GSA Field Trip #14:

Exploring an Eccentric Era of Explosivity and Extension in the Central Oregon Cascades Arc: The Deschutes Formation Ignimbrite Flare-up

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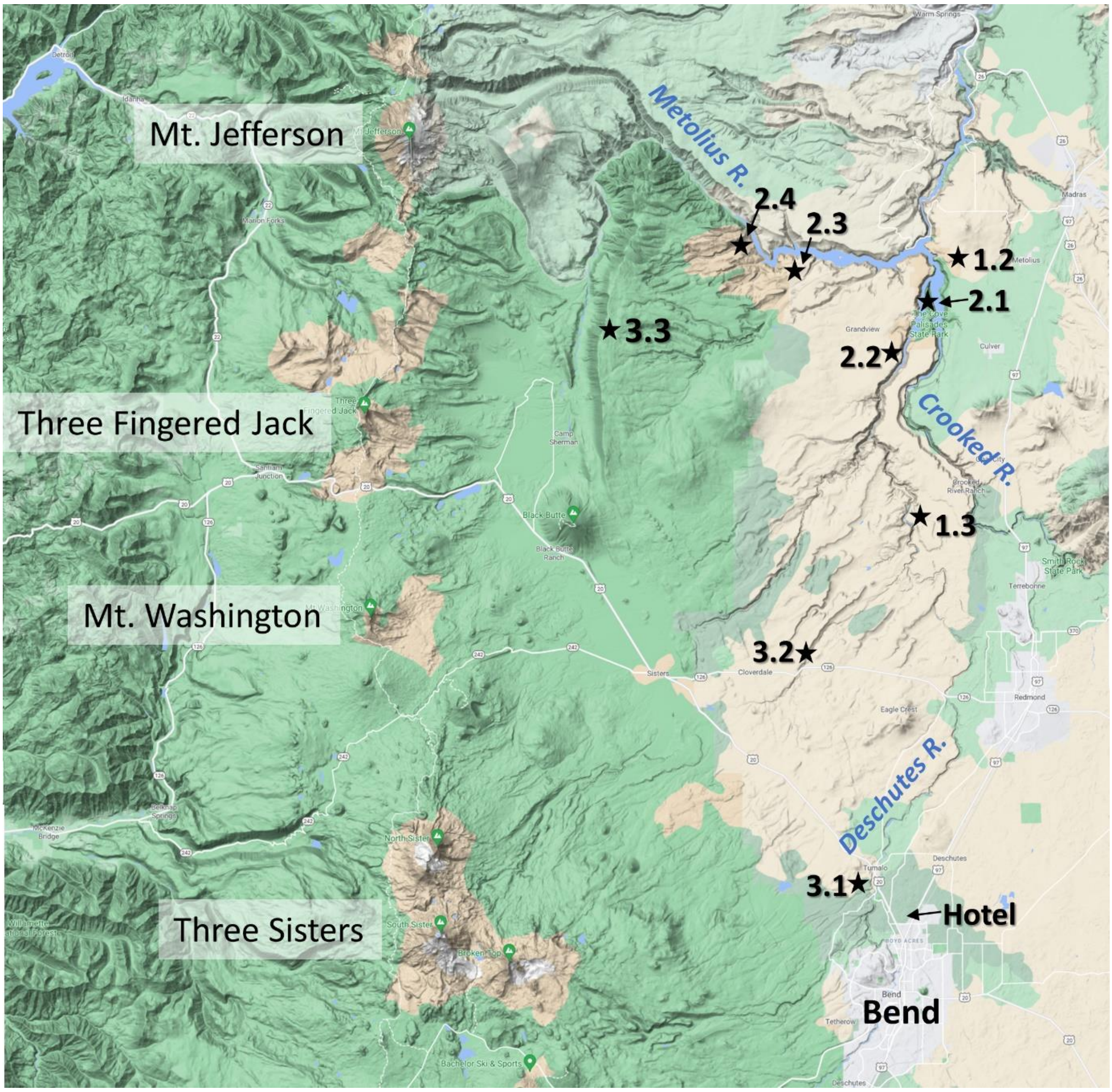

Figure 1: Map of Central Oregon with field trip stops labeled. Portland and stop 1.1 are to the North (not shown)

DAY 1: Thursday, October 14

0800: Leave Portland from Conference Center
Drive to White River car park on Mt Hood
Route (62 mi)- Take I-84 E to US-26 E. Take the State Route 35 N exit in Government Camp.

0930: Stop 1.1 Mount Hood at White River Carpark
Introduction to the Cascades arc and tectonic setting. Short hike to see Mount Hood block and ash flow deposit. Non-hiking alternative to Timberline Lodge and Cascade view.

Brief History of the Cascades Arc:

The Cascades volcanic arc has been active in Oregon since approximately 40 Ma and is the result of the subduction of the Juan de Fuca plate beneath the North American plate. Convergence has become progressively more oblique and convergence rates have decreased five-fold since 35 Ma (Verplanck and Duncan, 1987). By convention, the Cascades are spatiotemporally divided into the ancestral Western Cascades, which was most active prior to 7.5 Ma and erupted over an area approximately three to four times wider than the Quaternary arc, and the more recent High Cascades (7.5 Ma to present), which erupted over a much narrower belt east of the Western Cascades (Priest, 1990). Although this trip is focused on the Deschutes Formation (7.5-4 Ma), which records the initiation of the High Cascades, it is important to compare to "background" Cascades activity before and after to understand its uniqueness.

The evolution of the Cascades arc can be summarized by dividing its history into 4 volcanic episodes, where each episode represents distinct characteristics in the style, composition, volcanic productivity and locations of eruptions (Fig.2). The following divisions are a modified after the work of Priest (1990) and du Bray and John (2011).

The **Early Western Cascades (35-17 Ma)** erupted large volumes of predominantly tholeiitic basalt to andesite lava with minor local andesite stratovolcanoes and dacite to rhyolite domes (du Bray and John, 2011). Cascades volcanism was also explosive during this time, producing several tens of ignimbrite sheets, with a few calderas (Seligman et al., 2014) identified within the Western Cascades arc (e.g., ~25 km

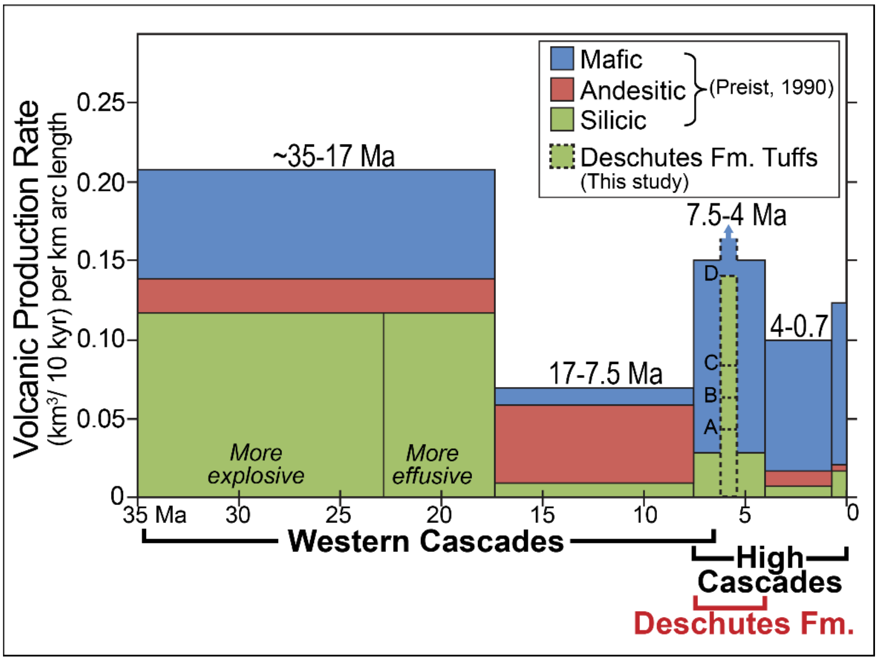

Figure 2: Volcanic Production through time from Pitcher et al., 2021. Dashed column represents volumetric rate of the 78 distinct explosive eruptions of the Deschutes Formation. (A) gives the minimum rate. (B) represents an estimate if an equal ignimbrite volume was deposited westward (C) also includes an additional co-ignimbrite tephra fall volume that is half that of the ignimbrite component. (D) is an estimate assuming the tephra fall component is nearly twice that of the ignimbrite. All data except the dashed column are from Priest (1990).

diameter Mohawk River Caldera, 32 Ma) and in the back-arc John Day Formation. The higher volcanic production during this time is consistent with higher convergence during the Oligocene. (Verplanck and Duncan, 1987). Compositions became more calc-alkaline beginning around 26 Ma and were marked by a shift to more effusive activity.

The **Late Western Cascades (17-7.5 Ma)** are characterized by very low rates of volcanic activity (Priest, 1990). Eruption rates were approximately three times lower than they were during the previous episode, possibly reflective of the decreasing convergence rate between the Juan de Fuca and North American plates (Priest, 1990). Columbia River Basalts flowed into northwest Oregon during this time, and the lack of significant interbedded volcaniclastic sediment is evidence of the relative inactivity in the northern Oregon and Southern Washington Cascades in this time period (Sherrod and Smith, 2000). Eruptions were primarily effusive, and two-pyroxene andesite lava flows became the dominant composition (Priest, 1990). Dacite to rhyolite compositions are almost completely absent, with the exception of the silicic volcaniclastic deposits of the Simtustus Formation (15.5-12 Ma), which we will drive through as we enter the northern part of the Deschutes Basin on our way to the next stop (du Bray and John, 2011; Smith, 1986).

Early High Cascades (7.5- 4 Ma) volcanism was characterized by a dramatic increase in volcanic activity beginning approximately 7.5 Ma, and was focused within a new arc axis, the High Cascades, located east of the ancestral Western Cascades (Priest, 1990).The initiation of the High Cascades was marked by the eruption of significant volumes of MORB-like Low-K tholeiitic basalt (0.1-0.5 wt. % K_2O) and basaltic andesite, a change from the almost exclusively calc-alkaline andesite compositions that dominated the previous 10 Ma (Conrey et al., 2004; Conrey et al., 1997). An 800 k.y. pulse of explosive volcanism also occurred during this time, producing hundreds of ignimbrites and tephra-fall layers which account for the highest volumetric rate of silicic magmatism in the Oregon Cascades since at least 17 Ma (Pitcher et al., 2017). This continued until the formation of the High Cascades Graben, beginning ~5.3 Ma, which ultimately cut off supply from the arc and arrested aggradation (Smith et al., 1987). This bimodal activity is well preserved within the Deschutes Formation, which will be the focus of this trip and will be discussed further at the next stop.

Late High Cascades (<4 Ma) volcanism in central Oregon was constrained within the newly formed High Cascades Graben and during the Pliocene, a broad mafic platform was built up by numerous overlapping shield volcanoes (Taylor, 1990). Quaternary volcanism in central Oregon continues to be characterized primarily by overlapping monogenetic basalt to basaltic andesite shield volcanoes which form the third highest volcanic vent density in the entire Quaternary arc (Hildreth, 2007). Larger, more intermediate composition stratovolcanoes include, from north to south, Mount Hood, Mt. Jefferson, Three-Fingered Jack, Mt Washington, and the Three Sisters, and evolved composition at these centers range up to true rhyolites (e.g., South Sister). Although central Oregon Quaternary High Cascades are predominantly mafic, felsic eruptions are more common there than in most of the Quaternary arc. There have been eight explosive eruptions since 700 ka, large enough to produce tephra-fall deposits, and five of these were larger than 0.1 km^3 (DRE) (Hildreth, 2007, and references therein). This includes pyroclastic eruptions from the Tumalo Volcanic Center, located 15-20 km east of the main arc axis (Sherrod et al., 2004), which we will stop at on our third day. However, overall, volcanic production rates of all compositions are much lower than during the 7.5-4 Ma Early High Cascades that produced the Deschutes Formation (Priest, 1990).

Large explosive, caldera-forming eruptions (CFEs) are not common in the Cascades arc. Only four CFEs are known (Kulshan, Mount Mazama, Rockland Ash, and Tuff of

Teepee Draw) (Hildreth, 2007). This caldera density is in the lower third of arcs worldwide (Hughes and Mahood, 2011). Instead, “steady state” activity of the arc tends to be effusive mafic activity with broadly spaced intermediate stratovolcanoes. Eruptive activity at these centers tend to be relatively effusive, with large explosive eruptions >1 km^3 being quite rare. Our first stop is at Mount Hood to get a glimpse of one such Quaternary Stratovolcano and to compare its effusive nature to that of the explosive volcanism of the Deschutes Formation.

Brief eruptive history of Mount Hood:

Mount Hood, Oregon, an archetypal subduction zone stratovolcano, is located about 70 km east of Portland, Oregon. Over the last ~500,000 years Mount Hood has repeatedly erupted crystal-rich andesites and low SiO_2 dacites. The volcano is dominated by extrusive eruptions of lava flows and domes, together with deposits related to dome collapse, debris flow and glaciation. There are no known plinian or subplinian eruptions. Lavas show similar phenocryst mineralogy, compositions, and textures, and are dominated by plagioclase together with pyroxene, amphibole, oxides, and occasional olivine. Bulk rock chemical variations, mineral compositions and textures and the presence of quenched mafic inclusions show that magma mixing has played a major role in the formation of almost all Mount Hood magmas.

The south side of Mount Hood has been the site of the two most recent eruptive phases of the volcano, both of which also involved dome extrusion at Crater Rock – located just to the south of the current summit. These earliest of these was the Timberline phase, an extensive dome eruption that occurred ~1500 years ago. A major sector collapse event associated with this produced a large debris flow and downstream lahar deposits, and constructed the relatively smooth surface – known at the Timberline surface, which dominates the morphology of the south side of the volcano. The most recent eruptive phase – and also Oregon’s youngest volcanic eruption – was the Old Maid phase. This was a dome eruption accompanied by block and ash flows and lahars that occurred in the 1780-1790’s. The distal impacts of sediment related to the Old Maid eruption on the Sandy River – which flows into the Columbia near Troutdale, Oregon – were observed by the Lewis and Clark expedition in 1807.

From our location at the White River snow park, a short hike allows us to view a Old Maid age block and ash flow deposit about half a mile hike upstream in the sides of the White River Valley. This flow consists of ~7 m thick poorly sorted deposit with blocks up to car size. Most blocks are dense, fresh, and crystal rich, although some highly altered blocks are also apparent. Many blocks are also polygonally-jointed, showing that they fractured in-situ from rapid cooling. The magma type here is a crystal-rich plagioclase-hornblende bearing low silica dacite with minor orthopyroxene and occasional small quenched mafic inclusions. The White River is also the source frequent debris flows, often the result of high precipitation “pineapple express” atmospheric river events. The most recent of these in 2006 did extensive damage to the highway 35 bridge near here, which has been extensively raised and modified as a result.

~1130: Lunch at White River car park

1200: continue to Cove Palisades overlook at Lake Billy Chinook. (44.5630, -121.26155)
Route- Head SW on OR-35 S and merge onto US-26 E. Follow for 50 mi and turn right onto NW Pelton Dam Rd. Follow for 6.7 mi. NW Pelton Dam Rd turns slightly right and becomes NW Elk Dr. Turn right onto SW Belmont Ln. Turn left onto SW Mountain View Dr. Turn right to stay on SW Mountain View Dr

__1330: Stop 1.2 Cove Palisades Overlook__

Viewpoint overlooking the Deschutes Formation and canyon-filling lavas at Lake Billy Chinook. Introduction of Deschutes Formation (tuffs and sediments) and Tetherow Butte Basalt

Lake Billy Chinook is at the confluence of the Deschutes, Crooked and Metolius Rivers. The Pelton dam, which impounds it is one of several on the Deschutes River, which flows north to join the Columbia. On the skyline you see the Quaternary cones of the Cascades arc. From north to South are Mt. Hood, Mt. Jefferson, Three-finger Jack, Mt. Washington, North, Middle and South Sister.

In the walls of the canyon are exposed the intercalated volcaniclastic sediments, basalt lava flows, and ash flow and air fall tuffs that make up the Deschutes Formation (7.5- 4.0 Ma), which is an unusual preservation of a sedimentary section immediately adjacent to the arc. The prominent basaltic prow is called the Peninsula and the point to the left (south) of it is called the Ship. The prominent pale tuff on the Ship is the Cove ignimbrite. It is not a regionally extensive unit and has an age of 5.68-5.7 Ma. The gray unit below it is the tuff of Jackson Butte (5.98 Ma) and an unnamed tuff above it is probably equivalent to tuffs exposed on Green Ridge. The Peninsula is made of a thick flow that filled a proto-Deschutes River canyon. It is 1.3 my old (Conrey et al., 2002). The base of the Deschutes Fm is constrained by a basal basalt exposed at Pelton Dam (7.4 Ma). You are standing on the Tetherow Butte Basalt (5.17 Ma, Pitcher et al., 2021), which marks the top of Deschutes Formation here in the east. The top of westernmost Deschutes Fm., is basalt on top of Green Ridge (5.34 Ma, Smith et al., 1987). Intercalation of periodic basalts and high eruption rates during Deschutes time allowed accumulation and preservation of this erodible record.

Important points about the Deschutes Formation include:

a. The suite is bimodal, in that the tuffs are dacite to rhyolite and they are intercalated with basalts and basaltic andesites that have low-K tholeiite affinities (Fig. 3). This is quite different from the Late Western Cascades volcanism of the previous 10 Ma, which was characterized by andesite lavas. The Deschutes tuffs were sourced from the newly formed High Cascades arc axis, whereas many of the basalts are more local.
b. At least 78 distinct pyroclastic units have been identified by Pitcher et al., 2021. Mapped paleodrainages, ignimbrite thickness, welding facies, and imbrication indicate two main ignimbrite sources: one near modern Three Sisters and one near modern Mt. Jefferson, indicating that these regions are

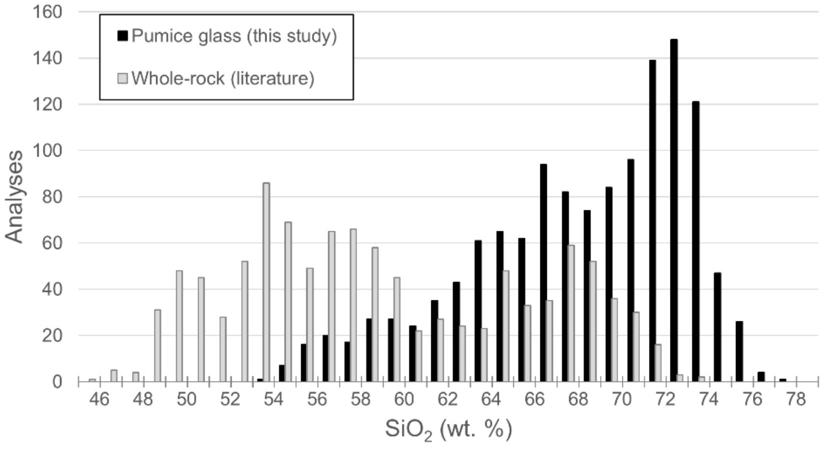

Figure 3: Frequency histogram of SiO_2 content of whole-rock (literature) and tephra glass (Pitcher et al., 2021), showing the bimodal nature of the Deschutes Formation

long-lived silicic and intermediate centers. We will see some of the Southern ignimbrites at our next stop, and we will become familiar with many of the northern ignimbrites tomorrow, both on a boat and on land.

c. Hyperconcentrated flood flow deposits, the sedimentary facies transitional between lahar and regular stream flow were first recognized and described here (Smith references).

Regional setting

The Deschutes Basin is bound to the west and southwest by the Cascades, to the east by the gently folded, mainly Oligocene John Day Formation (~30-20 Ma). We will see the prominent cliffs of the famous climbing locality, Smith Rocks, which is part of the intracaldera fill (>580 km^3) of the 29.5 Ma Crooked River caldera (McClaughry et al., 2009). To the north the Deschutes Fm overlies an older set of Miocene volcaniclastics (the Simtustus Fm), which in turn overlie Columbia River Basalt. To the south, the Deschutes Fm interfingers with basalts and rhyolites and sediments of the High Lava Plains province (Fig. 4).

In the present day, the Cascades arc of central Oregon and southern Oregon adjoins the Basin and Range province and is under extension as expressed by steep-sided grabens that die out northward, between Mt Jefferson and Mt Hood. To the east, the northern margin of the Basin and Range is in the High Lava Plains, which is a bimodal province with westward-younging rhyolite centers related to rollback and steepening of the Juan de Fuca slab beneath Cascadia (Ford et al. 2013; Long et al, 2012). Like basalts of the Deschutes Basin, the High Lava Plains basalts are low-K tholeiites (HAOT of Hart et al.,1984). Deschutes rhyolites share high-Fe affinity with rhyolites of the High Lava Plains (Pitcher et al., in prep) and are quite distinct from the low-Fe Quaternary High Cascades felsic magmas.

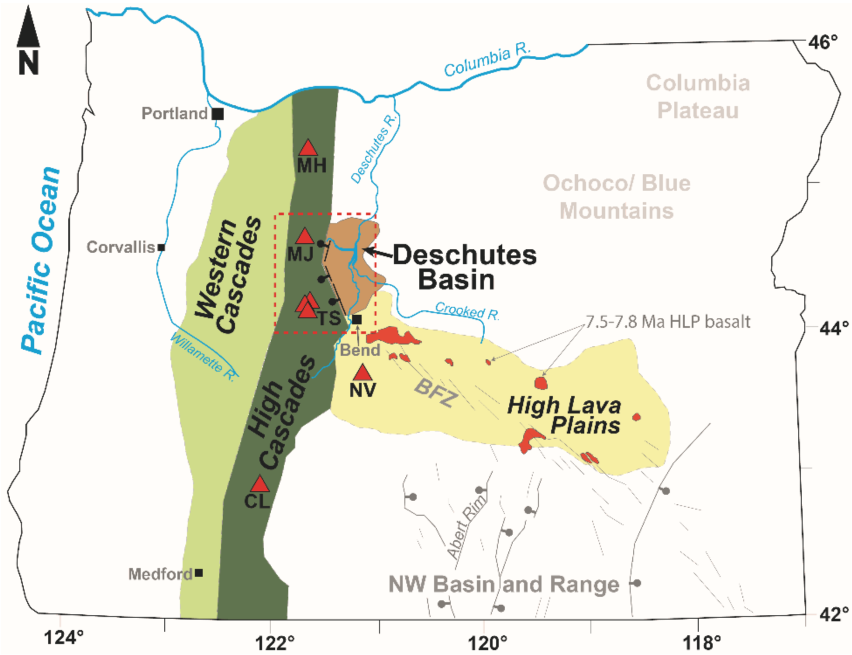

Figure 4: Map showing the location of the Deschutes Basin and other important geologic and physiographic features in central Oregon.

1425: Continue south to Steelhead Falls
Route- turn right on Lower Bridge Rd. Traveling on Tetherow Butte basalt. Right to Crooked River Ranch, left on Badger, stay left on Badger, right to Steelhead Falls

*1500: **Stop 1.3 Steelhead Falls trail**—1-mile hike. (Non-hiking alternative to see local outcrop of pumice fall deposit.)*
Hands-on view of regional ignimbrites and distal facies of Deschutes Formation.

Here we will see mainly distal facies of tuffs and volcaniclastic deposits, which dominate the section. This section includes 4 ignimbrites, from top to bottom they are the Peninsula Tuff, the Steelhead Falls Tuff (5.68 Ma), the McKenzie Canyon Tuff (5.76 Ma), and the Lower Bridge Tuff (5.93 Ma) (Fig. 4). These pyroclastic flows traveled a remarkable distance, as we are > 45 km northeast from the presumed southern source, near Three Sisters.

We will examine particularly the Steelhead Falls unit (SHF) and its basal pumice fall deposit. The tuff crops out continuously for ~2.5 km north of Steelhead Falls, along Deschutes River and in several isolated outcrops along Crooked river to the northeast. Unlike all of the other marker ignimbrites in the south, it cannot be traced any further west or southwest from here. This was enough of a puzzle that SHF tuff wasn't given its on designation in the most recent Geologic map of the area and is simply shown as undivided tuff (Sherrod et al., 2004). Pitcher et al. (2021) have correlated the unit to a much larger ignimbrite to the north, the Fly Creek Tuff (FCT). This correlation is based on several lines of evidence:

- Same $^{40}Ar/^{39}Ar$ ages: SHFT=5.68±0.02 and FCT=5.68±0.01Ma (Pitcher et al., 2017)
- Statistical similarity of glass compositions. Tephra correlations are based on multivariate statistical technique called Hotelling's T^2 test. In addition, the pumice-fall deposits, which are ubiquitously found beneath both units, are also compositionally identical
- Statistical similarity of SHFT and FCT plagioclase compositions (average (±1σ) An contents of 33.2 ± 5.9 and 33.1±6.0, respectively, and identical FeO weight % of 0.31±0.05
- Trace amphibole is found in both units, which is extremely rare for Deschutes Formation ignimbrites
- High crystallinity (5-12%) compared to most other units (< 5%)
- SHF is partially welded in its NW-most location, not welded further south even where much thicker (25 m)

Thus, we suggest that the SHF tuff is the lower flow unit of FCT, and that the total minimum volume is 7.9km3 (5.8 km3 DRE).

The SHF tuff outcrop that we will visit exemplifies classic tephra-fall and ignimbrite flow unit facies. The basal pumice fall tuff deposit can be distinguished from the ignimbrite (or ash flow tuff) deposit by several features: it is pumice clast-supported (rather than ash matrix-supported), pumice tends to be angular to subangular (rather than rounded), there is internal stratigraphy/bedding, and sorting is relatively good. These features are due to deposition by falling out of the plinian column. This particular pumice-fall coarsens upwards to the middle of the deposit where there is a lithic-rich layer. We interpret this as a ramp up to a climactic phase of the plinian eruption. This then grades into finer pumice, which may indicate a slight lull as finer particles rained out. Above this, there is a beautiful sharp contact with the overlying ignimbrite.

The ignimbrite here shows much of the classic flow unit facies described by Sparks and Walker in the 1970s (Fig. 5). We do not see the lithic-rich lag breccia (layer 1), likely because we are too distal. In the relatively thin layer 2a there is a slight coarsening upwards that results from interaction with the ground, causing fluidization, and dispersive forces pushing larger lithics upwards. The main body of the ignimbrite, layer 2b, shows a normal grading of lithics, in which the base has the largest and most abundant dense lithic fragments (Lithic concentrated zone, LCZ), and reverse grading in which larger pumice "float" to the top of the deposit (pumice concentrated zone, PCZ). Pumice here tend to be < 1 cm in diameter at the base but get slightly larger at the top. In many places in the Deschutes Fm., and around the world, this contrast in pumice size and abundance can be dramatic, (I have seen >1-m wide pumice clasts at the top of the Ito ignimbrite in Japan)! Layer 3, where preserved, is a fine ash deposit that results from co-ignimbrite ash that was elutriated off of the flow. At this particular outcrop, you can also see that the top of the ignimbrite is pink in color due tom being vapor-phase altered, as hot gasses escaped the cooling and compacting tuff.

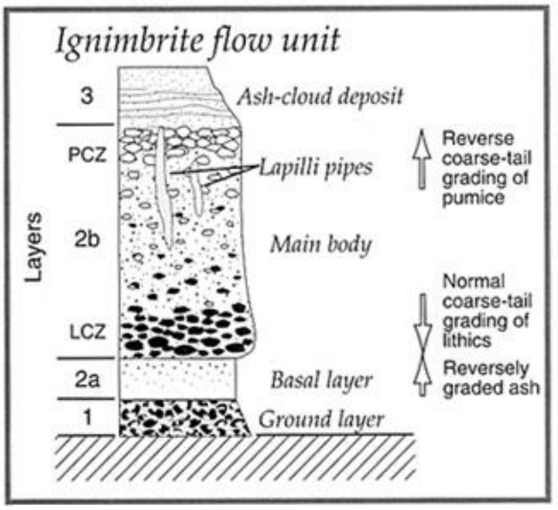

Figure 5: Classic Ignimbrite Flow unit cross section (after Sparks, 1973).

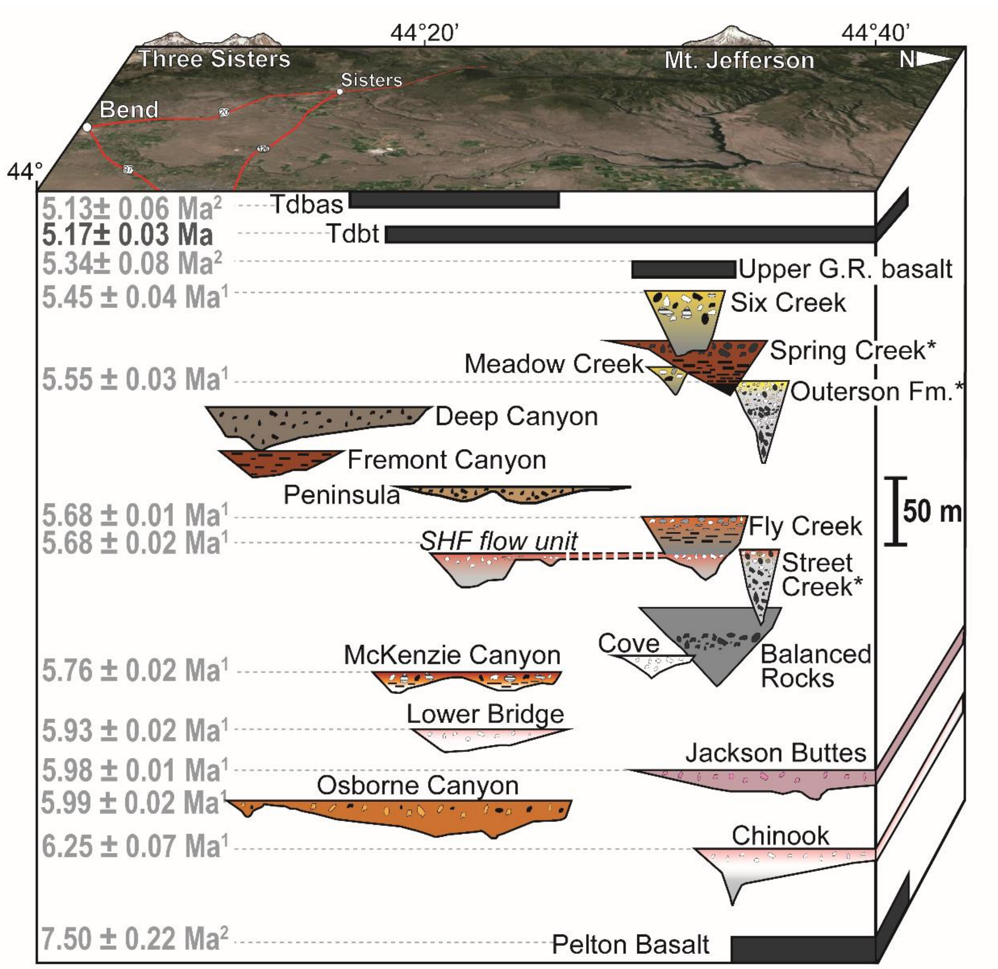

Figure 6: Schematic stratigraphic section showing major marker ignimbrites, their distinguishing characteristics, north-south position, and cross sectional area and relative thickness (note scale bar). The left side lists plagioclase $^{40}Ar/^{39}Ar$ ages (±2σ uncertainty) from [1]Pitcher et al., 2017 and [2]Smith et al., 1987

~1700: depart for Bend to Hotel: Best Western Plus Bend North. 20615 Grandview Dr, Bend, OR 97701
Route- Head southeast on NW Steelhead Falls Dr. Turn left onto NW Lower Bridge Way. Turn right onto US-97 S. Drive 18.7 mi and turn right onto Grandview Dr.

1822: sunset

1900: Depart motel for dinner in Bend.

DAY 2, Friday October 15

Breakfast bar at motel. Sign in for boat trip.

0800: Depart motel for boat landing at Lake Billy Chinook
Route- Take US-97 N for 29 mi. Continue on SW Culver Hwy. Take SW Feather Dr to SW Jordan Rd in Culver. Follow signs for Cove Palisades State Park.

As we slowly descend the grade from the plateau to the lake, look to the left to see the steep unconformity between the Deschutes Fm and the canyon-filling lava. To the right you can see the many volcaniclastic and pyroclastic units of the Deschutes Fm.

0900-1230: Half of group will take boat tour to lunch stop and half will go by van. Reverse after lunch. As we move east by land or by boat, you will notice a change from volcaniclastic sediment dominated distal facies to more tuff-dominated medial facies.
Boat trip: Views of Deschutes Formation tuffs, sediments, and intercalated basalt lavas with spectacular evidence of incision and canyon-filling lavas.

Land trip morning (reverse for afternoon):
As we leave the marina look up to the east to see the unconformity between the canyon-filing lava and the Deschutes Fm.
0915: ***Stop 2.1. The Ship.*** *Brief overview of local stratigraphy and petroglyph locality*

The carving in the stone is at least 2000 years old and is of a style as old as 6000 years. What is depicted has not been identified. The18-ton rock was rescued from flooding by the dam in 1964 from land ceded to the Wasco and Warm Springs tribes by treaty in 1855. The descendants in the area are part of the Confederated Tribes of Warm Springs Reservation of Oregon

0950: continue along highway 64.

0955: ***Stop 2.2. Pipe vesicles*** *in basalt. Take care as the outcrop is close to the road.*

Excellent pipe vesicles are found in the base of the compound pahoehoe basalt flow lobes intercalated in the Deschutes Formation. Pipe vesicles are elongated vesicles that are thought to form during late-stage migration of volatiles during cooling of pahoehoe lava flows. (Although a recent paper by Sheth, 2020 argues that they form by sinking of dense immiscible melt droplets, rather than buoyant rise of volatiles). In contrast “vesicle pipes” are cylinders filled with abundant (often spherical) vesicles. Try to determine the direction of flow by observing the direction that the pipe vesicles are bent. The lava was also able to raft sediment, possibly by invading the low density, unconsolidated material.

These relatively hot and dry low-K tholeiite (LKT) lavas are common in the Deschutes Formation; approximately 80% of primitive lavas have LKT compositions. In contrast LKTs make up less than 20% of primitive basalts erupted by the Quaternary central Oregon High Cascades (Pitcher et al., in prep; Pitcher and Kent, 2019). Note that this is an arc-adjacent alluvial fan facies of Deschutes Fm., as indicated by abundant cobble conglomerates.

1025: Continue along highway 64.
The road climbs onto a basalt plateau called the Canadian bench basalt (age) that is a low-K tholeiite and that flowed from Green Ridge in the west. The road is called Grandview, go left on Highway 64.

Along the gentle grade into Fly Creek, we drive through a section of 5 ignimbrites which overlie the basalt of Big Canyon that extends 23 km east to Madras. From youngest to oldest, the tuffs are: Six Creek, an unnamed tuff, Meadow Creek, Fly Creek, and Balanced Rocks Tuff. We have geochemically correlated the unnamed tuff to one that outcrops on the West flank of Green Ridge, where it is much thicker and contains abundant lithic fragments.

Note how different the Deschutes Fm is here compared to at the Ship. This area is much more tuff-dominated since we are 15 km closer to the source. The Deschutes Fm. becomes more lava-dominated west of here (we will see this tomorrow when we drive along and on the west Flank of Green Ridge). To the west is the thick Gunsight basaltic andesite that has a source to the west/southwest and is an example of inverted topography.

*~1100: **Stop 2.3. The Balancing Rocks-** Hoodoos formed by two marker ignimbrite units- The Fly Creek Tuff and the underlying Balanced Rocks Tuff. Welcome to Oregon's most underappreciated natural wonder!*

The Fly Creek Tuff (5.68 Ma), which forms the hard protective caps of the hoodoos is partially welded. Welding is the process of compaction and fusing of the volcanic glass (ash) particles within an ignimbrite that occurs during and after deposition. With more welding pumice gets flattened and can eventually turn into dense glass lenses called fiamme (Italian for flame). Here the Fly Creek Tuff has been welded enough to be called “partially welded with pumice”, meaning that pumice is flattened and there is a horizontal “eutaxitic” fabric, but pore space still exists and it hasn’t transformed into fiamme. In some locations to the west, closer to the source, the Fly Creek Tuff has been welded to the point of containing fiamme. We will visit a densely welded tuff with beautiful fiamme on day 3 (Curious readers can look ahead to Day 3 for descriptions and images of welding facies). Usually, the middle of the ignimbrite is most welded (where temperatures remain hottest). In this location, the upper, more friable, unwelded portion of the Fly Creek Tuff has been eroded away.

Note the “platy” fabric of the unit here. We interpret this to be the result of a process called rheomorphism, in which a pyroclastic flow comes to rest, but is still hot enough to allow some post-emplacement flow. This causes shear stress within the unit and can lead to a “platy fabric.” A similar platy fabric is the hallmark of andesite lava flows, which have the ideal viscosity to cause shear stress, leading to a “platy andesite outcrops.” (As a fun side note, platy andesite can be used under tires to get university vehicles unstuck from loose sand in poorly developed side roads).

Fly Creek Tuff is laterally extensive throughout the northern part of the Deschutes Basin and is thus one of the most important marker units in the Formation. The tuff contains crystal-rich (primarily plagioclase) rhyolite pumice, which are much more crystalline (~10% by volume) than almost all units within the Formation (Usually < 5 %). Although the lower flow unit of Fly Creek Tuff (exposed here) contains only rhyolite pumice, the upper nonwelded flow unit (eroded away here) contains two compositionally distinct populations of basaltic andesite scoria. Thus, the tuff shows silicic to mafic zonation, similar to Climactic Mount Mazama (Crater Lake) eruption. As mentioned on Day 1, we have correlated the Steelhead Falls member to this lower flow unit of Fly Creek Tuff.

The softer and nonwelded Balanced Rocks Tuff (initially called the Hoodoo Tuff, Conrey, 1985), forms the pillars of these hoodoos where protected by sloughed blocks of the Fly Creek Tuff. The Balanced Rocks Tuff ranges from dacite to rhyolite in composition. The tuff has two flow units (one continuous cooling unit), which is marked by an abrupt upward change from pumice-rich to a pumice-poor zone. The unit contains a wide range of pumice textures and compositions, containing light grey rhyolite pumice, dark grey partially inflated dacite clasts, and abundant "banded pumice". Thus, this tuff displays various degrees of mixing and mingling between compositionally distinct magmas. The banded pumice contains streaks of rhyolite/rhyodacite glass (68-71 wt. % SiO_2), which matches the composition of the grey pumice, intermingled with darker glass (62-63 wt. % SiO_2). Many Deschutes Formation tuffs have evidence of magma mixing or mingling, including: homogeneous pumice glass with 2 populations of plagioclase (complete mixing), compositionally-banded pumice (incomplete magma mingling), or the existence of two or more populations of compositionally distinct but homogeneous pumice glass (separate magmas tapped by the same eruption with no mingling). The Balanced Rocks Tuff also contains some rare partially melted granite xenoliths and K-altered tuff xenoliths, evidence of both shallow and deep assimilation (Conrey,1985). Finally, keep an eye out for lithic-rich "elutriation pipes." (aka "clastic dikes"). These presumably form as hot gasses force fine ash fragments out during cooling and compaction, leaving behind a higher concentration of coarse material.

Between the Fly Creek and Balanced Rocks tuffs there is a section of volcaniclastic sediments that includes a bed of accretionary lapilli. Accretionary lapilli are concentric balls of ash that form when ash is wet (often due to rain, which may be self-induced by the eruption cloud) and agglomerates in the eruption column.

11:55: depart for stop past Perry South Campground

*1205: **Stop 2.4. Proximal Chinook Tuff**: As time allows-The tuff exposure just past campground, emphasis is proximal facies of the Chinook Tuff, which is here all white and rhyolitic. Entrainment of clasts injected from the substrate indicates it ran over wet ground.*

*1230: **Lunch Stop** at Perry South Campground*

1330-1700: Reverse order of morning.

1700: meet at boat launch for the day's summary.

Discuss the evidence for this being an ignimbrite flare-up, and maybe a bit about dam history and armored landscape.

1740: Return to motel and dinner- on own recognizance.

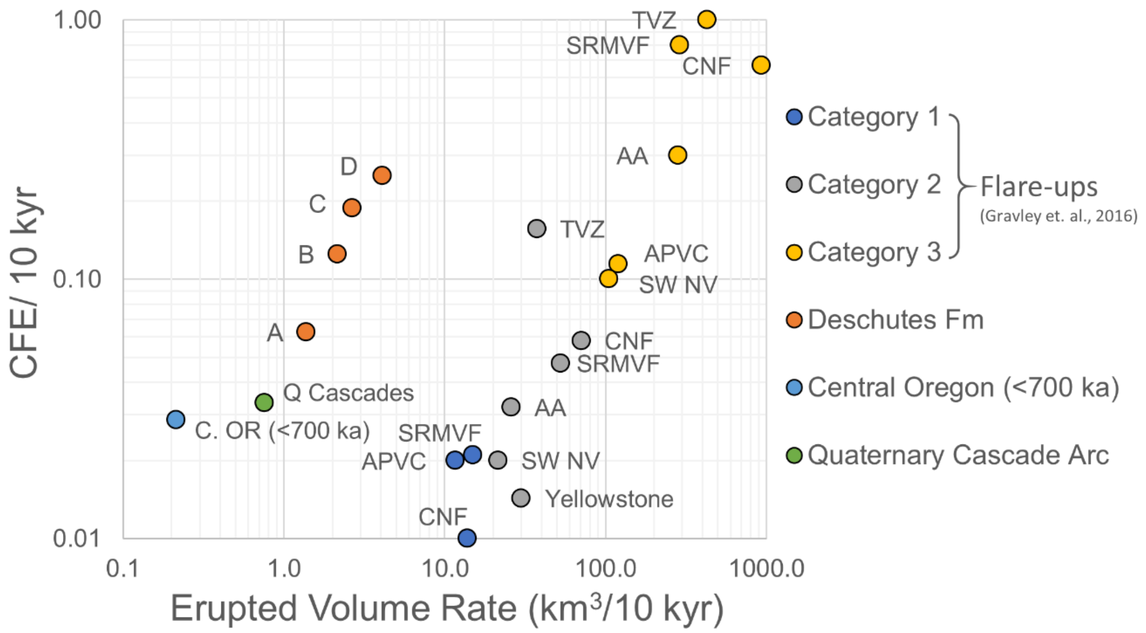

Figure 7: Comparison of the rate (per 10 kyr) of Deschutes Formation caldera-forming eruptions (CFE) and erupted pyroclastic volumes to the central Oregon Cascades, and the entire Quaternary Cascade arc (Hildreth, 2007), showing that the Deschutes Formation can be classified as an ignimbrite flare-up. Examples of other worldwide ignimbrite flare-ups from the compilation of Gravley et al. (2016), demonstrate that the Deschutes Formation is a unique style of flare up. Examples include Taupo Volcanic Zone (TVZ), Southern Rocky Mountain Volcanic Field (SRMVF), Central Nevada Field (CNF), Afro-Arabian volcanic field, Altiplano-Puna Volcanic Complex (APVC), Southwestern Nevada volcanic field (SW NV), and Yellowstone. The minimum (A) through maximum estimate values (D) for the Deschutes Formation correspond to those in Fig. 2.

Day 3. Saturday October 16

Breakfast at motel, checkout, bring down gear to load up.

0800: Depart motel
Drive to vicinity of Tumalo State Park

*0830: **Stop 3.1 Tumalo Tuff and Bend Pumice**. Example of continued explosive activity in the arc. Summary of local tuff stratigraphy and ages. Attributes of BP and TT. Ongoing work by Kent et al.*
0930: depart for Fremont Canyon Tuff.
Route- Take O. B. Riley Rd to US-20. Turn right onto Fryrear Rd. Turn right onto OR-126 E and follow 1 mi, down grade and park just past prominent curve and canyon

*1000: **Stop 3.2 Fremont Canyon Tuff**, welded facies*

The Fremont Canyon Tuff is a conspicuous southern-sourced ignimbrite because it is always at least partially welded. Welding usually occurs after an ignimbrite has been deposited and must involve 2 main processes: (1) physical compaction, which reduces the amount of pore space, and (2) sintering, which sticks (fuses) all of the particles together. With increasing intensity of welding, the ignimbrite becomes denser and stronger, loses porosity, and develops a flattened (foliated) fabric (eutaxitic texture) of increasingly flattened pumice. Eventually, pumice can lose all its porosity such that it turns into a glassy lens-shaped object called fiamme (Italian for flame). This welding process creates a spectrum of welding intensities, ranked from non-welded (rank I) to densely welded (rank VI) (Quane and Russel, 2005) (Fig. 8, Table 1). In comparison, Streck and Grunder (1995) classify these rankings as: nonwelded, incipiently welded, partially welded with pumice, partially welded with fiamme, and densely welded. Typically, the most welded portion of an ignimbrite will be a bit below the middle, where it remains hot, and there is more compression from overlying ignimbrite.

Table 1: Characteristic features for each rank of welding. (Table from Quane and Russell, 2005).

Rank	*Ash matrix*	*Pumice lapilli*
I	Unconsolidated[1], noncoherent[4], loosely packed[2], little to no adhesion between shards[3]	Lack deformation[3], randomly oriented[2]
II	[illegible]	[illegible]

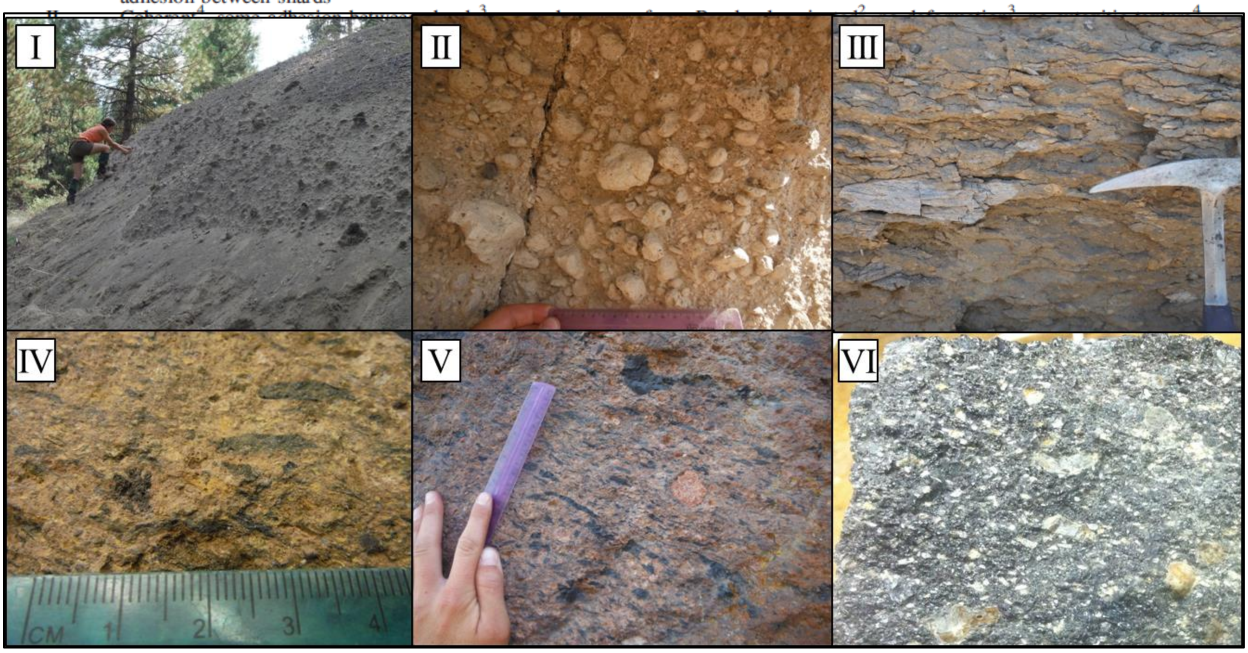

Figure 8: Pictures of outcrop-scale features for each welding ranking, all from the Deschutes Formation, Notice how, with increasing welding the outcrop becomes more consolidated, and the pumice become flattened and begin turning into black fiamme in Rank IV. The pictures of III and IV are of Fly Creek Tuff (which we visited at Balancing Rocks on Day 2, and V and VI are both of Fremont Canyon Tuff.

As we leave this outcrop, we will see another southern marker ignimbrite, the Deep Canyon Tuff (named after this canyon). This unit is characterized by large black dacitic pumice clasts and dense glassy vitrophyre. The tuff is comprised of multiple flow units and is up to 33 m thick and is the uppermost marker ignimbrite in the South. As we drive up the grade away from this stop, notice clear normal-fault displacement of the Deep Canyon Tuff. This is one of many normal faults in this area, collectively called the Sisters Fault Zone. These result from interarc extension. We will see much more dramatic expression of this extension and normal faulting at the next stop, Green Ridge.

1130: depart for Green Ridge
Route- Head west on OR-126 W. Turn right onto US-20 W. Turn right onto NF-11, about 5 miles west of Sisters roundabout. Turn left onto SW Green Ridge Rd/NF-1150 Turn left onto SW Green Ridge Rd/NF-1140. Fire tower is at (44.5345, -121.6075).

1230: Stop 3.3 ***Lunch and Green Ridge Fire Observatory***
Discussion of death of the Deschutes depositional regime with incredible views of Mt. Jefferson and the High Cascades Graben

You are standing on Green Ridge, on the hanging wall block of a north-south trending normal fault that forms the eastern edge of the Cascades Graben. The western flank of the ridge exposes a > 500 m thick section of the Deschutes Formation, with over 200 mapped lavas and tuffs. Pitcher et al., 2021 were able to successfully correlate several tuff units exposed on the west flank of the ridge to those on the gently sloping east flank.

Here, in this proximal location, the section is lava-dominated. There are diverse lavas including diktytaxitic basalt, low-K tholeiites, basaltic andesites, andesite, rare dacite, and one rhyodacite. Consider how much the Deschutes formation has changed in character since the first day at Steelhead falls, where the distal section was mostly volcanoclastic sediment, to the tuff-dominated medial sections along Lake Billy Chinook, to the proximal lava dominated section we are standing on.

<u>The Death of the Deschutes Formation:</u>

The uppermost basalt on Green Ridge is 5.3 Ma (Smith et al., 1987), suggesting Graben formation occurred around 5.3 Ma. Here, the 100–150 m of section between Six Creek Tuff and the uppermost lava is almost entirely lava flows and contain no ignimbrites (Conrey, 1985). Similarly, a marked lithological change occurs above the level of the Six Creek Tuff (5.45 ± 0.04 Ma, Pitcher et al., 2017), from sheet-flood and ignimbrite-dominated to paleosol dominated facies in the upper 50–100 m of many sections (Smith, 1986). However, several pumice-fall tuffs are found stratigraphically above Six Creek Tuff in the northern Deschutes Basin. Thus, as several previous authors have debated the important question: Was the notable decrease in deposition across the Deschutes Basin entirely the result of subsidence and graben-formation (and the flare-up continued after this time), or was pyroclastic volcanism waning prior to subsidence?

Since the post-subsidence proximal ignimbrite record is neither exposed nor intercepted by drill core (Hill, 1992; Hill and Priest, 1992), Pitcher et al. (2021) attempted to answer this question by noting trends in eruptive frequency prior to the initiation of graben subsidence. If subsidence were solely responsible, we would expect to see a continuously high eruption rate just prior to normal faulting and an abrupt decrease thereafter. The highest eruptive frequency in the north occurred 5.75-5.68 Ma, during which time eruptive frequency was 1.1-2.2 eruptions per 10 kyr (Fig. 9). The eruptive frequency then decreased by 30-40% during the subsequent 110 kyr (5.67-5.55 Ma) and decreased even further leading up to graben subsidence, marked by the uppermost Green Ridge lava (5.35 Ma). Thus, while graben subsidence of the High Cascades curtailed the distribution of ignimbrites into the Deschutes Basin, our eruption rate calculations indicate that the frequency of explosive eruptions was already decreasing at least ~200 kyr before graben formation (Fig. 9).

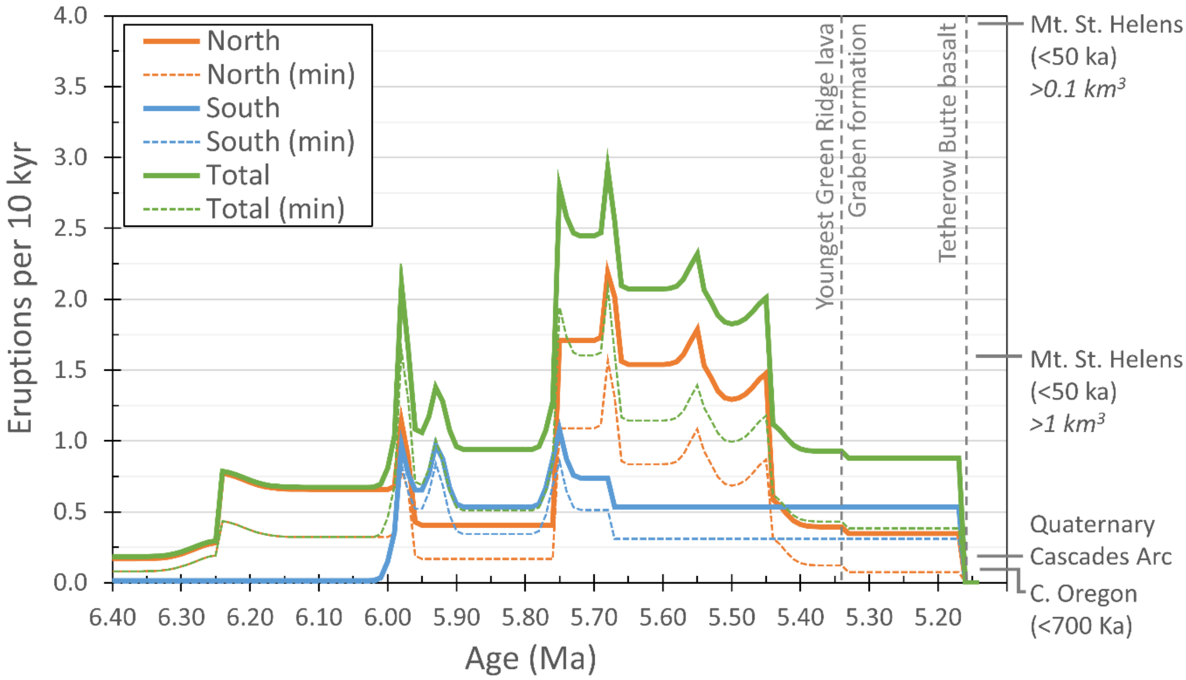

Figure 9: Estimated pyroclastic eruption frequency vs. time (from Pitcher et al., 2021). We collected geochemical data for 152 of the >250 total tuff samples. Our upper estimates of the eruptive frequency (solid lines) are calculated assuming that 49% of unanalyzed tuffs are from distinct eruptions. The minimum total frequencies (dashed lines) represent the unlikely scenario in which none of the unanalyzed tuffs are from new, distinct eruptions. See Pitcher et al., 2021 for more details

<u>The influence of extension on petrogenesis of the Deschutes Formation flare-up:</u>

We suggest that extension likely had a significant influence on the magmatic processes that led to the production of the unusual volume of silicic pyroclastic material that was erupted during Deschutes Formation ignimbrite flare-up. The geochemistry of tephra is consistent with a magmatic system that was hotter, drier and more reduced than that of the Quaternary Cascades. We propose a petrogenetic model for the earliest High Cascades in which crustal extension provided the mechanism to focus decompression melts (similar to those erupted in a cotemporaneous pulse across the High Lava Plains) into a new region of the crust and establishment volcanism along the new High Cascades arc axis. The predominance of LKT primitive basalts during this time provides evidence of the influx of these relatively dry decompression melts. Such extension allowed for penetration of these basalts into shallow levels of the crust and thermal priming of this crust under hot-dry-reduced conditions.

Following this thermal maturation period, the high basaltic flux into the upper crust led to a period of enhanced shallow crustal melting (Pitcher et al., 2021) that assisted in the production of the large volumes of hot-dry-reduced rhyolites of the Deschutes Formation. These crystal poor rhyolites exhibit high Fe, Na, Y, MREE, and low Eu and Sr, indicative of their formation within this hot and dry environment, and ilmenite-magnetite oxybarometry indicates melting must have occurred under reduced conditions. Furthermore, extensional faulting in the upper crust established a robust hydrothermal system (Ingebritsen and Mariner, 2010), and melting of these shallow hydrothermally altered rocks lead to the eruption of low-$\delta^{18}O$ felsic magmas.

However, the high flux of decompression melts and efficient crustal melting were temporary, leading to the relatively short duration (800 k.y., Pitcher et al., 2017) of this ignimbrite flare-up. Thus, the anomalously high production of silicic magma and rate of explosive volcanism recorded in the Deschutes Formation is mirrored by the unusual geochemistry of the eruptive products and are indicative of magmatic processes that were more dependent on extension than during the Quaternary.

By investigating the geodynamic and tectonic causes of this important period of unusual magmatism, we gain a more comprehensive understanding of the Cascades arc and the variability of magmatic processes through space and time.

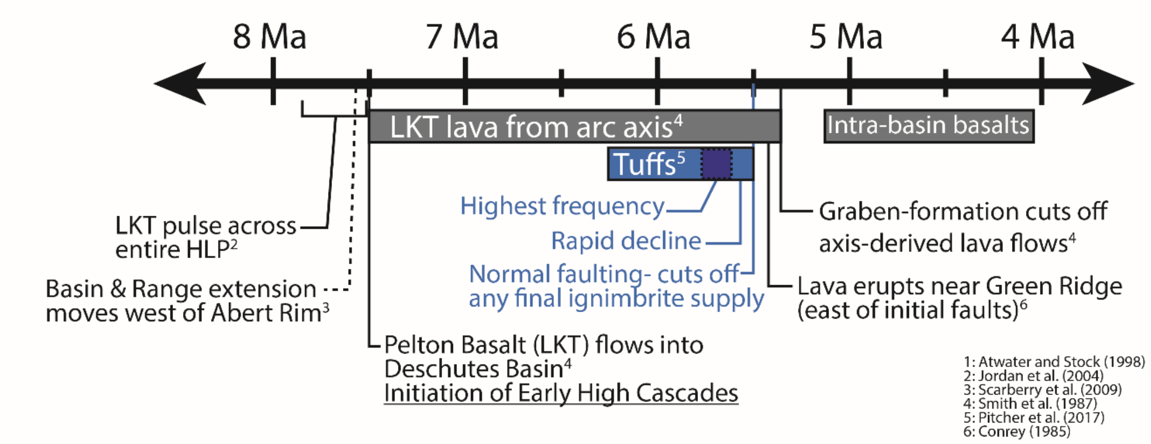

Figure 10: Timeline of regional tectonic and volcanic events and their temporal relationship to Deschutes Formation ignimbrite flare-up (blue). References for timeline events are: [1]Jordanet al. (2004); [2]Scarberry et al. (2010); [3]Smith et al. (1987); [4]Pitcher et al. (2017); [5]Conrey (1985).

1330: depart Green Ridge.
Route-Turn left onto SW Green Ridge Rd/NF-1140. Sharp left onto NF-1490. Follow thevery steep switchbacks down Green Ridge. Left on SW Metolius River Rd/NF-14. Take OR-20W

~1430: Roadside overview of young, dominantly mafic volcanism on Cascades axis, including Suttle Lake maar, many cinder cones and mafic lava fields, mafic stratocones Washington and North Sister (two kinds of basaltic andesite).

1510: depart for PDX
Route- via Highway 20 to 22 to I-5 north to Portland
1810: arrive PDX

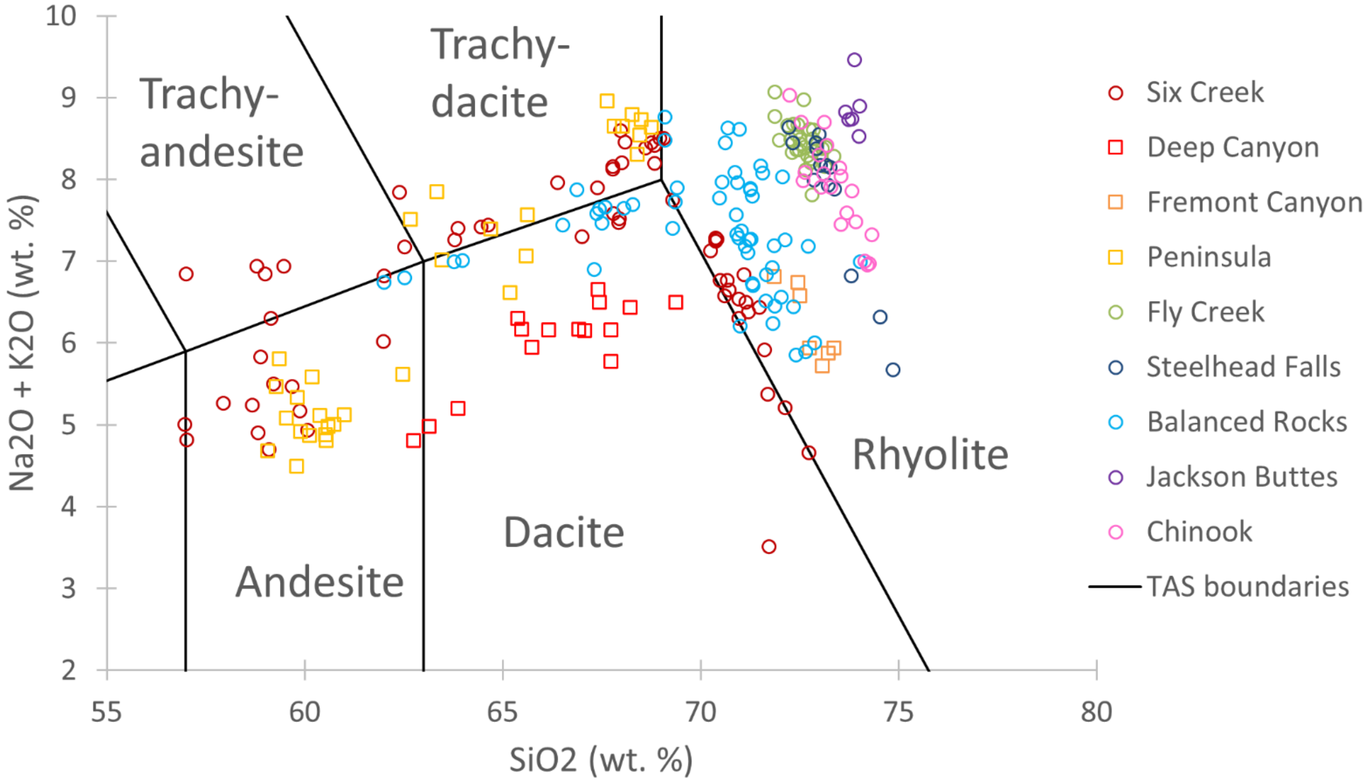

Figure 11: TAS diagram showing glass compositions of the major marker ignimbrites that we will see on this trip.

Table 1
Field characteristics of the 14 marker ignimbrites, as well as the Outerson Formation lithic-rich tuff, located west of the modern arc axis, which has an $^{40}Ar/^{39}Ar$ age (5.55 ± 0.03 Ma, this study) that is consistent with a Deschutes Formation origin.

Ignimbrite	Source	Max. thick-ness	Common outcrop color	Pumice populations	Composition	Welding	Crystallinity	Flow units	Other prominent features
Six Creek	North	82 m	Grey-yellow, buff	Black, grey, white, banded	Bimodal: andesite, rhyolite	None	1–3%	2–3	Large black pumice; only marker tuff traced to Green Ridge
Meadow Creek	North	15 m	Light grey	Black, grey	Dacite to rhyolite	None	2–3%	7	Similar appearance to Six Creek Tuff
Deep Canyon	South	33 m	Olive grey or light brown	Black	Dacite	None to moderate	<1%	Multiple	Contains black vitrophyre clasts
Fremont Canyon	South	19 m	Dark brown to red-brown	Black	Rhyolite	Moderate to dense	1–2%	1	Dense vitrophyre in some locations
Peninsula	South	12 m	Brown to grey	Grey, black	Andesite to trachydacite	Weak in places	<1%	1	Very channelized; contains large black bombs
Steelhead Falls	North	25 m	Pink-grey	White, grey	Rhyolite	Partial in one area	4–8%	1	Always overlies 1–2 m co-genetic fall unit; Similar in all aspects to Fly Creek Tuff lower flow unit. Likely correlated.
Fly Creek	North	49 m	Light grey to orange-grey	White, grey	Rhyolite	Partial to dense	7–10%	Multiple	Often welded; most crystal-rich unit; 1–2 m fall unit when base is exposed
Balanced Rocks	North	56 m	Light to dark grey (top)	Grey, black	Dacite to rhyolite	None	≤1%	2–3	Forms hoodoos capped by Fly Creek Tuff
McKenzie Canyon	South	23 m	White to red-orange (top)	White, black, banded	Bimodal: andesite, rhyolite	Partial to dense	2–3%	>5	Columnar where welded
Cove	North	18 m	White	Grey	Rhyolite	None	3–5%	1	Similar stratigraphic position as McKenzie Canyon Tuff
Lower Bridge	South	18 m	Pink-light grey	White, grey	Rhyolite	None	4–8%	2	Usually overlies 1–1.5 m accretionary lapilli
Jackson Buttes	North	23 m	Light grey to pink	Grey	Rhyolite	Partial in places	2–4%	>2	1st flow unit: large orange, pink and purple pumice, 2nd flow unit: fine white pumice; often welded (columns in places)
Osborne Canyon	South	28 m	Orange	Orange, black	Rhyolite	None	1–2%	2	Large orange pumice; forms hoodoos
Chinook	North	38 m	Grey-pink, white	White, grey	Rhyolite	None	3–4%	Multiple	Found at shoreline of Lake Billy Chinook; often contains rounded river cobbles
Outerson Fm. Lithic-rich tuff	North	62 m	Medium grey	White, dark grey	Bimodal: andesite, dacite	None	2–5%	2	Rich in volcanic lithics throughout; 1 m cobble-rich layer separates flow units

(From Pitcher et al., 2017)