

Sedimentary, volcanic, and structural processes during triple-junction migration: Insights from the Paleogene record in central Washington

Michael P. Eddy

Department of Geosciences, Princeton University, Princeton, New Jersey 08544, USA

Paul J. Umhoefer

School of Earth Sciences and Environmental Sustainability, Northern Arizona University, Flagstaff, Arizona 86011, USA

Robert B. Miller

Department of Geology, San Jose State University, San Jose, California 95192, USA

Erin E. Donaghy

*School of Earth Sciences and Environmental Sustainability, Northern Arizona University, Flagstaff, Arizona 86011, USA,
and ConocoPhillips, 600 North Dairy Ashford, Houston, Texas 77079, USA*

Melissa Gundersen

School of Earth Sciences and Environmental Sustainability, Northern Arizona University, Flagstaff, Arizona 86011, USA

Francesca I. Senes

Department of Geology, San Jose State University, San Jose, California 95192, USA

ABSTRACT

This guide describes a three-day field trip to the Paleogene sedimentary and volcanic rocks exposed between the Straight Creek–Fraser River and Entiat faults in the central Washington Cascades. These rocks record a history of deposition, deformation, and magmatism that can be linked to tectonic events along the North American margin using a robust chronology coupled with detailed sedimentological, stratigraphic, and structural studies. These events include deposition in a large sedimentary basin (Swauk basin) that formed in the forearc from <59.9–50 Ma; disruption and deformation of this basin related to the accretion of the Siletzia oceanic plateau between 51 and 49 Ma; the initiation, or acceleration of right-lateral, strike-slip faulting and the development of at least one strike-slip sedimentary basin (Chumstick basin) starting ca. 49 Ma; and the re-establishment of a regional depositional system after ca. 45–44 Ma (Roslyn basin) as strike-slip faulting was localized on the Straight Creek–Fraser River fault. These events are compatible with the presence of the Kula-Farallon ridge near the latitude of Washington ca. 50 Ma and its southward

movement, or jump, following the accretion of Siletzia. This trip visits key outcrops that highlight this history and links them to regional studies of sedimentation, faulting, and magmatism to better understand the geologic record of this tectonic setting.

INTRODUCTION

Plate reconstructions of the Pacific basin require subduction of at least one oceanic spreading center along the North American margin during the Paleogene (e.g., Atwater, 1970; Engebretson et al., 1985; Madsen et al., 2006). However, the location of the resulting triple-junction between the Kula, Farallon, and North American plates and the junction's relationship to the broader Cenozoic evolution of the western Cordillera remain uncertain. This uncertainty is due, in part, to the subduction of the magnetic spreading anomalies needed to constrain the position of the Kula-Farallon spreading center through time. Nevertheless, several lines of geologic evidence for Paleogene ridge-trench interaction on the North American margin have been used to constrain possible triple-junction positions. Along the southern Alaska margin (Fig. 1A), time-transgressive near-trench magmatism (61–50 Ma: Bradley et al., 1993, 2000), coeval basin disruption (Trop et al., 2003), and high temperature–low pressure forearc metamorphism (Sisson et al., 1989) all suggest southeastward triple-junction migration during the late Paleocene and early to middle Eocene. Likewise, the presence of near-trench magmatism (52–49 Ma: Groome et al., 2003; Madsen et al., 2006), geochemically anomalous backarc magmatism (Breitsprecher et al., 2003; Ickert et al., 2009), and basin disruption (Eddy et al., 2016) also suggest the presence of a triple-junction at the latitude of present-day Washington and southern British Columbia.

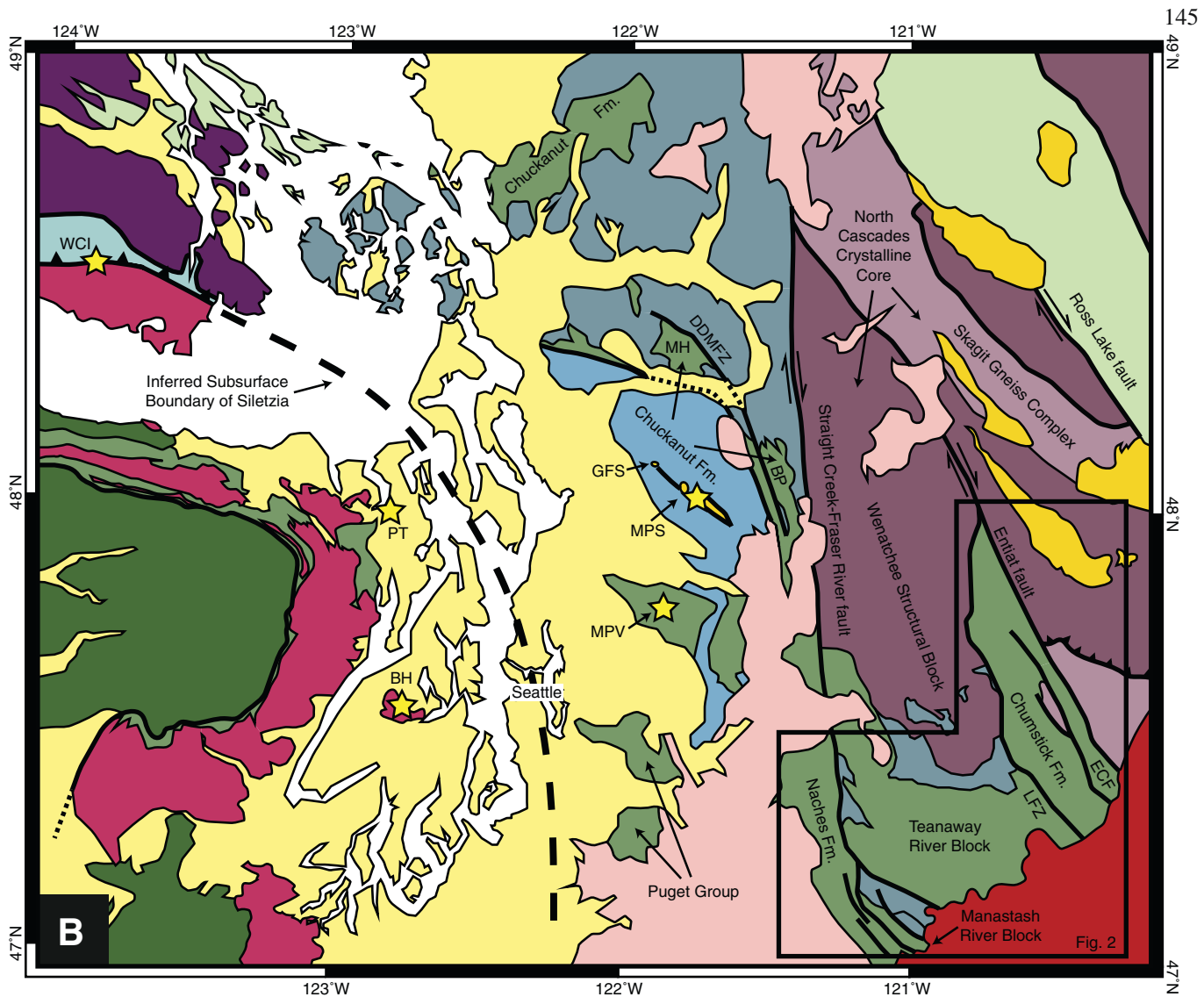
The above observations have led to several proposed plate reconstructions that place the Kula-Farallon ridge at the latitude of present-day Washington (Engebretson et al., 1985; Cowan, 2003; “Option A” in Haeussler et al., 2003), present-day Alaska (“Option B” in Haeussler et al., 2003), or hybrid models that invoke an additional oceanic plate (Resurrection) and place a triple-junction in both locations (“Option C” in Haeussler et al., 2003; Madsen et al., 2006). However, two observations complicate a direct link between the geology of the North American margin and Paleogene triple-junction locations. First, limited

paleomagnetic and geologic data from the southern Alaska margin suggest that these rocks are far traveled from a more southerly Paleogene location (Plumley et al., 1983; Bol et al., 1992; Cowan, 2003; O’Connell, 2009) leading to uncertainty in the latitude at which ridge-trench interaction occurred. Second, increasing geochemical, geophysical, and geochronologic data suggest that the Siletzia terrane of western Oregon, western Washington, and southwestern British Columbia and the Yakutat terrane of southern Alaska represent an oceanic plateau that developed immediately outboard of the continent and accreted to North America during this time (McCroory and Wilson, 2013; Wells et al., 2014; Phillips et al., 2017; Eddy et al., 2017). This plateau was likely formed above a long-lived Yellowstone hotspot (e.g., Murphy et al., 2003; Wells et al., 2014; Murphy, 2016), and interaction between this hotspot and the continental margin may have produced magmatic and structural effects similar to those that are expected during ridge-trench interaction. This field trip examines sedimentary and volcanic sequences in central Washington that record a distinctive history of sedimentation, deformation, and volcanism that can be linked to events along the North American margin through the use of an increasingly robust chronology complemented by a new generation of basin and structural studies. This history suggests that both a triple-junction and the ancestral Yellowstone hotspot interacted with this part of the North American margin at ca. 50 Ma.

REGIONAL OVERVIEW OF PALEOGENE GEOLOGY

The basement of central and western Washington is composed of metamorphic, plutonic, and sedimentary rocks that were assembled as part of a long-lived Mesozoic convergent margin, as well as the accreted Siletzia oceanic plateau (Fig. 1B). The history of Mesozoic terrane accretion and magmatism has been a source of intense study, but will only be discussed in this guide when relevant. These rocks include high-grade metamorphic and plutonic rocks in the North Cascades crystalline core and

Figure 1. Regional maps after Figure 1 in Eddy et al. (2016). (A) Map of the Pacific Northwest that shows possible locations for the Kula-Farallon spreading ridge during the early Paleogene, modified from Haeussler et al. (2003). If the terranes that compose southern Alaska are far-traveled from a more southerly location in the early Paleogene (e.g., Cowan, 2003), the range of possible positions would narrow along the Washington and British Columbia coasts. Alternatively, if the Chugach Terrane is not far-traveled, the Resurrection oceanic plate may have existed and would have resulted in two or more ridges intersecting North America (Haeussler et al., 2003; Madsen et al., 2006). (B) Generalized geologic map of central and northwest Washington, including southern Vancouver Island, modified from Walsh et al. (1987), Stoffel et al. (1991), Schuster et al. (1997), Dragovich et al. (2002), and Massey et al. (2005). Paleogene-aged sedimentary formations and regional strike-slip faults discussed in this paper are labeled and abbreviations are: MH—Mount Higgins area, BP—Barlow Pass area, ECF—Eagle Creek fault, LFZ—Leavenworth fault zone, and DDMFZ—Darrington–Devils Mountain fault zone. Stars denote the locations of Paleogene-aged adakites, abbreviated as BH—Bremerton Hills, MPV—Mt. Persis Volcanics; PT—Port Townsend; and peraluminous granites, abbreviated as WCI—Walker Creek intrusions, MPS—Mount Pilchuck suite (Tepper et al., 2004; Madsen et al., 2006; MacDonald et al., 2013). The calc-alkaline Granite Falls stock is abbreviated GFS (Dragovich et al., 2016). The heavy dashed line marks the inferred boundary between Siletzia and North America (Wells et al., 1998).



Eocene to Present

- Quaternary alluvium
- Columbia River Basalt Group (ca. 16 Ma)
- Sedimentary rock (33 Ma - Miocene)
- Cascade Arc magmatism (40 Ma - Present)

Paleocene and Eocene

- Major granitic intrusive complexes (50 - 45 Ma)
- Northern Siletzia (ca. 52 - 49 Ma)
- Sedimentary rock
- Ortho- and paragneiss with Eocene cooling ages

Mesozoic

- Leech River Schist
- Western and eastern melange belts
- Sedimentary rock
- Northwest Cascades System
- Ortho- and paragneiss with dominantly Mesozoic cooling ages
- Wrangellia

- Paleogene Adakites and Peraluminous Granites
- Faults
- Contacts

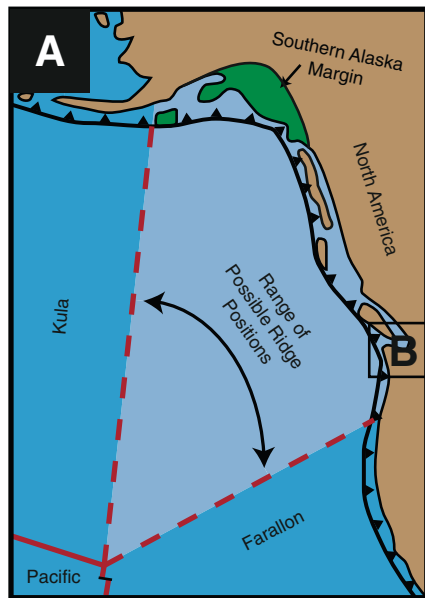


Figure 1.

accretionary belts of metamorphic, sedimentary, and plutonic rocks in the Northwest Cascades system (Fig. 1B; Misch, 1966; Brown, 1987) and western and eastern mélangé belts (Fig. 1B; Tabor, 1994). All of these rocks were in their current structural positions prior to the tectonic events discussed in this field guide, with the exception of a few 100 km of right-lateral offsets on Eocene strike-slip faults and the Skagit Gneiss Complex and Swakane Biotite Gneiss (Figs. 1B and 2), which were exhumed from mid-crustal depths during the early to middle Eocene (reviewed in Miller et al., 2016). At approximately the same time as these mid-crustal rocks were exhumed to the Earth's surface, geochemically diverse plutonic and volcanic rocks were emplaced in a near-trench setting along southern Vancouver Island (Groome et al., 2003; Madsen et al., 2006) and in western Washington (Cowan, 2003; Tepper et al., 2004), and adakitic and alkaline magmas were emplaced throughout eastern Washington and British Columbia (Breitsprecher et al., 2003; Ickert et al., 2009). These magmatic rocks have been attributed to the development of a slab window during ridge-trench interaction along this part of the margin ca. 50 Ma.

Outboard of the Mesozoic rocks lies the Siletzia terrane. It is exposed from the southern tip of Vancouver Island to southern Oregon and its tectonic origin has been debated. Hypotheses include an origin as an accreted oceanic plateau (e.g., Wells et al., 2014) and an origin as a marginal rift (Wells et al., 1984; Babcock et al., 1992, 1994; Brandon et al., 2014). Siletzia consists of thick sequences of basalt that transition from deep-water flows of normal mid-oceanic-ridge basalt (N-MORB) to shallow water and subaerial flows of enriched mid-oceanic-ridge basalt (E-MORB) and oceanic-island basalt (OIB) (e.g., Wells et al., 2014). The total estimated volume of basalt within Siletzia is $>1.7 \times 10^6$ km³ (Trehu et al., 1994; Wells et al., 2014) and is comparable to the volumes seen in large igneous provinces. This large volume, combined with isotopic evidence for the involvement of a 'plume-like' mantle source during magma generation (Pyle et al., 2009, 2015; Phillips et al., 2017), recent compilations of biostratigraphic and radiometric age constraints that show that the terrane was built over a relatively short period of time between 55 and 48 Ma (Wells et al., 2014; Eddy et al., 2017), and the documentation of regional shortening ca. 50 Ma in southern Vancouver Island (Johnston and Acton, 2003), Washington (Eddy et al., 2016), and Oregon (Wells et al., 2000, 2014) have bolstered the hypothesis that Siletzia represents an accreted oceanic plateau. Plate reconstructions that place a potentially long-lived Yellowstone hotspot near present-day Oregon and Washington ca. 50 Ma (e.g., Engebretson et al., 1985) provide a plausible tectonic setting to generate an oceanic plateau, and we consider Siletzia to represent a plateau that developed above this hotspot immediately prior to its attempted subduction (e.g., Wells et al., 2014). The Yakutat terrane along the southern Alaska margin (Fig. 1A) is of a similar age, has similar stratigraphy, and has similar magma compositions, and several authors have suggested that it represents a displaced fragment of the Siletzia oceanic plateau (e.g., Davis and Plafker, 1986; Wells et al., 2014).

Paleogene sedimentary rocks are exposed throughout central and western Washington (Fig. 1B). To the west these rocks are structurally imbricated with and overlie the Siletzia terrane, while in the east they are exposed as structurally isolated sedimentary sequences along and between major strike-slip faults. The exposure pattern in central Washington is likely a consequence of Eocene syn- and post-depositional strike-slip faulting and contractional deformation (discussed in following sections) and Miocene and younger faulting and folding (Fig. 2; Cheney and Hayman, 2009a, 2009b). Generally, the sedimentary rocks are fluvial and lacustrine in the Chumstick Formation, Teanaway River block, and the Chuckanut Formation (Fig. 1B; Frizzell, 1979; Johnson, 1984; Tabor et al., 1984; Taylor et al., 1988; Evans, 1994; Evans and Ristow, 1994), deltaic and shallow marine in the Puget Group and underlying rocks (Fig. 1B; Vine, 1969; Buckovic, 1979; Johnson and O'Connor, 1994), and variably deep and shallow marine on the Olympic Peninsula (Fig. 1B; Einarsen, 1987; Babcock et al., 1994). Depositional and temporal relationships between these areas are now better understood using a new generation of high-precision geochronology and basin studies (Fig. 3; Gilmour, 2012; Breedlovestrout et al., 2013; Donaghy, 2015; Eddy et al., 2016, 2017). However, some regional relationships remain poorly constrained.

On the Olympic Peninsula, most sedimentary rocks postdate the accretion of Siletzia (Babcock et al., 1994; Eddy et al., 2017) and are part of a large sedimentary basin that formed along the continental margin between 48 and 45 Ma and was the site of active deposition until the Miocene. The Eocene Puget Group partially overlaps in time with deposition of this basin and may represent its eastern extension early during its depositional history. We tentatively suggest that this basin formed in a forearc setting based on the appearance of a belt of calc-alkaline magmatism in western Washington ca. 45 Ma: including the 45 Ma Granite Falls stock (Fig. 1B; Dragovich et al., 2016), 47–36 Ma andesitic magmatism in the Mount Persis volcanics and associated granodioritic intrusions (Fig. 1B; Dragovich et al., 2009, 2011, 2013; MacDonald et al., 2013), and abundant 45–40 Ma tuffs in the Tukwila Formation of the Puget Group (Fig. 1B; Vine, 1969; Tabor et al., 1993, 2000). By ca. 35 Ma, the basin formed the forearc to the ancestral Cascades arc.

The Paleogene sedimentary and volcanic rocks described in this guide lie inboard of forearc rocks and record three distinct periods of sediment accumulation: (1) deposition in a regional basin (Swauk basin) that formed adjacent to the presumed Paleocene and Eocene subduction zone between <59.9 and 50 Ma; (2) basin disruption, regional bimodal volcanism, and development of at least one strike-slip basin (Chumstick basin) between ca. 49 and 45 Ma; and (3) a return to a more regional depositional system (Roslyn basin) after ca. 45–44 Ma, possibly coeval with more localized strike-slip faulting (Fig. 3). This depositional and structural history is the subject of this guide and is discussed in more detail in the following sections.

The youngest rocks encountered on this trip are volcanic and plutonic rocks related to the late Eocene to modern Cascade

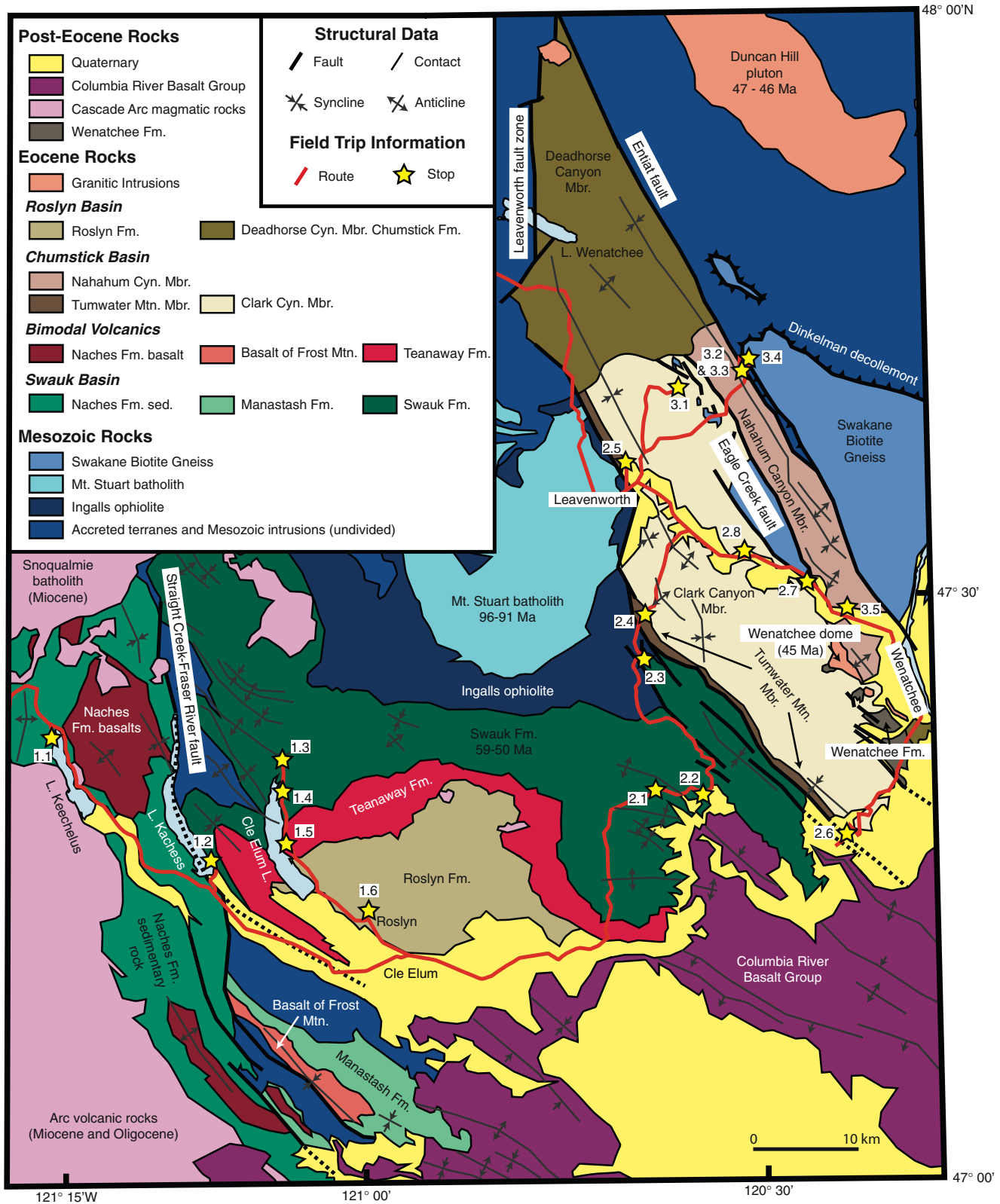


Figure 2. Geologic map of the field-trip area highlighting the Eocene sedimentary and volcanic rocks and showing the locations described in this guide. The map is adapted from 1:100,000 scale mapping by Tabor et al. (1982, 1987, 2000, 2002). Please note that the sedimentary rocks in the Naches Formation may either be related to the Swauk basin or the overlying bimodal volcanism.

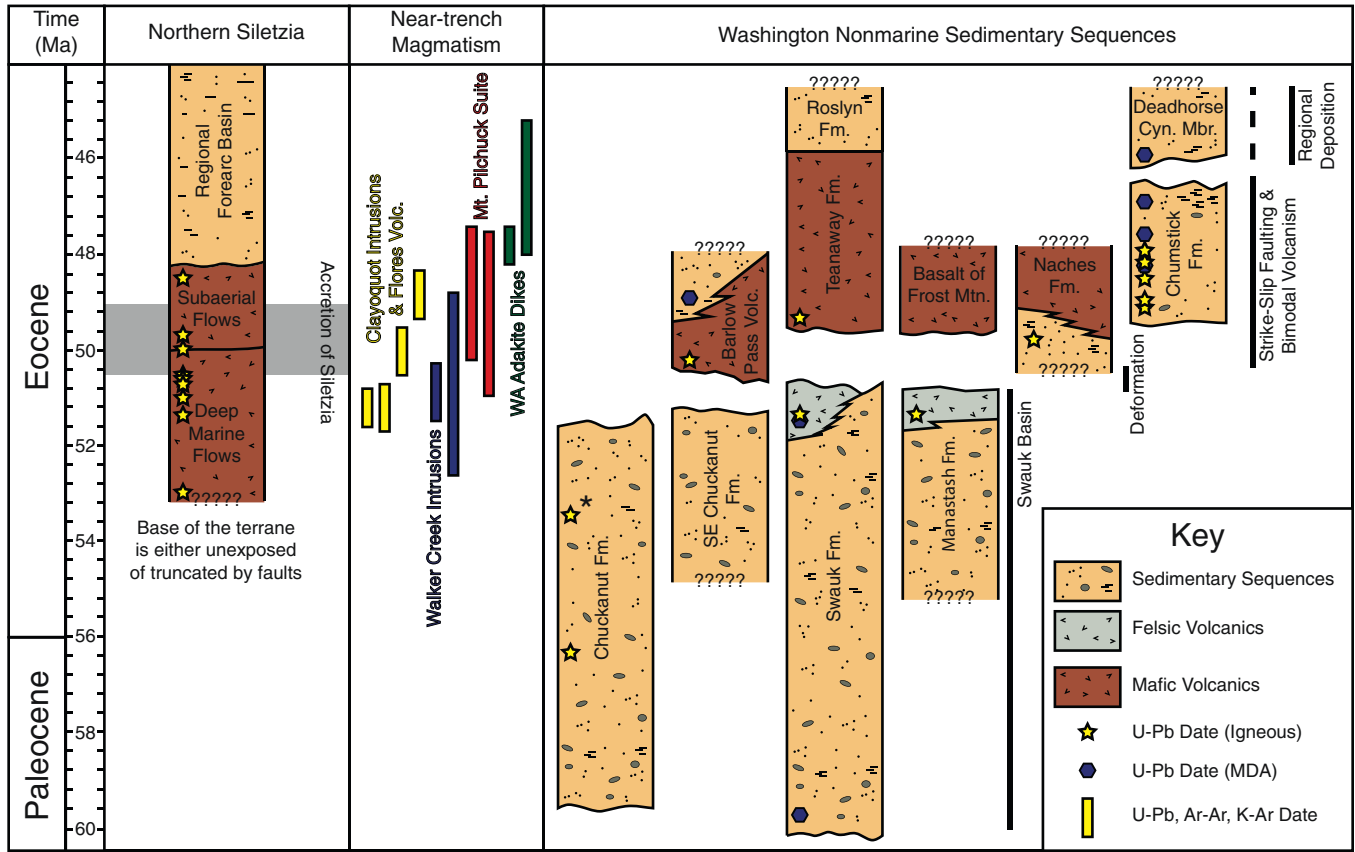


Figure 3. Temporal evolution of the sedimentary sequences in central Washington compared to available geochronology from northern Siletzia and near-trench magmatism in western Washington and southern Vancouver Island, modified from figure 8 in Eddy et al. (2016). All geochronology is shown with 2σ uncertainties, with the exception of the chemical abrasion–isotope dilution–thermal ionization mass spectrometry (CA-ID-TIMS) data from Breedlovestrout et al. (2013) and Eddy et al. (2016, 2017), which have uncertainties smaller than the symbol. Other geochronology is from (1) Clayoquot Intrusions and Flores Volcanics (Irving and Brandon, 1990; Madsen et al., 2006), (2) Walker Creek Intrusions (Groome et al., 2003), (3) Mt. Pilchuck Suite (Yeats and Engels, 1971), and (4) adakite dikes from western Washington (Tepper et al., 2004). All CA-ID-TIMS dates are from Eddy et al. (2016, 2017), with the exception of the date denoted by a *, which is from Breedlovestrout et al. (2013). Maximum depositional age is abbreviated MDA.

arc and the Miocene Columbia River Basalt Group. While not entered in the road log, fresh roadcuts of the Miocene Snoqualmie batholith are exposed along I-90 near Snoqualmie Pass and exposures of the Columbia River Basalt cap the high ridges to the south and east of the stops described in this guide.

DESCRIPTION OF PALEOGENE SEDIMENTARY AND VOLCANIC UNITS IN CENTRAL WASHINGTON

Swauk Basin

A series of late Paleocene to middle Eocene non-marine sedimentary sequences are currently exposed along and between major strike-slip faults in central and western Washington, including both the northwestern and southeastern outcrop belts of the Chuckanut Formation (Fig. 1B; Johnson, 1984; Evans and Ristow, 1994), Naches Formation (Figs. 1B and 2; Foster, 1960;

Tabor et al., 1984), Manastash Formation (Figs. 1B and 2; Tabor et al., 1984), and Swauk Formation (Fig. 2; Tabor et al., 1984; Taylor et al., 1988). These sequences are dominantly composed of thick sections of arkosic sandstone, mudstone, and minor conglomerate that were deposited in fluvial and lacustrine systems near Washington’s Paleogene coastline. Historically, the depositional relationship between these sequences has been contentious, with different hypotheses suggesting that they represent distinct strike-slip basins (Johnson, 1985), that they are erosional remnants of transgressive sedimentary sequences (Cheney, 1994, 2003; Cheney and Hayman, 2009a, 2009b), or that they represent a period of regional extension followed by a transition to strike-slip faulting, folding, and basin formation (Evans, 1994). It has been difficult to test these competing models because previous geochronology from these sedimentary units lacked the precision and accuracy to make robust correlations between isolated outcrop areas at the <1 Ma scale. However, recent U-Pb zircon

geochronology from these sequences has shown that they were all deposited between <59.9 and 50 Ma, and that they share similar depositional histories involving a period of deposition along west-flowing rivers from <59.9 to ca. 51.3 Ma, followed by a reversal in paleoflow and a period of shortening between 51.3 and 49.9 Ma (Eddy et al., 2016).

These observations suggest that these now-separated sedimentary and volcanic sequences once formed a coherent, integrated depositional system between <59.9 and 49.9 Ma, which Eddy et al. (2016) named the Swauk basin. Restoration of 125 km of post-50 Ma right-lateral, strike-slip displacement (e.g., Umhoefer and Miller, 1996) on the Straight Creek–Fraser River fault further illustrates the close spatial relationship between these units during their deposition, and that they likely formed a coherent northwest-southeast-trending basin (Fig. 4). The tectonic setting of the Swauk basin is anomalous; several observations suggest that the angle of the subducting slab was very shallow during the early Eocene (e.g., Humphreys, 2009). These observations include a magmatic lull in the North Cascades arc from ca. 60–50 Ma (Miller et al., 2016), evidence for a broad region of thickened crust from western to eastern Washington that persisted from the Late Cretaceous until ca. 50 Ma

exhumation (Whitney, 1992; Gordon et al., 2008, 2010; Kruckenberg et al., 2008; Miller et al., 2016), and Eocene magmatism in the Challis-Kamloops belt far from the plate boundary. In most areas where flat slab subduction occurs the forearc is uplifted and eroded (Finzel et al., 2011) and the steady subsidence of the Swauk basin remains a mystery.

This field trip visits the Swauk Formation, which is the largest exposed portion of the former Swauk basin (Fig. 2). It lies between the Straight Creek and Leavenworth fault zones with a composite thickness of ~8000 m (Figs. 2 and 5; Tabor et al., 1984, 2000). The base of the formation rests unconformably on the Jurassic Ingalls ophiolite and is locally marked by Fe-rich laterite. Detrital zircons from the first few meters of sandstone above this laterite are as young as 59.919 ± 0.098 Ma and provide a maximum age for initial deposition of the Formation (Eddy et al., 2016). (All CA-ID-TIMS [chemical abrasion–isotope dilution–thermal ionization mass spectrometry] dates within the text are reported with 2σ analytical uncertainties.) A U–Pb zircon date for a tuff in the Chuckanut Formation is 56.835 ± 0.050 Ma, and constrains initial deposition in the greater Swauk basin to between 59.9 and 56.8 Ma (Eddy et al., 2016). The lower part of the Swauk Formation remains poorly studied. It consists of

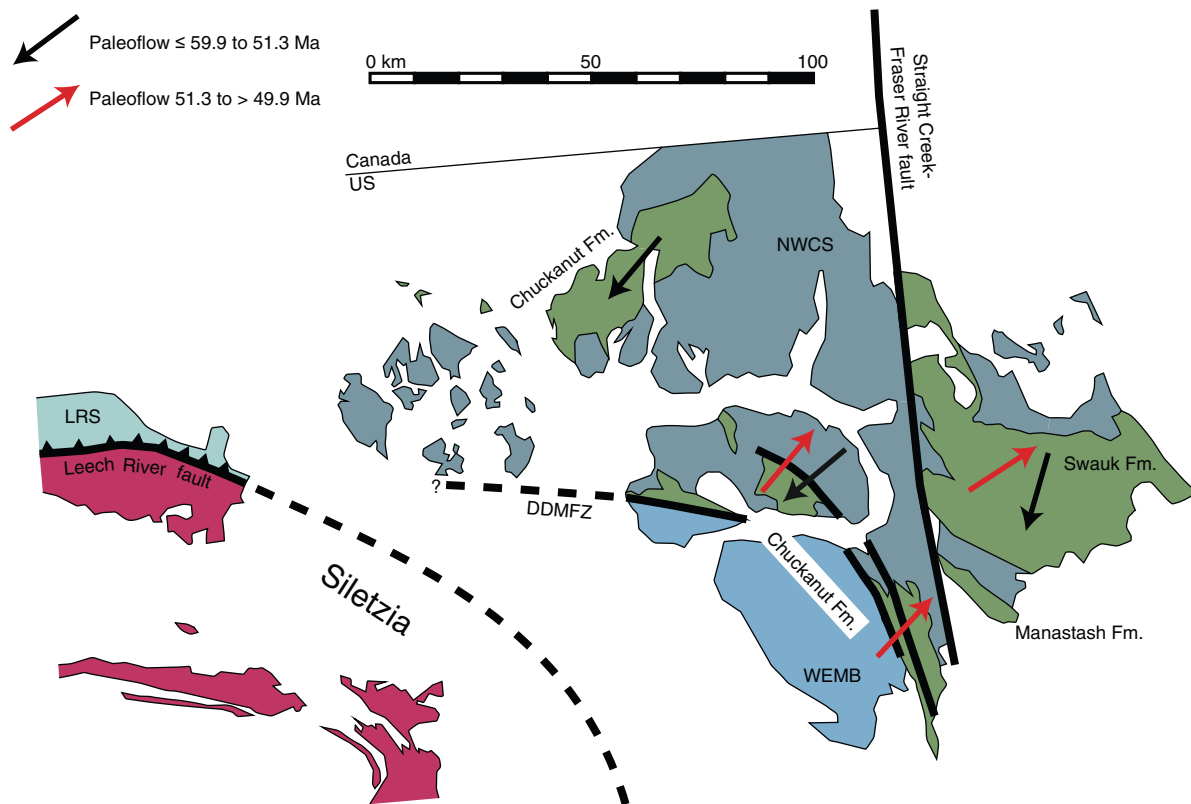


Figure 4. Map showing the relative position of the formations that compose the Swauk basin with restoration of 125 km of dextral offset on the Straight Creek–Fraser River fault after figure 7 in Eddy et al. (2016). Paleoflow data are summarized from Johnson (1985), Taylor et al. (1988), and Evans and Ristow (1994). The positions of the Northwest Cascades system (NWCS), western and eastern mélangé belts (WEMB), Leech River Schist (LRS), and Siletzia are also shown. The Darington–Devils Mountain fault zone is abbreviated DDMFZ.

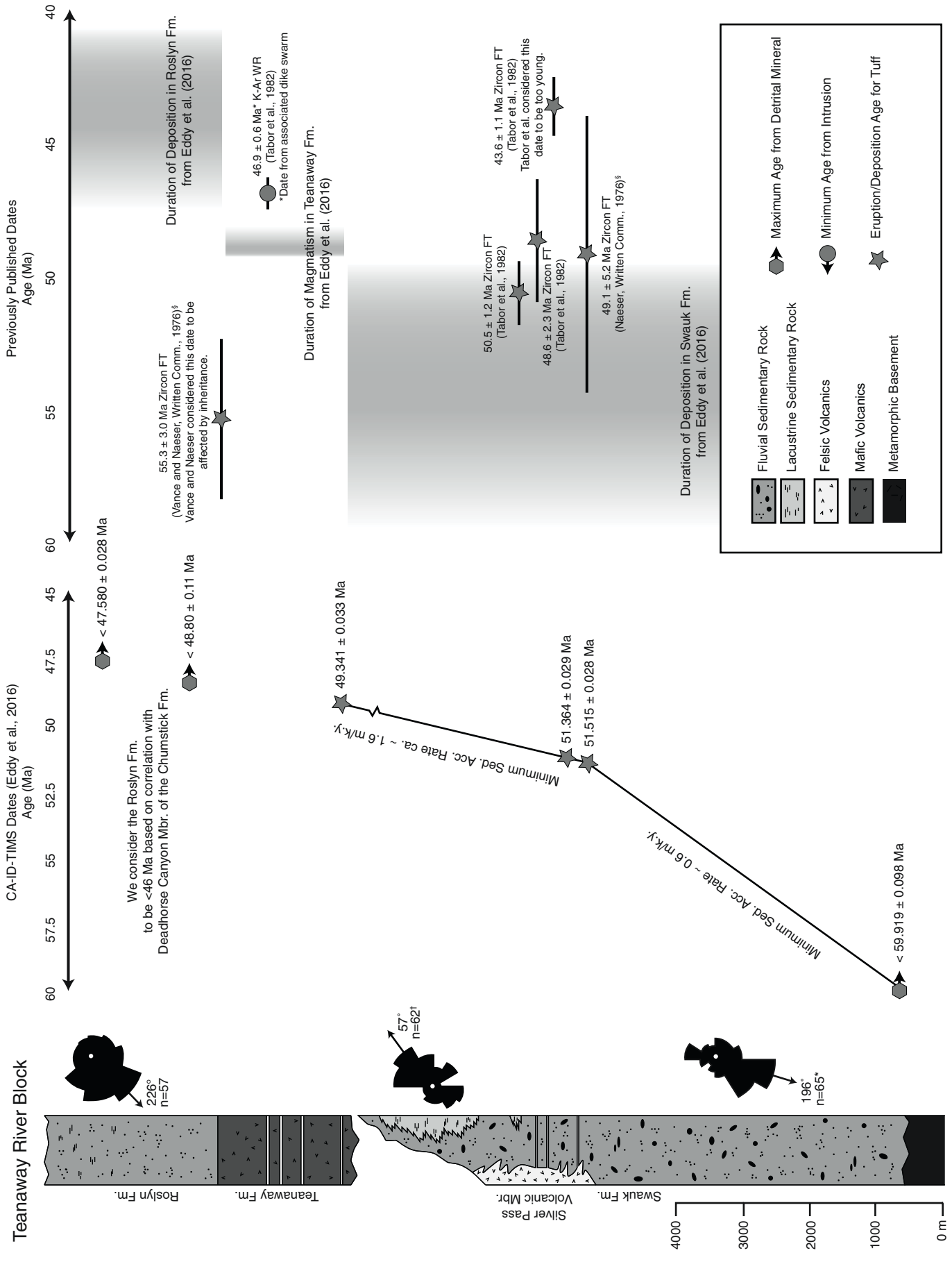


Figure 5.

Figure 5. Stratigraphic columns of the Teanaway River structural block (Fig. 1B) modified from figure 5 in Eddy et al. (2016). Thicknesses are from Clayton (1973), Tabor et al. (1982, 1984, 2000), and Taylor et al. (1988), and paleocurrent data (shown as rose diagrams) are from Barnett (1985), Johnson (1985), and Taylor et al. (1988). The rose diagrams for the lower and upper Swauk Formation represent measurements from the sandstone of Swauk Pass (*) and shale facies of Tronsen Ridge (†), respectively. Minimum sediment accumulation rates are shown for the Swauk Formation and assumed to be linear using the geochronology presented in Eddy et al. (2016). Older geochronology is also shown for comparison. Dates denoted with § are written communications reported in Tabor et al. (1982). CA-ID-TIMS—chemical abrasion–isotope dilution–thermal ionization mass spectrometry.

arkosic sandstone with minor conglomerate that was deposited along SSW-flowing fluvial systems (Taylor et al., 1988). The uppermost part of the lower Swauk Formation is interbedded with silicic tuffs that were likely sourced from a volcanic center in the western part of the formation where the volcanic deposits are thickest and form the Silver Pass Volcanic Member (Tabor et al., 2000). U-Pb zircon dates for tuffs associated with the Silver Pass Volcanic Member range from 51.515 ± 0.029 Ma to 51.364 ± 0.029 Ma and largely confirm the basin-wide correlation of these volcanic rocks (Fig. 5; Eddy et al., 2016).

Shortly after deposition of the tuffs of the Silver Pass Volcanic Member, the fluvial system that fed the Swauk Formation changed from south-southwest-directed paleoflow to northeast-directed paleoflow (Figs. 4 and 5; Taylor et al., 1988). We use this reversal in paleoflow and the appearance of these tuffs to informally separate the lower and upper Swauk Formation. A similar reversal in paleoflow from south-southwest to northeast has been documented throughout other parts of the now dismembered Swauk basin (Fig. 4; Evans and Ristow, 1994; Eddy et al., 2016). We attribute this change in paleoflow direction to uplift of the Northwest Cascades system and western and eastern mélangé belts in response to collision of Siletzia with the former subduction zone (Fig. 1B). In the southeastern outcrop belt of the Chuckanut Formation, the change in paleoflow direction is accompanied by an influx of chert, phyllite, vein quartz, and tuff clasts in conglomerate (Evans and Ristow, 1994), which are common lithologies in the accretionary rocks outboard of the Swauk basin. The thick section of west-derived strata in the upper Swauk Formation is best observed along Tronsen Ridge (Fig. 6), and recent geochronology suggests that this section was deposited at rates exceeding 1.6 m/k.y. (Fig. 5). Following the change of paleoflow direction, the Swauk basin was folded into a northwest- to west-northwest-trending fold-and-thrust belt (Johnson, 1984; Tabor et al., 1984; Evans and Ristow, 1994; Doran, 2009; Eddy et al., 2016; Gundersen, 2017). Within the Swauk Formation, this deformation is bracketed to have occurred between eruption of the youngest dated tuff (51.364 ± 0.029 Ma) within the Silver Pass Volcanic Member and a 49.341 ± 0.033 Ma rhyolite near the base of the overlying Teanaway Formation (Fig. 5).

Bimodal Volcanism

Basalts and basaltic andesites interbedded with minor rhyolite and fluvial sedimentary rock unconformably overlie the deformed strata of the Swauk basin. The Straight Creek–Fraser

River and Darrington–Devils Mountain fault zones separate these volcanic rocks into isolated units named the Barlow Pass Volcanics, Naches Formation, Basalt of Frost Mountain, and Teanaway Formation (Figs. 1B and 2). Limited geochemical data exist for these magmatic rocks and their relationship to tectonic events along the North American margin is open to interpretation. However, initial studies show that they include a mix of MORB-like and arc-like characteristics, which Tepper et al. (2008) attributed to decompression melting of mantle previously modified by subduction processes. U-Pb zircon dates indicate that the timing of bimodal volcanism is broadly correlative between units, and Eddy et al. (2016) suggested that they originally blanketed the deformed Swauk basin and have since been dismembered during right-lateral, strike-slip faulting (Fig. 1B).

This trip visits outcrops of the Teanaway Formation, which forms one of the southern exposures of the belt of bimodal volcanics (Fig. 2). It is ~800–1200 m thick and unconformably overlies the deformed Swauk Formation (Clayton, 1973; Tabor et al., 1984). Extrusive rocks include flows of basalt and basaltic andesite (~30%) and mafic pyroclastic rock (~60%) interbedded with subordinate sedimentary and rhyolitic rocks (Clayton, 1973). Flows range in thickness from ~1 m to 45 m and are typically massive with some of the thicker flows exhibiting columnar jointing (Clayton, 1973). Pyroclastic rocks include tuff, lapilli tuff, and tuff breccia that were deposited in shallow water. These rocks can be observed in roadcuts along U.S. 97 (Fig. 7A). Minor rhyolites are exposed throughout the Teanaway Formation.

The basalts and basaltic andesites of the Teanaway Formation were fed through an impressive dike swarm that intrudes the Swauk Formation (Fig. 7B; Smith, 1904; Foster, 1958; Tabor et al., 1982, 2000; Doran, 2009). The density of dikes in the Swauk Formation varies from sparse near the Straight Creek and Leavenworth fault zones to >50% of the rock volume in the narrow central region of the Swauk outcrop belt. Strikes of more than 400 dikes in five detailed transects average from 040° to 019° , indicating orogen-oblique extension (Mendoza, 2008; Doran, 2009; Miller et al., 2016). Mean dike thicknesses in these transects range from 12 to 20 m. In two well-exposed transects in the western and central part of the swarm, minimum extensions are 16% and 43%, respectively (Doran, 2009). The dikes are geochemically similar to the overlying flows, but tend to be less differentiated (Ivener and Tepper, 2013).

A flow-banded rhyolite near the base of the eastern part of the Teanaway Formation has a U-Pb zircon eruption date of 49.341 ± 0.033 Ma and provides an important temporal constraint on the



Figure 6. Panoramic photo of Swauk Formation from Blewett Pass on U.S. 97. The roadcut in the foreground is the uppermost part of the informal lower Swauk Formation discussed in the field guide. Tronsen ridge is in the background and contains lacustrine and fluvial rocks belonging to the informal upper Swauk basin.

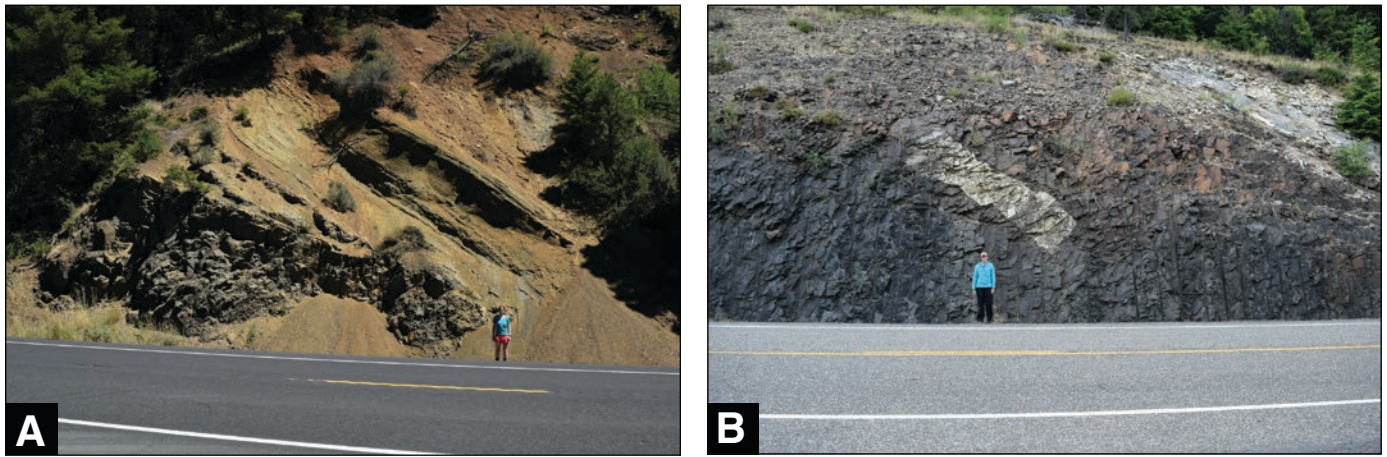


Figure 7. Photographs of the Teanaway Formation and associated dikes. Note the person for scale in both photos. (A) Mafic tuffs interbedded with flows along U.S. 97. (B) Basaltic dike cutting the Swauk Formation and incorporating a meter-scale xenolith of sandstone.

beginning of volcanism. No dates for the top of the Teanaway Formation exist. However, the absence of basaltic flows and dikes in the Chumstick Formation suggests that magmatism had ceased by the time deposition of that unit began (slightly before 49.147 ± 0.041 Ma). If so, then the magmatism that fed the Teanaway Formation was extremely short lived ($<194 \pm 53$ k.y.). Alternatively, magmatism may have been focused to the west of the Leavenworth fault zone and been longer lived.

Chumstick Basin

The Chumstick Formation is exposed between the Leavenworth and Entiat fault zones (Figs. 1B and 2; Gresens et al., 1981) and is divided by the Eagle Creek fault (Fig. 8; Evans, 1994). Evans (1994) split the Chumstick Formation into four members: Tumwater Mountain, Clark Canyon, Nahahum Canyon, and Deadhorse Canyon. The Tumwater Canyon, Clark Canyon, and Nahahum Canyon Members are fault bounded and show evidence for deposition in two distinct sub-basins during

regional strike-slip faulting. Collectively, we refer to these two depositional systems as the Chumstick basin. The Deadhorse Canyon Member shows little evidence for syn-depositional faulting and will be discussed in the following section.

The western Chumstick sub-basin lies between the Leavenworth and Eagle Creek fault zones and is filled by a thick (>10 km) section of arkosic sandstone and conglomerate of the Clark Canyon and Tumwater Mountain Members (Figs. 2 and 8). The Clark Canyon Member was dominantly deposited by west-flowing streams and interfingers with the Tumwater Mountain Member near the Leavenworth fault zone (Fig. 8; Evans, 1994). The Tumwater Mountain Member was derived from the west and contains sandstone, conglomerate, and monolithologic boulder conglomerate (Fig. 9) that were shed from a topographic high along the western margin of the Leavenworth fault zone (Evans, 1994; Donaghy, 2015). Some of the monolithologic conglomerate is clearly sourced from the Jurassic Ingalls ophiolite and Cretaceous Mount Stuart batholith (Cashman and Whetten, 1976; LaCasse, 2013). The most southerly boulder conglomerate is

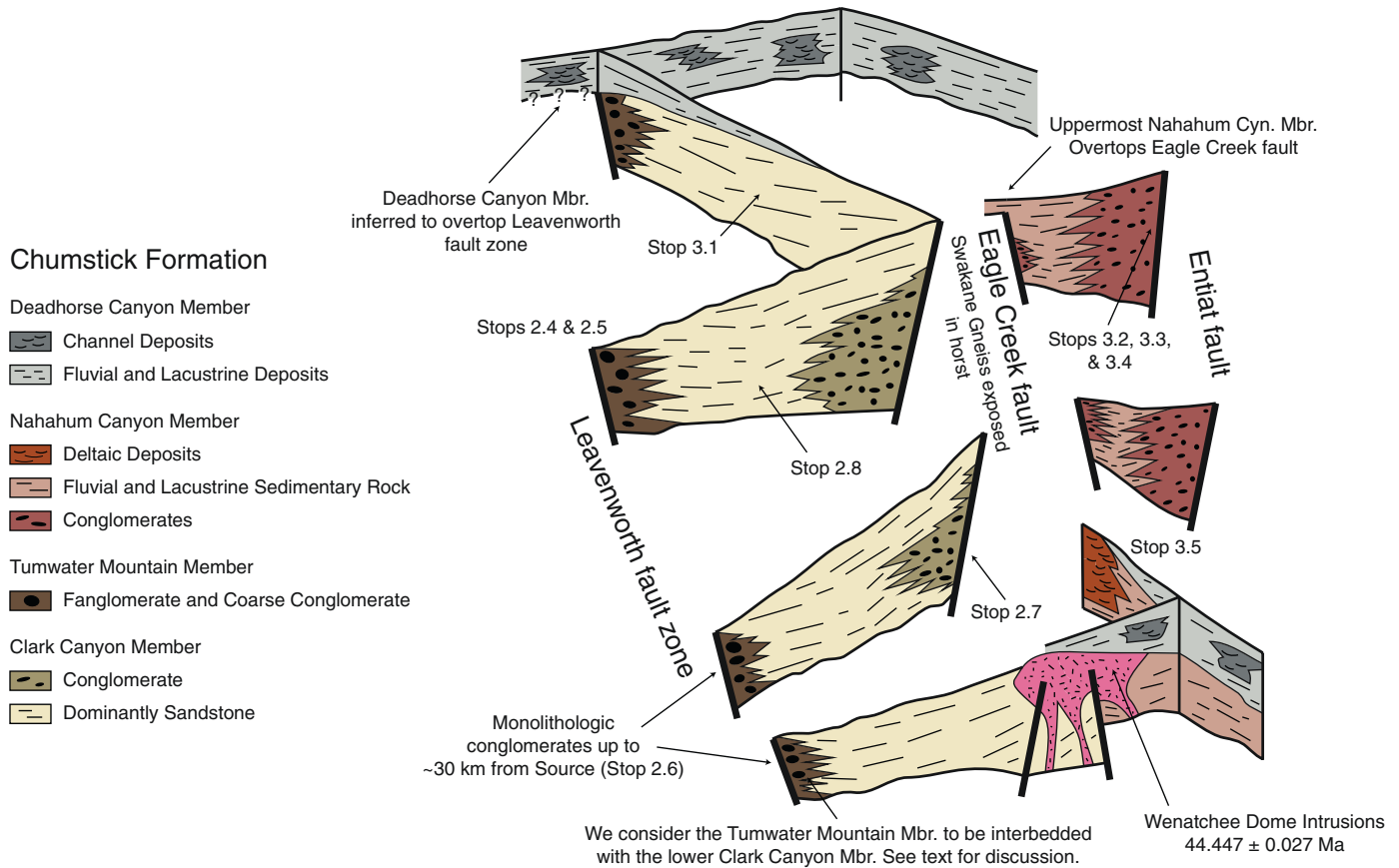


Figure 8. Fence diagram of the Chumstick basin modified from figure 5 in Evans (1994). The approximate locations of several of the field-trip stops within the Chumstick basin are shown, as are notable features of the basin.

~30 km south of its potential source regions and may indicate at least 30 km of syn- or post-depositional right-lateral slip on the Leavenworth fault zone (Fig. 2).

Eighteen silicic tuffs are interbedded with the Clark Canyon Member and provide useful stratigraphic marker horizons (McClincy, 1986). U-Pb zircon dates from these tuffs, combined with maximum depositional ages from detrital zircons in sedimentary rocks demonstrate that deposition began slightly before 49.147 ± 0.041 and ended after 47.847 ± 0.085 Ma (Fig. 10; Eddy et al., 2016). During this time, sediment accumulation rates were high (Fig. 10; 6–7 m/k.y. in the lower Clark Canyon Member and 2–3 m/k.y. in the middle Clark Canyon Member) within the western Chumstick sub-basin. Extrapolating these rates to the top of the section and considering the age of the overlying



Figure 9. Photograph of monolithologic boulder conglomerate in the Tumwater Mountain Member of the Chumstick Formation. Clasts are traced in black outlines and are up to a meter in diameter. They are exclusively of tonalitic composition and give U-Pb zircon dates of ca. 95–90 Ma (LaCasse, 2013). The boulders are likely sourced from the Cretaceous Mount Stuart batholith ~30 km along-strike of the Leavenworth fault zone to the north.

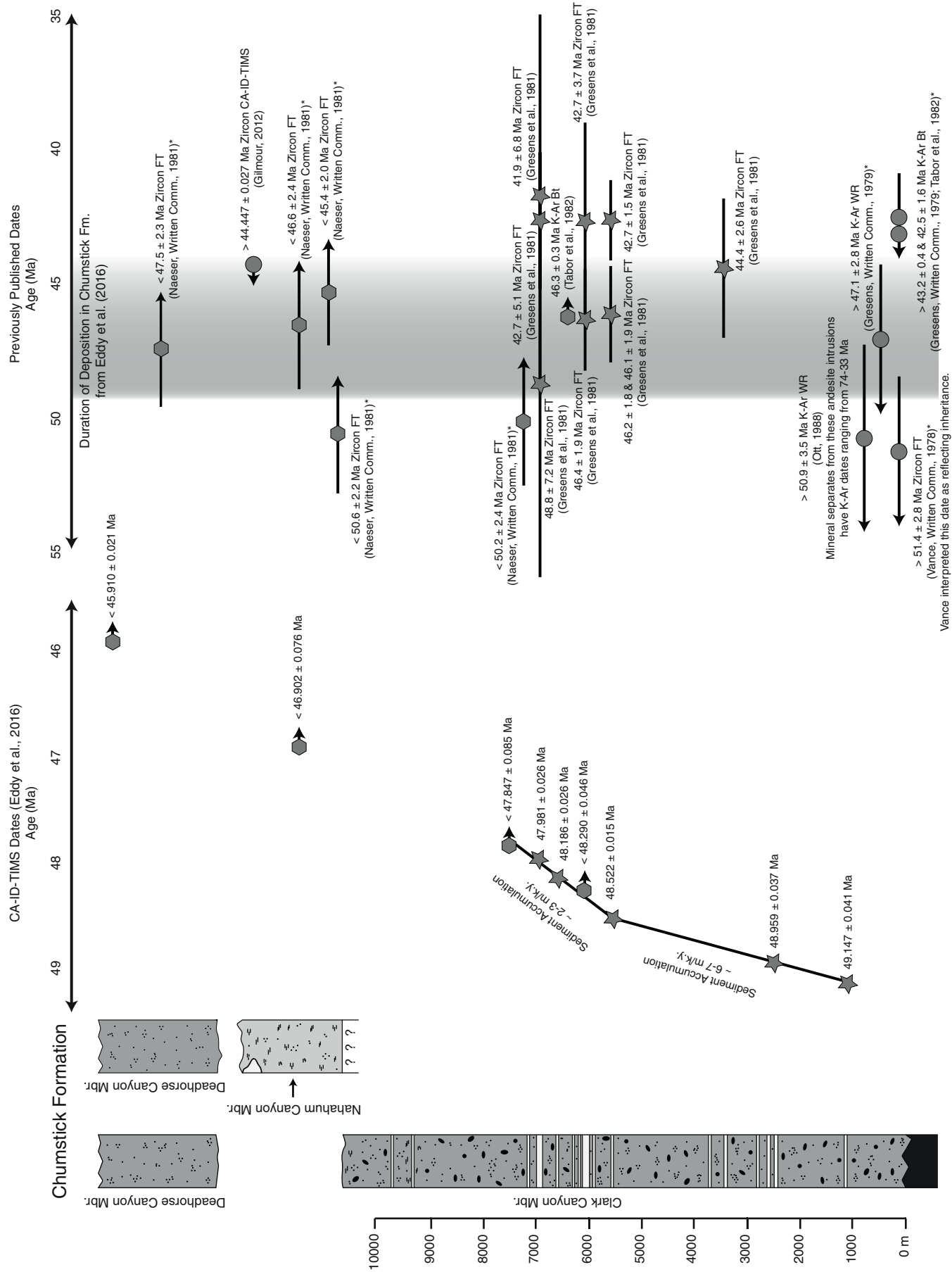


Figure 10.

Figure 10. Stratigraphic columns for the Chumstick Formation after figure 6 in Eddy et al. (2016). The Tumwater Mountain Member is not shown, but is interbedded with the Clark Canyon Member along the Leavenworth fault zone. Thicknesses and paleocurrent data are from Evans (1994). Columns are hung so that correlative members are adjacent to one another. A comparison between previously published dates and those published in Eddy et al. (2016) is also shown. All dates denoted with a * are written communications reported in Tabor et al. (1982) or Tabor et al. (1987). Sediment accumulation rates are calculated for selected intervals and assumed to be linear. Symbols are the same as Figure 5. CA-ID-TIMS—chemical abrasion–isotope dilution–thermal ionization mass spectrometry, FT—fission track, WR—whole rock.

units suggest that deposition of the Clark Canyon Member in the western Chumstick sub-basin ended between 47.0 and 46.5 Ma (Donaghy, 2015).

The eastern Chumstick sub-basin lies between the Eagle Creek and Entiat faults and is filled with fluvial and lacustrine strata of the Nahahum Canyon Member (Fig. 8). U-Pb zircon geochronologic data demonstrate that the Nahahum Canyon Member is younger than the Clark Canyon and Tumwater Mountain Members and suggest that the eastern Chumstick sub-basin is temporally distinct from the western Chumstick sub-basin (Fig. 10). Within the eastern sub-basin, the rocks become coarser toward the Eagle Creek and Entiat faults, and paleocurrent indicators suggest drainage from topographic highs along both margins met to form a basin-axial fluvial and lacustrine system (Fig. 8; Evans, 1994). These observations are consistent with the development of a strike-slip basin between the Eagle Creek and Entiat faults (Evans, 1994). The timing of deposition in the eastern sub-basin is less well constrained than in the western sub-basin, but deposition must have occurred between ca. 46.902 ± 0.076 Ma and $>44.447 \pm 0.027$ Ma based on available age data (Fig. 10; Gilmour, 2012; Eddy et al., 2016). The Deadhorse Canyon Member of the Chumstick Formation is disconformably to unconformably deposited above the strata in the eastern and western Chumstick sub-basin (Fig. 8; Evans, 1994). This unit will be discussed in the following section and we do not consider it to be part of the Chumstick basin.

The depositional setting of the Clark Canyon, Tumwater Mountain, and Nahahum Canyon Members of the Chumstick Formation has been controversial and has important implications for tectonic reconstructions of the region. The interpretations fall into three broad categories: those that favor deposition in a restricted, purely strike-slip basin (Johnson, 1985, 1996); those that interpret these rocks as an erosional remnant of a much larger, regional depositional system (Cheney, 2003; Cheney and Hayman, 2009a, 2009b); and those that interpret an early period of deposition during regional extension followed by tectonic partitioning into a strike-slip basin (Evans, 1994, 1996). Much of this disagreement has centered on the utility of interbedded tuffs as stratigraphic marker horizons (e.g., Cheney and Hayman, 2009a, 2009b) and uncertainties in the relative ages of volcanic and sedimentary units adjacent to the Chumstick basin (e.g., Evans, 1996; Johnson, 1996). However, recent U-Pb zircon geochronology has confirmed the Evans (1994) stratigraphy and shown that the Chumstick Formation is younger than the adjacent Swauk Formation (Figs. 5 and 10). These new data, combined with the

sedimentological and stratigraphic evidence for deposition of the Clark Canyon, Tumwater Mountain, and Nahahum Canyon Members of the Chumstick Formation during active strike-slip faulting have strengthened the case for a strike-slip basin origin for both the western (Donaghy, 2015) and eastern (Evans, 1994) Chumstick sub-basins.

The evidence for a strike-slip origin of the younger, eastern Chumstick sub-basin is well documented and includes the development of a basin axial drainage system, marginal coarse-grained facies, and soft sediment deformation related to syn-depositional earthquakes (Evans, 1994). However, the evidence for syn-depositional strike-slip motion during deposition of the older, western Chumstick sub-basin is more contentious. We consider depocenters that rapidly migrated to the north during deposition of the western sub-basin (Donaghy, 2015), high sediment accumulations rates (6–7 m/k.y.) in the lower and middle parts of the western sub-basin (Fig. 10; Eddy et al., 2016), and the presence of monolithologic boulder conglomerate in the Tumwater Mountain Member offset from their source areas by up to 30 km to be evidence for its origin as a strike-slip basin. Of these lines of evidence, the displaced boulder conglomerate in the Tumwater Mountain Member provides the clearest evidence for syn-depositional strike-slip faulting. Nevertheless, it is difficult to constrain the age of the oldest, and potentially most offset, boulder conglomerate. Rocks in the Clark Canyon Member that are interbedded with tuffs dated to 48.186 ± 0.026 Ma and 48.959 ± 0.037 Ma strike into, and are interpreted to interfinger with, the Tumwater Mountain Member around a north-northwest-plunging syncline above the oldest conglomerate and provide a minimum age for the oldest part of the Tumwater Mountain Member (McClincy, 1986; Donaghy, 2015; Eddy et al., 2016). Thus, there is good evidence that right-lateral motion had started on the Leavenworth fault zone by ca. 49 Ma, if not slightly earlier, and controlled deposition in the western Chumstick sub-basin through ca. 47–46.5 Ma.

Roslyn Basin

Fluvial sedimentary rocks overlie the Teanaway Formation and the strata that filled the western and eastern Chumstick sub-basins. To the west of the Leavenworth fault zone, these rocks are known as the Roslyn Formation and consist of arkosic sandstone, siltstone, and abundant coal seams that conformably overlie the Teanaway Formation and were deposited along west-flowing streams (Figs. 2 and 5; Tabor et al., 1984). There is no

clear proximal to distal relationship with the Leavenworth fault zone that would suggest relief on this structure during deposition of this unit. East of the Leavenworth fault zone, fluvial and lacustrine sedimentary rocks of the Deadhorse Canyon Member of the Chumstick Formation overlie the northern portions of the strata in the western and eastern Chumstick sub-basins (Figs. 2 and 8; Evans, 1994). These rocks were deposited across the Eagle Creek fault zone (Figs. 2 and 8), indicating no large displacement on this structure after their deposition (Fig. 2; Evans, 1994). Evans (1994) also inferred that the Deadhorse Canyon Member was deposited across the Entiat and Leavenworth fault zones based on paleoflow and lithologic data that do not suggest topography on these faults during its deposition.

Maximum depositional ages from detrital zircons are $<47.580 \pm 0.028$ Ma for the Roslyn Formation (Fig. 5; Eddy et al., 2016) and $<45.910 \pm 0.021$ Ma for the Deadhorse Canyon Member (Fig. 10; Eddy et al., 2016). Evans (1994) correlated these two units on the basis of similar paleoflow directions and the absence of evidence for displacement along the Leavenworth fault zone during their deposition. This interpretation is compatible with the existing geochronology (Figs. 5 and 10), and Eddy et al. (2016) suggested that these two units were deposited in a regional depositional system that they named the Roslyn basin. Re-established east to west sediment transport across the region is consistent with the presence of middle Eocene deltaic strata in the Puget Group (Vine, 1969; Buckovic, 1979) and marine strata on the Olympic Peninsula (Babcock et al., 1994). However, the Straight Creek–Fraser River fault may have been active during the deposition of these rocks, and it is unclear whether there was sediment transport across it during this time. Within the area described in this guide, deposition in the Roslyn basin ceased between the middle Eocene and the Oligocene, as the Oligocene Wenatchee Formation (Gresens et al., 1981) unconformably overlies the Eocene strata of the region.

DISCUSSION

Regional History of Dextral Strike-Slip Faulting

The Ross Lake, Entiat, Eagle Creek, Leavenworth, Straight Creek–Fraser River, and Darrington–Devils Mountain fault zones (Fig. 1B) record a complex history that likely includes Paleocene and Eocene right-lateral motion (e.g., Umhoefer and Miller, 1996). Both the magnitude of displacement and the timing of motion on these structures remain only partly constrained. Nevertheless, there is abundant evidence for acceleration, or even initiation, of right-lateral motion ca. 50 Ma.

On the Ross Lake fault (Fig. 1B), right lateral displacement is constrained to have occurred between 65 and 48 Ma, based on $^{40}\text{Ar}/^{39}\text{Ar}$, K–Ar, and U–Pb ages of deformed rocks and U–Pb zircon dates on intrusions that seal the structure (Miller and Bowering, 1990; Miller et al., 2016). Mylonite in the Ross Lake fault zone is as young as 49 Ma (Miller and Bowering, 1990) and demonstrates that some of this motion occurred after ca. 50 Ma and

before the structure was intruded by ca. 48 Ma granites (Miller et al., 2016). However, a deformed pluton within the Ross Lake fault zone in Canada that is ca. 44 Ma in age may suggest that motion continued for another 4–5 m.y. along the northernmost part of the structure (Haugerud et al., 1991).

Right-lateral displacements on the faults bounding the Chumstick basin (Leavenworth, Eagle Creek, and Entiat faults) are implied by its interpretation as a strike-slip basin active between ca. 49 and ca. 44.4 Ma (Donaghy, 2015; Eddy et al., 2016). Displacement of 30 km or more along the Leavenworth fault zone was likely during this time, as evidenced by the offset between distinctive boulder conglomerate in the Tumwater Mountain Member of the Chumstick Formation and their source region. Likewise, the Eagle Creek and Entiat faults appear to have been active during the development of the eastern Chumstick sub-basin (Evans, 1994) after ca. 47–46.5 Ma (Donaghy, 2015). Displacements on these structures are poorly constrained. However, motion on both structures appears to have finished by deposition of the $<45.910 \pm 0.021$ Ma Deadhorse Canyon Member of the Chumstick Formation (Fig. 10), as it overtops the Eagle Creek fault and is inferred to have spanned the Entiat fault (Evans, 1994). A better age constraint for the end of motion on the Eagle Creek fault may come from 44.447 ± 0.027 Ma rhyolite domes that intrude the structure (Gilmour, 2012). However, there is evidence for syn-depositional emplacement of these domes within the Nahahum Canyon Member of the Chumstick Formation (Evans, 1994), and the presence of an echelon folds in the Nahahum Canyon Member suggests that some motion continued after this date.

During deposition of the Nahahum Canyon Member, the Clark Canyon and Tumwater Mountain Members were folded on axes parallel to the northwest segments of the Leavenworth fault zone. This fold pattern is one line of evidence for a shift from northwest-striking to more north-striking strike-slip faults with transpression concentrated along northwest fault segments. Motion on the Leavenworth fault zone, as well as the Straight Creek–Fraser River fault, likely continued to deform the Swauk and Teanaway Formations. Motion on these two structures may have also have provided a transtensional setting for the Teanaway dike swarm prior to, or coeval with, initial deposition in the Chumstick basin (Vance and Miller, 1981). This continued deformation is best illustrated by the trends of fold axes within the Swauk Formation that curve to the northwest in the west near the Straight Creek fault, to west-northwest or east-southeast in the more strongly folded central region, to mostly northwest closer to the Leavenworth fault zone (Fig. 2; Tabor et al., 1982, 2000; Doran, 2009; Gundersen, 2017).

Matching Mesozoic terranes on either side of the Straight Creek–Fraser River fault suggests that ~125–150 km of right-lateral displacement occurred between the latest Cretaceous and 35 Ma (Umhoefer and Miller, 1996), when it was sealed by intrusions related to the modern Cascade arc (Misch, 1966; Tabor et al., 2003). Rocks of the Swauk basin restore adjacent to one another across this fault (Fig. 4). Therefore, Eddy et al. (2016)

suggested that all ~125 km of motion on this fault occurred after ca. 50 Ma basin disruption and inversion. The Darrington–Devils Mountain fault zone also contains fault blocks near Barlow Pass that appear to be displaced from the Swauk and Manastash Formations, implying large magnitude right-lateral displacements after deposition of the Swauk basin (Tabor, 1994). These constraints on the timing and magnitude of right-lateral displacements on strike-slip faults throughout Washington are shown in Figure 11, and strongly suggest that motion either initiated, or significantly accelerated, on the strike-slip faults in central Washington following the disruption and inversion of the Swauk basin ca. 50 Ma, localized on the Straight Creek–Fraser River fault ca. 45–44 Ma, and ceased by the latest Eocene.

Accretion of Siletzia and Bimodal Volcanism

The Siletzia oceanic plateau accreted to North America ca. 50 Ma and led to the formation of a fold-and-thrust belt that has been documented in southwest Oregon (Wells et al., 2000, 2014) and on Vancouver Island (Johnston and Acton, 2003). In central Washington, disruption, shortening, and inversion of the Swauk basin occurred between 51.3 and 50 Ma and is also likely related to this accretionary event (Fig. 3; Eddy et al., 2016). This

expanded record of shortening suggests that accretion likely occurred along the length of the Siletzia plateau over 1–2 m.y. In western Washington, new geochronology from Siletzia shows that the terrane was constructed immediately before and during accretion between 53 and 48 Ma (Fig. 3; Eddy et al., 2017), suggesting that the plateau was only 0–2 m.y. in age when it entered the Paleogene subduction zone. Such a young age at the time of accretion, and the terrane's consequent buoyancy, may help explain why it jammed the subduction zone rather than subducting.

Geophysical evidence shows that Siletzia remains connected to subducted oceanic crust under present-day eastern Oregon, eastern Washington, and western Idaho (Gao et al., 2011; Schmandt and Humphreys, 2011). The presence of a 'hanging slab' suggests that slab breakoff occurred after Siletzia's accretion. This process may be recorded by a time-transgressive belt of magmatism that migrated through eastern Washington toward the trench from ca. 54–47 Ma (Tepper, 2016). L. Kant and J. Tepper (2017, personal commun.) suggested that the western end of this belt may be represented by the bimodal volcanics discussed in this guide. However, distinguishing magmatism due to the potential presence of slab windows, slab breakoff and rollback, and continued interaction between a hotspot and the North American margin is challenging.

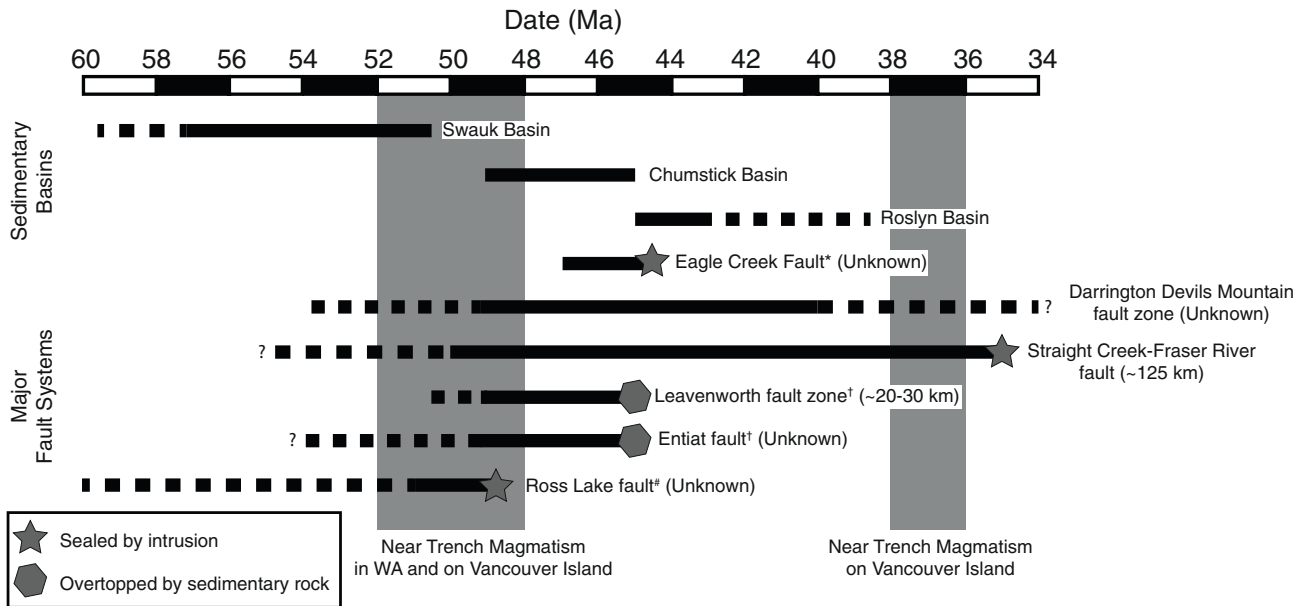


Figure 11. Timelines for major periods of deposition within the Swauk, Chumstick, and Roslyn basins compared to the timing of near-trench intrusions and right-lateral motion on major strike-slip faults throughout Washington (WA). The age of igneous intrusions that seal the fault (star) or sedimentary rocks that overtop the fault (hexagon) are also shown. Periods of uncertain deposition or motion are shown as dashed lines. *Note that there is some evidence that motion continued along Eagle Creek fault during intrusion of the Wenatchee Dome complex at 44.447 ± 0.059 Ma (Evans, 1994). However, since this intrusive complex spans the trace of the fault, we consider the magnitude of this motion to be limited. †Both the Leavenworth and Entiat faults are presumed to be spanned by the Roslyn basin based on paleoflow and lithologic data (see Evans, 1994). The age of this basin is only constrained by maximum depositional ages, and motion may have continued into the late Eocene. #The Ross Lake fault zone was sealed by several granitic intrusions between 49 and 48 Ma in Washington. However, Haugerud et al. (1991) dated a deformed pluton within the northernmost part of the fault zone in Canada that gave a U-Pb zircon date of ca. 44 Ma, indicating that some motion continued until at least 44 Ma along this part of the fault zone.

Evidence for Presence of Triple-Junction and Eocene Tectonics of the Pacific Northwest

The location of the Kula-Farallon ridge along the western margin of North America during the Paleogene has been a long-standing problem. The simplest geometry places this ridge in the vicinity of present-day British Columbia, Washington, and Oregon (e.g., Engebretson et al., 1985), but the record of seafloor spreading needed to confirm this position has been subducted. The most convincing geologic evidence for subduction of the Kula-Farallon ridge is a belt of 61–50 Ma near-trench magmatism in the Sanak-Baranof plutonic belt along the southern Alaska margin (Fig. 1A) within the Chugach and Prince William terranes that is time-transgressive from west to east (Fig. 12A; Bradley et al., 1993, 2000). These plutons are geochemically diverse and similar to the magmatism expected during the passage of a slab window. This observation has been key to arguments for subduction of the Kula-Farallon ridge along the southern Alaska margin (e.g., Haeussler et al., 2003). However, there is controversy regarding whether the Chugach, Prince William, and Yakutat terranes have experienced significant northward motion. Limited paleomagnetic data suggest that these rocks may have been trans-

lated in the Sanak-Baranof plutonic belt along the southern Alaska margin (Fig. 1A) within the Chugach and Prince William terranes that is time-transgressive from west to east (Fig. 12A; Bradley et al., 1993, 2000). These plutons are geochemically diverse and similar to the magmatism expected during the passage of a slab window. This observation has been key to arguments for subduction of the Kula-Farallon ridge along the southern Alaska margin (e.g., Haeussler et al., 2003). However, there is controversy regarding whether the Chugach, Prince William, and Yakutat terranes have experienced significant northward motion. Limited paleomagnetic data suggest that these rocks may have been trans-

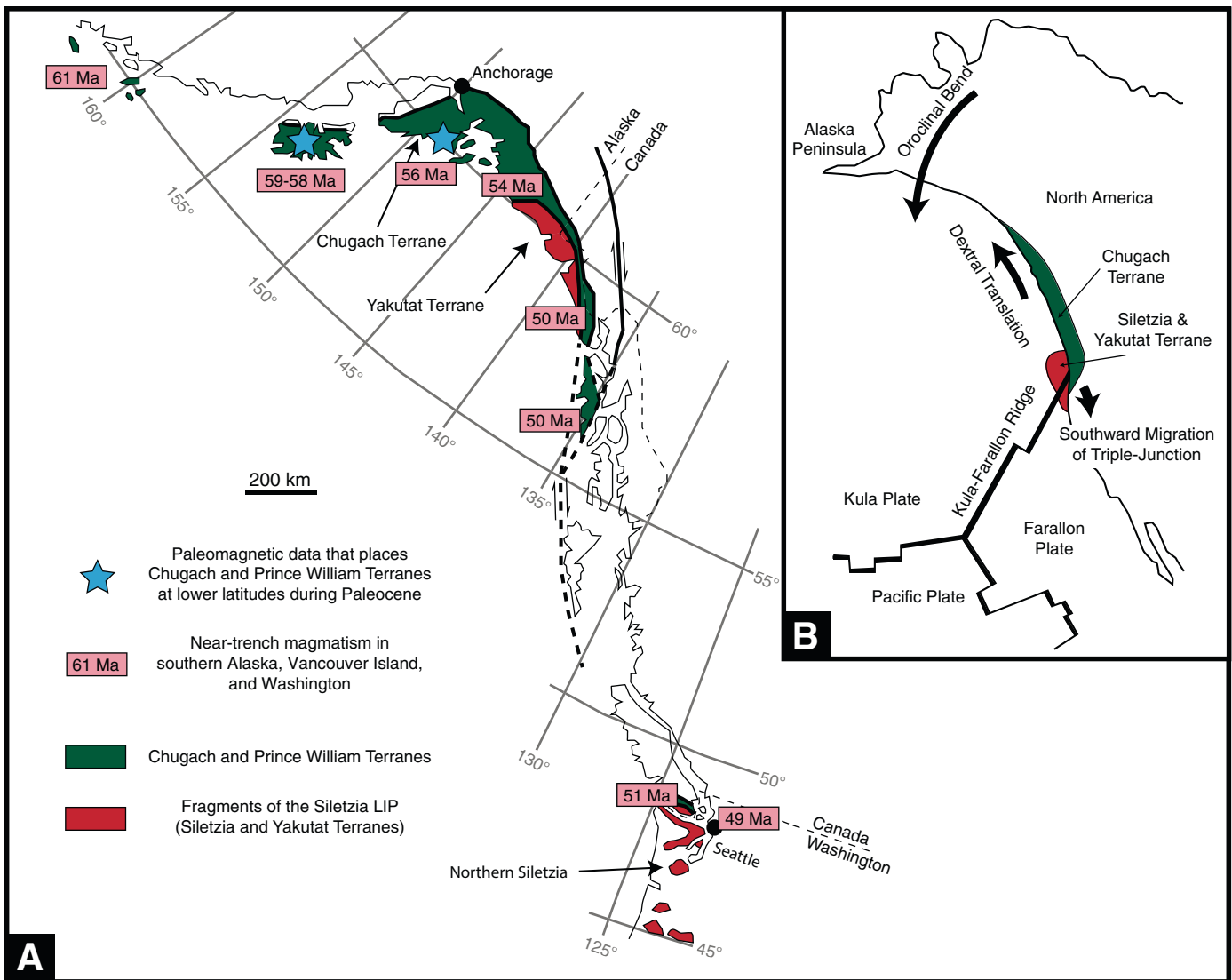


Figure 12. (A) Geologic map showing the current location of the Chugach, Yakutat, and Siletzia terranes modified from Cowan (2003). The location and age of early and middle Eocene near-trench magmatism in the Sanak-Baranof belt (Bradley et al., 1993; Kusky et al., 2003) and in Washington (Cowan, 2003; Groome et al., 2003; Madsen et al., 2006) are also shown, as well as the locations in the Chugach terrane where paleomagnetic data suggest that it is far-traveled from a more southerly Paleogene location (Plumley et al., 1983; Bol et al., 1992; O’Connell, 2009). (B) Our preferred regional plate configuration for ca. 50 Ma modified from Bradley et al. (1993). We show the Kula-Farallon ridge intersecting North America near the latitude of Washington as the Siletzia oceanic plateau accretes and speculate that the Chugach terrane was translated northward to its present location along the northern arm of this triple-junction. LIP—large igneous province.

lated >1000 km since the late Paleocene (Plumley et al., 1983; Bol et al., 1992; O'Connell, 2009), but no single structure or set of structures appears to have accommodated this displacement.

Nevertheless, restoring these terranes to a position ~1100 km to the south, in agreement with the paleomagnetic data, places them along the coast of British Columbia (Fig. 12B). Such a restoration places 51–50 Ma near-trench magmatism on Baranof Island adjacent to 51–49 Ma near-trench magmatism on southern Vancouver Island and in western Washington, juxtaposes similar schist bodies (Cowan, 2003), and places the Yakutat terrane adjacent to the lithologically and stratigraphically similar Siletzia terrane (e.g., Wells et al., 2014). Additional restoration of ~125 km of right-lateral, strike-slip faulting in the Pacific Northwest places the southern tip of Vancouver Island adjacent to the basins examined during this trip (Fig. 12B). In this view, the Kula–Farallon ridge intersected the North American margin along British Columbia and migrated southward from 61 to 49 Ma to account for the time-transgressive near-trench magmatism in the Sanak–Baranof Belt and in southwestern British Columbia and western Washington. Most plate reconstructions agree that the Kula plate was moving rapidly to the north or north-northwest during this time (e.g., Atwater, 1970; Engebretson et al., 1985; Stock and Molnar, 1988; Madsen et al., 2006; McCrory and Wilson, 2013), and, consequently, the northern arm of this triple-junction would have had a strong right-lateral, strike-slip component. We speculate that the Chugach, Prince William, and Yakutat terranes migrated northward along this plate boundary during the late Paleocene and Eocene (Fig. 12B; e.g., Cowan, 2003).

We consider the ~10–15 m.y. of accelerated right-lateral, strike-slip faulting in central Washington to represent the best evidence for a southward jump of the Kula–Farallon–North America triple-junction following Siletzia's accretion (Fig. 13). This record of strike-slip faulting is in accord with data that suggest northward translation of the Chugach, Prince William, and Yakutat terranes and provides a simple explanation for this motion. Interestingly, a second period of near-trench magmatism occurred on Vancouver Island between 39 and 35 Ma (Madsen et al., 2006) coeval with our best constraints for the end of motion on the Straight Creek–Fraser River fault (Fig. 11). This second period of near-trench magmatism may represent the northward migration of the Kula–Farallon–North America triple-junction. Such migration is required to establish the modern plate geometry in our model (Fig. 13). In this case, the cessation of major right-lateral, strike-slip faulting would represent renewed juxtaposition of the Farallon plate with North America, and, consequently, less oblique motion along the plate boundary.

Isotopic evidence for the involvement of a plume-like mantle source during generation of the magmas that compose Siletzia and Yakutat terranes (Phillips et al., 2017), their great thickness (e.g., Trehu et al., 1994), and the relatively short eruption period (Wells et al., 2014; Eddy et al., 2017) all suggest that they developed as an oceanic plateau above a hotspot. Plate reconstructions place a hypothetical long-lived Yellowstone hotspot near the coasts of Oregon and Washington during the Eocene (e.g., Engebretson

et al., 1985) and it may have been the source for Siletzia/Yakutat magmatism. Several lines of evidence suggest that this plateau was centered on an oceanic spreading ridge similar to modern Iceland. These include partial ophiolites on southern Vancouver Island (Massey, 1986) and western Washington (Clark, 1989) that are 1–0 m.y. older than the age of Siletzia's accretion (Eddy et al., 2017) as well as the distribution of crustal ages throughout the terrane (e.g., Duncan, 1982; McCrory and Wilson, 2013; Wells et al., 2014; Eddy et al., 2017). Such young and thick crust would be difficult to subduct (e.g., Cloos, 1993) and may explain why Siletzia accreted rather than subducting. We speculate that following accretion of Siletzia, the Kula–Farallon–North America triple-junction jumped to the south (Fig. 13). Such a jump can explain the transition to, or acceleration of, right-lateral, strike-slip motion throughout central and western Washington at ca. 50 Ma. As stated above, we consider this initiation, or acceleration, of right-lateral, strike-slip motion to be the most convincing evidence for the presence of a triple-junction at this latitude ca. 50 Ma. Previously, the primary evidence for a triple-junction at this latitude was the presence of ca. 50 Ma near-trench magmatism (e.g., Groome et al., 2003; Haeussler et al., 2003; Madsen et al., 2006). However, interaction between the North American margin and the Yellowstone hotspot could have produced much of the near-trench magmatism in this area, making its tectonic significance ambiguous without the additional record of strike-slip faulting.

Generalized Effects of Ridge-Trench Interaction on Sedimentary Basin Evolution

The Paleogene of central and western Washington likely represents a geologic setting in which a ridge-centered oceanic plateau was accreted to the continent (e.g., Wells et al., 2014; Eddy et al., 2017), making it difficult to use this area as a generalized model for ridge-trench interaction. Nevertheless, rapid changes in the stresses along plate boundaries should be common in areas of triple-junction migration (Thorkelson, 1996; Sisson et al., 2003), and we consider the Paleogene sedimentary and volcanic rocks visited on this field trip to represent an area where this transition is well documented. In this area, the change is represented by the disruption and dismemberment of a large forearc basin immediately followed by the development of a distinct strike-slip basin coincident with near-trench magmatism, accretion of Siletzia, and presumed southward migration of the Kula–Farallon–North America triple-junction (Eddy et al., 2016). A second period of near-trench magmatism ca. 39–35 Ma on Vancouver Island is also coincident with the termination of major right-lateral motion on the Straight Creek–Fraser River fault. This cessation may represent another change to stresses along the plate boundary as the Kula–Farallon–North America triple-junction migrated to the north.

Southeastward migration of the Kula–Farallon–North America triple-junction during the early Eocene is similarly recorded in the depositional history of the Matanuska Valley–Talkeetna

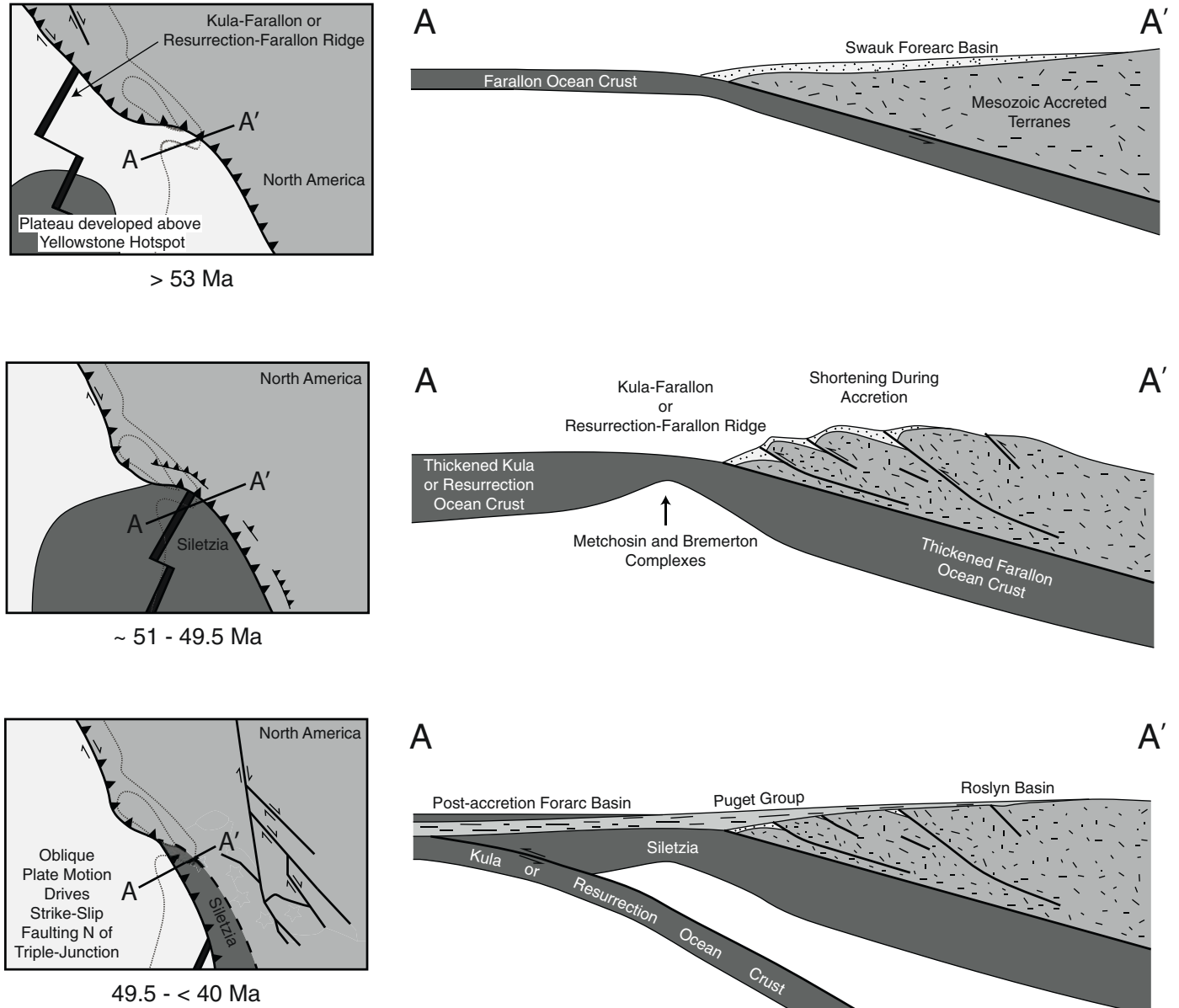


Figure 13. Proposed history of Siletzia’s construction and accretion after Eddy et al. (2017) and following Wells et al. (2014). Ocean crust of normal thickness belonging to the Farallon plate was subducting at the latitude of Washington prior to 53 Ma. From 53 to 48 Ma an oceanic plateau developed along the Kula-Farallon, or Resurrection-Farallon, oceanic spreading center. The attempted subduction of this young oceanic plateau (ca. 51–48 Ma) jammed the subduction zone, led to regional shortening, and a jump of the Kula–Farallon–North America, or Resurrection–Farallon–North America triple-junction to the south. Oblique motion between the Kula, or Resurrection, and North American plates drove dextral strike-slip faulting along the North American margin during this time. After ca. 45–44 Ma, a regional depositional system is re-established and includes marine sedimentary rocks now on the Olympic Peninsula, deltaic sedimentary rocks exposed as the Puget Group, and the nonmarine Roslyn basin further inboard.

Mountains forearc basin, which contains evidence for syn-depositional, right-lateral displacements along basin margin faults (Trop et al., 2003). Disagreements over the timing and magnitude of displacements along the strike-slip faults that separate this basin from the Chugach and Prince William terranes preclude directly

linking this transition to the timing of the adjacent near-trench magmatism at a fine scale (e.g., Trop et al., 2003). However, the timing of near-trench plutonism along the southern Alaska margin is broadly similar to basin subsidence and right-lateral, strike-slip faulting in this area.

Ultimately, recognizing the record of ridge-trench interaction in plate-margin sedimentary basins requires a multidisciplinary approach that synthesizes a region's magmatic, structural, and depositional history. In isolation, none of the indicators of this process (i.e., near-trench magmatism, changes to fault kinematics, geochemically anomalous magmatism in the arc and backarc, and basin disruption) provide conclusive evidence for this tectonic setting. However, together they may provide strong evidence for the presence of a triple-junction.

CONCLUSIONS

The sedimentary and volcanic rocks discussed in this field guide record a distinctive history of deposition, magmatism, and deformation during the late Paleocene to middle Eocene that can be directly tied to events along the North American margin using an increasingly robust chronology, coupled with traditional sedimentological, stratigraphic, and structural studies. In the area between the Straight Creek–Fraser River and Entiat faults, we see evidence for the following major events: (1) Swauk basin deposition from <59.9 to ca. 50 Ma in an anomalous forearc setting; (2) a short pulse of contractional deformation between 51.3 and 49 Ma likely related to the accretion of the Siletzia terrane; (3) initiation or acceleration of right-lateral, strike-slip faulting across the region starting ca. 49 Ma, which led to the formation of the Chumstick basin; and (4) possible localization of strike-slip faulting on the Straight Creek–Fraser River fault ca. 45–44 Ma. This history strongly suggests that overthickened oceanic crust of the Siletzia terrane accreted at ca. 50 Ma and that accretion was immediately followed by initiation or acceleration of right-lateral, strike-slip faulting. This transition to right-lateral, strike-slip faulting is consistent with the southward movement of the Kula–Farallon–North America triple-junction following the accretion of Siletzia, as plate reconstructions consistently predict oblique right-lateral motion between North America and the Kula plate during this time. Magmatism associated with this transition could have occurred in a variety of tectonic settings, including above areas of slab breakoff, slab window formation, and/or interaction between the North American margin and the ancestral Yellowstone hotspot.

ROAD LOG

We depart from Seattle and drive east on I-90 through glacial deposits that fill much of the Puget Lowland (Fig. 1B). Near Issaquah we drive past high topography to the south of I-90. The bedrock of this area is composed of middle Eocene and Oligocene sedimentary and volcanic rocks of the Puget Group and overlying Blakeley Formation (Fig. 1B). Farther east we enter plutonic and volcanic rocks related to the late Eocene to present Cascade arc, including impressive roadcuts of tonalite and granodiorite belonging to the Miocene Snoqualmie batholith west of Snoqualmie Pass. The road log begins at the bottom of the Exit 52 off-ramp on I-90 East. Distances are given in miles,

and the locations of all stops are reported as decimal degrees, datum WGS84.

■ Day 1

The focus of Day 1 is the geologic history of the Swauk basin, the bimodal volcanic rocks that overlie it, and its successor, the Roslyn basin. Other field guides to this area include Evans and Johnson (1989), Cheney (2003), Cheney and Hayman (2007, 2009b), and Miller et al. (2009). Helpful geologic maps of this area include the Snoqualmie Pass and Wenatchee 30' × 60' quadrangles by Tabor et al. (2000) and Tabor et al. (1982), respectively.

Mileage	Description
0.0	Take Exit 54 on I-90 East and turn right on WA-906 and continue straight onto Hyak Drive East for one mile. Mileage begins at the bottom of the interstate off-ramp.
1.0	Intersection of Hyak Drive East and U.S. National Forest Service Road (NF) 9070. Turn left onto NF 9070 and continue.
1.1	Enter outcrops of the Mount Catherine rhyolite member of the Eocene Naches Formation.
1.2	Park at the southern end of the outcrops.

Stop 1.1. Mount Catherine Rhyolite Member of the Naches Formation (47.3805° N, 121.3916° W)

The outcrops at this stop belong to the Mount Catherine Rhyolite Member of the Naches Formation (Foster, 1960; Tabor et al., 1984). This member includes ash flow tuffs that are interbedded with the dominantly sedimentary lower Naches Formation. A U-Pb zircon date from this outcrop is 49.711 ± 0.024 Ma (Eddy et al., 2016). Highly flattened pumice is common, along with phenocrysts of quartz and feldspar. The transition from the dominantly sedimentary lower Naches Formation to the dominantly bimodal volcanics of the upper Naches Formation mirrors the transition from sedimentary deposition to bimodal volcanism throughout the Swauk basin. However, unlike the rest of the former Swauk basin, the contact between these sedimentary rocks and the overlying volcanics is described as conformable (Tabor et al., 1984). Therefore, it is unclear whether the lower Naches Formation is correlative to the Swauk and Chuckanut Formations, but escaped deformation, or whether it represents renewed deposition after regional deformation. The presence of conglomerate rich in chert clasts (Foster, 1960; Tabor et al., 2000) may suggest that the accretionary rocks to the west were uplifted and eroding during deposition of the lower Naches Formation and supports their correlation to the uppermost Swauk Formation or lowermost Teanaway Formation. Regardless, the bimodal volcanics that compose the upper Naches Formation are of the same age as the basalts and rhyolites that blanket the former Swauk basin and are likely correlative to the Barlow Pass Volcanics (e.g., Vance, 1957; Evans and Ristow, 1994; Tabor, 1994), Teanaway Formation (Clayton, 1973; Tabor et al., 1984), and Basalt

of Frost Mountain (Tabor et al., 1984). These volcanics underlie the mountains on the east side of Lake Keechelus and are visible from this stop (Fig. 2).

Mileage	Description
1.2	Turn vehicle around and drive back toward Hyak.
1.4	Intersection of NF 9070 and Hyak Drive East. Turn right onto Hyak Drive East.
2.4	Turn right onto on-ramp for I-90 East. Drive on I-90 East for 15.1 miles, with the upper Naches Formation on the left and views of the lower Naches Formation, including the Mount Catherine Rhyolite across Lake Keechelus.
17.5	Take Exit 70 on I-90 East toward Easton/Sparks Road.
17.8	Turn left on Lake Easton Road.
17.9	Turn left on West Sparks Road.
18.5	Turn right on Kachess Dam Road.
18.8	Continue straight onto NF 4818.
20.2	Park at pulloff on NF 4818. Walk to the lakeshore and head south and west along the shoreline. If the water level is low, head as far west as possible for the best view of the unconformity between the Swauk and Teanaway Formations.

Stop 1.2. Overview of Straight Creek–Fraser River Fault and Unconformity between Swauk and Teanaway Formations (47.2756° N, 121.1887° W)

The southern end of the Straight Creek–Fraser River fault runs through the middle of Lake Kachess (Fig. 2) and separates the Naches Formation to the west from the Swauk, Teanaway, and Roslyn Formations in the Teanaway River block to the east (Figs. 1B and 2). Mesozoic rocks on either side of the fault appear to be displaced by between 100 and 150 km of right-lateral motion that must have occurred between the Late Cretaceous and late Eocene, when the fault was sealed by intrusions related to the modern Cascade arc (Fig. 1B; Misch, 1966; Umhoefer and Miller, 1996; Tabor et al., 2003). On the basis of a similar depositional history, Frizzell (1979), Eddy et al. (2016), and others correlated the Chuckanut and Swauk Formations across this fault and considered them to have been deposited in a single basin (Swauk basin) that was dismembered by motion on the Straight Creek–Fraser River fault (Fig. 4). If this hypothesis is correct, then much of the right-lateral displacement on this structure occurred between 50 and 35 Ma (Fig. 11).

On the high ridge to the east, the angular unconformity between the Swauk and Teanaway Formations is visible. Here, rocks belonging to the Silver Pass Volcanic Member of the Swauk Formation dip steeply (50–70°) to the east, and are overlain by gently dipping (25–30°) basalt flows of the Teanaway Formation. Both units are folded as part of a regional syncline (Fig. 2) that was likely formed during motion of the Straight Creek–Fraser River fault. However, this structure can be traced into a gentle syncline within the Columbia River

basalts (Fig. 2), indicating that it has been reactivated during Miocene or younger shortening (e.g., Cheney, 2003). The Silver Pass Volcanic Member is a thick package of rhyolite, dacite, and andesite. A U-Pb zircon eruption date for one rhyolite from the above ridges is 51.364 ± 0.029 Ma (Eddy et al., 2016). The Silver Pass Volcanic Member is inferred to be a volcanic center that fed the silicic tuffs in the eastern Swauk Formation (Tabor et al., 1984). One of these tuffs will be visited at Stop 2.1 and has a similar U-Pb zircon eruption age, supporting the correlation of these rocks.

Mileage	Description
20.2	Turn vehicle around and drive back toward West Sparks Road.
21.6	Continue straight onto Kachess Dam Road.
21.9	Turn left onto West Sparks Road.
22.5	Turn right onto Lake Easton Road and immediately turn left onto on-ramp for I-90 East.
32.3	Take Exit 80 off of I-90 East.
32.5	Turn left onto Bullfrog Road.
34.6	At traffic circle take first exit and stay on Bullfrog Road.
35.3	At traffic circle continue straight onto WA-903 North.
35.8	WA-903 North turns into 1st Street as you enter Roslyn, Washington.
36.9	Take a sharp left turn onto West Nevada Avenue (WA-903 N).
37.2	Take a sharp right turn onto North 7th Street (WA-903 N) and continue on WA-903 N for 12.2 miles.
49.4	Turn around at Red Mountain campground and continue straight on WA-903 South.
49.6	Pull off of WA-903 S for Stop 1.3.

Stop 1.3. Swauk Formation and Teanaway Dike (47.3632° N, 121.1026° W)

This stop is a roadcut of typical arkosic sandstone within the Swauk Formation. Beds dip moderately to steeply to the south. Plant fossils can be found in the middle of the roadcut. While the correlative Chuckanut Formation is well known for its fossil Eocene flora, the fossils in the Swauk Formation are less well studied (e.g., Mustoe et al., 2007; Breedlovestrout et al., 2013). Cross bedding can be seen in the sandstone at the southern end of the outcrop. These outcrops are part of our informal lower Swauk Formation, which was deposited by west- or southwest-flowing streams (Taylor et al., 1988). However, the western part of the Swauk Formation, including the areas to the north and west of this outcrop, remains poorly studied. At the northern end of the outcrop, a basaltic dike cuts the sandstone and is part of the dike swarm that fed the Teanaway Formation. This dike swarm will be discussed in more detail at Stop 1.4.

Mileage	Description
49.6	Continue on WA-903 South.
51.4	Pull off on side of WA-903 S for Stop 1.4.

Stop 1.4. Teanaway Dikes (47.3378° N, 121.1054° W)

This stop highlights roadcuts through some of the thick basaltic dikes that fed the basalt flows and mafic tuffs that comprise the Teanaway Formation. This dike swarm intrudes an area that is ~75 km wide in an east-west direction and ~18 km wide in a north-south direction, and pervasively intrudes the central Swauk Formation (Foster, 1958; Tabor et al., 1984). The average strike of more than 400 dikes measured throughout the swarm is ~025–030° (e.g., Miller et al., 2016), and the average strike of dikes in the area around this road ($n = 53$) is 036° (Doran, 2009). Estimates for the amount of extension represented by the dike swarm range from 15%–40% (Doran, 2009; Miller et al., 2016). At this roadcut, large xenoliths (>2 m) of arkosic sandstone from the Swauk Formation are included in the dikes (Fig. 7B). The sandstone that hosts these dikes has cross bedding, convolute bedding, and mudstone intraclasts. There is a small north-vergent thrust fault ~20 m south of the main dikes.

Mileage	Description
51.4	Continue on WA-903 South.
53.0	Roadcuts of basalt flows belonging to the Teanaway Formation. The unconformable contact between the Swauk and Teanaway Formations is not exposed along WA-903 S, but is just to the north of this roadcut.
54.6	Pull off on side of WA-903 S for Stop 1.5.

Stop 1.5. Teanaway Formation (47.2927° N, 121.1007° W)

Here we visit a roadcut of a massive basalt flow within the Teanaway Formation. Flows comprise ~30% of the Teanaway Formation and are typically massive, with only a few flows exhibiting prominent columnar jointing (Clayton, 1973). The rest of the Teanaway Formation is composed of mafic tuff and basaltic breccia with minor interbedded sedimentary and silicic volcanic rocks. Basaltic breccia can be seen <40 m up the gravel side road leading to the north from this stop. These flows form the easternmost part of the bimodal volcanics that blanketed the deformed Swauk basin at ca. 49 Ma. The tectonic setting of these basalts remains an open question, with possibilities that include magmatism above a slab window, above an area of slab breakoff, or interaction between the continental margin and the Yellowstone hotspot.

Mileage	Description
54.6	Continue on WA-903 South.
61.6	Take a sharp left turn onto West Nevada Avenue (WA-903).
61.9	Take a sharp right onto 1st Street (WA-903).
72.2	Turn right onto East Washington Avenue.
72.5	Park on East Washington Avenue and walk uphill into a small city park in Roslyn for Stop 1.6.

Stop 1.6. Roslyn Formation (47.2262° N, 120.9886° W)

This stop visits outcrops of arkosic sandstone that belong to the upper Roslyn Formation. These strata were deposited by

west-flowing streams and have no documented proximal to distal relationship to major faults. Several coal seams are present within the upper Roslyn Formation and were mined during the late nineteenth and early twentieth century. Evans (1994) correlated the Roslyn Formation to the Deadhorse Canyon Member of the Chumstick Formation as they both appear to have been deposited after the end of major strike-slip faulting on the Entiat, Eagle Creek, and Leavenworth fault zones (Fig. 2). Nevertheless, the age of the Roslyn Formation remains an open question. Detrital zircons separated from a lag deposit in this outcrop gave a maximum depositional age of 47.580 ± 0.028 Ma (Eddy et al., 2016), leaving it permissible that it is the same age as parts of the rocks that filled the Chumstick basin. However, we consider this unlikely given the lack of evidence for syn-depositional faulting along the eastern side of the Roslyn Formation.

End of Day 1.**■ Day 2**

Day 2 visits the eastern Swauk Formation and parts of the older, western Chumstick sub-basin. We focus on the disruption of the Swauk basin ca. 51.3–50 Ma, development of the Chumstick basin ca. 49 Ma contemporaneous with or shortly after eruption of the Teanaway Formation, and the history of dextral displacements on the Leavenworth fault zone. Some of these stops have been described previously by Evans and Johnson (1989), Cheney (2003), Cheney and Hayman (2007, 2009b), and Miller et al. (2009). Please see these guides for additional information and alternative interpretations. The geologic maps for the Wenatchee (Tabor et al., 1982) and Chelan (Tabor et al., 1987) 30' × 60' quadrangles are helpful supplements for these stops.

Mileage	Description
0.0	Mileage starts at the intersection of West 1st Street and Billings Street in Cle Elum. Continue east on West 1st Street (WA-903 East).
2.2	Continue straight onto WA-10/WA-970 E.
4.7	Continue straight on WA-970 E.
12.3	Continue straight onto U.S. 97 North.
13.9	Pass mafic tuffs in the Teanaway Formation (Fig. 7A). Up to 60% of the Teanaway Formation is composed of water-lain mafic tuffs such as this (Clayton, 1973).
14.5	Cross the contact between the Teanaway and Swauk Formations.
23.6	Turn left onto the dirt road leading into the quarry. Drive 0.25 miles into quarry, or, if the road is impassable, park where available and walk.

Stop 2.1. Silicic Tuff within Swauk Formation (47.3345° N, 120.6328° W)

This stop visits volcanoclastic deposits exposed in a quarry along U.S. 97 just to the west of Blewett Pass. These rocks are likely a distal part of the Silver Pass Volcanic Member of the Swauk Formation (Tabor et al., 1984), and mark the beginning

of the transition between our informal division of the lower and upper Swauk Formation. Just a few hundred meters up-section is where the reversal of paleoflow from west- to east directed is recorded (Taylor et al., 1988). We will stop near this boundary at Stop 2.2. The dominant lithology at this stop is lapilli tuff, which can be seen in the western half of the outcrop. Taylor et al. (1988) traced this tuff along strike for ~8 km. Eddy et al. (2016) reported a U-Pb zircon date of 51.515 ± 0.028 Ma from this locality that they interpreted as an eruption/deposition age. However, the tuff is significantly reworked in some areas and N. McLean only recovered detrital Mesozoic zircons from a different sample in this outcrop (written commun. cited in Miller et al., 2009). A Teanaway dike can also be observed within the quarry. Backfill is serpentinite from the Ingalls ophiolite and not from the outcrop. This stop was previously described as Stop 1.11 in Cheney (2003) and Stop 1.18 in Cheney and Hayman (2007).

Mileage	Description
23.6	Turn left off of spur road onto U.S. 97 North. Continue north through outcrops of the lower Swauk Formation.
26.9	Turn right into the large parking lot. Continue onto NF-9716.
27.4	Turn right into parking lot for Swauk Forest Discovery trail. Toilets are available at the trailhead. Walk back downhill on road NF-9716 to an overlook of a large outcrop on the north side of U.S. 97 and of the long ridge to the northeast.

Stop 2.2. Overview of Swauk Formation from Blewett Pass (47.3346° N, 120.5788° W)

This stop provides an overview of the Swauk Formation. In the foreground is a large roadcut through the sedimentary rocks within the transition between our informal division between the lower and upper Swauk Formations (Fig. 6). It is composed of interbedded sandstone and mudstone that belong to the sandstone facies of Swauk Pass (Taylor et al., 1988). These rocks were the last part of the Swauk basin to be deposited along west- or southwest-flowing fluvial systems (Taylor et al., 1988). Just up-section from this roadcut the Swauk Formation records a reversal in dominant paleoflow directions, marking the end of the transition to our informal upper Swauk Formation. In the foreground and middle ground to the northeast, a thick succession of debris-flow fan and lacustrine deposits is exposed on Tronsen Ridge (Fig. 6; Tabor et al., 1982; Taylor et al., 1988; Evans and Johnson, 1989). These rocks form the upper Swauk Formation and are cut by the Teanaway dike swarm, though fewer dikes cut these rocks than in the rest of the Swauk Formation. The upper Swauk Formation was dominantly deposited along east-flowing streams that emptied into lakes near the Leavenworth fault zone. We interpreted this change in paleoflow to be related to uplift along the plate boundary during accretion of Siletzia. Some of the rocks belonging to the upper Swauk Formation will be visited at Stop 2.3. Coarse conglomerate interbedded with the upper Swauk Formation (Breccia of

Devils Gulch) along the Leavenworth fault zone suggest that some topography may have been present on this structure during the deposition of the latest Swauk Formation (Taylor et al., 1988) at ca. 50 Ma. The Jurassic Ingalls Ophiolite and the Cretaceous Mount Stuart batholith underlie the high peaks to the northwest. This stop corresponds to Stop 2 in Evans and Johnson (1989), Stop 1-2 in Cheney (2003), Stop 1-16 in Cheney and Hayman (2007), Stop 3-4 in Cheney and Hayman (2009b), and Stop 1-2 in Miller et al. (2009).

Mileage	Description
27.4	Turn left out of the trailhead parking lot on NF-9716.
27.9	Turn right onto U.S. 97 North.
40.1	Turn right onto NF-7204 (Ruby Creek Road) and continue for 0.2 miles.
40.3	Park along NF-7204 for Stop 2.3.

Stop 2.3. Conglomerate Facies of Tronsen Creek (47.4481° N, 120.6524° W)

This stop highlights conglomerate within the upper Swauk Formation that belong to the conglomerate facies of Tronsen Creek (Taylor et al., 1988). Johnson and Miller (1987), Evans and Johnson (1989), and Miller et al. (2009) described these outcrops in previous field guides. Here, the Swauk Formation is in contact with the Ingalls Ophiolite along a strand of the Leavenworth fault zone. Outcrops at the northern end of the stop are composed of deformed mafic rocks and serpentinite of the ophiolite. Further to the south, the conglomerate facies of Tronsen Creek is exposed as a 32-m-thick section of conglomerate and sandstone. Many of the clasts are of rock types within the Ingalls ophiolite and can be as large as 45 cm in diameter. Johnson and Miller (1987) and Evans and Johnson (1989) interpreted these outcrops as alluvial fan deposits along a local fault scarp. Such local topography is consistent with increased tectonic activity during deposition of the upper Swauk Formation, and potentially reflects early strike-slip motion on the Leavenworth fault zone.

Along this part of the Leavenworth fault zone, Senes et al. (2015) reported that beds ($n = 285$) in the Swauk Formation have a mean west-northwest strike, oblique to the northwest-striking (~320–330°) fault segments. Very gently east-southeast-plunging folds are indicated by poles to beds, and beds in the Chumstick Formation east of the Leavenworth fault zone have similar strikes and define gently northwest-plunging folds (Senes et al., 2015). Map-scale (>2 km wavelength) folds in both the Swauk and Chumstick Formations near the fault zone trend 270°–315° (Tabor et al., 1982; Senes et al., 2015). The overall obliquity of folds to the Leavenworth fault zone strongly supports dextral strike-slip.

Mileage	Description
40.3	Turn vehicle around and drive on NF-7204 toward U.S. 97.
40.5	Turn right on U.S. 97 North and continue for 2.5 miles.
43.0	Turn onto Old Blewett Road and park for Stop 2.4.

Stop 2.4. Tonalite Fanglomerate in the Tumwater Mountain Member of the Chumstick Formation at Old Blewett Road (47.4833° N, 120.6526° W)

This stop visits a roadcut in monolithologic boulder conglomerate (fanglomerate) along U.S. 97. Taylor et al. (1988) considered it to represent a down-dropped block of coarse conglomerate that is found along the eastern edge of the upper Swauk Formation (Breccia of Devils Gulch) and Cheney and Hayman (2009a, 2009b) also mapped it as a diamictite within the Swauk Formation. However, Evans (1994) mapped it as part of the Tumwater Mountain Member of the Chumstick Formation. We agree with Evans (1994) and consider it to be a marginal facies of the Chumstick basin along the Leavenworth fault zone based on its similarity to the rest of the Tumwater Mountain Member. The conglomerate is entirely composed of tonalitic and granodioritic boulders set in a matrix of immature sandstone derived from the same lithology. LaCasse (2013) reported a U-Pb zircon date of 91.0 ± 2.3 Ma and Al-in-hornblende pressure estimates of 1–4 kbar from a tonalite boulder, which are consistent with the age and emplacement depth of the southeastern Mount Stuart batholith (Fig. 2; Ague and Brandon, 1996; Matzel et al., 2006). Similar conglomerate elsewhere within this belt contains clasts of serpentinite suggestive of their derivation from the Ingalls Ophiolite (Fig. 2; Cashman and Whetten, 1976). These rocks were likely deposited on alluvial fans that came off of topographic highs along the Leavenworth fault zone (e.g., Evans, 1994). This corresponds to Stop 1-7 in Cheney (2003).

Mileage	Description
43.0	Return to U.S. 97 North.
49.4	Turn left onto ramp for U.S. 2 West and continue for 4.2 miles.
53.6	Turn right onto WA-209 and immediately turn left onto Fir Street and continue on this road as it bends to the left and becomes Pine Street.
54.2	Turn right on Ski Hill Drive.
54.4	Park on the right side of the road just south of Village View Drive for a short overview of the Leavenworth fault, Tumwater Mountain and Clark Canyon Members of the Chumstick Formation along the western margin of the western Chumstick sub-basin. See description for Stop 2.5.
55.1	Continue on Ski Hill Drive into the parking lot for the Leavenworth Ski Hill for Stop 2.5.

Stop 2.5. Sandstone near the Boundary between the Clark Canyon and Tumwater Mountain Members of the Chumstick Formation (47.6139° N, 120.6685° W)

At mileage 54.4, the panoramic view from west to north includes: the Cretaceous Mount Stuart batholith high on Tumwater Mountain, the Leavenworth fault between the batholith and south-facing exposures of the Tumwater Mountain Member (conglomerate and sandstone) of the Chumstick Formation,

and the sandstone-dominated, NE-dipping strata above the ski hill to the north. At the base of the ski hill in Leavenworth, we visit outcrops of the Clark Canyon Member and continue the overview of the west side of the western Chumstick sub-basin. Looking west, the Leavenworth fault zone separates the Mount Stuart batholith and Ingalls Ophiolite from rocks belonging to the Chumstick Formation about halfway up the high ridge. Here, the Tumwater Mountain Member shows rapid facies changes from boulder conglomerate to sandstone and minor conglomerate that Evans (1994) and Donaghy (2015) interpreted to represent colluvial fans and fluvial deposits proximal to a topographic high along the Leavenworth fault. These west-derived facies are mapped through a large north-northwest-trending syncline and interfinger with the dominantly east-derived strata of the Clark Canyon Member of the Chumstick Formation. Detrital zircon data from the Tumwater Mountain and Clark Canyon Members have distinct Mesozoic age peaks that correspond to the ages of bedrock on the western and eastern side of the Chumstick basin, respectively, further supporting the hypothesis that the two members were sourced from opposite sides of the basin (Donaghy, 2015).

Mileage	Description
55.1	Turn left onto Titus Road.
56.5	Turn Left onto Pine Street.
56.6	Continue onto Fir Street as the road bends to the right and then left. Turn right on WA-209 at the end of Fir Street and then immediately turn left onto U.S. 2 East. Continue on U.S. 2 E for 18.6 miles.
75.2	Continue onto North Wenatchee Avenue.
77.2	Turn slightly onto North Miller Street.
77.5	Turn right onto North Chelan Avenue.
79.2	Continue straight as Chelan Avenue merges into Mission Street.
80.1	Continue straight as Mission Street turns into Squilchuck Road.
87.1	Turn right onto Mission Ridge Road.
91.1	Turn vehicle around in parking area for ski runs and head northeast on Mission Ridge Road.
91.2	Park on the side of Mission Ridge Road for Stop 2.6.

Stop 2.6. Tonalite Fanglomerate in the Tumwater Mountain Member of the Chumstick Formation at Mission Ridge (47.2965° N, 120.3960° W)

This stop visits a monolithologic fanglomerate at the southern end of the Tumwater Mountain Member of the Chumstick Formation. The outcrop is similar to the one visited at Stop 2.4 and consists entirely of boulder-sized clasts of tonalite that were likely sourced from the Mount Stuart batholith. U-Pb zircon geochronology from a clast in this outcrop suggests that it crystallized 90.6 ± 3 Ma (LaCasse, 2013). This age is consistent with the boulders' derivation from the southeastern part of the Mount Stuart batholith (voluminous 91 Ma phase of Matzel et al., 2006). Boulders in this conglomerate are up to 3 m in diameter and it is

unlikely that they traveled far. Instead, their presence likely indicates 30–40 km of syn- or post-depositional right-lateral motion on the Leavenworth fault zone. To the southeast, the Leavenworth fault zone disappears underneath the Columbia River basalts (Fig. 2). Thus, assuming that this conglomerate also continues, the proposed offset is likely a minimum estimate for the total offset between ca. 49 and 47–46.5 Ma, when the Clark Canyon and Tumwater Mountain Members of the Chumstick Formation were deposited (Fig. 10).

Alternatively, the boulders in this outcrop may have been locally derived from bedrock now covered by the Columbia River Basalt Group (Fig. 2). This interpretation would require minimal right-lateral displacement on the Leavenworth fault zone during deposition of the Clark Canyon and Tumwater Mountain Members of the Chumstick Formation. We do not consider this possibility to be likely for two reasons: (1) These rocks appear to be of the same age and of similar composition to the southeastern Mount Stuart batholith, providing a compelling link to that intrusion, and (2) the older Swauk Formation forms the bedrock to the west of this location. Thus, any crystalline basement in this area was covered by sedimentary rock prior to deposition of the Tumwater Mountain Member.

Mileage	Description
91.2	Continue on Mission Ridge Road toward Squilchuck Road.
95.1	Turn left onto Squilchuck Road.
102.1	Continue straight as Squilchuck Road becomes Mission Street.
105.1	Turn right onto North Miller Street.
105.3	Continue straight as North Miller Street turns slightly left and becomes North Wenatchee Avenue.
107.5	Continue straight as North Wenatchee Avenue becomes U.S. 2 West.
115.1	Turn right onto Nahahum Canyon Road.
115.2	Park for Stop 2.7.

Stop 2.7. Conglomerate in the Clark Canyon Member of the Chumstick Formation near the Eagle Creek Fault (47.5268° N, 120.4706° W)

This is a brief stop to observe conglomerate of the Clark Canyon Member of the Chumstick Formation near its contact with the Swakane Biotite Gneiss along the western strand of the Eagle Creek fault (Fig. 2). This fault is down to the west and is, in part, responsible for the uplift of the large horst of the Swakane Biotite Gneiss that separates the western and eastern Chumstick sub-basins. This strand of the fault appears to have been activated after deposition of the Clark Canyon Member, as Evans (1994) described the deposits of the Clark Canyon Member closest to the fault to represent distal fan deposits derived from the east. He speculated that coarser, more proximal, facies were uplifted and eroded during motion on this fault. Here, we see steeply dipping beds of conglomerate and sandstone that were deformed by motion on this structure. These strata and equivalent strata

to the south of the Wenatchee River form a large southwest-dipping homocline that forms the main part of the southern Chumstick basin. The oldest dated tuff in the Chumstick basin was sampled from ~4 km south of here (Fairview Canyon tuff, 49.147 ± 0.041 Ma; Eddy et al., 2016), and can be traced northward to this area.

Mileage	Description
115.2	Turn car around and head toward U.S. 2.
115.3	Turn onto U.S. 2 West.
117.5	Turn right onto North Dryden Road.
118.0	Turn into parking lot for Peshastin Pinnacles State Park for Stop 2.8.

Stop 2.8. Clark Canyon Member of the Chumstick Formation at Peshastin Pinnacles State Park (47.5396° N, 120.5201° W)

The final stop of the day is at Peshastin Pinnacles State Park. This park includes steeply dipping beds of the Clark Canyon Member of the Chumstick Formation and is a popular climbing location. The sedimentary rocks at this stop include coarse-grained sandstone beds with pebble and gravel lag deposits near their bases, lenticular sandstone beds, and organic-rich mudstone (Donaghy, 2015). These rocks are all interpreted to represent deposition along streams that drained highlands to the east (Evans, 1994; Donaghy, 2015). The beds here are stratigraphically between tuffs dated to 48.959 ± 0.037 Ma and 48.522 ± 0.015 Ma (Eddy et al., 2016). The steep dips are related to the folding that occurred after the development of the Eagle Creek fault (similar to Stop 2.7), which lies ~1.5 km to the northeast. Most of the western Chumstick sub-basin is deformed into moderate to open folds in the central part of the Clark Canyon Member, and into a large homocline south of the Wenatchee River. We will summarize the movement history of the major basin-bounding faults at this stop.

Mileage	Description
118.0	Turn left onto North Dryden Road and follow it back to U.S. 2.
118.5	Junction of North Dryden Road and U.S. 2.

End of Day 2.

■ **Day 3**

Day 3 continues to focus on the Chumstick basin and involves stops in the western Chumstick sub-basin to look at tuffs interbedded with the Clark Canyon Member, and stops in the eastern Chumstick sub-basin to look at lacustrine rocks within the Nahahum Canyon Member. We also examine the Entiat fault, which formed the eastern boundary of the Chumstick basin. Some of these stops were previously described in Evans and Johnson (1989). Cheney and Hayman (2007, 2009b) also visited this area and provide an alternative interpretation of the Chumstick Formation to the one presented herein. The geologic maps

of the Wenatchee (Tabor et al., 1982) and Chelan (Tabor et al., 1987) 30' × 60' quadrangles cover this area.

Mileage	Description
0.0	Road log begins at junction of U.S. 2 and WA-209 in Leavenworth. Continue onto WA-209 North for 6 miles.
6.0	Turn right onto Clark Canyon Road and continue for 2.3 miles driving through roadcuts and outcrops of the Clark Canyon Member of the Chumstick Formation.
8.3	Turn vehicle around and park for Stop 3.1.

Stop 3.1. Tuffs within the Clark Canyon Member of the Chumstick Formation (47.6781° N, 120.6024° W)

The Clark Canyon Member of the Chumstick Formation is unique in that it contains 18 volcanic tuffs that can be traced over distances >10 km along strike and used as stratigraphic markers (McClincy, 1986; Evans, 1994). U-Pb zircon dates from these tuffs have recently been used to quantify extremely high sediment accumulation rates (up to 6–7 m/k.y. in the lower part of the Clark Canyon Member and 2–3 m/k.y. in this part of the member; Eddy et al., 2016). This stop highlights two of these tuffs, Clark Canyon #6 and Clark Canyon #7 (McClincy, 1986). Clark Canyon #7 (47.67842° N, 120.60191° W) is the stratigraphically lower of the two horizons and is composed of two distinct beds. The lower tuff bed is <1 m thick and is rich in pumice and lithic fragments, while the upper tuff bed is highly silicified and overlain by a thick (~2 m) debris flow containing clasts of tuff and pumice. Fossil leaves are common near the top of the upper tuff (e.g., McClincy, 1986). A U-Pb zircon eruption/deposition date for the upper tuff of 48.290 ± 0.046 Ma was reported by Eddy et al. (2016). Clark Canyon #6 (47.67788° N, 120.60229° W) is exposed nearby and is a greenish, very thick (~3 m), highly silicified vitric tuff. Numerous plant fossils can be found at its base. These tuffs were visited as Stop 8 in Evans and Johnson (1989). The Clark Canyon Member dominantly represents distal fan deposits that were derived from the east (Evans and Johnson, 1989; Evans, 1994). Detrital zircon data from this section support this interpretation (Donaghy, 2015). This stop corresponds to Stop 8 in Evans and Johnson (1989).

Mileage	Description
8.3	Continue on Clark Canyon Road back toward the Chumstick Highway.
10.6	Turn left on Chumstick Highway.
14.5	Turn left onto Eagle Creek Road.
16.9	Pass roadcut of Clark Canyon #2 tuff on the north side of Eagle Creek Road.
19.0	Cross a strand of the Eagle Creek fault zone and pass through 0.8 miles of the Swakane Biotite Gneiss. The gneiss forms the basement for the eastern Chumstick basin and is uplifted as a horst within the Eagle Creek fault zone.
20.3	Turn left onto NF-7520.

21.5	Continue straight on NF-7520.
21.9	Continue straight on NF-7520.
24.3	Park along NF-7520 for Stop 3.2.

Stop 3.2. Faulted Conglomerate in the Nahahum Canyon Member of the Chumstick Formation (47.7017° N, 120.5255° W)

The outcrop at this stop consists of conglomerate within the Nahahum Canyon Member of the Chumstick Formation. These rocks were deposited along the eastern side of the Chumstick basin after the formation of the eastern sub-basin (Fig. 8). The eastern Chumstick sub-basin was bounded by the Eagle Creek and Entiat faults and contains evidence for syn- and post-depositional strike-slip on these structures. We attribute the deformation and fracturing at this outcrop to syn-depositional motion on the Entiat fault. The age of the rocks in the eastern Chumstick sub-basin is less well constrained than those in the western Chumstick sub-basin. A maximum depositional age of 46.902 ± 0.076 Ma was reported for sandstone within the middle Nahahum Canyon Member by Eddy et al. (2016), and Gilmour (2012) reported a date of 44.447 ± 0.027 Ma for rhyolite domes that intrude the Eagle Creek fault. These dates imply that the eastern sub-basin was deposited rapidly between <46.902 ± 0.076 and 44.447 ± 0.027 Ma. However, there is evidence for contemporaneous hydrothermal activity during deposition of the Nahahum Canyon Member, suggesting that magmatism and faulting may have been coeval with, or continued after, the 44.447 ± 0.027 Ma intrusion of the Wenatchee dome complex. Both eastern and western sub-basins were then deformed and the Deadhorse Canyon Member of the Chumstick Formation was unconformably to disconformably deposited across them. This member overtops the Eagle Creek fault (Fig. 2) and is interpreted to have overtopped the Entiat and Leavenworth fault zones (Evans, 1994). Evans (1994) speculated that the Deadhorse Canyon Member formed a continuous depositional system with the Roslyn Formation, and we agree with this interpretation.

Mileage	Description
24.3	Continue on NF-7520 for 0.3 miles.
24.6	Park on NF-7520 for Stop 3.3.

Stop 3.3. Entiat Fault Damage Zone (47.7039° N, 120.5222° W)

Just up the road from Stop 3.2 we enter highly deformed crystalline rocks of the Napeequa Schist. This unit likely represents an oceanic accretionary complex that was incorporated in the North Cascades orogen during the Cretaceous. It consists dominantly of micaceous quartzite and siliceous schist (likely metachert), amphibolite to mafic gneiss, biotite schist, and less common metaperidotite and marble (Tabor et al., 1987; Paterson et al., 2004). The schist experienced peak pressures of ~1.0 GPa during the Late Cretaceous (Valley et al., 2003) and was exhumed by the Eocene, as clasts of Napeequa Schist are found in the Chumstick Formation (Paterson et al., 2004).

Stops 3.2 and 3.3 represent the damage zone for the Entiat fault. The full width of this damage zone at Stops 3.2 and 3.3 is ~20 m within the Chumstick Formation and ~100 m in the adjacent metamorphic rocks (Pence and Miller, 2015). The damage zone in the crystalline rocks at Stop 3.3 is marked by abundant slickensides and numerous steep faults, which dominantly strike northwest, but with considerable deviation about the mean. Separations on the faults are <40 cm and both dextral strike-slip and dip-slip faults are present. Locally, steep faults cut moderately dipping ones.

Approximately 700 m from the main fault is a ≥25-m-wide zone of greenschist-facies mylonites (not seen on this trip) in the metamorphic rocks (Laravie, 1976; Pence and Miller, 2015). The strike of foliation in the mylonites is sub-parallel to oblique to the main fault trace and dips moderately to steeply. Most lineations trend northwest or southeast, and are dominantly gently plunging. Kinematic indicators suggest dextral movement (Pence and Miller, 2015). Microstructures and overprinting mineral assemblages in the metamorphic rocks indicate low-temperature ductile deformation (Regime 1 of Hirth and Tullis, 1992). Subsequent strong cataclasis was imposed on the mylonites. Overall, the motion in the Entiat fault zone was marked by ductile deformation followed by brittle reactivation and migration of deformation to the southwest. Both dip-slip (down-to-southwest) and dextral strike-slip are recorded.

The Entiat fault has no reliable offset markers. However, the width of the fault zone and the linear and long (175 km: Figs. 1B and 2) nature of the fault suggest that it has at least a few 10s of km of offset. Tabor et al. (1987) estimated a maximum of 30–40 km of dextral displacement using “a major fold axis in metamorphic units” as a piercing point. Along the northern part of the Entiat fault similar lithologic units are found on both sides of the fault, suggesting diminished offset to the northwest. Additionally, there is no obvious match for the fault on the western side of the Straight Creek–Fraser River fault (Umhoefer and Miller, 1996). Based on these observations and the distribution of Eocene structures in the metamorphic rocks to the east of the Entiat fault, we suggest that some of the slip on the Entiat fault stepped to the right to the Ross Lake fault zone through the Skagit Gneiss Complex and adjacent metamorphic rocks north of where the Entiat and Leavenworth faults merge (Fig. 1B; Haugerud et al., 1991; Miller et al., 2016).

Mesozoic metamorphic and plutonic rocks that comprise the Wenatchee structural block (Fig. 1B), including the Mount Stuart batholith, which forms the highest topography in the south-southwest. In contrast to the metamorphic rocks east of the Leavenworth fault zone, which were exhumed to the upper crust in the Eocene, these rocks had already cooled to below the $^{40}\text{Ar}/^{39}\text{Ar}$ closure temperatures for hornblende (~500–550 °C), muscovite (~350–415 °C), and biotite (~300–350 °C) by the Late Cretaceous (Matzel, 2004). The Eagle Creek fault runs through the moderately high topography in the foreground and separates the western and eastern Chumstick sub-basins. Within this high topography are several exposures of the Swakane Biotite Gneiss, which form the northern extension of the large horst within the Eagle Creek fault zone (Fig. 2). On the west side of the Eagle Creek fault lie the Clark Canyon and Tumwater Mountain members of the Chumstick Formation, which filled the western sub-basin and were visited at Stops 2.4–2.8, and 3.1. To the east lies the Nahahum Canyon Member of the Chumstick Formation, which filled the eastern sub-basin and was visited at Stop 3.2 and will be visited at Stop 3.5. To the west-northwest, the Deadhorse Canyon Member of the Chumstick Formation overtops the Eagle Creek fault (Fig. 2; Evans, 1994).

This stop is entirely within the Swakane Biotite Gneiss at the eastern margin of the Entiat fault zone. Good outcrops of these rocks can be seen on NF 7801 just downhill from this stop. These rocks form the most deeply exhumed level of the North Cascades orogen with peak metamorphic pressures up to 1.2 GPa (e.g., Valley et al., 2003). They represent sedimentary rocks thrust under the base of the arc in the Late Cretaceous (Matzel et al., 2004). Exhumation of the Swakane Biotite Gneiss occurred after metamorphism at ca. 68 Ma (Matzel et al., 2004); Gatewood and Stowell, 2012) and at least, in part, during slip on the Eocene Dinkelman décollement (Fig. 2), which separates the Swakane Biotite Gneiss from the Napeequa Schist (Paterson et al., 2004). Farther to the north, the Skagit Gneiss Complex (Fig. 1B), which records peak metamorphic pressures of 0.8–1.0 GPa, was rapidly exhumed in the Eocene (Whitney, 1992; Gordon et al., 2010; Miller et al., 2016). Such rapid exhumation may be related to Siletzia’s accretion, triple-junction migration, and the strike-slip faulting that formed the Chumstick basin.

Mileage	Description
24.6	Continue on NF-7520.
25.1	Continue on NF-7520 around sharp bend in the road.
25.7	Merge onto NF-7801 at sharp right bend in the road and continue for 0.4 miles to intersection of NF-7801 and Entiat Summit Road.
26.1	Park for Stop 3.4. Toilets are available at this stop.

Stop 3.4. Entiat Fault and Chumstick Basin Overview (47.7066° N, 120.5144° W)

This stop highlights a nice view across the Chumstick basin to the west. In the distance, the high topography is underlain by

Mileage	Description
26.1	Turn cars around and drive back down NF-7801.
26.5	Merge onto NF-7520 at sharp left bend in the road and retrace earlier route on NF-7520 toward Eagle Creek Road.
31.8	Turn right onto Eagle Creek Road.
37.6	Arrive at intersection of Eagle Creek Road and the Chumstick Highway and turn left.
39.7	Turn left onto U.S. 2 East.
54.5	Turn off of U.S. 2 E onto East Main Street/Easy Street and continue for 2.3 miles.
56.8	Park at southern end of outcrop for Stop 3.5.

Stop 3.5. Stream and Lake Deposits in the Nahahum Canyon Member of the Chumstick Formation (47.4777° N, 120.3704° W)

Our final stop is one of the type sections for the Nahahum Canyon Member of the Chumstick Formation (Gresens et al., 1981; Evans, 1994). It was described in detail as Stop 11 in Evans and Johnson (1989) and we only summarize their description here. The outcrop consists of sandy channel deposits, dunes, and turbidite sequences (Gresens et al., 1981; Evans, 1994). Paleocurrent indicators suggest that these beds formed part of a delta where the basin-axial drainage system within the eastern Chumstick sub-basin emptied into a lake (Evans, 1994).

Mileage	Description
56.8	Turn car around and head north on East Main Street/Easy Street.
57.0	Turn left on Sunnyslope Road.
57.2	Turn right onto U.S. 2 West. From here the trip returns to Seattle via U.S. 2 or back through Cle Elum and I-90, depending on traffic conditions.

End of road log.

ACKNOWLEDGMENTS

This field guide leans heavily on prior research done on the Paleogene sedimentary and volcanic rocks throughout central Washington, including numerous doctoral, master's, and undergraduate theses. We thank our colleague Sam Bowring for his many contributions to our research in the North Cascades. Funding for our projects in this part of the North Cascades has come from National Science Foundation grants EAR-0511062 and EAR-1119358 to R.B. Miller, EAR-1119063 to P.J. Umhoefer, and EAR-0510591 and EAR-1118883 to S.A. Bowring. This manuscript benefited from thoughtful reviews by Jim Evans and Becky Dorsey, as well as the editorial handling of Ralph Haugerud.

REFERENCES CITED

- Agué, J.J., and Brandon, M.T., 1996, Regional tilt of the Mount Stuart batholith, Washington, determined using aluminum-in-hornblende barometry: Implications for northward translation of Baja British Columbia: Geological Society of America Bulletin, v. 108, p. 471–488, doi:10.1130/0016-7606(1996)108<0471:RTOTMS>2.3.CO;2.
- Atwater, T., 1970, Implications of plate tectonics for the Cenozoic tectonic evolution of North America: Geological Society of America Bulletin, v. 81, p. 3513–3536, doi:10.1130/0016-7606(1970)81[3513:IOPTFT]2.0.CO;2.
- Babcock, R.S., Burmester, R.R., Engebretson, D.C., Warnock, A.C., and Clark, K.P., 1992, A rifted margin origin for the Crescent basalts and related rocks in the northern Coast Range Volcanic Province, Washington and British Columbia: Journal of Geophysical Research, v. 97, p. 6799–6821, doi:10.1029/91JB02926.
- Babcock, R.S., Suczek, C.A., and Engebretson, D.C., 1994, The Crescent “Terrane,” Olympic Peninsula and Southern Vancouver Island: Washington Division of Geology and Earth Resources Bulletin, v. 80, p. 141–157.
- Barnett, D.B., 1985, A paleoenvironmental reconstruction of the upper Roslyn Formation, central Washington, with implications for coal exploration [M.S. thesis]: Cheney, Washington, Eastern Washington University, 334 p.
- Bol, A.J., Coe, R.S., Gromme, C.S., and Hillhouse, J.W., 1992, Paleomagnetism of the Resurrection Peninsula, Alaska: Implications for the tectonics of southern Alaska and the Kula-Farallon ridge: Journal of Geophysical Research, v. 97, p. 17,213–17,232, doi:10.1029/92JB01292.
- Bradley, D.C., Haeussler, P.J., and Kusky, T.M., 1993, Timing of early Tertiary ridge subduction in southern Alaska, in Dusel-Bacon, Cynthia, and Till, A.B., eds., Geologic Studies in Alaska by the U.S. Geological Survey: U.S. Geological Survey Bulletin 2068, p. 163–177.
- Bradley, D.C., Parrish, R., Clendenen, W., Lux, D., Layer, P.W., Heizler, M., and Donley, D.T., 2000, New geochronological evidence for the timing of early Tertiary ridge subduction in southern Alaska, in Kelley, K.D., and Gough, L.P., eds., Geologic Studies in Alaska by the U.S. Geological Survey, 1998: U.S. Geological Survey Professional Paper 1615, p. 5–21.
- Brandon, M.T., Hourigan, J., and Garver, J.I., 2014, New evidence for backarc basin interpretation for Eocene Coast Range terrane: Geological Society of America Abstracts with Programs, v. 46, no. 6, p. 657.
- Breedlovestrout, R.L., Evraets, B.J., and Totman Parrish, J., 2013, New Paleogene paleoclimate analysis of western Washington using physiognomic characteristics from fossil leaves: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 392, p. 22–40, doi:10.1016/j.palaeo.2013.08.013.
- Breitsprecher, K., Thorkelson, D.J., Groome, W.G., and Dostal, J., 2003, Geochemical confirmation of the Kula-Farallon slab window beneath the Pacific Northwest in Eocene time: Geology, v. 31, p. 351–354, doi:10.1130/0091-7613(2003)031<0351:GCOTKF>2.0.CO;2.
- Brown, E.H., 1987, Structural geology and accretionary history of the Northwest Cascades system, Washington and British Columbia: Geological Society of America Bulletin, v. 99, p. 201–214, doi:10.1130/0016-7606(1987)99<201:SGAAHO>2.0.CO;2.
- Buckovic, W.A., 1979, The Eocene deltaic system of west-central Washington, in Armentrout, J.M., Cole, M.R., and TerBest, H., eds., Cenozoic Paleogeography of the Western United States: Society of Economic Paleontologists and Mineralogists, Pacific Coast Section, Pacific Coast Paleogeography Symposium 3, p. 147–164.
- Cashman, S.M., and Whetten, J.T., 1976, Low-temperature serpentinization of peridotite fanglomerates on the west margin of the Chiwaukum graben, Washington: Geological Society of America Bulletin, v. 87, p. 1773–1776, doi:10.1130/0016-7606(1976)87<1773:LSOPFO>2.0.CO;2.
- Cheney, E.S., 1994, Cenozoic unconformity-bounded sequences of central and eastern Washington: Washington Division of Geology and Earth Resources Bulletin 80, p. 115–139.
- Cheney, E.S., 2003, Regional Tertiary sequence stratigraphy and regional structure on the eastern flank of the central Cascade Range, Washington, in Swanson, T.W., ed., Western Cordillera and Adjacent Areas: Geological Society of America Field Guide 4, p. 177–199, doi:10.1130/0-8137-0004-3.177.
- Cheney, E.S., and Hayman, N.W., 2007, Regional Tertiary sequence stratigraphy and structure on the eastern flank of the central Cascade Range, Washington, in Stelling, P., and Tucker, D., eds., Floods, Faults, and Fire: Geological Field Trips in Washington State and Southwest British Columbia: Geological Society of America Field Guide 9, p. 179–208, doi:10.1130/2007.fl.d009(09).
- Cheney, E.S., and Hayman, N.W., 2009a, The Chiwaukum structural low: Cenozoic shortening of the central Cascade Range, Washington State, USA: Geological Society of America Bulletin, v. 121, p. 1135–1153, doi:10.1130/B26446.1.
- Cheney, E.S., and Hayman, N.W., 2009b, The Chiwaukum structural low, eastern Cascade Range, Washington, in O'Connor, J.E., Dorsey, R.J., and Madin, I.P., eds., Volcanoes to Vineyards: Geologic Field Trips through the Dynamic Landscape of the Pacific Northwest: Geological Society of America Field Guide 15, p. 19–52, doi:10.1130/2009.fld015(02).
- Clark, K.P., 1989, The stratigraphy and geochemistry of the Crescent Formation basalts and the bedrock geology of associated igneous rocks near Bremerton, Washington [M.S. thesis]: Bellingham, Washington, Western Washington University, 171 p.
- Clayton, D.N., 1973, Volcanic history of the Teanaway Basalt, east-central Cascade Mountains, Washington [M.S. thesis]: Seattle, University of Washington, 55 p.
- Cloos, M., 1993, Lithospheric buoyancy and collisional orogenesis: Subduction of orogenic plateaus, continental margins, island arcs, spreading ridges,

- and seamounts: Geological Society of America Bulletin, v. 105, p. 715–737, doi:10.1130/0016-7606(1993)105<0715:LBACOS>2.3.CO;2.
- Cowan, D.S., 2003, Revisiting the Baranof–Leech River hypothesis for early Tertiary coastwise transport of the Chugach–Prince William terrane: Earth and Planetary Science Letters, v. 213, p. 463–475, doi:10.1016/S0012-821X(03)00300-5.
- Davis, A.S., and Plafker, G., 1986, Eocene basalts from the Yakutat terrane: Evidence for the origin of an accreting terrane in southern Alaska: Geology, v. 14, p. 963–966, doi:10.1130/0091-7613(1986)14<963:EBFTYT>2.0.CO;2.
- Donaghy, E.E., 2015, Structure, stratigraphy, and provenance of Eocene sedimentary rocks in the Chumstick basin, central Washington [M.S. thesis]: Flagstaff, Arizona, Northern Arizona University, 236 p.
- Doran, B.A., 2009, Structure of the Swauk formation and Teanaway dike swarm, Washington Cascades [M.S. thesis]: San Jose, California, San Jose State University, 97 p.
- Dragovich, J.D., Logan, R.L., Schasse, H.W., Walsh, T.J., Lingley, W.S., Jr., Norman, D.K., Gerstel, W.J., Lapen, T.J., Schuster, E., and Meyers, K.D., 2002, Geologic Map of Washington–Northwest Quadrant: Washington Department of Natural Resources Geologic Map GM-50, scale 1:250,000, 3 sheets, 72 p. text.
- Dragovich, J.D., Littke, H.A., Anderson, M.L., Hartog, R., Wessel, G.R., DuFrane, S.A., Walsh, T.J., MacDonald, J.H., Jr., Mangano, J.F., and Cakir, R., 2009, Geologic Map of the Snoqualmie 7.5-Minute Quadrangle, King County, Washington: Washington Division of Geology and Earth Resources Geologic Map GM-75, scale 1:24,000, 2 sheets.
- Dragovich, J.D., Anderson, M.L., Mahan, S.A., Koger, C.J., Saltonstall, J.H., MacDonald, J.H., Jr., Wessel, G.R., Stoker, B.A., Bethel, J.P., Labadie, J.E., Cakir, R., Bowman, J.D., and DuFrane, S.A., 2011, Geologic Map of the Monroe 7.5-Minute Quadrangle, King and Snohomish Counties, Washington: Washington Division of Geology and Earth Resources Open File Report 2011-1, scale 1:24,000, 1 sheet, 24 p. text.
- Dragovich, J.D., Littke, H.A., Mahan, S.A., Anderson, M.L., MacDonald, J.H., Jr., Cakir, R., Stoker, B.A., Koger, C.J., Bethel, J.P., DuFrane, S.A., Smith, D.T., and Villeneuve, N.M., 2013, Geologic Map of the Sultan 7.5-Minute Quadrangle, King and Snohomish Counties, Washington: Washington Division of Geology and Earth Resources Map 2013-01, scale 1:24,000, 1 sheet, 52 p. text.
- Dragovich, J.D., Mavor, S.P., Anderson, M.L., Mahan, S.A., MacDonald, J.H., Jr., Tepper, J.H., Smith, D.T., Stoker, B.A., Koger, C.J., Cakir, R., DuFrane, S.A., Scott, S.P., and Justman, B.P., 2016, Geologic Map of the Granite Falls 7.5-Minute Quadrangle, Snohomish County, Washington: Washington Division of Geology and Earth Resources Map 2016-03, scale 1:24,000, 1 sheet, 63 p. text.
- Duncan, R.A., 1982, A captured island chain in the coast range of Oregon and Washington: Journal of Geophysical Research, v. 87, p. 10,827–10,837, doi:10.1029/JB087iB13p10827.
- Eddy, M.P., Bowring, S.A., Umhoefer, P.J., Miller, R.B., McLean, N.M., and Donaghy, E.E., 2016, High-resolution temporal and stratigraphic record of Siletzia's accretion and triple junction migration from non-marine sedimentary basins in central and western Washington: Geological Society of America Bulletin, v. 128, p. 425–441, doi:10.1130/B31335.1.
- Eddy, M.P., Clark, K.P., and Polenz, M., 2017, Age and volcanic stratigraphy of the Eocene Siletzia oceanic plateau in Washington and Vancouver Island: Lithosphere, v. 9, p. 652–664, doi:10.1130/L650.1.
- Einarsen, J.M., 1987, The petrography and tectonic significance of the Blue Mountain Unit, Olympic Peninsula, Washington [M.S. thesis]: Bellingham, Washington, Western Washington University, 175 p.
- Engelbreton, D.C., Cox, A., and Gordon, R.G., 1985, Relative Motions between Oceanic and Continental Plates in the Pacific Basin: Geological Society of America Special Paper 206, 60 p., doi:10.1130/SPE206-p1.
- Evans, J.E., 1994, Depositional history of the Eocene Chumstick Formation: Implications of tectonic partitioning for the history for the Leavenworth and Entiat–Eagle Creek fault systems, Washington: Tectonics, v. 13, p. 1425–1444, doi:10.1029/94TC01321.
- Evans, J.E., 1996, Depositional history of the Eocene Chumstick Formation: Implications of tectonic partitioning for the history of the Leavenworth and Entiat–Eagle Creek fault systems, Washington: Reply: Tectonics, v. 15, p. 510–514, doi:10.1029/95TC03695.
- Evans, J.E., and Johnson, S.Y., 1989, Paleogene strike-slip basins of central Washington: Swauk Formation and Chumstick Formation, in Joseph, N.L., Stoffel, K.L., Evans, J.G., Kiilsgaard, T.H., Korosec, M.A., Logan, R.L., Miller, F.K., Phillips, W.M., Powell, R.E., Schasse, H.W., Schuster, J.E., Waggoner, S.X., Walsh, T.J., and Whipple, J.W., eds., Geologic Guidebook for Washington and Adjacent Areas: Washington Division of Geology and Earth Resources Information Circular 86, p. 213–238.
- Evans, J.E., and Ristow, R.J., Jr., 1994, Depositional history of the southeastern outcrop belt of the Chuckanut Formation: Implications for the Darrington–Devils Mountain and Straight Creek fault zones, Washington (USA): Canadian Journal of Earth Sciences, v. 31, p. 1727–1743, doi:10.1139/e94-154.
- Finzel, E.S., Trop, J.M., Ridgway, K.D., and Enkelmann, E., 2011, Upper plate proxies for flat-slab subduction processes in southern Alaska: Earth and Planetary Science Letters, v. 303, p. 348–360, doi:10.1016/j.epsl.2011.01.014.
- Foster, R.J., 1958, The Teanaway dike swarm of central Washington: American Journal of Science, v. 256, p. 644–653, doi:10.2475/ajs.256.9.644.
- Foster, R.J., 1960, Tertiary geology of a portion of the central Cascade mountains, Washington: Geological Society of America Bulletin, v. 71, p. 99–126, doi:10.1130/0016-7606(1960)71[99:TGOAPO]2.0.CO;2.
- Frizzell, V.A., Jr., 1979, Petrology and Stratigraphy of Paleogene Nonmarine Sandstones, Cascade Range, Washington: U.S. Geological Survey Open-File Report 79-1149, 151 p.
- Gao, H., Humphreys, E.D., Yao, H., and van der Hilst, R.D., 2011, Crust and lithosphere structure of northwestern U.S. with ambient noise tomography: Terrane accretion and Cascade arc development: Earth and Planetary Science Letters, v. 304, p. 202–211, doi:10.1016/j.epsl.2011.01.033.
- Gatewood, M.P., and Stowell, H.H., 2012, Linking zircon U-Pb and garnet Sm-Nd ages to date loading and metamorphism in the lower crust of a Cretaceous magmatic arc, Swakane Gneiss, WA, USA: Lithos, v. 146–147, p. 128–142, doi:10.1016/j.lithos.2012.04.030.
- Gilmour, L.A., 2012, U/Pb ages of Eocene and younger rocks on the eastern flank of the central Cascade Range, Washington, USA [M.S. thesis]: Seattle, University of Washington, 48 p.
- Gordon, S.M., Whitney, D.L., Teyssier, C., Grove, M., and Dunlap, W.J., 2008, Timescales of migmatization, melt crystallization, and cooling in a Cordilleran gneiss dome: Valhalla complex, southeastern British Columbia: Tectonics, v. 27, TC4010, doi:10.1029/2007TC002103.
- Gordon, S.M., Bowring, S.A., Whitney, D.L., Miller, R.B., and McLean, N., 2010, Timescales of metamorphism, deformation, and crustal melting in a continental arc, North Cascades, USA: Geological Society of America Bulletin, v. 122, p. 1308–1330, doi:10.1130/B30060.1.
- Gresens, R.L., Naeser, C.W., and Whetten, J.W., 1981, Stratigraphy and age of the Chumstick and Wenatchee Formations: Tertiary fluvial and lacustrine rocks, Chiwaukum graben, Washington: Geological Society of America Bulletin, v. 92, p. 841–876, doi:10.1130/GSAB-P2-92-841.
- Groome, W.G., Thorkelson, D.J., Friedman, R.M., Mortensen, J.K., Massey, N.W.D., Marshall, D.D., and Layer, P.W., 2003, Magmatic and tectonic history of the Leech River Complex, Vancouver Island, British Columbia: Evidence for ridge-trench intersection and accretion of the Crescent terrane, in Sisson, V.B., Roeske, S.M., and Pavlis, T.L., eds., Geology of a Transpressional Orogen Developed during Ridge-Trench Interaction along the North Pacific Margin: Geological Society of America Special Paper 371, p. 327–353, doi:10.1130/0-8137-2371-X.327.
- Gundersen, M., 2017, A record of the evolving Eocene tectonics of the Pacific Northwest in the Swauk Formation, central Washington [M.S. thesis]: Flagstaff, Arizona, Northern Arizona University, 216 p.
- Haeussler, P.J., Bradley, D.C., Wells, R.E., and Miller, M.L., 2003, Life and death of the Resurrection plate: Evidence for its existence and subduction in the northeastern Pacific in Paleocene-Eocene time: Geological Society of America Bulletin, v. 115, p. 867–880, doi:10.1130/0016-7606(2003)115<0867:LADOTR>2.0.CO;2.
- Haugerud, R.A., Van der Heyden, P., Tabor, R.W., Stacey, J.S., and Zartman, R.E., 1991, Late Cretaceous and early Tertiary plutonism and deformation in the Skagit Gneiss Complex, North Cascade Range, Washington and British Columbia: Geological Society of America Bulletin, v. 103, p. 1297–1307, doi:10.1130/0016-7606(1991)103<1297:LCAETP>2.3.CO;2.
- Hirth, G., and Tullis, J., 1992, Dislocation creep regimes in quartz aggregates: Journal of Structural Geology, v. 14, p. 145–159, doi:10.1016/0191-8141(92)90053-Y.
- Humphreys, E., 2009, Relation of flat subduction to magmatism and deformation in the western United States, in Kay, S.M., Ramos, V.A., and Dickinson, W.R., eds., Backbone of the Americas: Shallow Subduction, Plateau

- Uplift, and Ridge and Terrane Collision: Geological Society of America Memoir 204, p. 85–98, doi:10.1130/2009.1204(04).
- Ickert, R.B., Thorkelson, D.J., Marshall, D.D., and Ullrich, T.D., 2009, Eocene adakitic volcanism in southern British Columbia: Remelting of arc basalt above a slab window: *Tectonophysics*, v. 464, p. 164–185, doi:10.1016/j.tecto.2007.10.007.
- Irving, E., and Brandon, M.T., 1990, Paleomagnetism of the Flores volcanics, Vancouver Island, in place by Eocene time: *Canadian Journal of Earth Sciences*, v. 27, p. 811–817, doi:10.1139/e90-083.
- Ivener, D., and Tepper, J.H., 2013, Petrology and Eruptive Styles of Central WA Teanaway Basalt: Uplift and bimodal volcanism in subsiding Eocene basin: Abstract V33E-2832 presented at 2013 Fall Meeting, AGU, San Francisco, California, 9–13 December.
- Johnson, S.Y., 1984, Stratigraphy, age, and paleogeography of the Eocene Chuckanut Formation, northwest Washington: *Canadian Journal of Earth Sciences*, v. 21, p. 92–106, doi:10.1139/e84-010.
- Johnson, S.Y., 1985, Eocene strike-slip faulting and nonmarine basin formation in Washington, *in* Biddle, K.T., and Christie-Blick, N., eds., *Strike-Slip Deformation, Basin Formation and Sedimentation*: Society of Economic Paleontologists and Mineralogists, Special Publication 37, p. 283–302, doi:10.2110/pec.85.37.0283.
- Johnson, S.Y., 1996, Depositional history of the Eocene Chumstick Formation: Implications of tectonic partitioning for the history of the Entiat–Eagle Creek fault systems, Washington: Comment: *Tectonics*, v. 15, p. 506–509, doi:10.1029/95TC03694.
- Johnson, S.Y., and Miller, R.B., 1987, Ingalls tectonic complex and Swauk Formation, Ruby Creek area, Cascade Mountains, Washington, *in* Hill, M.L., ed., *Cordilleran Section of the Geological Society of America*: Boulder, Colorado, Geological Society of America, Centennial Field Guide 1, p. 363–368.
- Johnson, S.Y., and O'Connor, J.T., 1994, Stratigraphy, sedimentology, and provenance of the Raging River Formation (early? and middle Eocene), King County, Washington: U.S. Geological Survey Bulletin v. 2085-A, p. A1–A33.
- Johnston, S.T., and Acton, S., 2003, The Eocene southern Vancouver Island oroclinal—A response to seamount accretion and the cause of fold-and-thrust belt and extensional basin formation: *Tectonophysics*, v. 365, p. 165–183, doi:10.1016/S0040-1951(03)00021-0.
- Kruckenberger, S.C., Whitney, D.L., Teyssier, C., Fanning, C.M., and Dunlap, W.J., 2008, Paleocene-Eocene migmatite crystallization, extension, and exhumation in the hinterland of the northern Cordillera: Okanogan dome, Washington, USA: *Geological Society of America Bulletin*, v. 120, p. 912–929, doi:10.1130/B26153.1.
- Kusky, T.M., Bradley, D.C., Donely, D.T., Rowley, D., and Haeussler, P.J., 2003, Controls on intrusion of near-trench magmas of the Sanak-Baranof Belt, Alaska, during Paleogene ridge subduction, and consequences for forearc evolution, *in* Sisson, V.B., Roeske, S.M., and Pavlis, T.L., eds., *Geology of a Transpressional Orogen Developed during Ridge-Trench Interaction along the North Pacific Margin*: Geological Society of America Special Paper 371, p. 269–292, doi:10.1130/0-8137-2371-X.269.
- LaCasse, T.J., 2013, Using a coarse-grained conglomerate to investigate lateral offset along the Leavenworth fault zone, North Cascades, Washington [Undergraduate thesis]: Northfield, Minnesota, Carleton College, 40 p.
- Laravie, J.A., 1976, Geologic field studies along the eastern border of the Chiwaukum graben, central Washington [M.S. thesis]: Seattle, University of Washington, 55 p.
- MacDonald, J.H., Jr., Dragovich, J.D., Littke, H.A., Anderson, M., and Dufrene, A.S., 2013, The volcanic rocks of Mount Persis: An Eocene continental arc that contains adakitic magmas: *Geological Society of America Abstracts with Programs*, v. 45, no. 7, p. 392.
- Madsen, J.K., Thorkelson, D.J., Friedman, R.M., and Marshall, D.D., 2006, Cenozoic to Recent plate configurations in the Pacific basin: Ridge subduction and slab window magmatism in western North America: *Geosphere*, v. 2, p. 11–34, doi:10.1130/GES00020.1.
- Massey, N.W.D., 1986, Metchosin igneous complex, southern Vancouver Island: Ophiolite stratigraphy developed in an emergent island setting: *Geology*, v. 14, p. 602–605, doi:10.1130/0091-7613(1986)14<602:MICSVI>2.0.CO;2.
- Massey, N.W., MacIntyre, D.G., Desjardins, P.J., and Cooney, R.T., 2005, *Geology of British Columbia*: B.C. Ministry of Energy, Mines, and Petroleum Resources Geoscience Map 2005-3, scale 1:1,000,000, 3 sheets.
- Matzel, J.E.P., 2004, Rates of tectonic and magmatic processes in the North Cascades continental magmatic arc [Ph.D. thesis]: Cambridge, Massachusetts Institute of Technology, 249 p.
- Matzel, J.E.P., Bowring, S.A., and Miller, R.B., 2004, Protolith age of the Swakane Gneiss, North Cascades, Washington: Evidence of rapid underthrusting of sediments beneath an arc: *Tectonics*, v. 23, TC6009, doi:10.1029/2003TC001577.
- Matzel, J.E.P., Bowring, S.A., and Miller, R.B., 2006, Time scales of pluton construction at differing crustal levels: Examples from the Mount Stuart and Tenpeak intrusions, North Cascades, Washington: *Geological Society of America Bulletin*, v. 118, p. 1412–1430, doi:10.1130/B25923.1.
- McClincy, M.J., 1986, Tephrostratigraphy of the Middle Eocene Chumstick Formation, Cascade Range, Douglas County, Washington [M.S. thesis]: Portland, Oregon, Portland State University, 254 p.
- McCrorry, P.A., and Wilson, D.S., 2013, A kinematic model for the formation of the Siletz-Crescent forearc terrane by capture of coherent fragments of the Farallon and Resurrection plates: *Tectonics*, v. 32, p. 718–736, doi:10.1002/tect.20045.
- Mendoza, M.K., 2008, Tectonic implications of Eocene Teanaway dike swarm in the eastern Swauk basin, central Washington: *Geological Society of America Abstracts with Programs*, v. 40, no. 1, p. 66.
- Miller, R.B., and Bowring, S.A., 1990, Structure and chronology of the Oval Peak batholith and adjacent rocks: Implications for the Ross Lake fault zone, North Cascades, Washington: *Geological Society of America Bulletin*, v. 102, p. 1361–1377, doi:10.1130/0016-7606(1990)102<1361:SACOTO>2.3.CO;2.
- Miller, R.B., Gordon, S.M., Bowring, S.A., Doran, B.A., McLean, N.M., Michels, Z.D., Shea, E.K., Whitney, D.L., Wintzer, N.E., and Mendoza, M.K., 2009, Linking deep and shallow crustal processes in an exhumed continental arc, North Cascades, Washington, *in* O'Connor, J.E., Dorsey, R.J., and Madin, I.P., eds., *Volcanoes to Vineyards: Geologic Field Trips through the Dynamic Landscape of the Pacific Northwest*: Geological Society of America Field Guide 15, p. 373–406, doi:10.1130/2009.fld015(19).
- Miller, R.B., Gordon, S.M., Bowring, S.A., Doran, B., McLean, N.M., Michels, Z., Shea, E., and Whitney, D.L., 2016, Linking deep and shallow crustal processes during regional transtension in an exhumed continental arc, North Cascades, northwestern Cordillera (USA): *Geosphere*, v. 12, p. 900–924, doi:10.1130/GES01262.1.
- Misch, P., 1966, Tectonic evolution of the northern Cascades of Washington State—A west Cordilleran case history: *Canadian Institute of Mining and Metallurgy*, v. 8, p. 101–148.
- Murphy, J.B., 2016, The role of the ancestral Yellowstone plume in the tectonic evolution of the western United States: *Geoscience Canada*, v. 43, p. 231–250, doi:10.12789/geocanj.2016.43.105.
- Murphy, J.B., Hynes, A.J., Johnston, S.T., and Keppie, J.D., 2003, Reconstructing the ancestral Yellowstone plume from accreted seamounts and its relationship to flat-slab subduction: *Tectonophysics*, v. 365, p. 185–194, doi:10.1016/S0040-1951(03)00022-2.
- Mustoe, G.E., Dillhoff, R.M., and Dillhoff, T.A., 2007, Geology and paleontology of the early Tertiary Chuckanut Formation, *in* Stelling, P., and Tucker, D.S., eds., *Floods, Faults, and Fire: Geological Field Trips in Washington State and Southwest British Columbia*: Geological Society of America Field Guide 9, p. 121–135, doi:10.1130/2007.
- O'Connell, K., 2009, Sedimentology, structural geology, and paleomagnetism of the Ghost Rocks Formation: Kodiak Islands, Alaska [M.S. thesis]: Davis, California, University of California, 112 p.
- Ott, L.E., 1988, Economic Geology of the Wenatchee Mining District, Chelan County, Washington [Ph.D. thesis]: Moscow, Idaho, University of Idaho, 270 p.
- Paterson, S.R., Miller, R.B., Alsleben, H., Whitney, D.L., Valley, P.M., and Hurlow, H., 2004, Driving mechanisms for >40 km of exhumation during contraction and extension in a continental arc, Cascades core, Washington: *Tectonics*, v. 23, TC3005, doi:10.1029/2002TC001440.
- Pence, J.E., and Miller, R.B., 2015, Structural analysis and evolution of the Entiat fault zone, a major Eocene structure of the North Cascades, Washington: *Geological Society of America Abstracts with Programs*, v. 47, no. 4, p. 59.
- Phillips, B.A., Kerr, A.C., Mullen, E.K., and Weis, D., 2017, Oceanic mafic magmatism in the Siletz terrane, NW North America: Fragments of an Eocene oceanic plateau: *Lithos*, v. 274–275, p. 291–303, doi:10.1016/j.lithos.2017.01.005.

- Plumley, P.W., Coe, R.S., and Byrne, T., 1983, Paleomagnetism of the Paleocene Ghost Rocks Formation, Prince William Terrane, Alaska: *Tectonics*, v. 2, p. 295–314, doi:10.1029/TC002i003p00295.
- Pyle, D.G., Duncan, R.A., Wells, R.E., Graham, D.W., Harrison, B.K., and Hanan, B.B., 2009, Siletzia: An oceanic large igneous province in the Pacific Northwest: Geological Society of America Abstracts with Programs, v. 41, no. 7, p. 369.
- Pyle, D.G., Duncan, R.A., Wells, R.E., Graham, D.W., Hanan, B.B., Harrison, B.K., and Haileab, B., 2015, Longevity of Yellowstone hotspot volcanism: Isotopic evidence linking the Siletzia LIP (56 Ma) and early Columbia River Basalt Group (17 Ma) mantle sources: Abstract V31E-3060 presented at 2015 Fall Meeting, AGU, San Francisco, California, 14–18 December.
- Schmandt, B., and Humphreys, E., 2011, Seismically imaged relict slab from the 55 Ma Siletzia accretion to the northwest United States: *Geology*, v. 39, p. 175–178, doi:10.1130/G31558.1.
- Schuster, J.E., Gulick, C.W., Reidel, S.P., Fecht, K.R., and Zurenko, S., 1997, Geologic Map of Washington–Northeast Quadrant: Washington Division of Geology and Earth Resources Geologic Map GM-45, scale 1:250,000, 2 sheets, 20 p. text.
- Senes, F.I., Miller, R.B., and Umhoefer, P.J., 2015, Deformation in and near the Eocene Leavenworth fault zone, North Cascades, Washington: Geological Society of America Abstracts with Programs, v. 47, no. 4, p. 60.
- Sisson, V.B., Hollister, L.S., and Onstott, T.C., 1989, Petrologic and age constraints on the origin of a low-pressure/high-temperature metamorphic complex, southern Alaska: *Journal of Geophysical Research*, v. 94, p. 4392–4410, doi:10.1029/JB094iB04p04392.
- Sisson, V.B., Pavlis, T.L., Roeske, S.M., and Thorkelson, D.J., 2003, Introduction: An overview of ridge-trench interactions in modern and ancient settings, in Sisson, V.B., Roeske, S.M., and Pavlis, T.L., eds., *Geology of a Transpressional Orogen Developed during Ridge-Trench Interaction along the North Pacific Margin*: Geological Society of America Special Paper 371, p. 1–18, doi:10.1130/0-8137-2371-X.1.
- Smith, G.O., 1904, Mount Stuart Folio: U.S. Geological Survey Geologic Atlas of the United States Folio GF-106, scale 1:125,000, 4 sheets, 10 p. text.
- Stock, J., and Molnar, P., 1988, Uncertainties and implications of the Late Cretaceous and Tertiary position of North America relative to the Farallon, Kula, and Pacific plates: *Tectonics*, v. 7, p. 1339–1384, doi:10.1029/TC007i006p01339.
- Stoffel, K.L., Joseph, N.L., Waggoner, S.Z., Gulick, C.W., Korosec, M.A., and Bunning, B.B., 1991, Geologic Map of Washington—Northeast Quadrant: Washington Division of Geology and Earth Resources Geologic Map GM-39, scale 1:250,000, 3 sheets, 36 p. text.
- Tabor, R.W., 1994, Late Mesozoic and possible early Tertiary accretion in western Washington state: The Helena-Haystack mélange and the Darrington-Devils Mountain fault zone: Geological Society of America Bulletin, v. 106, p. 217–232, doi:10.1130/0016-7606(1994)106<0217:LMAPET>2.3.CO;2.
- Tabor, R.W., Waitt, R.B., Jr., Frizzell, V.A., Jr., Swanson, D.A., Byerly, G.R., and Bentley, R.D., 1982, Geologic Map of the Wenatchee 1:100,000 Quadrangle, Central Washington: U.S. Geological Survey Miscellaneous Investigations Series I-1311, scale 1:100,000, 1 sheet, 26 p. text.
- Tabor, R.W., Frizzell, V.A., Jr., Vance, J.A., and Naeser, C.W., 1984, Ages and stratigraphy of lower and middle Tertiary sedimentary and volcanic rocks of the central Cascades: Application to the tectonic history of the Straight Creek fault: Geological Society of America Bulletin, v. 95, p. 26–44, doi:10.1130/0016-7606(1984)95<26:AASOLA>2.0.CO;2.
- Tabor, R.W., Frizzell, V.A., Jr., Whetten, J.R., Waitt, R.B., Swanson, D.A., Byerly, G.R., Booth, D.B., Hetherington, M.J., and Zartman, R.E., 1987, Geologic Map of the Chelan 30-Minute by 60-Minute Quadrangle, Washington: U.S. Geological Survey Miscellaneous Investigations Series I-1661, scale 1:100,000, 1 sheet, 29 p. text.
- Tabor, R.W., Frizzell, V.A., Booth, D.B., Waitt, R.B., Whetten, J.T., and Zartman, R.E., 1993, Geologic Map of the Skykomish River 30- by 60-Minute Quadrangle, Washington: U.S. Geological Survey Miscellaneous Investigations Series I-1963, scale 1:100,000, 1 sheet, 42 p. text.
- Tabor, R.W., Frizzell, V.A., Jr., Booth, D.B., and Waitt, R.B., 2000, Geologic Map of the Snoqualmie Pass 30' × 60's Minute Quadrangle, Washington: U.S. Geological Survey Geologic Investigations Series I-2538, scale 1:100,000, 1 sheet, 57 p. text.
- Tabor, R.W., Booth, D.B., Vance, J.A., and Ford, A.B., 2002, Geologic Map of the Sauk River 30- by 60-Minute Quadrangle, Washington: U.S. Geological Survey Geologic Investigations Series I-2592, scale 1:100,000, 2 sheets, 67 p. text.
- Tabor, R.W., Haugerud, R.A., Hildreth, W., and Brown, E.H., 2003, Geologic Map of the Mount Baker 30' × 60' Quadrangle, Washington: U.S. Geological Survey Geologic Investigations Series I-2660, scale 1:100,000, 2 sheets, 73 p. text.
- Taylor, S.B., Johnson, S.Y., Fraser, G.T., and Roberts, J.W., 1988, Sedimentation and tectonics of the lower and middle Eocene Swauk Formation in the eastern Swauk basin, central Cascades, central Washington: *Canadian Journal of Earth Sciences*, v. 25, p. 1020–1036, doi:10.1139/e88-100.
- Tepper, J.H., 2016, Eocene breakoff and rollback of the Farallon slab—An explanation for the “Challis event”? Geological Society of America Abstracts with Programs, v. 48, no. 4, doi:10.1130/abs/2016CD-274512.
- Tepper, J.H., Clark, K., Asmerom, Y., and McIntosh, W., 2004, Eocene adakites in the Cascadia forearc: Implications for the position of the Kula-Farallon ridge: Geological Society of America Abstracts with Programs, v. 36, no. 4, p. 69.
- Tepper, J.H., Nelson, B.K., Clark, K., and Barnes, R.P., 2008, Heterogeneity in mantle sources for Eocene basalts in Washington: Trace element and Sr-Nd isotopic evidence from the Crescent and Teanaway basalts: Abstract V41D-2121, 2008 Fall Meeting, AGU, San Francisco, California, 15–19 December.
- Thorkelson, D.J., 1996, Subduction of diverging plates and the principles of slab window formation: *Tectonophysics*, v. 255, p. 47–63, doi:10.1016/0040-1951(95)00106-9.
- Trehu, A.M., Asudeh, I., Brocher, T.M., Luetgert, J.H., Mooney, W.D., Nabelek, J.L., and Nakamura, Y., 1994, Crustal architecture of the Cascadia forearc: *Science*, v. 266, p. 237–243, doi:10.1126/science.266.5183.237.
- Trop, J.M., Ridgeway, K.D., and Spell, T.L., 2003, Sedimentary record of transpressional tectonics and ridge-subduction in the Tertiary Matanuska Valley–Talkeetna Mountains forearc basin, southern Alaska, in Sisson, V.B., Roeske, S.M., and Pavlis, T.L., eds., *Geology of a Transpressional Orogen Developed during Ridge-Trench Interaction along the North Pacific Margin*: Geological Society of America Special Paper 371, p. 89–118, doi:10.1130/0-8137-2371-X.89.
- Umhoefer, P.J., and Miller, R.B., 1996, Mid-Cretaceous thrusting in the southern Coast Belt, British Columbia and Washington, after strike-slip fault reconstruction: *Tectonics*, v. 15, p. 545–565, doi:10.1029/95TC03498.
- Valley, P.M., Whitney, D.L., Paterson, S.R., Miller, R.B., and Alsleben, H., 2003, Metamorphism of the deepest exposed arc rocks in the Cretaceous to Paleogene Cascades belt, Washington: Evidence for large-scale vertical motion in a continental arc: *Journal of Metamorphic Geology*, v. 21, p. 203–220, doi:10.1046/j.1525-1314.2003.00437.x.
- Vance, J.A., 1957, The geology of the Sauk River area in the Northern Cascades of Washington [Ph.D. thesis]: Seattle, Washington, University of Washington, 312 p.
- Vance, J.A., and Miller, R.B., 1981, The movement history of the Straight Creek fault in Washington State, in Monger, J.W.H., ed., *The Last 100 Million Years (Mid-Cretaceous to Holocene) of Geology and Mineral Deposits in the Canadian Cordillera*: Geological Association of Canada, Cordilleran Section Programme and Abstracts, p. 39–41.
- Vine, J.D., 1969, Geology and Coal Resources of the Cumberland, Hobart, and Maple Valley Quadrangles, King County, Washington: U.S. Geological Survey Professional Paper 624, 67 p.
- Walsh, T.J., Korosec, M.A., Phillips, W.M., Logan, R.L., and Schasse, H.W., 1987, Geologic Map of Washington—Southwest Quadrant: Washington Division of Geology and Earth Resources Geologic Map GM-34, scale 1:250,000, 2 sheets, 28 p. text.
- Wells, R.E., Engebretson, D.C., Snively, P.D., Jr., and Coe, R.S., 1984, Cenozoic plate motions and the volcano-tectonic evolution of western Oregon and Washington: *Tectonics*, v. 3, p. 275–294, doi:10.1029/TC003i002p00275.
- Wells, R.E., Weaver, C.S., and Blakely, R.J., 1998, Fore-arc migration in Cascadia and its neotectonic significance: *Geology*, v. 26, p. 759–762, doi:10.1130/0091-7613(1998)026<0759:FAMICA>2.3.CO;2.
- Wells, R.E., Jayko, A.S., Niem, A.R., Black, G., Wiley, T., Baldwin, E., Moleenaar, K.M., Wheeler, K.L., DuRoss, C.B., and Givler, R.W., 2000, Geologic Map and Database of the Roseburg 30' × 60' Quadrangle, Douglas and Coos Counties, Oregon: U.S. Geological Survey Open-File Report 2000-376, scale 1:100,000, 2 sheets, 55 p. text.
- Wells, R., Bukry, D., Friedman, R., Pyle, D., Duncan, R., Haeussler, P., and Wooden, J., 2014, Geologic history of Siletzia, a large igneous province in the Oregon and Washington Coast Range: Correlation to the geomagnetic

- polarity time scale and implications for a long-lived Yellowstone hotspot: *Geosphere*, v. 10, p. 692–719, doi:10.1130/GES01018.1.
- Whitney, D.L., 1992, High-pressure metamorphism in the western Cordillera of North America: An example from the Skagit Gneiss, North Cascades: *Journal of Metamorphic Geology*, v. 10, p. 71–85, doi:10.1111/j.1525-1314.1992.tb00072.x.
- Yeats, R.S., and Engels, J.C., 1971, Potassium-argon ages of plutons in the Skykomish-Stillaguamish areas, North Cascades, Washington: U.S. Geological Survey Professional Paper 750-D, p. D34–D38.

MANUSCRIPT ACCEPTED BY THE SOCIETY 31 JULY 2017

