Extension-related volcanism continued into late Miocene and Pliocene time, with eruptions of minor mafic lavas and three widespread ash-flow tuffs (the 9.7 Ma Devine Canyon Tuff, 8.4 Ma Prater Creek Tuff, and 7.1 Ma Rattlesnake Tuff) from calderas buried beneath the Harney Basin to the west of the study area (Greene, 1973; Streck and Ferns, 2004; Jordan et al., 2003; Ferns and McClaughry, 2013; Ford et al., 2013; McClaughry et al., 2019). Faulting continued into Pliocene time and displaced the previously mentioned units and created the uplifted Castle Rock and Ironside Mountain ridgelines.

RESULTS

Within the study area, thick deposits of tuff and mafic lava flows were identified at Castle Rock and Ironside Mountain, which are separated from each other by outcrops of the Mesozoic Weathersby Formation and Tureman Ranch tonalite. We interpret these two areas to be volcanic centers and sources of the Dinner Creek Tuff units. In the following section, we discuss the findings of our field mapping by describing the tuff deposits at Castle Rock, the tuff deposits at Ironside Mountain, and the mafic lava flows at both locations. Figure 4 shows a geologic map of the study area.

Castle Rock Tuff Deposits

The tuff deposits in the vicinity of Castle Rock are, from oldest to youngest: (1) a densely welded and sometimes flow-banded rheomorphic tuff (Tdit1); (2) a tuffaceous breccia that crops out along the northern margins of the densely welded tuff (Tmb); (3) a volcaniclastic section that consists of many individual incipiently welded tuffs (Tts) and interbedded sediments that non-conformably overlie the densely welded tuff and underlie aphyric mafic lava flows; and (4) a dark colored, incipiently welded tuff (Tdit4) that is interbedded with the aphyric lava flows.

The densely welded tuff crops out along the summit and surrounding flanks of Castle Rock and has historically been identified as the Dinner Creek Tuff (Kittleman et al., 1965; Haddock, 1967; Woods, 1976). The tuff consists mostly of devitrified, crystalline groundmass with roughly 5% euhedral feldspar phenocrysts that are up to 3 mm in length and 5% lithic fragments of mostly mafic lava with minor shale and granitic fragments up to 2 cm in length. In Jerry Canyon and at Lost Creek (cf. Figs. 1B and 4), quartz-filled veins and vugs are common within the tuff. Flow banding along flattened ($<$4 mm thick),

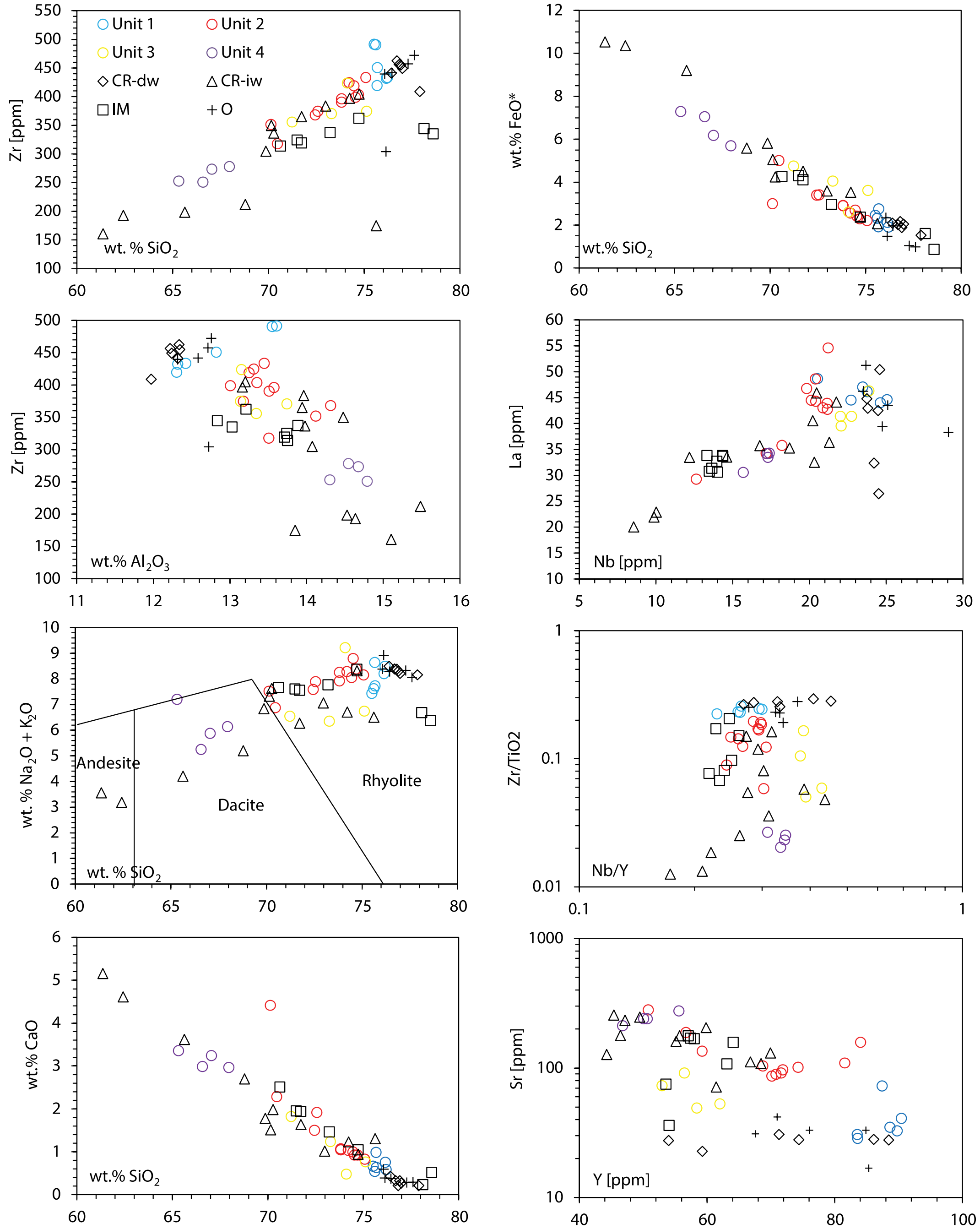

Figure 5. Bi-variate plots of tuff samples. Units 1–4 are samples from Dinner Creek Tuff (DIT) units 1–4 from Streck et al. (2015). CR-dw—densely welded and rheomorphic tuff samples around Castle Rock; CR-iw—incipiently welded tuffs around Castle Rock; IM—rheomorphic, glassy partially welded, and fine-grained tuffs at Ironside Mountain; O—outflow tuff samples from outcrops outside of Castle Rock or Ironside Mountain. No Th data for Tim's Peak Basalt samples.

stretched pumice clasts is pervasive throughout the tuff and creates a slaty habit in most outcrops.

The densely welded tuff is rhyolitic with 75–77 wt% SiO_2, 7–9 wt% total alkali contents (wt% $Na_2O + K_2O$), 11–12 wt% Al_2O_5, and <3 wt% FeO* and CaO (Fig. 5). Select trace element compositions vary from 400 ppm to 500 ppm for Zr, 40–55 ppm for La, 22–30 ppm for Nb, 50–90 ppm for Y, and 20–30 ppm for Sr. The composition of the feldspar is generally An_{10} and plots along the boundary between albite, oligoclase, and anorthoclase (Fig. 6). The geochemical and feldspar data indicate that the densely welded tuff is correlative with the Dinner Creek Tuff unit 1 (DIT1) (cf. Streck et al., 2015).

In the vicinity of Castle Rock, the thickness of the DIT1 varies from 100 m to ~300 m. The thickest deposits occur in Jerry Canyon, along the east side of Castle Rock (Figs. 1B, 4, and 7A), and at Black Butte, where the tuff is at least 300 m thick. The tuff is up to 200 m thick along the west side of Lost Creek and within the headwaters of Bully Creek (Figs. 1B and 4). Outcrops along the west slope of Castle Rock and at Hunter Mountain (~5 km southeast of Castle Rock) are at least 100 m thick. These are minimum thicknesses since the base of these deposits is not exposed. The only place where the base of the DIT1 is exposed is on the summit of Castle

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[1] Supplemental Material. Bulk chemical data of samples of this study and plotted in figures 5, 9, and 10. Please visit https://doi.org/10.1130/GSAB.S.17216726 to access the supplemental material, and contact editing@geosociety.org with any questions.

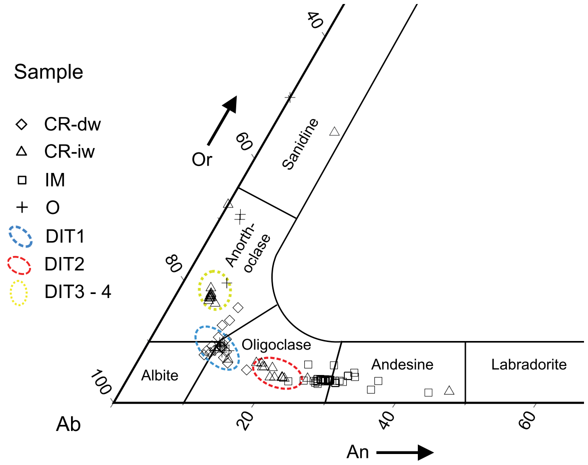

Figure 6. Albite corner of feldspar ternary diagram shows Dinner Creek Tuff (DIT) fields 1–4 from Streck et al. (2015) and feldspar data from this study. CR-dw—Castle Rock caldera densely welded and rheomorphic tuffs; CR-iw—incipiently welded tuffs around Castle Rock caldera; IM—Ironside Mountain caldera tuffs; O—outflow tuffs.

Rock (Fig. 7B). This outcrop overlies tholeiitic lava flows that are correlated with Grande Ronde Basalt (see below) and consists of a basal vitrophyre that grades upward into densely welded tuff with a total approximate thickness of 80 m.

At Jerry Canyon and Lost Creek, the DIT1 is vertical to sub-vertical (>75° dip) and foliated (Fig. 7C). East of these areas, the DIT1 generally dips 25–40° east/southeast. The outcrop atop Castle Rock and the outcrops within canyons along the western/southwestern flanks of Castle Rock generally dip 20–50° west/southwest.

The northern limit of the DIT1 outcrops extends from Black Butte in the western part of the study area northeast to the headwaters of Bully Creek (Fig. 4). A tuffaceous breccia (unit Tmb in Fig. 4) is nonconformably in

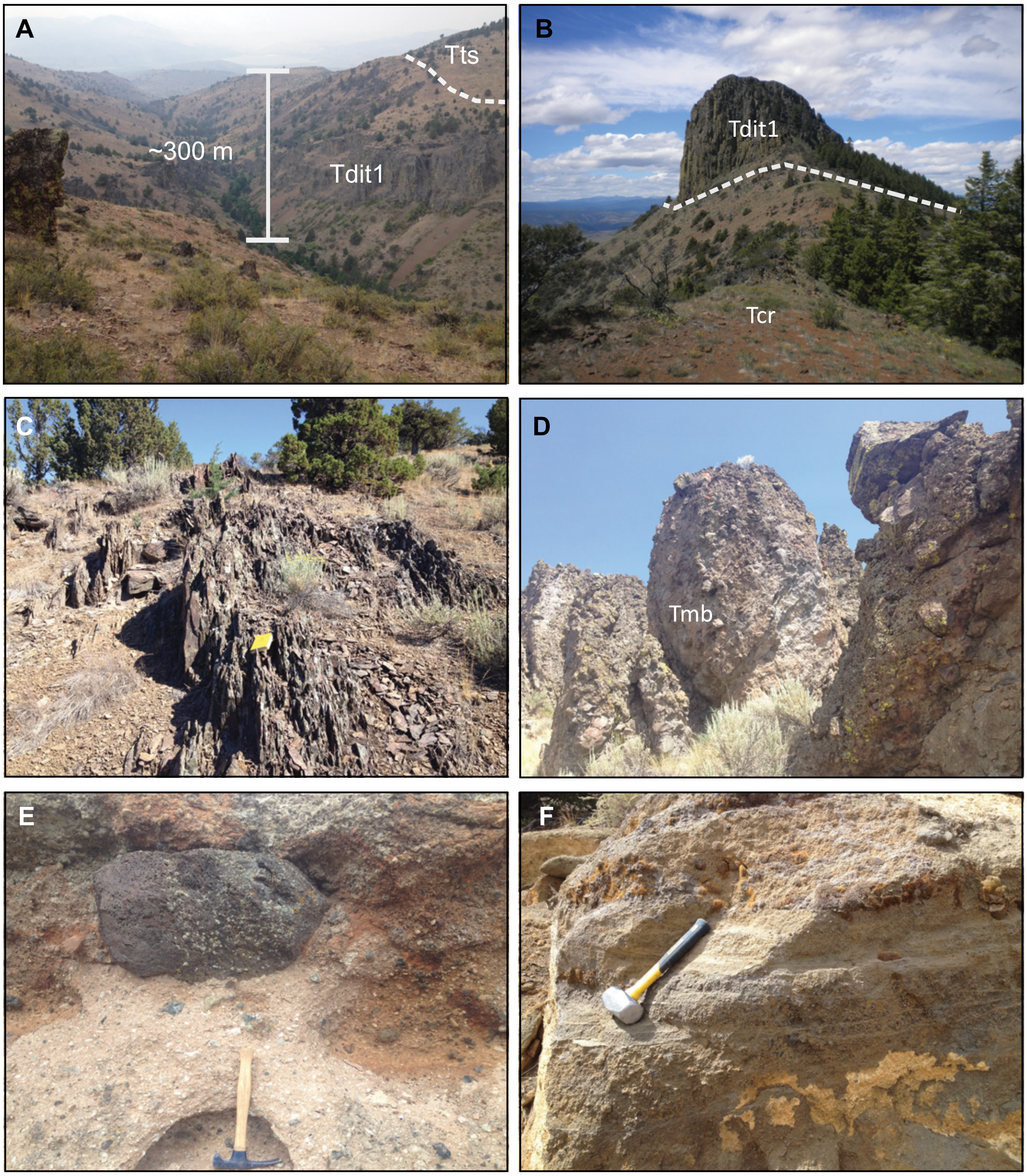

Figure 7. (A) View looks south down Jerry Canyon, along the eastern flank of Castle Rock, where ~300 m of densely welded Dinner Creek Tuff (DIT1) is exposed in the canyon walls. Incipiently welded tuff overlies the Dinner Creek Tuff on the western side of the canyon (right side of image). (B) View looks north at Castle Rock summit, where outcrop of Dinner Creek Tuff (DIT1) overlies uplifted, tholeiitic Grande Ronde Basalt lava flows. (C) Vertically foliated, densely welded Dinner Creek on the ridgeline east of Lost Creek. Notebook is shown for scale. (D) Mega-breccia deposits along Lost Creek, north of Castle Rock. Dacite, shale, and trachy-basalt fragments are up to 3 m in length. (E) Mafic lithic fragment in incipiently welded tuffs at Lost Creek. Hammer is shown for scale. (F) Water reworked tuff in Bully Creek Canyon, northeast of Castle Rock. Hammer is shown for scale. Unit abbreviations are same as on Figures 4 and 12.

contact with the DIT1 there. This unit contains abundant sub-rounded to sub-angular lithic fragments up to 3 m in length set within a tuff matrix (Fig. 7D). Lithic fragments make up to 40% of the unit. The lithic fragments are mostly Ring Butte trachybasalt and Weathersby Formation shale fragments. The tuffaceous breccia overlies Weathersby Formation shale and siltstone along the west side of Lost Creek and the southern flanks of Sheepshead Rock. The tuffaceous breccia is massive and lacks internal structure.

Incipiently welded pumice lapilli tuffs (mostly ash-flow tuffs but some fallout tuffs, correlative with DIT2) and interbedded volcaniclastic sediments (Tts) unconformably overlie the DIT1 and underlie aphyric lava flows (Ta in Fig. 4) in the vicinity of Castle Rock. The incipiently welded tuffs dip 5–40° west, while outcrops along the southeastern and eastern slopes of Castle Rock dip 5–30° east/southeast. Unflattened pumice clasts up to 8 cm in length are common. Along the base of the section, lithic fragments of DIT1 are common, whereas mafic lithic fragments predominate farther up section. Mafic lithic fragments up to 20 cm in length are common in tuffs in the upper part of this unit (Fig. 7E). Rounded pumice clasts in some epiclastic tuff units are indicative of slight water re-working (Fig. 7F). Other sediments are interbedded with the tuffs at Lost Creek and along the southern flanks of Castle Rock. At Lost Creek, the sediments are medium- to coarse-grained sandstones and coarse-grained conglomerates and show faint cross-bedding. On the southern flanks of Castle Rock, more fine-grained claystone or mudstone is interbedded with incipiently welded tuffs. These fine-grained sediments exhibit "popcorn" weathering, which is indicative of high bentonite content.

The volcaniclastic section is best exposed along the east side of Lost Creek, where tuffs and interbedded fluvial sediments make up ~40 layers with an approximate thickness of 200 m. Individual tuffs vary in thickness from 0.5 m to 15 m, while fluvial sediments are <0.5–1 m thick. On the western and southern flanks of Castle Rock, the volcaniclastic section is exposed in canyons where it can be up to 80 m thick. Correlation of individual tuffs across the study area is difficult due to the overlying aphyric lava flows and normal faulting that has displaced tuff outcrops.

The incipiently welded tuffs are rhyolitic except for the stratigraphically highest tuffs, which are andesitic to dacitic. The overall range in SiO_2 is 62–74 wt%, and the tuffs have higher concentrations of CaO, FeO*, MgO, TiO_2, and Al_2O_3 than DIT1 (Fig. 5). The concentrations of incompatible trace elements vary among individual tuff units but are generally lower than those in samples from DIT1. On the other hand, compatible trace elements such as Sr are more elevated in the incipiently welded tuff samples than in those from DIT1. In most tuffs, the feldspar data cluster in the oligoclase field (An_{20}), with the exception of the most mafic tuffs, which contain andesine phenocrysts (Fig. 6). The major/trace element and feldspar data indicate that the rhyolitic tuff samples are correlative with DIT2.

The youngest tuff in the study area is a prominent 10–20-m-thick, incipiently welded pumice lapilli tuff (Tdit4 in Fig. 4) that crops out along the western and eastern flanks of Castle Rock. The tuff overlies aphyric lava flows on both the eastern and western flanks of Castle Rock and underlies aphyric lava flows (Ta) on the western flank. It can be distinguished from the older incipiently welded tuffs by the predominance of dark gray to black largely unflattened pumice clasts. Lithic fragments typically consist of aphyric lavas up to 3 cm in length. The tuff is mostly dacitic (65–68 wt% SiO_2) and has higher FeO*, CaO, and Al_2O_3 than DIT1 or the older incipiently welded tuffs. The trace elements Zr (200–300 ppm), La (20–35 ppm), Nb (10–17 ppm), and Y (44–50 ppm) are lower in concentrations than the older tuffs, but Sr (160–250 ppm) concentration is higher. Feldspars are anorthoclase and andesine. Based on the chemical and anorthoclase feldspar data, this tuff is correlative with the 15 Ma DIT4 (cf. Streck et al., 2015).

Ironside Mountain Tuff Deposits

Tuff deposits encompass the entirety of Ironside Mountain and are in fault contact with shale and siltstone of the Weathersby Formation and Tureman Ranch tonalite (Fig. 8A). The tuffs at Ironside Mountain consist of, in stratigraphic order from to oldest to youngest, (1) fine-grained devitrified tuff that crops out on the northern half of the mountain; (2) densely welded, flow-banded tuff that crops out along the southern half of the mountain; and (3) partially welded tuff with noticeable vitric globular fragments, which sometimes resemble fiamme, overlies the densely welded tuff on the southern half of the mountain. Aphyric mafic dikes and sills cut across tuff deposits and the contact zone between tuffs and surrounding Mesozoic country rock. Aphyric mafic lava overlies the moderately welded tuff on the summit of Ironside Mountain.

The fine-grained, devitrified tuff lacks visible phenocrysts, pumices, and lithic fragments when hand sampled. In thin section, the tuff has a microcrystalline texture with minor opaque Fe-oxides. Along contacts with mafic dikes, calcite veins and zeolites are common. Some float samples of the devitrified tuff exhibited faint flow-banding, but no flow-banded outcrops of devitrified tuff were found. The devitrified tuff crops out across the northern half of Ironside Mountain, where it is cut by numerous mafic dikes and sills (Fig. 8B). The contact with overlying densely welded tuff is concealed. A notable outcrop of devitrified tuff occurs along the southern slopes of Ironside Mountain, where a devitrified tuff dike cuts northwest across Tureman Ranch tonalite (Fig. 8C). The dike is ~1.5 m thick and can be traced along the surface for ~1 km.

Densely welded to rheomorphic tuff crops out on the southern slope of the mountain. The rheomorphic aspect of DIT2 here is similar to the rheomorphic DIT1 outcrops at Castle Rock, with flow banding along flattened pumice clasts, <2 mm euhedral feldspar phenocrysts, and <1 cm mafic lithic fragments. Foliation is vertical to sub-vertical along the contacts with the surrounding Mesozoic country rock, but it has a more pervasive 20–50° southeast dip in the interior of the mountain. The densely welded rheomorphic tuff is ~200 m thick.

Partially welded tuff overlies the densely welded tuff along the southern half of Ironside Mountain. The partially welded tuff has the same 25–40° southeast dip as the underlying densely welded tuff. Flattened pumice clasts and vitric fragments up to 8 cm in length are common in the partially welded tuff. Densely welded tuff lithic fragments up to 4 cm in length occur sporadically throughout outcrops (Fig. 8D). The partially welded tuff has an approximate thickness of 100 m. Aphyric mafic lava (Ta in Fig. 4) overlies the moderately welded tuff on the summit of Ironside Mountain.

All of the tuff samples from Ironside Mountain are rhyolitic. Densely and partially welded tuff samples mostly have 70–74 wt% SiO_2, but some of the devitrified tuff samples contain >78 wt% SiO_2, which indicates some secondary gain of silica. Major element compositions of the densely to partially welded tuffs are similar to those of DIT2 and DIT3 (Fig. 5). The only exception is the composition of the devitrified tuff samples that have some major element compositions that are more similar to those of DIT1. On the other hand, in terms of trace elemental concentrations (e.g., Zr, La, Nb, and Y), all Ironside Mountain tuff samples are similar to DIT2 and DIT3, and they also overlap with the incipiently welded tuff data from Castle Rock described above. The composition of feldspar phenocrysts ranges from An_{20} to An_{40}; compositions overlap with plagioclase data for DIT2 from Streck et al. (2015) and with plagioclase compositions of incipiently welded tuff from Castle Rock, yet the An values are higher. Feldspar compositions are distinctly different from those of DIT 1 and DIT3 (cf. Streck et al., 2015; Hanna and Streck, 2017; Hanna, 2018). Based on bulk rock and mineral

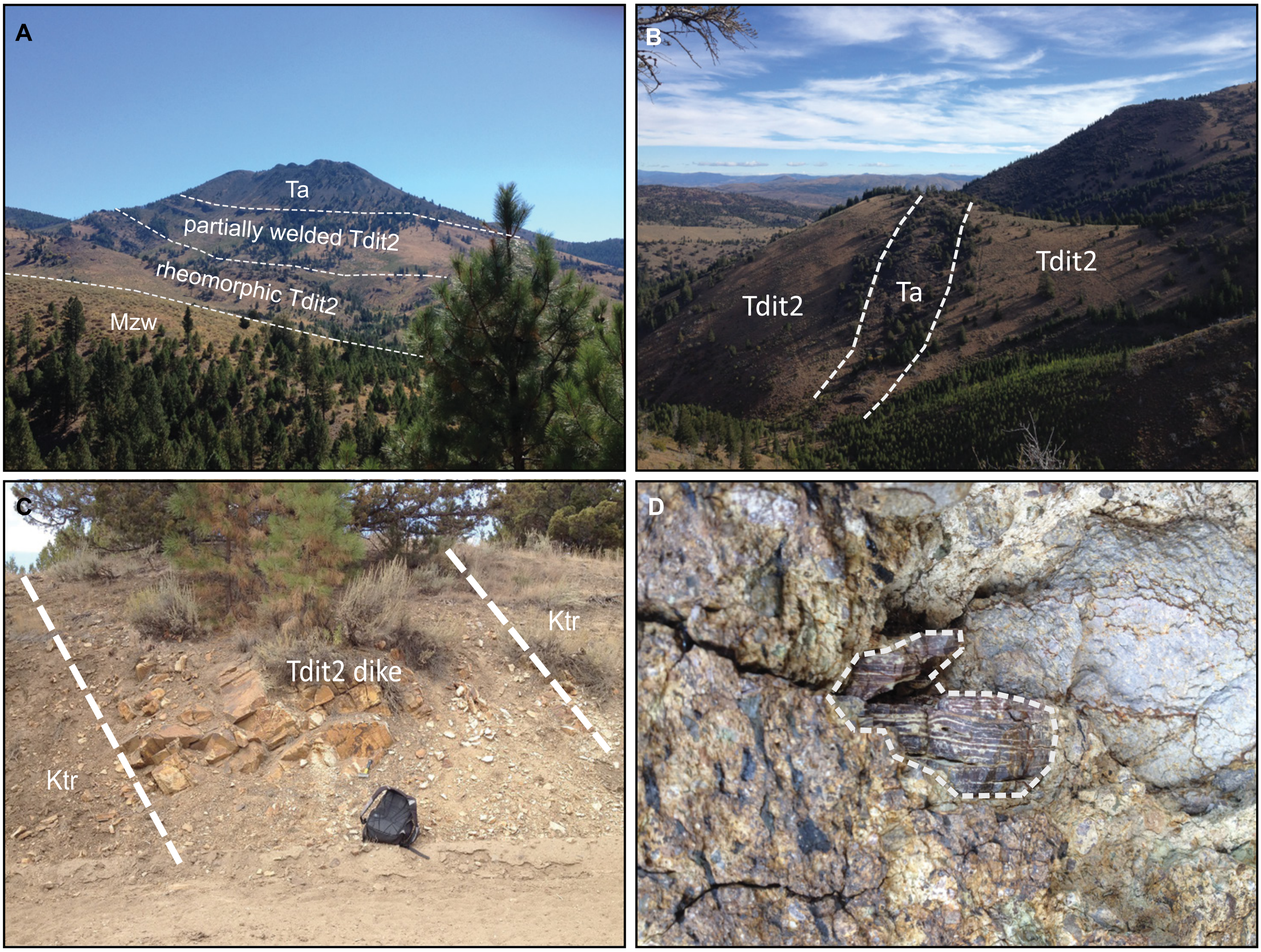

Figure 8. (A) View looks northwest at Ironside Mountain, with locations of approximate contacts of geologic units. (B) View looks north along western slope of Ironside Mountain at aphyric icelandite dike (Ta) intruding into fine-grained Dinner Creek Tuff unit 2 (DIT2). (C) Fine-grained Dinner Creek Tuff unit 2 (DIT2) dike intrudes into Tureman Ranch tonalite along southern flank of Ironside Mountain. (D) Partially welded tuff on southern flank of Ironside Mountain with lithic fragment of rheomorphic tuff (outlined).

compositions, all tuff units at Ironside Mountain best correlate with Dinner Creek Tuff unit 2.

Lavas of Study Area

In this section, we compare whole-rock major and trace element geochemical data from samples in the study area to data from regional units such as late Oligocene–early Miocene volcanic rocks at Calamity Butte, the main-phase Columbia River Basalt Group (Steens, Imnaha, Picture Gorge, and Grande Ronde Basalt including the local Hunter Creek Basalt), the Strawberry Volcanics, and Tim's Peak Basalt (Figs. 9–11). This evaluation is the basis for correlating lavas that occur in the study area with the geological units of the region (see below). This has not been done recently, and a modern reevaluation of exposed lava units is necessary.

Lowry (1968) mapped porphyritic lava flows in the center of the study area as the Ring Butte andesite, but our geochemical data indicate that these lavas are actually mildly tholeiitic trachybasalts with moderate MgO (~6 wt%) and FeO* (9–10 wt%) contents. Overall, major elemental compositions of Ring Butte trachybasalt are akin to the Strawberry Volcanics, Steens Basalt, Imnaha Basalt, Grande Ronde Basalt, and Tim's Peak Basalt. However, trace element signatures such as high Sr (>1000 ppm), Zr/Y, Ce/Zr, and Nb/Y ratios are distinct from all Miocene basaltic units. Ring Butte lavas are also petrographically distinct and carry large (~>500 µm) hornblende and clinopyroxene phenocrysts in addition to olivine (Cruz, 2017). Similar high Sr basalts are found among late Oligocene–early Miocene volcanics of the Calamity Butte area located ~100 km to the west of the study area midway between the towns of Burns and John Day (Fig. 1; Cruz and Streck, 2017), and we correlate Ring Butte lavas with these (see Discussion).

Porphyritic intermediate lava flows in the northwestern corner of the study area (Tlm in Fig. 4) range from andesite to dacite and are strongly calc-alkaline with low FeO* concentrations (6–2 wt%). Compared with other units, they have high Zr/Y, Ba/Nb, La/Nb, Ce/Nb, and low Ce/Zr ratios. Compositionally similar andesites-dacites are found among volcanic rocks

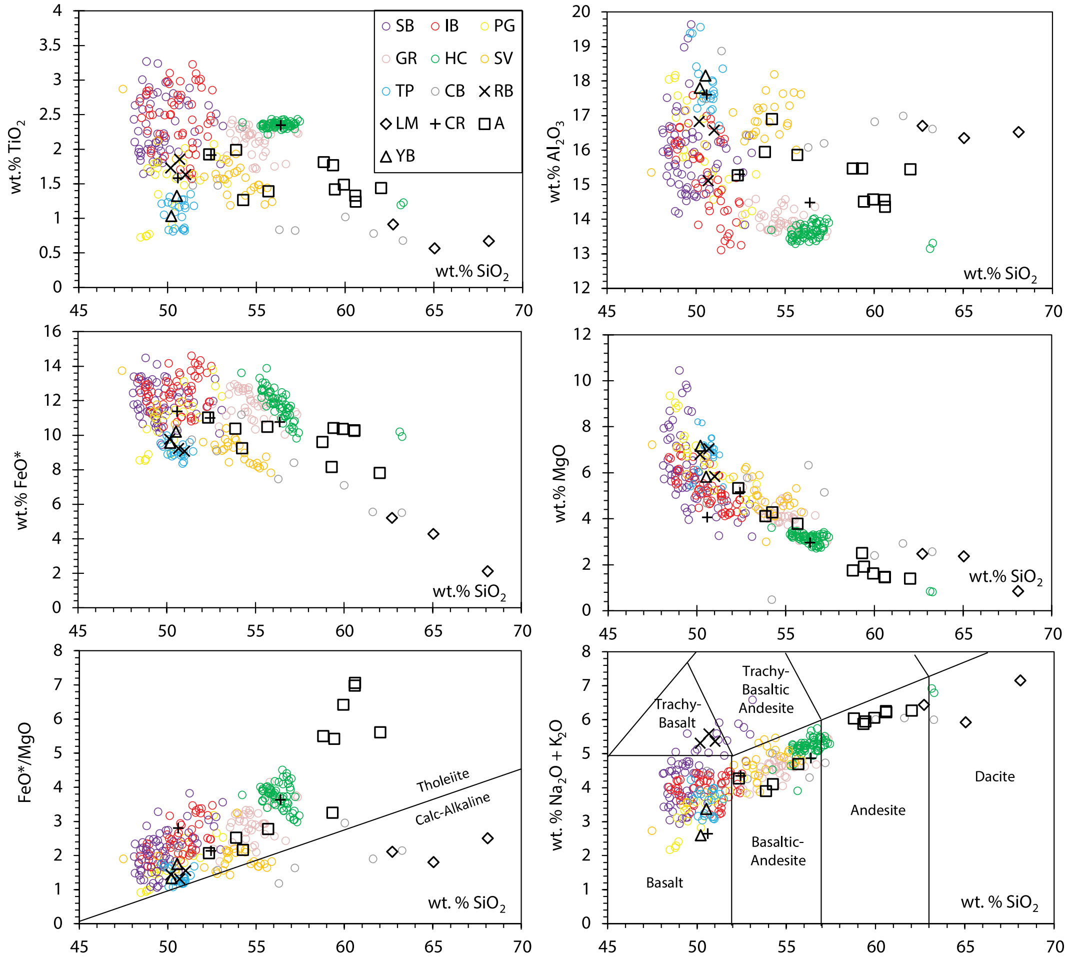

Figure 9. Major element bivariate plots of mafic lava samples from this study are plotted against data from regional volcanic units. DIT—Dinner Creek Tuff unit. Regional samples: CB—late Oligocene–early Miocene volcanics from Calamity Butte quadrangle; SB—Steens Basalt; IB—Imnaha Basalt; PG—Picture Gorge Basalt; GR—Grande Ronde Basalt; SV—Strawberry Volcanics; HC—Hunter Creek Basalt; TP—Tim's Peak Basalt. Samples from this study: RB—Ring Butte trachy-basalt; LM—Little Malheur River andesite; CR—Castle Rock lava flows (pre-DIT1); A—aphyric lava flows (post-DIT1); YB—young porphyritic basalt (post-DIT4). Data from regional units are from Johnson et al. (1998), Hooper et al. (2002), Wolff et al. (2008), Steiner (2015), Cruz and Streck (2017), and Webb et al. (2018).

of late Oligocene–early Miocene age around Calamity Butte. Calc-alkaline andesites are also abundantly found among the 15–12 Ma Strawberry Volcanics (Steiner and Streck, 2013), yet trace element signals of our samples differ from those of the Strawberry andesites. In addition, the stratigraphic position of these porphyritic intermediate lava flows makes them unlikely to belong to the mid-Miocene Strawberry Volcanics. We also assign them a late Oligocene/early Miocene age.

The tholeiitic basaltic lavas that underlie the DIT1 at Castle Rock (labeled CR in Figs. 9–10) are older than ca. 16.2 Ma and are compositional comparable to lavas of the main-phase Columbia River Basalt Group. More specifically, the sample of porphyritic basalt from the base of the section is matched best to the Picture Gorge Basalt with high Al$_2$O$_3$, low Zr, low Th, and low Nb. The basalt has a pattern similar to that of the Picture Gorge on mantle-normalization and REE diagrams (Fig. 11). Two samples from the middle and upper parts of the section match up well with the Grande Ronde Basalt (including Hunter Creek Basalt) in major and trace element contents, although the less silicic of the two often plots close to Imnaha Basalt samples. However, trace elements or trace element ratio plots (e.g., Nb versus SiO$_2$, Ba/Nb versus Nb/Y, and Ce/Nb versus Ce/Zr; Fig. 10) are supportive of a correlation with Grande Ronde Basalt and argue against an Imnaha Basalt lineage.

The aphyric lava flows that overlie the DIT1 (labeled A in Figs. 10–11) are compositionally variable. The total alkali vs. SiO$_2$ and FeO/MgO vs. SiO$_2$ plots distinguish two groups among samples of aphyric lava flows that immediately post-date unit 1 of the Dinner Creek Tuff. One group is basaltic andesitic in composition, and samples of the other are Fe-rich (8–10 wt% FeO*) andesites known as icelandites (Carmichael, 1964). Basaltic andesite samples plot most consistently on the major element trace element graphs with the Grande Ronde Basalt. On the mantle-normalization and REE plots, the basaltic andesites overlap with Imnaha and upper Steens Basalt of the Columbia River Basalt Group. However, basaltic andesites are too silicic to be Steens, Imnaha, and Picture Gorge Basalt lavas and are most consistent with being Grande Ronde Basalt-type lavas. Hunter Creek Basalt also belongs to this group. The fine grained, seemingly aphyric nature in hand samples is also consistent with the lithology of most Grande Ronde Basalt lavas.

The icelandites are too silicic to plot with regional units on the major/trace element graphs but trend back best to the basaltic andesite of this study. On the mantle-normalization and REE plots, the icelandites generally plot alongside the Grande Ronde Basalts with more elevated concentrations of incompatible elements and very prominent Nb-Ta, Sr, and Ti troughs. Consistent with their evolved tholeiitic composition, it is likely that icelandites evolved from the regionally tholeiitic Columbia River Basalt Group (i.e., Grand Ronde) magmas that developed their own unique signatures.

Finally, the porphyritic basalt that overlies the DIT4, Hunter Creek Basalt, and volcaniclastic sediments in the southern part of the Castle Rock caldera plots alongside the Tim's Peak Basalt in major element plots and with the Tim's Peak and Picture Gorge Basalts in trace element graphs; thus, we correlate porphyritic lavas with the ca. 13.8 Ma Tim's Peak Basalt of the greater Malheur Gorge area (cf. Camp et al., 2003).

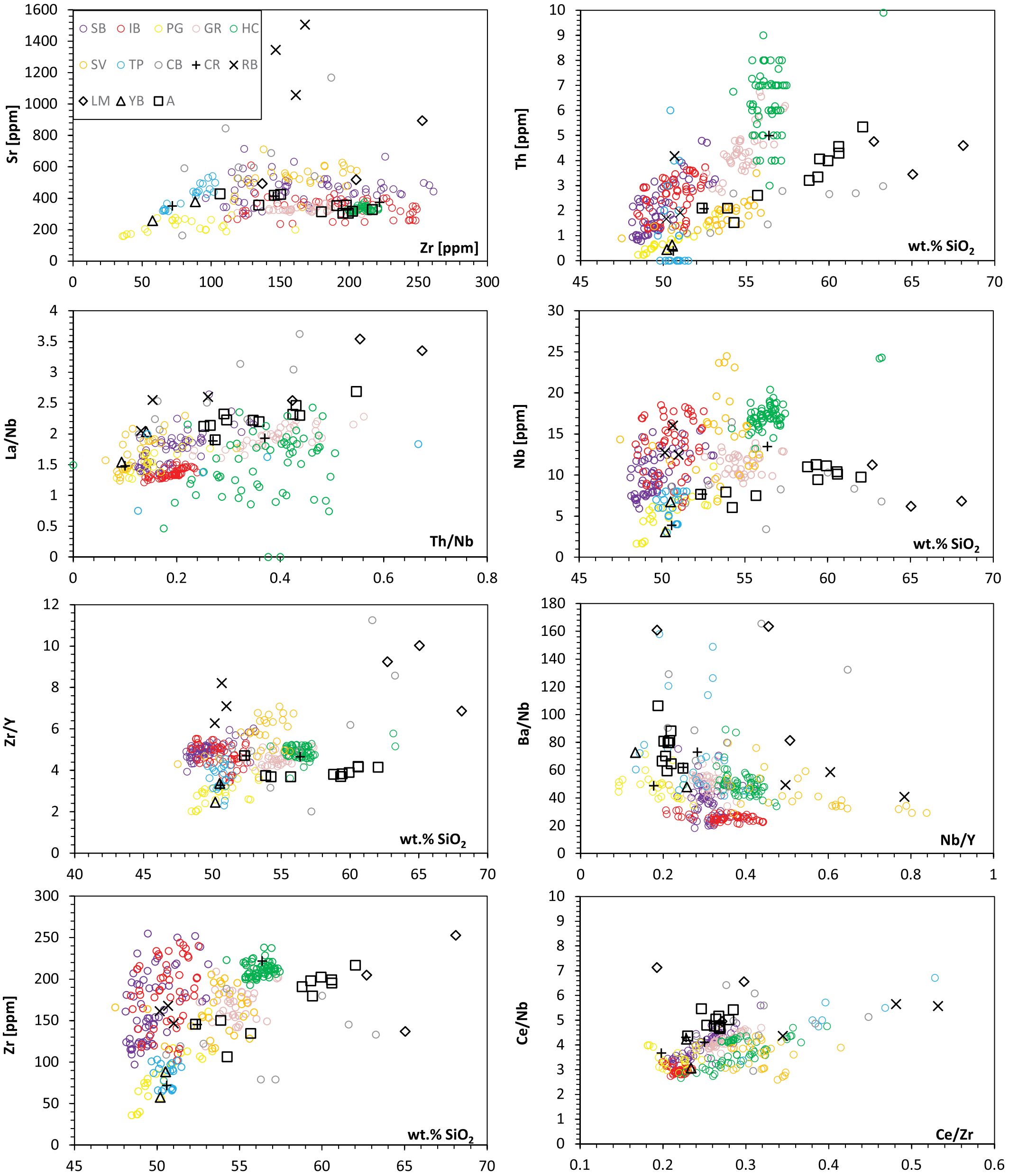

Figure 10. Trace element bivariate plots of mafic lava samples from this study are plotted against data from regional volcanic units. Regional samples: CB—late Oligocene–early Miocene volcanics from Calamity Butte quadrangle; SB—Steens Basalt; IB—Imnaha Basalt; PG—Picture Gorge Basalt; GR—Grande Ronde Basalt; SV—Strawberry Volcanics; HC—Hunter Creek Basalt; TP—Tim's Peak Basalt. Samples from this study: RB—Ring Butte trachy-basalt; LM—Little Malheur River andesite; CR—Castle Rock lava flows (pre-DIT1); A—aphyric lava flows (post-DIT1); YB—young porphyritic basalt (post-DIT4); DIT—Dinner Creek Tuff unit. Data from regional units are from Johnson et al. (1998), Hooper et al. (2002), Wolff et al. (2008), Steiner (2015), Cruz and Streck (2017), and Webb et al. (2018).

DISCUSSION

Dinner Creek Tuff Eruption Sites

Based on our field mapping and analytical data, we posit that two calderas are located within the study area: the Castle Rock caldera is the source of the 16.16 Ma DIT1, and the Ironside Mountain caldera is the source of the 15.6 Ma DIT2. Topographic rims are lacking at both calderas, which makes their presence not immediately obvious. The following sections describe the two calderas using the data presented thus far. Figure 12 shows a geologic map of the study area with caldera boundaries and cross-section lines, and Figure 13 shows cross-sections. Both calderas lie within the area of the proposed general storage sites of main-phase Columbia River Basalt magmas (Wolff et al., 2008; Streck et al., 2015; Webb et al., 2018).

Castle Rock Caldera

The extent of the Castle Rock caldera is defined by >200-m-thick outcrops of densely welded DIT1 and overlying volcaniclastic sediments in the southern part of the study area; we interpret the DIT1 in this location to be intra-caldera tuff. The thick, intra-caldera tuff outcrops end abruptly along a northeast-trending margin that separates the intra-caldera deposits to the south from the north/northwest-dipping shale of the Weathersby Formation and Ring Butte trachybasalt lava flows to the north. We interpret this margin as the northwestern boundary of the caldera that strikes northeast from Black Butte at the confluence of Lost Creek and the Little Malheur River up to Sheepshead Rock and then continues northeast out of the study area (Fig. 12). As mentioned before, the tuff at this location is sub-vertical and could be the result of tilting near the caldera wall during collapse (Lipman, 1997). The tuffaceous megabreccia that occurs along this margin is interpreted to have formed during caldera collapse, as the up to 3-m-long lithic fragments consist mostly of older lava flows and shale. Ring fractures may underlie the area here, as numerous mafic/silicic dikes (Fig. 14A) cut across the

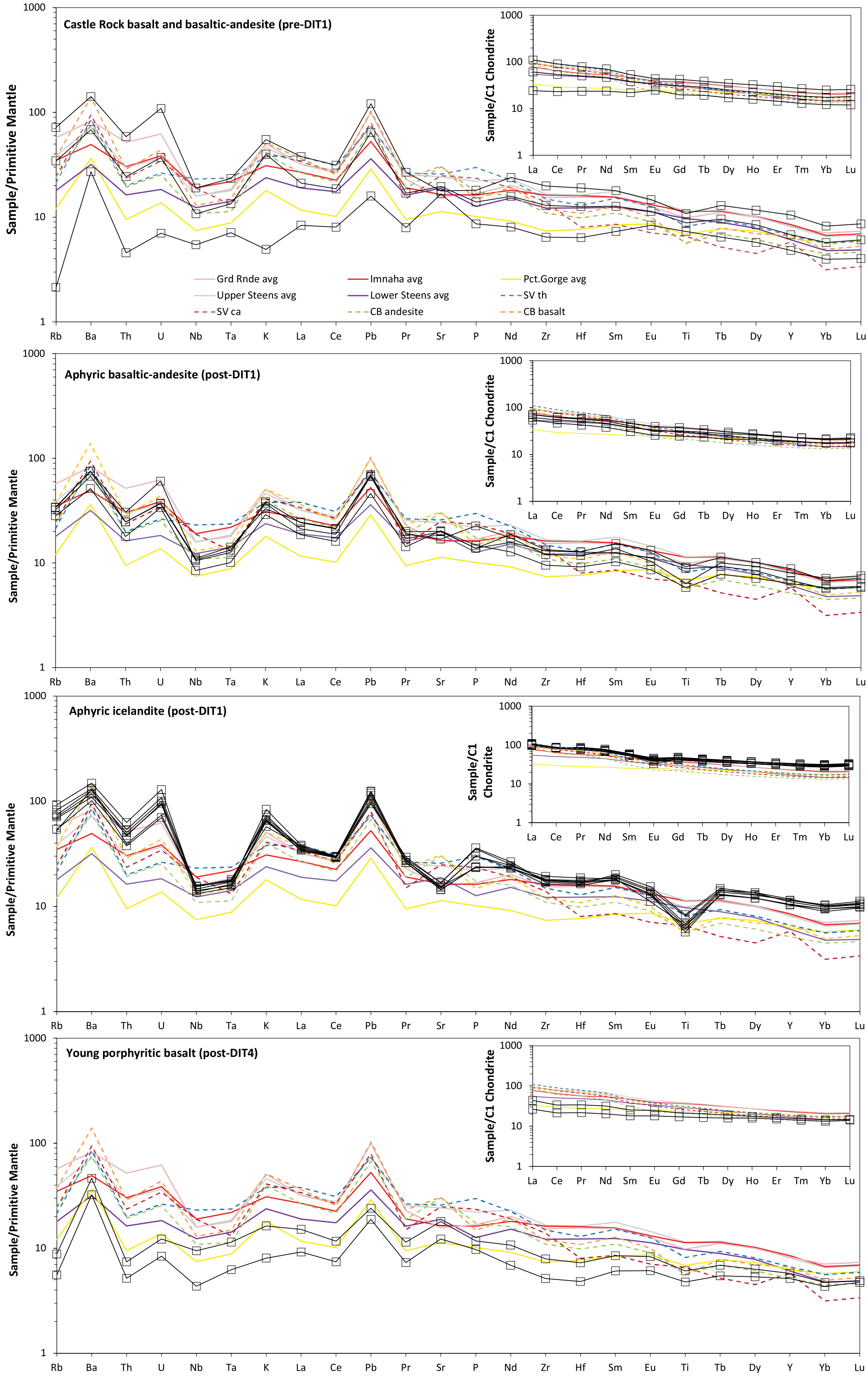

Figure 11. Mantle normalization plots and chondrite-normalized rare earth element plots of samples from this study are compared with average values for the Lower/Upper Steens, Picture Gorge, Imnaha, and Grande Ronde members of the Columbia River Basalt Group; calc-alkaline and tholeiitic lavas of the Strawberry Volcanics (SV); and late Oligocene–early Miocene basalt/andesite lavas from the Calamity Butte quadrangle (CB). Graphs from top to bottom: pre-DIT1 tholeiitic lavas at Castle Rock, post-DIT1 aphyric basaltic-andesite lavas, post-DIT1 aphyric icelandite, and post-DIT4 porphyritic basalt. Data are from Wolff et al. (2008), Steiner (2015), and Cruz and Streck (2017). Primitive mantle values are from Sun and McDonough (1989), and chondrite values are from McDonough and Sun (1995).

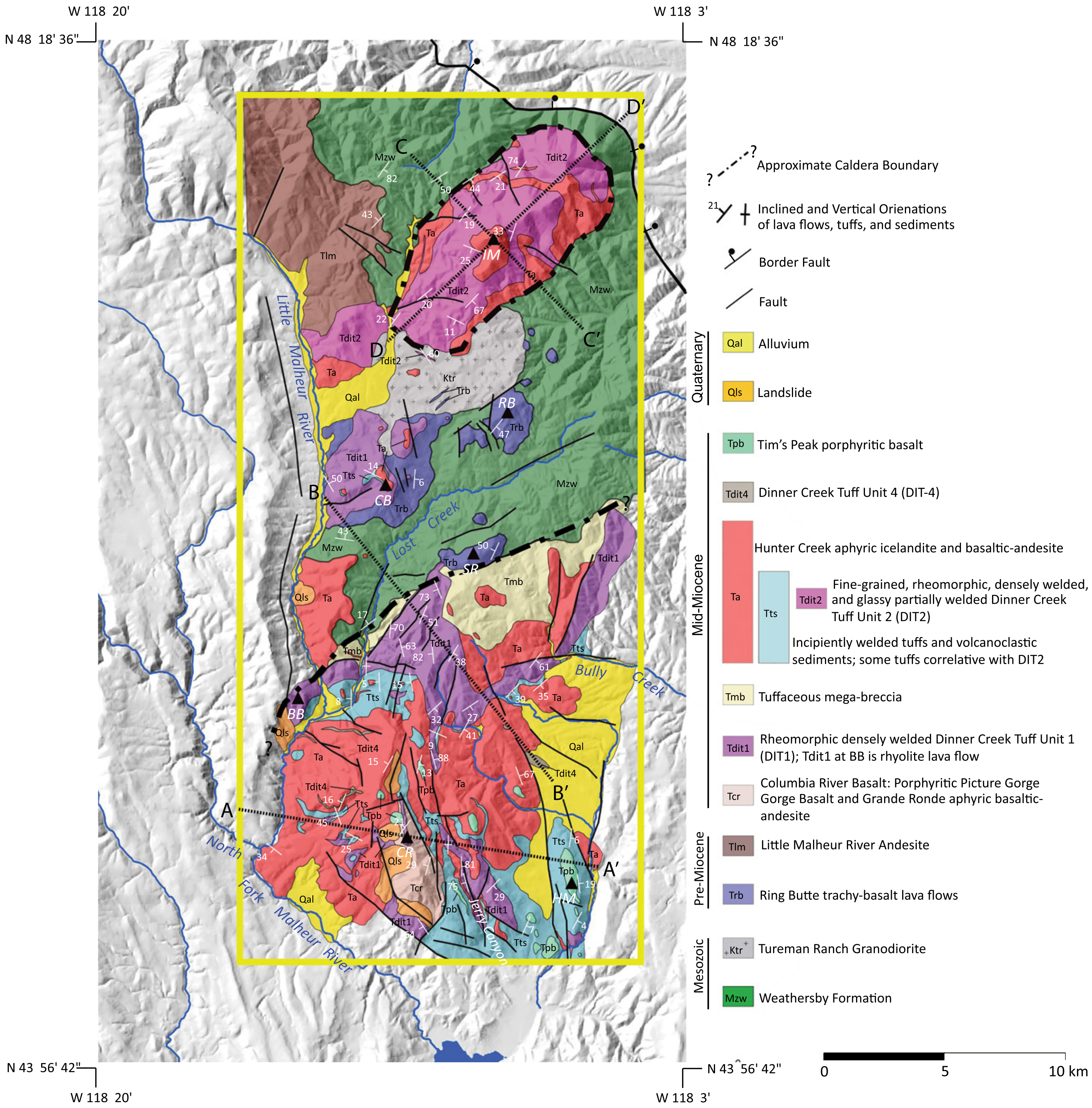

Figure 12. Geologic map of study area shows geologic units, orientations, approximate boundaries of the Castle Rock and Ironside Mountain calderas, and cross-section lines.

intra-caldera tuff, and hydrothermal alteration produced quartz veining and quartz-filled vugs within the tuff and pyrite mineralization within the nearby trachybasalt lava flows. The largest post-caldera intrusive body is Black Butte, a prominent hill at the confluence of Lost Creek and Little Malheur River (Fig. 14B) that has an elongated, dome-like shape and major and trace element composition similar to that of the DIT1. Unlike other intra-caldera tuff outcrops, Black Butte lacks the sub-vertical foliation and deformed fiamme. Black Butte appears to be a rhyolite lava dome with DIT1 composition that erupted atop ring dikes following caldera collapse. No contacts with surrounding rocks were observed, but a basal vitrophyre that is poorly exposed along the eastern flank of the butte could represent an intrusive contact between the silicic lava and country rock. Black Butte, the smaller dikes east of Lost Creek, and younger normal faults that displace the caldera

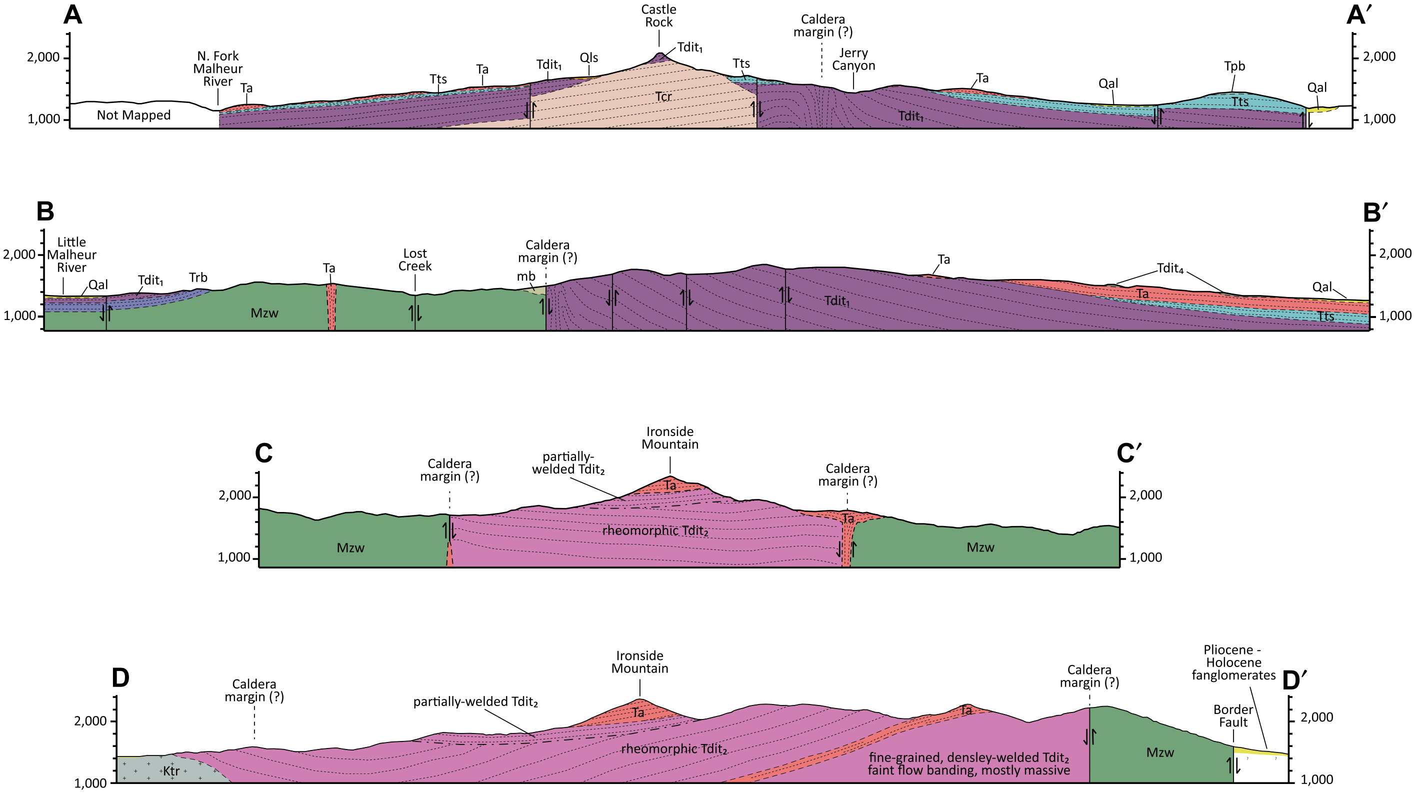

Figure 13. Cross-sections A–A′, B–B′, C–C′, and D–D′. Cross-sections C–C′ and D–D′ profiles are based on profiles from Thayer and Brown (1973). Unit abbreviations are same as on Figures 4 and 12.

floor tend to strike north by northeast, which indicates that underlying ring faults may have similar orientations.

The boundary of the caldera is difficult to discern south of Black Butte due to Hunter Creek-type lava flows that overlie and obscure older stratigraphy. At least 100 m of Dinner Creek Tuff unit 1 outcrops occur within canyons along the western flanks of Castle Rock, but they dip

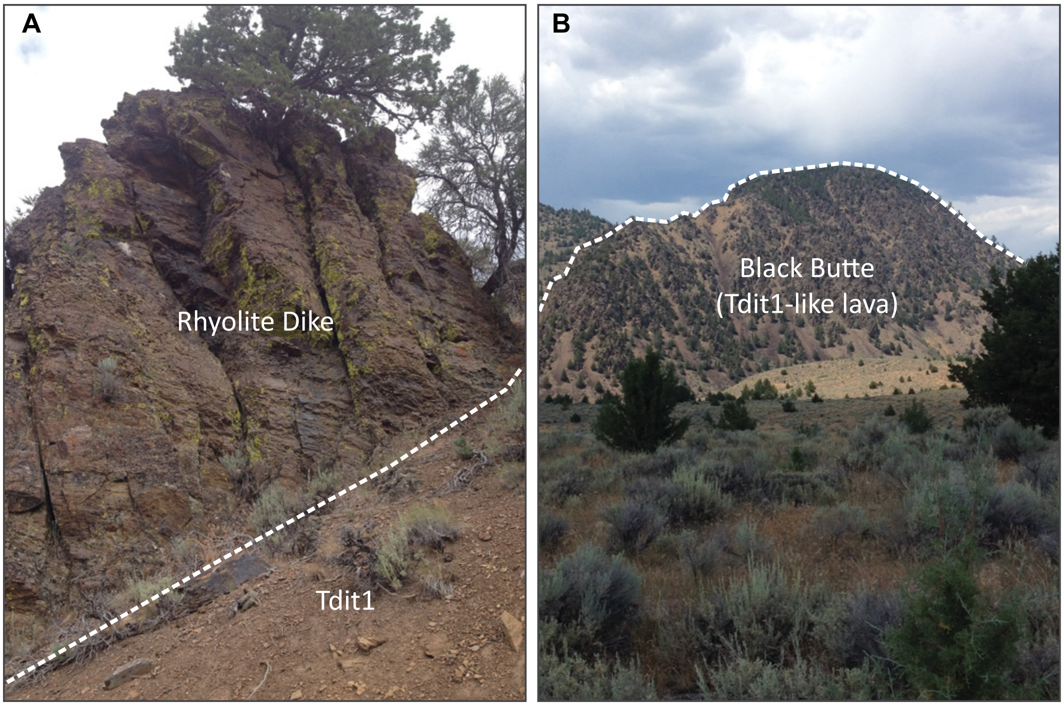

Figure 14. (A) Rhyolite lava spire intrudes into Dinner Creek Tuff unit 1 (DIT1) along ridgeline east of Lost Creek. (B) View looks west toward Black Butte.

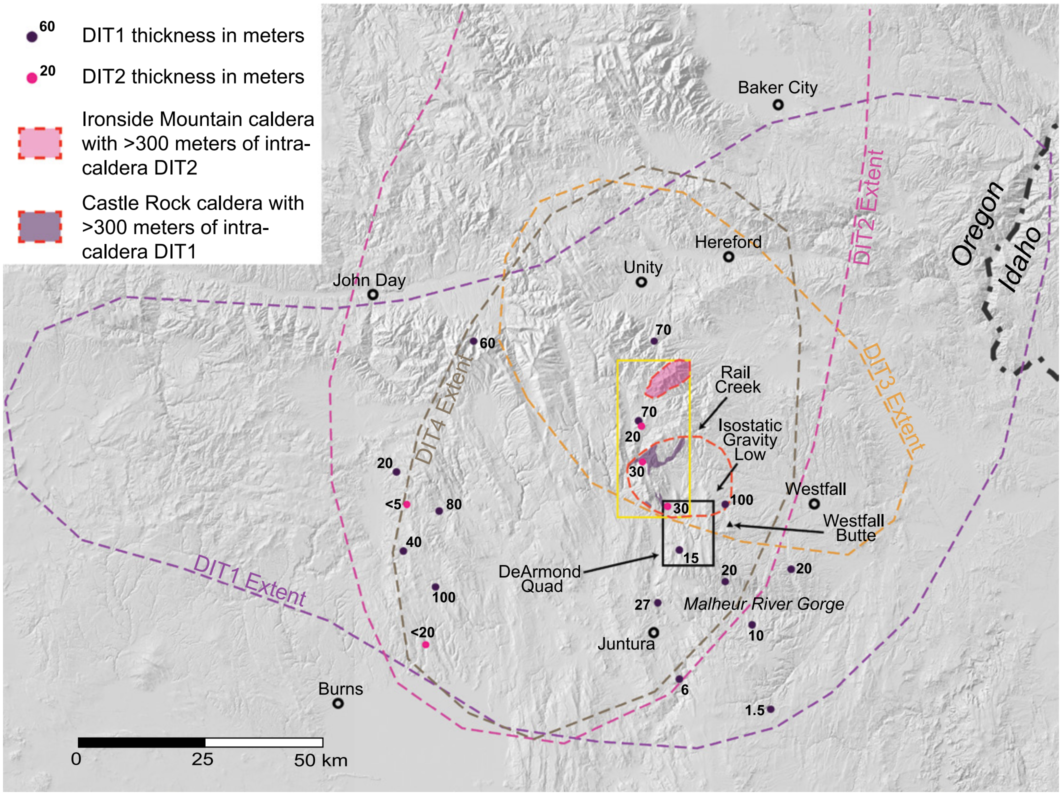

Figure 15. Regional map shows extent of Dinner Creek Tuff (DIT) units 1–4 across eastern Oregon, USA, from Hanna (2018). Yellow rectangle is approximate boundary of study area. Red dashed lines are approximate boundaries of Castle Rock and Ironside Mountain calderas. Outflow deposits of DIT1 and DIT2 with thickness in meters are shown as purple and pink circles, respectively. Boundaries of DeArmond 7.5′ quadrangle, locations of Rail Creek and Westfall Butte, and isostatic gravity low from Griscom and Halvorson (1994) are also shown. Tuff thickness data are from Haddock (1967), Steiner (2015), Isom and Streck (2016), Cruz and Streck (2017), and Webb et al. (2018).

moderately (<50°) northwest and lack the vertical foliation of the outcrops at Lost Creek, which indicates they may not be intra-caldera tuff deposits. About 5 km to the southeast, a sample of rhyolite lava flows interbedded with andesite lava flows west of the N. Fork Malheur River yielded an age of 16.3 Ma, which pre-dates the DIT1 (Streck et al., 2015). Outcrops of the tuff thin to less than 100 m farther west and further indicate that the western boundary of the caldera is east of the N. Fork Malheur River and near Castle Rock (Cruz and Streck, 2017).

The >300-m-thick outcrops of Dinner Creek Tuff unit 1 in Jerry Canyon, east of Castle Rock, contain common quartz-filled vugs and veins and intrusive rhyolite lava spires, and they exhibit sub-vertical orientations similar to those of the Lost Creek outcrops. Minor outcrops of possible tuffaceous mega-breccia containing <2-m-long lithic fragments of aphyric basalt of Malheur Gorge overlie the intra-caldera tuff in places, although they are not as extensive as the mega-breccia outcrops to the north. From these observations, it seems that the western margin of the caldera is located along the eastern flank of Castle Rock. The intra-caldera tuff deposits trend north/northwest along the western flank of Castle Rock before being buried beneath volcaniclastic sediments and Hunter Creek basaltic andesite and icelandite lava flows. The Lost Creek and Jerry Canyon margins are offset by ~4 km, disrupting a continuous caldera boundary. The offset could indicate that the caldera collapsed in a more piecemeal, chaotic style as opposed to the classical, cohesive piston type of collapse or that the caldera has been disrupted by later faulting (Lipman, 1997; Cole et al., 2005; Acocella, 2006).

Outside of the study area, the caldera is defined by tuff thicknesses and post-caldera vents. Northeast of the study area, at Rail Creek, Lowry (1968) mapped a 300-m-thick section of partially welded tuffs containing pumice fragments over 1 m in length, which he interpreted to be vent proximal (Fig. 15). North of Rail Canyon, the Weathersby Formation crops out and Dinner Creek Tuff outcrops are lacking. Twenty km southeast of Castle Rock, a 14–12 Ma rhyolite dome complex, called Westfall Butte, overlies outcrops of DIT1 that are at least 100 m thick and contain greater than 20% basalt lithic fragments (Evans and Binger, 1997). On the southern and eastern flanks of Westfall Butte, the tuff thins rapidly to <20 m. These two volcanic centers could have erupted along the margins of the caldera atop ring faults.

Volcaniclastic sediments and lava flows mapped as Tim's Peak Basalt by Haddock (1967) overlie DIT1 within Bully Creek Canyon, which trends east–west between the Rail Canyon and Westfall Butte volcanic centers. An isostatic gravity low occurs in this area, northeast of Westfall Butte, and may be representative of thick volcaniclastic sedimentary deposits and underlying intra-caldera tuff that filled in the central and eastern parts of the Castle Rock caldera (Griscom and Halvorson, 1994; Evans and Binger, 1997; Fig. 15).

South of the study area, tuff outcrops thin to <50 m at Beulah Peak, which is 15 km south of Castle Rock, and to less than 30 m along the rim of the Malheur Gorge at Juntura (Fig. 15). These tuff outcrops are clearly outflow deposits. Outcrops of similar thickness occur in the hills north and east of Juntura. These thicknesses indicate that the southern margin of the caldera is north of the Malheur Gorge and Juntura (Haddock, 1967; Evans, 1990).

Faulting followed the eruption of the 13.5 Ma Tim's Peak Basalt, disrupting the caldera floor along north- and northeast-trending normal faults and creating the ridgelines east of Lost Creek, which is southeast of Sheepshead Rock, and east of Castle Rock. Castle Rock itself is a horst that is bounded on the west, east, and south by normal faults that have caused the 600 m of uplift along its southern flank. While some of the uplift may be due to caldera floor resurgence, based on opposing dips of volcaniclastic sediments on either side of Jerry Canyon, most of the uplift is probably due to regional Miocene extensional faulting (Woods, 1976; Cummings et al., 2000).

The distribution of DIT1 over 25,000 km^2 of eastern and central Oregon (Hanna and Streck, 2017; Hanna, 2018), with an estimated outflow volume of 250 km^3, would suggest a circular caldera with a diameter of 15–20 km based on similar sizes of other tuff deposits (Smith, 1979; Spera and Crisp, 1981; Geshi et al., 2014). The area described above defines an oval caldera that extends east–west from Castle Rock to Westfall Butte for 20 km and north–south from Rail Creek down to Hunter Creek for 15 km and fits the presumed size (Fig. 15). Using these dimensions and the maximum exposed thickness of intra-caldera tuff (300 m), a volume estimate for the intra-caldera DIT1 within the Castle Rock caldera is 70 km^3. This is a minimum estimate, and it is based on the lack of basal exposures of intra-caldera tuff deposits.

Ironside Mountain Caldera

The Ironside Mountain caldera, which is located in the northern part of the study area, encompasses the entirety of Ironside Mountain, with approximate dimensions of 11 × 6 km (Fig. 12). The caldera margins are defined by the contact between intra-caldera DIT2 and Mesozoic shale/granodiorite and post-caldera Hunter Creek icelandite lava flows. The intra-caldera tuff is subvertical along the contact with country rocks but dips inward toward the center of the mountain farther away from the margins. The total thickness of exposed intra-caldera tuff is ~900 m.

Two tuff dikes are exposed along the southern and western margins of the caldera and are possible vents for some of the DIT2 tuff. The dike along the southern margin of the caldera strikes northwest across granodiorite for approximately 1 km. It dips ~60° northeast, toward the interior of the caldera, and is ~2 m thick. The dike has a fine-grained, white crystalline groundmass that is similar in appearance to the altered DIT2 that crops out across the central and northern parts of Ironside Mountain, which indicates that it may have been altered by hydrothermal alteration. A second dike cuts northward across older Hunter Creek icelandite along the western margin of the caldera. The dike is vertical, brecciated, and varies from 2 m to 3 m. Samples from these dikes have major and trace element and feldspar compositions that are similar to those of DIT2, and the dikes likely belong to the ring dike system that is associated with the Ironside Mountain caldera. The clustering of basaltic andesite and icelandite intrusions within the intra-caldera tuff along the margins of the caldera could also be indicative of the underlying faults that served as conduits for the DIT2 and Hunter Creek lava flows after collapse of the Ironside Mountain caldera.

Unlike at the Castle Rock caldera, no volcaniclastic sediments or mega-breccia deposits are preserved within the Ironside Mountain caldera. One reason for this may be that the caldera has undergone a greater amount of uplift than the Castle Rock caldera, which caused the erosion of sediments and mega-breccia deposits from the margins of the caldera and exposed the ponded intra-caldera tuffs and mafic intrusions in the interior of the caldera. This uplift may also be responsible for the extreme relief between the caldera interior and the surrounding shale and granodiorite, which have low relief and have been eroded into round hills and ridges. This uplift occurred along a northwest-trending normal fault that is located immediately north of the caldera. This fault was called the Border Fault by Thayer and Brown (1973) and displaces intra-caldera DIT2 and Mesozoic country rock along the northern margin of the caldera over 800 m above Miocene to Pliocene sediments in the basin directly north of Ironside Mountain.

The estimated outflow volume of the DIT2 is on the order of 110 km^3 (Hanna and Streck, 2017; Hanna, 2018). This would suggest a caldera with a circular dimension of ~13 km (cf. Smith, 1979; Spera and Crisp, 1981; Geshi et al., 2014). The proposed Ironside Mountain caldera is 11 km × 6 km and thus smaller than the suggested size for the estimated outflow volume of tuff. This area could be representative of the very inner part of the caldera. The outer part of the caldera, between the ring faults and the topographic rim, which would have been filled with mega-breccia, may have been completely eroded during uplift along the Border Fault, decreasing the apparent size of the caldera (Smith and Bailey, 1968; Lipman, 1997; Cole et al., 2005). Based on the 900 m thickness of tuff, a volume estimate for intra-caldera DIT2 is 47 km^3. Like the estimate for the intra-caldera DIT1 at the Castle Rock caldera, this is probably a minimum estimate, as the base of the intra-caldera tuff is not exposed.

Sources of Dinner Creek Tuff Units 3 and 4

The 15.45 Ma DIT3 was not identified within the study area, and the 15 Ma DIT4 was found to be scattered outcrops along the western and eastern flanks of Castle Rocks with a maximum thickness of 20 m. The lack of significant amounts of either tuff indicate that they were sourced from vents outside of the study area. The DIT3 has mostly been recognized near the town of Westfall, which is 35 km east of Castle Rock, where it is interbedded with volcaniclastic sediments known as the Bully Creek Formation (Ferns et al., 1993; Streck and Ferns, 2004; Streck et al., 2015; Fig. 15). These sediments and volcanic deposits were deposited within the western part of the Oregon-Idaho Graben (Cummings et al., 2000). The source of the DIT3 may be located east of Westfall, along the western margin of the graben. The DIT4 may have a source that is more proximal to the study area. Lowry (1968) mapped ash-flow tuff outcrops with similarly dark gray to black pumice clasts ~5 km east of the study, along the south side of Bully Creek, which were over 100 m thick. Thick tuff deposits also have been mapped southeast of the study area, within the DeArmond Mountain 7.5′ quadrangle, and could represent a small caldera source for DIT4 (Fig. 15).

Temporal Relation of Dinner Creek Tuff Units and Regional Lavas

As mentioned before, previous researchers have only used petrography to correlate mafic units in the study area with regional volcanic units. In this section, we correlate lava flows within the study area to the Columbia River Basalt Group and other mid-Miocene and older volcanic rocks using our geochemical data. Table 2 shows the stratigraphy of the study area using our geochemical and field mapping data.

The oldest volcanic units in the Dinner Creek Tuff Eruptive Center are the porphyritic andesite in the northwest corner of the study area and the Ring Butte trachybasalt in the center of the study area, based on their stratigraphic positions atop the Mesozoic basement and below the DIT1. The geochemical data indicate that these lavas are distinct from the Columbia River Basalt Group and other mid-Miocene volcanic rock, and they correlate best with late Oligocene to early Miocene calc-alkaline lavas that underlie the mid-Miocene Strawberry Volcanics west of the study area. Those lavas produced ^{40}Ar/^{39}Ar ages of 24–19 Ma (Isom and Streck, 2016; Cruz and Streck, 2017). Robyn (1977) also acquired a K/Ar age of 19 Ma for similar porphyritic andesite lava flows 10 km west of Ironside Mountain outside of the study area. These late Oligocene–early Miocene ages preclude the correlation of these volcanic rocks with the Eocene Clarno Formation that earlier researchers made (Brown and Thayer, 1966; Lowry, 1968). Instead, the porphyritic andesite and Ring Butte trachybasalt appear to be eastern extensions of a 24–18 Ma calc-alkalic volcanic field that is largely buried beneath the mid-Miocene Strawberry Volcanics.

The geochemical data indicate that main-phase Columbia River Basalt Group tholeiitic lava flows underlie the DIT1 at Castle Rock. Haddock (1967), Woods (1976), and Evans (1990) correlated this section with the basalt of Malheur Gorge that was later found to be a composite volcanic unit consisting of overlapping Steens, Imnaha, and Grande Ronde Basalt lava

TABLE 2. STRATIGRAPHY OF MAFIC UNITS WITHIN THE STUDY AREA AND THEIR CORRELATION WITH REGIONAL UNITS (CAHOON ET AL., 2020)

Stratigraphy	Mafic lava type	Mineral phases	Texture	SiO_2 (wt%)	CA vs. Th	Regional mafic unit
Youngest	Porphyritic basalt	olv, plag, ca-pyx	diktytaxitic	<51	Th	Tim's Peak (13.5 Ma.)
	Aphyric basaltic-andesite and icelandite	plag	microlitic	53–62	Th	Late Stage Grande Ronde Basalt lavas (15.9–15 Ma)
DIT4 (15 Ma)						
	Aphyric basaltic-andesite and icelandite	plag	microlitic	53–62	Th	Late Stage Grande Ronde Basalt lavas (15.9–15 Ma)
DIT2 (15.6 Ma)						
	Aphyric basaltic-andesite and icelandite	plag	microlitic	53–62	Th	Late Stage Grande Ronde Basalt lavas (15.9–15 Ma)
DIT1 (16.16 Ma)						
	Castle Rock aphyric basaltic-andesite	plag, ca-pyx	diktytaxitic	52–57	Th	Grande Ronde Basalt (16.2–15.9 Ma)
	Castle Rock porphyritic basalt	plag, ca-pyx, ol?	sub-ophitic	<51	Th	Picture Gorge Basalt (16.2 Ma*)
	Little Malheur River andesite and dacite	plag, ca-pyx	diktytaxitic	62–68	CA	Late Oligocene–early Miocene volcanics (24–19 Ma)
Oldest	Ring Butte trachy-basalt	hbl, plag, ca-pyx	diktytaxitic, trachyitic	50–52	Th	Late Oligocene–early Miocene volcanics (24–19 Ma)

*Ar/Ar date from Cahoon et al. (2020).

flows that are exposed in the Malheur Gorge, which is 40 km southeast of the study area (Hooper et al., 2002; Camp et al., 2003). Our geochemical data indicate that the basal basalt lava flows at Castle Rock are eastward extensions of the Picture Gorge Basalt. Previous researchers had restricted the extent of the Picture Gorge Basalt to the area southeast to northeast of the town of John Day (Figs. 1A and 2B), but a recent study by Cahoon et al. (2020) showed that the Picture Gorge does extend this far east. Cahoon et al. (2020) dated the basal sample from Castle Rock yielding an ^{40}Ar/^{39}Ar age of 16.23 Ma. Aphyric tholeiitic lavas overlie the Picture Gorge Basalt and underlie DIT1. Compositional data from one sample from the lower portion and one sample from directly below DIT1 indicate that aphyric lavas correlate with the Grande Ronde Basalt. Therefore, the basalt of Malheur Gorge at Castle Rock records a Columbia River Basalt Group stratigraphy consisting of Picture Gorge Basalt overlain by Grande Ronde Basalt. This is similar to recently described Columbia River Basalt Group stratigraphy along the western portion of Malheur Gorge (Cahoon et al., 2020).

At 16.16 Ma, the DIT1 erupted from the Castle Rock caldera and was deposited atop the previously mentioned volcanic units. The aphyric lava (Ta) flows that are younger than DIT1 are the most difficult to correlate. Previous researchers had correlated these lavas with either the Hunter Creek Basalt or the Strawberry Volcanics due to the black aphyric groundmass, slaty to blocky habit, and prominent reddish-brown weathering rind (Haddock, 1967; Woods, 1976). Recent field mapping east of the study area and ^{40}Ar/^{39}Ar age dates have constrained the Hunter Creek Basalt, which is part of the uppermost Grande Ronde Basalt stratigraphy (cf. fig. 8 of Reidel et al., 2013), to 16.11–16.02 Ma, immediately following eruption of the DIT1 (Webb et al., 2018). This is corroborated by field evidence from outside the study area, where the Hunter Creek Basalt directly overlies the DIT1 with no evidence of paleosol development or intervening deposition (Evans, 1990; Evans and Binger, 1997). The close temporal and spatial relation of the DIT1 and Hunter Creek Basalt is further indicated by the similarities in composition of mafic magmatic components of the DIT1 with those of Hunter Creek Basalt (Evans, 1990; Streck et al., 2015; Webb et al., 2018).

We infer that basaltic andesite and icelandite samples that are (1) exposed above and below (or intrude) DIT2 at the Ironside Mountain caldera are above, (2) intercalated with incipiently welded tuffs but younger than DIT1 at Castle Rock caldera, or (3) are dikes crossing the volcanic stratigraphy at both calderas, are related to late tholeiitic magmatism post-dating, yet related to, the main Grande Ronde Basalt. We envision that late-stage magmatic evolution of local Grande Ronde magmatic reservoirs within the Dinner Creek Tuff Eruptive Center (cf. Wolff et al., 2008; Webb et al., 2018) led to their composition.

The porphyritic basalt that overlies the previously mentioned units in the southern part of the Castle Rock caldera is correlated with the Tim's Peak Basalt based primarily on stratigraphic position. Even though the data overlap with Tim's Peak and Picture Gorge Basalt, the position of the lavas atop the tuffs and the older tholeiitic lava indicate that it must post-date the mid-Miocene volcanic sequence and is therefore part of the Tim's Peak Basalt.

Paleogeography

The results of this study have implications for the mid-Miocene paleogeography around the two calderas and provide additional data for potential impingement areas of the mantle upwelling that led to the eruption of the Columbia River Basalt Group (e.g., Shervais and Hanan, 2008; Pierce and Morgan, 2009; Camp, 2013). The rise of buoyant mantle below continental lithosphere often leads to uplift, and the temporal relation between uplift, volcanism, and deformation has been used to differentiate between mantle upwelling due to a plume versus the passive rise of mantle due to tectonic rifting. We combine results of this study with mapping in areas further west (Isom and Streck, 2016; Cruz and Streck, 2017), northwest (Steiner, 2015), and north to northeast (Evans, 1990; Large, 2016). These areas combined encompass an approximately circular area with a diameter of 100 km that is centered on the prominent central outcrop gap of Columbia River Basalt Group lavas in northeastern Oregon (Figs. 1A and 2A).

The most striking field observation of this study is the lack of thick, main-phase Columbia River Basalt Group lavas in the area between Castle Rock and Ironside Mountain. Only in the southern part of the study area are Columbia River Basalt Group correlative lavas exposed, and this was likely the marginal part of the basin wherein lavas ponded to a minimum thickness of 600 m as is seen along Malheur Gorge (Hooper et al., 2002; Camp et al., 2003). On the other hand, pre-DIT1 tholeiitic lavas are lacking from the area between Castle Rock and Ironside Mountain, where DIT1 directly overlies older Ring Butte trachybasalts or pre-Tertiary units and where the only mafic lavas are Fe-rich basaltic andesite and icelandites that are younger than 16.16 Ma. Columbia River Basalt Group lava flows are also lacking in the area immediately west of the study area, which is bounded by Burns in the southwest, John Day in the northwest, Hereford in the northeast, and Castle Rock in the southeast (Fig. 1). Stratigraphic sections within the area illustrate that Dinner Creek Tuff or basal lavas of the Strawberry Volcanics (ca. 16.2–15 Ma; Steiner and Streck, 2013) and rhyolites of the Unity and Dooley Mountain area overlie either deformed Mesozoic accreted terranes or Oligocene to late Miocene (ca. 24–19 Ma) volcanic rocks.

We argue that this lack of main-phase Columbia River Basalt Group lavas at these locations is due to non-deposition instead of erosion. We do not exclude the possibility that a few thin lavas were emplaced in this area and were later eroded, but it would be difficult to assume the erosion of hundreds of meters of Columbia River Basalt Group lavas while the Dinner Creek Tuff units and other volcanic rocks that are barely younger than the main-phase Columbia River Basalt Group lavas were not eroded. This is particularly evident along the perimeter of this area such as at Castle Rock, where one goes from a stratigraphy of Dinner Creek Tuff overlying Mesozoic basement rocks and early Cenozoic trachybasalt lava flows to Dinner Creek tuff overlying >600 m of Columbia River Basalt Group-equivalent tholeiitic lava flows with the tuff being intercalated in the upper part of the mafic lava stratigraphy. This paleogeographic high coincides largely with the convergence zone of the large-scale fracture pattern identified by Glen and Ponce (2002), who argued that their pattern is consistent with the imposition of a point source of stress at the base of the crust and a regional stress field aligned with the presumed mid-Miocene stress direction. It is therefore possible that this point source of stress also caused this uplift within the area discussed. Our new results provide supporting evidence that the mantle upwelling leading to the Columbia River Basalt Group impinged farther north. This is the area discussed by Camp (2013), as "near Vale" that was also proposed by Shervais and Hanan (2008) instead of the area along the Oregon-Nevada border near the McDermitt Caldera Complex that is generally favored by many workers. New data also demonstrate that a number of arguments brought forth by Camp (2013) against the "near Vale" area, such as the lack of older rhyolites, need to be revised (Streck et al., 2017; Webb et al., 2018).

CONCLUSIONS

Field mapping and analytical data from tuff samples indicate that two calderas are present within the study area: the Castle Rock and Ironside Mountain calderas. The Castle Rock caldera formed during the eruption of the 16.16 Ma DIT1. The northwestern boundary of the caldera is roughly defined by the juxtaposition of over 300 m of densely welded rheomorphic, intra-caldera tuff and tuffaceous mega-breccia deposits against Mesozoic Weathersby Formation shale and pre-Miocene Ring Butte trachybasalt lava flows. Following collapse of the caldera, fluvial and lacustrine volcaniclastic sediments and outflow deposits of DIT 2 and DIT4 were deposited into the caldera. Subsequently, aphyric basaltic andesite and icelandite lavas correlative to the regional Hunter Creek Basalt (a late Grande Ronde Basalt unit) intruded into the caldera floor deposits.

The Ironside Mountain caldera formed during the eruption of the 15.6 Ma DIT2. The caldera is an 11 km × 6 km depression wherein over 900 m of intra-caldera, rheomorphic and partially welded tuff are bounded by Weathersby Formation shale and Tureman Ranch granodiorite. After collapse of the caldera, aphyric basaltic andesite and icelandite dikes and sills (reflecting a younger pulse of Hunter Creek Basalt) intruded into the tuff, mostly along the margins of the caldera, altering much of the tuff and extruding onto the caldera floor. The caldera floor has been uplifted along a northwest-trending fault just north of the caldera.

Mafic lava flows within the study area were correlated with regional mafic units using geochemical and petrographic data. Pre-Dinner Creek Tuff porphyritic andesite and trachybasalt, which were previously considered to be eastern extensions of the Eocene Clarno Formation, have been tentatively correlated with Oligocene and early Miocene lavas flows west of the study area. Porphyritic and aphyric basaltic lava flows underlying DIT1 at the type locality of Castle Rock are correlated with the Picture Gorge and Grande Ronde Basalt members of the Columbia River Basalt Group. Aphyric basaltic andesite and icelandite that intrude into and overlie DIT1 and DIT2 are westward extensions of the Hunter Creek Basalt that were erupted along the margins of the calderas. Porphyritic basalt lava flows that overlie the Hunter Creek Basalt and volcaniclastic sediments at the Castle Rock caldera are correlative with the 13.5 Ma Tim's Peak Basalt. The distribution of lavas and tuff can be used as evidence that pre-caldera Columbia River Basalt Group lavas onlapped at Castle Rock on a mid-Miocene topographic high prior to caldera formation. This area appears to be part of a broader mid-Miocene topographic high that stretched north- and westward for tens of kilometers based on similar stratigraphic data found at Castle Rock, and it may be related to the regional uplift at initial impingement of the mantle upwelling that produced the Columbia River Basalt Group.

The Castle Rock and Ironside Mountain calderas exemplify the bimodal volcanism of the Columbia River magmatic province. The eruption of rhyolites was closely pre- and post-dated by local and regional tholeiitic lavas belonging to the Columbia River Basalt Group. The local eruption of evolved tholeiitic lavas likely helped to conceal calderas, but their presence also illustrates close proximity and temporality of mafic and rhyolitic magmas at depth at these rhyolite centers. Consequently, the stratigraphy of both the Castle Rock and Ironside Mountain calderas somewhat differs from that of rhyolite calderas dominated by silicic and calc-alkaline intermediate pre- and post-caldera volcanism.

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