7-1-2022

Stratigraphy, age, and provenance of the Eocene Chumstick basin, Washington Cascades; implications for paleogeography, regional tectonics, and development of strike-slip basins: Reply

Erin E. Donaghy
College of Science

Paul J. Umhoefer
Northern Arizona University

Michael P. Eddy
College of Science

Robert B. Miller
San Jose State University, robert.b.miller@sjsu.edu

Taylor LaCasse
Carleton College, USA

Recommended Citation
Erin E. Donaghy, Paul J. Umhoefer, Michael P. Eddy, Robert B. Miller, and Taylor LaCasse. "Stratigraphy, age, and provenance of the Eocene Chumstick basin, Washington Cascades; implications for paleogeography, regional tectonics, and development of strike-slip basins: Reply" *Bulletin of the Geological Society of America* (2022): 2172-2176. https://doi.org/10.1130/B36426.1

THE GEOLOGICAL SOCIETY
OF AMERICA®

Stratigraphy, age, and provenance of the Eocene Chumstick basin, Washington Cascades; implications for paleogeography, regional tectonics, and development of strike-slip basins: Reply

Erin E. Donaghy[1,†], Paul J. Umhoefer[2,§], Michael P. Eddy[1], Robert B. Miller[3], and Taylor LaCasse[4]
[1]*Department of Earth, Planetary, and Atmospheric Sciences, Purdue University, West Lafayette, Indiana 47907, USA*
[2]*School of Earth Science and Sustainability, Northern Arizona University, Flagstaff, Arizona 86011, USA*
[3]*Department of Geology, San Jose State University, San Jose, California 95192, USA*
[4]*Department of Geology, Carleton College, Northfield, Minnesota 55057, USA*

INTRODUCTION

We welcome the comment by Evans (2022) and the opportunity to further discuss our study of the Chumstick Formation. The correlation of fault-bound nonmarine sedimentary units in central and western Washington has been a topic of interest, and debate, for many years (Frizzell, 1979; Taylor et al., 1988; Gresens et al., 1981; Gresens, 1983; Evans and Johnson, 1989; Evans, 1994; Cheney and Hayman, 2009). However, many questions about the regional correlation of these units were resolved with the publication of a suite of internally consistent high-precision ^{206}Pb/^{238}U zircon dates from volcanic interbeds throughout the early to middle Eocene stratigraphy (Eddy et al., 2016). This data set confirmed the timing of sediment deposition of the different members within the Chumstick Formation. Donaghy et al. (2021) provides a detailed study of the Chumstick Formation, which builds on earlier research by Gresens et al. (1981, 1983), McClincy (1986), and Evans (1994) by incorporating new geochronologic information and additional clast counts, detrital zircon geochronology, and facies mapping. We interpret large parts of the Chumstick Formation to represent a spatially and temporally distinct sedimentary system between the Leavenworth and Entiat fault zones that likely formed as a pull-apart basin. Evans (2022) objects to several of the interpretations presented in Donaghy et al. (2021) regarding the relationship between different members of the Chumstick Formation and surrounding sedimentary units, the timing of strike-slip faulting, and the regional tectonic setting of these rocks. We discuss each of these points in the following sections.

GEOCHRONOLOGY

Many of Evans (2022) objections to the stratigraphic correlations in Eddy et al. (2016) and Donaghy et al. (2021) rely on K-Ar and fission track geochronology. The precision of these measurements is low, with most measurements falling between 4% and 8% error (total range in all measurements is 1%–16% error). In contrast, the precision of all measurements used for stratigraphic correlations by Eddy et al. (2016) and Donaghy et al. (2021) range between 0.03% and 0.17%. Additionally, the previous geochronologic data does not obey stratigraphic superposition (see fig. 10 in Eddy et al., 2017) while the newer data does. For example, previously published data in the lowermost Chumstick Formation has a range of ages consisting of: 50.9 ± 3.5 Ma (Ott, 1988; K-Ar), 47.1 ± 2.8 Ma (R.L. Gresens, written commun., 1979; K-Ar), 51.4 ± 2.8 Ma (J.A. Vance, written commun., 1978; zircon fission track), 43.2 ± 0.4 (R.L. Gresens, written commun., 1979; K-Ar), and 42.5 ± 1.6 Ma (Tabor et al., 1982; K-Ar). As a result, many of the dates discussed by Evans (2022), including these ages from the lowermost Chumstick Formation, encompass the entire Eddy et al. (2016) data set within their range and uncertainty.

In general, geochronologic data has become increasingly precise, and presumably more accurate, over the past 50 years as methods have matured and analytical uncertainties are better characterized. Direct comparison between dates produced decades ago and modern geochronology is difficult and requires ensuring that the same parameters were used during data reduction (i.e., decay constants, standardization procedures, etc.). Most of the necessary metadata for this exercise is unavailable for the geochronologic data produced during the 1970s, 1980s, and 1990s within the Chumstick Formation because data reporting standards were different and because much of the data is within difficult to obtain "gray" literature. Accordingly, we do not rely on these dates in our chronostratigraphy for the Eocene nonmarine sedimentary sequences in Washington. This issue was discussed on page 428 in Eddy et al. (2016), and the lack of internal consistency was highlighted in figures 5 and 10 in Eddy et al. (2017). Evans' (2022) use of this geochronologic data and an incomplete treatment of its uncertainty play an important role in the stratigraphic discrepancies described below.

STRATIGRAPHIC QUESTIONS

Evans (2022) questions several stratigraphic correlations made in Eddy et al. (2016) and Donaghy et al. (2021). These include: (1) the age of the stratigraphically lowest rocks in the Chumstick Formation and their possible correlation to the adjacent, and largely older, Swauk Formation; (2) the relationship between the Tumwater Mountain Member and the rest of the Chumstick Formation; and (3) the relationship between the Deadhorse Canyon Member and the adjacent Roslyn Formation. We address each of these issues below. We acknowledge that there are several instances where our previous publications do not use the U.S. Geological Survey approved name for a tuff, fault, formation, or member. Most of these names were modified into our colloquial "field" terms for the units and should be easily connected to the approved names (e.g., Fairview tuff instead of Fairview Canyon tuff). We apologize for any confusion that this has created.

Age of the Lowermost Chumstick Formation

The oldest exposures of the Chumstick Formation (lower to middle Clark Canyon Member)

[†] edonaghy@purdue.edu.
[§] Deceased 24 November 2021.

GSA Bulletin; July/August 2022; v. 134; no. 7/8; p. 2172–2176; https://doi.org/10.1130/B36426.1; 1 figure.

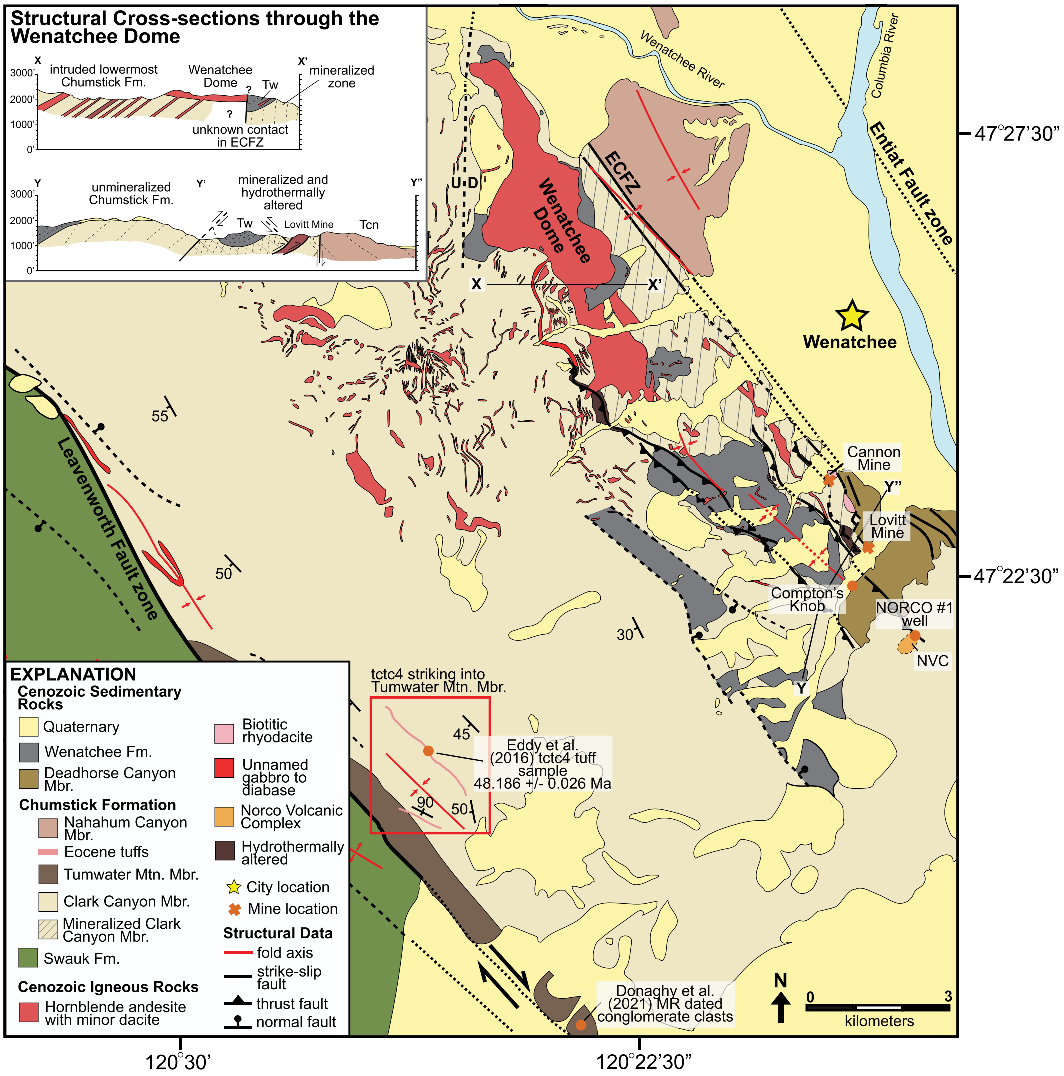

Figure 1. Generalized geologic map modified from Tabor et al. (1982), Gresens (1983), Margolis (1987, 1989), and Evans (1994) showing the complex Wenatchee Dome and Eagle Creek fault zone (ECFZ) in the southern Chumstick basin. Cross-sections are selected from Gresens (1983) and highlight the structural uncertainty and complexity of juxtaposed unmineralized and mineralized units with hydrothermally altered zones within the ECFZ. These faults through the Lovitt Mine have debated history of right-lateral and/or reverse motion, and are discussed in Margolis (1987, 1989). Additionally, thrust faults mapped by Gresens (1983) through cross section line Y–Y′–Y″ were mapped as normal faults by Tabor et al. (1982). The red box highlights where the Clark Canyon #4 tuff (tctc4) is mapped by Tabor et al. (1982) striking into Tumwater Mountain Member conglomerates along the Leavenworth fault zone. Tabor et al. (1982) originally mapped this tuff as the Eagle Creek tuff and McClincy (1986) mapped this as the East Mission Creek tuff, but correlated it to tctc4 based on geochemistry. Strike and dip measurements are from Tabor et al. (1982). MR—Mission Ridge Ski Hill; NVC—Norco Volcanic Complex; tctc4—Clark Canyon tuff #4.

form a west-dipping homocline to the south of the Wenatchee River (Fig. 1). The base of this section crops out in a structurally complex zone along and within the Eagle Creek fault zone west of Wenatchee, Washington (Fig. 1). The stratigraphic thickness, age, and correlation of these rocks to the rest of the Chumstick Formation and/or to the adjacent Swauk Formation has been controversial. Researchers have considered these rocks to be either part of the Swauk Formation that is unconformably overlain by the Chumstick Formation (Gresens, 1983; Ott, 1988), an early part of the Chumstick Formation that is age equivalent to the Swauk Formation (Evans 1994), or the earliest sedimentary rocks within a spatially and temporally distinct Chumstick basin (Tabor et al., 1982).

Evans (2022) describes the stratigraphy of the sedimentary rocks within the Eagle Creek fault zone from a core drilled in the 1930s (NORCO #1) and observations from underground mine workings. This stratigraphy has been divided into a mineralized and unmineralized section separated by a volcanic unit, known as the Compton tuff (Ott, 1988; Margolis 1987; Fig. 1). The mineralized section was mapped by Gresens (1983) as the Swauk Formation. However, Margolis (1987, 1989) later interpreted them to represent propylitic alteration of the Chumstick Formation. Regardless, alteration and the possibility of structural repetition make it difficult to determine the stratigraphic correlatives of sedimentary rocks within the Eagle Creek fault zone.

The ~1000 m of unmineralized section below the Fairview Canyon tuff is interpreted by Evans (2022) to be within the Clark Canyon Member and represents the oldest part of the Chumstick Formation. Following the stratigraphy of Evans (1994), Eddy et al. (2016) showed this section in their figure 6. Donaghy et al. (2021) acknowledged the uncertainties in stratigraphic thicknesses derived from the structurally complex Eagle Creek fault zone and truncated our section ~500 m below the Fairview Canyon tuff. Extending the sediment accumulation rates calculated between the Fairview Canyon tuff and overlying Yaksum Canyon tuffs (6.9 mm/yr; Donaghy et al., 2021) to the base of the Clark Canyon Member leads to dates of 49.22 Ma (500 m below Fairview Canyon tuff) or 49.29 Ma (1000 m below Fairview Canyon tuff) for the base of the exposed section. This age difference (70 k.y.) is negligible for our interpretation of the tectonic evolution of the region. Either date would indicate that the Clark Canyon Member of the Chumstick Formation is younger than the Swauk Formation, which was deposited and deformed prior to the eruption of the 49.3 Ma basaltic Teanaway Formation.

Evans (2022) points out that the sedimentary rocks within the Eagle Creek fault zone are finer grained than the rest of the Clark Canyon Member and interbedded with several andesite flows and other volcanic rocks. He uses several K-Ar dates to suggest that the sediment accumulation rates were lower within this part of the section and that these rocks are age equivalent to the Swauk Formation. It is possible that the sediment accumulation rates were lower and that our age estimate for the base of the section is too young given lithological differences discussed above. However, previous studies of nonmarine sedimentary basins indicate that mudstone sequences typically have greater sediment accumulation rates than sandstone sequences (Huerta et al., 2011; Crowell, 2003b, 1974a, 1974b), so lower sediment accumulation rates are unlikely. Furthermore, Evans (2022) relies on K-Ar geochronology that lacks the precision needed for age control in this section. The oldest K-Ar date used in Evans' (2022) analysis is 50.9 ± 3.5 Ma (Ott, 1988) for an interbedded andesite flow, and the youngest date is 46.2 ± 1.8 Ma (Margolis, 1989) for an ash flow tuff (Compton tuff) that caps the section in question. Putting aside the issues inherent in the use of geochronologic data produced decades ago (see discussion above), the uncertainties associated with these dates encompass the entire age range proposed for the Clark Canyon Member by Donaghy et al. (2021), 49.22 through 46.50 Ma, and cannot be used to critically evaluate the depositional model of Eddy et al. (2016) or Donaghy et al. (2021). A future high-precision age for the Compton tuff would be a welcome test of any additional stratigraphic questions within the Eagle Creek fault zone.

Our high-precision U-Pb zircon geochronologic data demonstrate that the Swauk Formation and Chumstick Formation are largely distinct in time. The Swauk Formation was deposited and deformed prior to eruption of the 49.3 Ma Teanaway Formation (Eddy et al., 2016) and the vast majority of the Chumstick Formation was deposited after the eruption/deposition of the 49.147 ± 0.041 Ma Fairview Canyon tuff. Only the stratigraphically lowest few hundred meters of the Chumstick Formation could be age equivalent to the Swauk Formation, and only if sediment accumulation rates were much lower than in the rest of the Clark Canyon Member. Instead, we prefer a model whereby initial sediment accumulation in the Clark Canyon Member started ca. 49.3–49.2 Ma and is age-equivalent to the 49.3 Ma basaltic Teanaway Formation to the west of the Leavenworth fault zone. Topography controlled by the Leavenworth fault zone likely prevented basalt from flowing into the Chumstick basin, but the presence of lava flows within the oldest Clark Canyon Member is consistent with a period of volcanism during initial sediment accumulation. The lithological changes in the Clark Canyon Member can also be explained within the context of a pull-apart basin, as lithofacies change rapidly in time and space as these basins evolve (discussed below).

Stratigraphic Position of the Tumwater Mountain Member

The Tumwater Mountain Member is exposed along the Leavenworth fault zone as a thin band of west-derived, coarse conglomerates that provides evidence for topography along the fault zone. This unit also provides excellent evidence for dextral strike-slip faulting along the Leavenworth fault zone because monolithologic boulder conglomerates are offset by ~30 km from their source rocks (Donaghy et al., 2021). In addition, the Tumwater Mountain Member also contains soft sediment deformation consistent with syndepositional earthquakes (Evans, 1988). Thus, the stratigraphic position of the Tumwater Mountain Member within the Chumstick Formation is critical in determining when the Leavenworth fault zone was active.

Evans (2022) uses stratigraphic and paleocurrent data presented in Evans (1988, 1994) to infer that the Tumwater Mountain Member is only interbedded with the youngest part of the Clark Canyon Member. In contrast, Donaghy et al. (2021) used lithofacies mapping, paleocurrents from Evans (1988, 1994), and geochronology-based stratigraphic correlations from Eddy et al. (2016) to recognize interfingering between the east-directed depositional systems of the Tumwater Mountain Member and the west-directed depositional systems of the Clark Canyon Member lower in the section. Previous mapping by Tabor et al. (1982) and McClincy (1986) supports this interpretation and shows a tuff striking into the Tumwater Mountain Member along the southernmost exposures of the Leavenworth fault zone (Fig. 1: Tabor et al., 1982; McClincy, 1986). This tuff was previously mapped as the Eagle Creek tuff by Tabor et al. (1982), but geochronology from Eddy et al. (2016) confirmed that it was the Clark Canyon #4 tuff, matching McClincy's (1986) correlation. Thus, there is good evidence that an axial depositional system near the Leavenworth fault zone had formed by 48.186 ± 0.026 Ma (Eddy et al., 2016), resulting in interfingering of the Tumwater Mountain and the Clark Canyon Members. Evidence for this axial fluvial system and mixing of east- and west-derived sedimentary systems is further supported by the compositional and geochronologic provenance data presented in Donaghy et al. (2021). Older parts of the Chumstick Formation along the Leavenworth fault zone are covered by the Columbia River Basalts and quaternary deposits (Fig. 1) and the relationship between these two Members prior to 48.186 ± 0.026 Ma is ambiguous. We think it is likely that they are also interbedded beneath the Columbia River Basalts, but this inference requires extensive drilling to test.

Our date for initial interfingering between the Clark Canyon and Tumwater Mountain Members of the Chumstick Formation is older than the one presented in Evans (2022). Evans (2022) assigns an age of <46 Ma to the Tumwater Mountain Member on the basis of a 46.3 ± 0.3 Ma K-Ar date from biotite separated from a granodioritic conglomerate clast near the Mission Ridge Ski Area (Fig. 1; Tabor et al., 1982, 1984). This location is stratigraphically below the 48.186 ± 0.026 Ma Clark Canyon #4 tuff, rendering this young 46.3 ± 0.3 Ma clast incompatible with our chronostratigraphy. Donaghy et al. (2021) used U-Pb zircon geochronology to date granodiorite and tonalite clasts from boulder conglomerates within the Tumwater Mountain Member at the same outcrop. These U-Pb zircon ages indicate that the granodiorite and tonalite clasts within the Tumwater Mountain Member are 92–91 Ma and consistent with an origin from the Mount Stuart Batholith. We suggest that the old K-Ar date cited by Evans (2022) is not as robust a constraint on the depositional age of the Tumwater Canyon Member as our combined chronostratigraphy and clast ages, but we acknowledge that the granodiorite could be of Eocene age.

Relationship between the Deadhorse Canyon Member and Roslyn Formation

Both Eddy et al. (2016) and Donaghy et al. (2021) correlate the Deadhorse Canyon Member of the Chumstick Formation with the Roslyn Formation to the west of the Leavenworth fault zone. This correlation has weaker geochronologic support as both units only have maximum depositional ages (Eddy et al., 2016). The Roslyn Formation maximum depositional ages overlap with the upper Clark Canyon Member, but the maximum depositional age in the Deadhorse Canyon Member is younger than both the Clark Canyon and Nahahum Canyon Members. However, as explained in both papers, this correlation was made because the Deadhorse Canyon Member overtops the faults that bound the rest of the Chumstick Formation (Evans, 1994) and appears to have been deposited after major motion on these structures had terminated. Neither the Deadhorse Canyon Member nor the Roslyn Formation show proximal to distal relationships that would indicate nearby topographic relief, and paleocurrent data indicates that both were deposited along west-directed fluvial systems (Tabor et al., 1984; Evans, 1994). Additionally, the Roslyn Formation lacks the abundant tuffs present in the Clark Canyon Member and evidence for syndepositional strike-slip faulting. Based on these observations, we consider both units to be part of a single depositional system, and therefore correlate the Deadhorse Canyon Member to the Roslyn Formation. However, it is possible that the assignment of the Deadhorse Canyon Member to the Chumstick Formation should be revisited at a future date, but it does not impact the strike-slip basin story documented in underlying Members.

STRIKE-SLIP FAULTING DURING DEPOSITION OF THE CHUMSTICK FORMATION

The history of the Leavenworth fault zone and of Cenozoic strike-slip faulting in central Washington has been a longstanding topic of debate (Tabor et al., 1982, 1987; Taylor et al., 1988; Cheney and Hayman, 2009). Numerous studies (Gresens, 1982; Johnson 1984, 1985, 1996; Taylor et al., 1988; Evans and Johnson, 1989) suggest dextral oblique slip for the Leavenworth fault zone. In contrast, Evans (1994, 1996) presents a two-phase model in which there was initial extension followed by a transition to strike-slip faulting. Johnson (1996) addressed several structural inconsistencies with the purely extensional initial phase of motion on the Leavenworth fault zone and we will not comment on them here. We will instead focus on our sedimentologic and stratigraphic evidence for initiation and evolution of the Chumstick basin in a strike-slip setting.

Calculated sediment accumulation rates between the Fairview Canyon and Clark Canyon #2 tuffs are far higher than those generally associated with extensional basins (Schlische, 1991; Friedmann and Burbank, 1995; Balázs et al., 2017). Using the basin's numerous tuffs as marker beds, Donaghy et al. (2021) also documented spatial variations in stratigraphic thickness and lithofacies within age equivalent strata in the Clark Canyon Member that are consistent with a northward migrating basin depocenter (see fig. 10 in Donaghy et al., 2021). These relationships can be explained by the conveyor belt model that was popularized by work on the Miocene pull-apart(?) Ridge Basin in California (Crowell 1974a, 1974b, 2003b). Shingling of strata is also necessary to fit the ~9 km of basin fill (Clark Canyon Member) into a basin that is only estimated to be only ~3.5 km deep based on vitrinite reflectance (Evans, 1988, 1994). Although Evans (1988, 1994) also interpreted rapidly migrating depocenters, he does not link it to strike-slip faulting on the Leavenworth fault zone, and it is unclear how this mechanism would work along a purely extensional fault.

Evans (2022) states that the best depositional evidence for syndepositional strike-slip faulting is preserved in the Tumwater Mountain and Nahahum Canyon Members of the Chumstick Formation. Both contain soft sediment deformation as evidence for syndepositional earthquakes and the Nahahum Canyon Member has a distribution of facies consistent with formation as a pull-apart basin between the Entiat and Eagle Creek fault zones (Evans, 1994; Donaghy et al., 2021). We agree on these points and add two more: (1) the displacement of monolithologic boulder conglomerates within the Tumwater Mountain Member from their likely source west of the Leavenworth fault zone, and (2) northward shingling of the main basin depocenter (Donaghy et al., 2021). We disagree, however, with Evans' (2022) age assignment for the Tumwater Mountain Member.

As discussed above, we consider the Tumwater Mountain Member to be interbedded with the Clark Canyon Member from at least 48.186 ± 0.026 Ma based on its relationship with the Clark Canyon #4 tuff north of the Mission Ridge Ski Area (Fig. 1). This interpretation implies that dextral strike-slip faulting on the Leavenworth fault zone began by at least 48.186 Ma, and possibly earlier if the Tumwater Mountain Member is even older beneath the Miocene Columbia River Basalts to the south. We consider it likely based on depositional and stratigraphic architectural patterns documented in the Clark Canyon Member.

In our preferred interpretation, motion on the Leavenworth and Entiat faults initiated, or accelerated, as deposition of the Chumstick Formation began ca. 49.3–49.2 Ma. Evans (1988) suggests that the Eagle Creek fault zone represented a major basement fault and that it was the master fault during basin initiation with northward shingling depocenters along its trace during an initial extension. In contrast, we interpret the interfingering of Tumwater Mountain Member conglomerates with finer-grained Clark Canyon Member strata along the basin axis to be consistent with maximum subsidence near the Leavenworth fault zone. This geometry, along with northward shingling strata, indicates that this structure served as the master fault and the main basin depocenter migrated with the northward propagating tip of the Leavenworth fault zone. This interpretation does not preclude formation of the southern strand of the Eagle Creek fault zone during this time (Fig. 1; Evans 2022). Indeed, it would be consistent with initial stages of strike-slip basin formation as a result of extension and crustal thinning between the Leavenworth fault zone and Eagle Creek fault zone (Mann et al., 1983; Christie-Blick and Biddle 1985). Subsequently, the Eagle Creek fault zone reactivated/initiated during basin reorganization, causing sediment accumulation to cease to the west of this structure and the formation of a smaller pull-apart basin in which the Nahahum Canyon Member was deposited. During this time, the western subbasin was deformed and inverted, resulting in recycled sedimentary clasts from the Clark Canyon Member within Nahahum Canyon Member conglomerates (Donaghy et al., 2021). These changes are consistent with the inward migration of faulting into strike-slip basins as regional strike-slip faults straighten (Zhang et al., 1989) and is consistent with the best available geochronology of the Chumstick Formation.

SIGNIFICANCE TO REGIONAL TECTONIC INTERPRETATIONS

Evans (2022) questions whether a change in the timing of initial strike-slip faulting on the faults associated with the Chumstick Formation would affect Eddy et al.'s (2016) model of basin evolution in relation to Siletzia's accretion. Numerous workers (e.g., Wells et al., 1984, 2014; Schmandt and Humphreys, 2011; Eddy et al., 2016) suggest that Washington was juxtaposed with the Kula or Resurrection plate following accretion of Siletzia (see fig. 9 in Eddy et al., 2016, or fig. 13 in Eddy et al., 2017). Either plate had a strongly dextral oblique component of motion relative to North America during the Eocene, which likely drove dextral strike-slip faulting. Thus, the question of when regional strike-slip faulting accelerated after Siletzia's collision is related to the time needed for two tectonic plates to couple following their juxtaposition. The Eddy et al. (2016) and Donaghy et al. (2021) interpretation of accelerated right-lateral strike-slip faulting at 50–49 Ma would suggest that coupling occurred soon after Washington was juxtaposed with the Kula or Resurrection plate. A slightly younger date, as suggested by Evans (2022), for acceleration, or initiation, of strike-slip motion on the Leavenworth, Eagle Creek, or Entiat fault zones would indicate a longer lag time between juxtaposition of tectonic plates and the accelerated strike-slip faulting. Although the timing does not impact our tectonic interpretation, we stand by our chronostratigraphy and interpretation of the Chumstick Formation deposition within a strike-slip basin setting, and do not consider the chronology used in Evans (2022) to be robust for the reasons outlined above.

ACKNOWLEDGMENTS

Financial support for this project was provided by the National Science Foundation grants EAR-1119063 to P.J. Umhoefer and EAR-1119358 to R.B. Miller. The research was further supported by graduate research grants to E.E. Donaghy from the Geological Society of America, the American Association of Petroleum Geologists Nancy Setzer Murray Memorial fund, and the Pioneer Research Scholarship Fund. The manuscript has benefited from the thoughtful comments of two anonymous reviewers and editorial feedback from Science Editor Wenjiao Xiao. We would also like to acknowledge our coauthor, Paul J. Umhoefer, who unexpectantly passed away over the course of this study. Paul J. Umhoefer had a long career in tectonics and basin analysis and was a great mentor to his students. He provided invaluable contributions to this project and to the field of Cordilleran tectonics, and will be missed by family, friends, and the geologic community.

REFERENCES CITED

Balázs, A., Granjeon, D., Matenco, L., Sztanó, O., and Cloetingh, S., 2017, Tectonic and climatic controls on asymmetric half-graben sedimentation: Inferences from 3-D numerical modeling: Tectonics, v. 36, p. 2123–2141, https://doi.org/10.1002/2017TC004647.

Cheney, E.S., and Hayman, N.W., 2009, The Chiwaukum Structural Low: Cenozoic shortening of the Cascade Range, Washington State, USA: Geological Society of America Bulletin, v. 121, p. 1135–1153, https://doi.org/10.1130/B26446.1.

Christie-Blick, N., and Biddle, K.T., 1985, Deformation and basin formation along strike-slip faults, *in* Biddle, K.T., and Christie-Blick, N., eds., Strike-Slip Deformation, Basin Formation, and Sedimentation: SEPM Special Publication 37, p. 1–34, https://doi.org/10.2110/pec.85.37.0001.

Crowell, J.C., 1974a, Sedimentation along the San Andreas fault, California, *in* Dott, R.H., Jr., and Shaver, R.H., eds., Modern and Ancient Geosynclinal Sedimentation: Society of Economic Paleontologists and Mineralogists Special Publication 19, p. 292–303, https://doi.org/10.2110/pec.74.19.0292.

Crowell, J.C., 1974b, Origin of late Cenozoic basins in southern California, *in* Dickinson, W.R., ed., Tectonics and Sedimentation: Society of Economic Paleontologists and Mineralogists Special Publication 22, p. 190–204, https://doi.org/10.2110/pec.74.22.0190.

Crowell, J.C., 2003b, Tectonics of Ridge Basin region, southern California, *in* Crowell, J.C., ed., Evolution of Ridge Basin, Southern California: An Interplay of Sedimentation and Tectonics: Geological Society of America Special Paper 367, p. 157–204, https://doi.org/10.1130/0-8137-2367-1.157.

Donaghy, E.E., Umhoefer, P.J., Eddy, M.P., Miller, R.B., and LaCasse, T., 2021, Stratigraphy, age, and provenance of the Eocene Chumstick basin, Washington Cascades; implications for paleogeography, regional tectonics, and development of strike-slip basins: Geological Society of America Bulletin, v. 133, p. 2418–2438, https://doi.org/10.1130/B35738.1.

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 nonmarine sedimentary basins in central and western Washington: Geological Society of America Bulletin, v. 128, p. 425–441, https://doi.org/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 on Vancouver Island: Lithosphere, v. 9, p. 652–664, https://doi.org/10.1130/L650.1.

Evans, J.E., 1988, Depositional environments, basin evolution and tectonic significance of the Eocene Chumstick Formation, Cascade Range, Washington [Ph.D. thesis]: Seattle, University of Washington, 325 p.

Evans, J.E., 1994, Depositional history of the Eocene Chumstick Formation: implications of tectonic partitioning for the history of the Leavenworth and Entiat–Eagle Creek fault systems, Washington: Tectonics, v. 13, no. 6, p. 1425–1444, https://doi.org/10.1029/94TC01321.

Evans, J.E., 1996, Reply to Comment on "Depositional history of the Eocene Chumstick Formation: implications of tectonic partitioning for the history of the Leavenworth and Entiat-Eagle Creek fault systems, Washington": Tectonics, v. 15, p. 510–514, https://doi.org/10.1029/95TC03695.

Evans, J.E., 2022, Stratigraphy, age, and provenance of the Eocene Chumstick basin, Washington Cascades; implications for paleogeography, regional tectonics, and development of strike-slip basins [Comment]: Geological Society of America Bulletin, v. 134, https://doi.org/10.1130/B36157.1.

Evans, J.E., and Johnson, S.Y., 1989, Paleogene strike-slip basins of central Washington: Swauk Formation and Chumstick Formation: Washington Division of Geology and Earth Resources, Information Circular, v. 86, p. 215–237.

Friedmann, J.S., and Burbank, D.W., 1995, Rift basins and supradetachment basins: intracontinental extensional end-members: Basin Research, v. 7, p. 109–127, https://doi.org/10.1111/j.1365-2117.1995.tb00099.x.

Frizzell, V.A., 1979, Petrology and stratigraphy of Paleogene nonmarine sandstones, Cascade Range, Washington [Ph.D. thesis]: Stanford, California, Stanford University, 169 p.

Gresens, R.L., 1982, Cenozoic geology of central Washington state, II, Implications for plate tectonics and alternatives for the origin of the Chiwaukum graben: Northwest Science, v. 56, p. 259–264.

Gresens, R.L., 1983, Geology of the Wenatchee and Monitor quadrangles, Chelan and Douglas Counties, Washington: Washington Division of Earth Resources Bulletin, v. 75, p. 1–75.

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. 223–236, 841–876, https://doi.org/10.1130/GSAB-P2-92-841.

Huerta, P., Armenteros, I., and Silva, P.G., 2011, Large-scale architecture in non-marine basins: The response to the interplay between accommodation space and sediment supply: Sedimentology, v. 58, no. 7, p. 116–1736, https://doi.org/10.1111/j.1365-3091.2011.01231.x.

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, https://doi.org/10.1139/e84-010.

Johnson, S.Y., 1985, Eocene strike-slip faulting and nonmarine basins formation in Washington, *in* Biddle, K.T., and Christie-Blick, N., eds., Strike-slip Deformation, Basin Formation, and Sedimentology: SEPM Special Publication 37, p. 283–302, https://doi.org/10.2110/pec.85.37.0283.

Johnson, S.Y., 1996, Comment on "Depositional history of the Eocene Chumstick Formation: implications of tectonic partitioning for the history of the Leavenworth and Entiat–Eagle Creek fault systems, Washington": Tectonics, v. 15, no. 2, p. 506–509, https://doi.org/10.1029/95TC03694.

LaCasse, T.J., 2013, Using a coarse-grained conglomerate to investigate lateral offset along the Leavenworth Fault Zone, North Cascades, Washington [unpublished undergraduate research]: Carleton College, 40 p.

Mann, P., Hempton, M.R., Bradley, D.C., and Burke, K., 1983, Development of pull-apart basins: The Journal of Geology, v. 91, p. 529–554, https://doi.org/10.1086/628803.

Margolis, J., 1987, Structure and hydrothermal alterations associated with epithermal Au-Ag mineralization, Wenatchee heights, Washington [M.S. thesis]: Seattle, Washington, University of Washington, 90 p.

Margolis, J., 1989, Arkose-hosted, aquifer-controlled, epithermal Au-Ag mineralization, Wenatchee, Washington: Economic Geology, v. 84, p. 1891–1902, https://doi.org/10.2113/gsecongeo.84.7.1891.

McClincy, M.J., 1986, Tephrostratigraphy of the middle Eocene Chumstick Formation, Cascade Range, Douglas County, Washington [M.S. thesis]: Portland, Oregon, Portland State University, 125 p.

Ott, L.E., 1988, Economic geology of the Wenatchee mining district, Chelan County, Washington [Ph.D. dissertation]: Boise, Idaho, University of Idaho, 270 p.

Schlische, R.W., 1991, Half-graben basin filling models: new constraints on continental extensional basin development: Basin Research, v. 3, p. 123–141, https://doi.org/10.1111/j.1365-2117.1991.tb00123.x.

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, https://doi.org/10.1130/G31558.1.

Tabor, W., Waitt, R.B., Frizzel, V.A., 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, 1-1311, 26 p.

Tabor, R.W., Frizzel, 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, https://doi.org/10.1130/0016-7606(1984)95<26:AASOLA>2.0.CO;2.

Tabor, R.W., Frizzel, 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.

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 eastern Swauk basin, central Cascades, central Washington: Canadian Journal of Earth Sciences, v. 25, p. 1020–1036, https://doi.org/10.1139/e88-100.

Wells, R.E., Engebretson, D.C., Snavely, P.D., Coe, R.S., and Anonymous, 1984, Cenozoic plate motions and the volcanic-tectonic evolution of western Oregon and Washington: Tectonics, v. 3, no. 2, p. 275–294, https://doi.org/10.1029/TC003i002p00275.

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, https://doi.org/10.1130/GES01018.1.

Zhang, P., Burchfiel, B.C., Chen, S., and Deng, Q., 1989, Extinction of pull-apart basins: Geology, v. 17, p. 814–817, https://doi.org/10.1130/0091-7613(1989)017<0814:EOPAB>2.3.CO;2.

Science Editor: Wenjaio Xiao
Associate Editor: Dongfang Song

Manuscript Received 14 December 2021
Revised Manuscript Received 3 March 2022
Manuscript Accepted 22 March 2022

Printed in the USA