Revisiting the Leavenworth fault, southeastern North Cascade Range, Washington

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Abstract

The SW boundary of the ~49-45 Ma fluvial Chumstick Fm in central Washington has been mapped as the Leavenworth fault: a steeply dipping feature, perhaps with largely dextral strike slip, active during regional Paleogene wrench faulting related to accretion of Siletzia. Older crystalline rocks and fluvial strata of the ~63-51 Ma Swauk Fm lie SW of the Leavenworth fault. Farther NE, the steep, NW-striking, dextral Entiat fault separates Chumstick strata from crystalline rocks.

Ongoing geologic mapping of the Tiptop 7.5' quadrangle, calculation of strikes and dips from bedding traces evident in lidar topography, and a focus on developing a restorable structural interpretation lead to several conclusions: (1) In the Tiptop quadrangle, the Leavenworth fault is a SW-dipping thrust that places complexly-folded Swauk Fm above a thick W-dipping homocline of Chumstick Fm. (2) Coarse monolithologic fanglomerates mapped by earlier workers as Chumstick Fm and cited as evidence for syn-Chumstick displacement on the Leavenworth fault are better interpreted as part of the Swauk Fm. (3) On Tumwater Mtn NW of Leavenworth, the "Leavenworth fault" mapped by earlier workers is subparallel to bedding in the adjacent polymict conglomerate and is evidently the basal contact of the Chumstick Fm. (4) E and SE of Tumwater Mtn, the NW-plunging, 2+ km-amplitude Peshastin syncline is rootless, indicating an underlying decollement which I interpret as the up-dip continuation of the Leavenworth thrust in the Tiptop quad. (5) Down-plunge projection of this geology suggests that crystalline rocks on Tumwater Mtn and the east end of Icicle Ridge overlie Chumstick Fm.

SW-NE shortening of the Chumstick Fm predates ~35 Ma deposition of the overlying Wenatchee Fm, as evinced by a profound angular unconformity beneath Wenatchee strata. Shortening continued after deposition of the Wenatchee Fm, as it is involved in NE-verging thrusts south of the city of Wenatchee. Trends of fold axes associated with the Leavenworth thrust are parallel to the strike-slip Entiat fault, indicating either interludes of NE-SW compression during Paleogene wrench faulting or—more likely—nearly complete partitioning of transpressive strain into domains of NE-SW shortening and NW-SE strike slip.

PREVIOUS WORK

Page (1939) described the contact along Tumwater Mountain (47° 37'–40' N) between fluvial arkose on the east and crystalline rocks to the west as a depositional contact.

Willis (1953) identified the Leavenworth fault and mapped it as extending from near Tiptop Mountain (47° 26' N) to Basalt Peak (47° 58' N). He described it as a nearly vertical structure with displacement (east side down) that locally exceeds 10,000 ft.

Tabor and others (1982, 1987) mapped the Chiwaukum low and surroundings at a scale of 1:100,000. Their maps, which show the Leavenworth fault as a nearly vertical structure, have been the basis of most subsequent investigations. In the Chiwaukum low, their maps were largely compiled from larger-scale mapping by Whetten and colleagues (1976, 1978, 1980a-c) and Gresens (1983). To the north, the Leavenworth fault separates middle Eocene Chumstick Fm on the east from Cretaceous crystalline basement (Cretaceous Mt Stuart batholith, Jurassic Ingalls Ophiolite and metamorphic equivalents) on the west. Farther south, the west wall of the fault is the Paleocene and early Eocene Swauk Formation. The Entiat fault, at the northeast margin of the Chiwaukum low, juxtaposes Chumstick Fm with crystalline rocks of the Swakane Biotite Gneiss and the Napeequa Schist. Mapped in some detail by Laravie (1976), it is generally understood to have significant dextral oblique-slip (e.g., Schermer and others, this meeting).

More recent work has been largely stratigraphic and sedimentologic. McClincy (1986) sampled tuffs mapped by Whetten and colleagues and showed that they could be correlated by their chemistry over significant distances. Evans (1994) proposed that the Leavenworth fault was inactive in early Chumstick time and that conglomerate and breccia of his Tumwater Mountain member recorded later oblique slip. Johnson (1996) argued for dextral strike-slip on the Leavenworth fault throughout Chumstick deposition. Donaghy and others (2021) presented stratigraphic, sedimentologic, and geochronologic data and described the Chumstick as deposited in a strike-slip basin bounded by the Leavenworth fault.

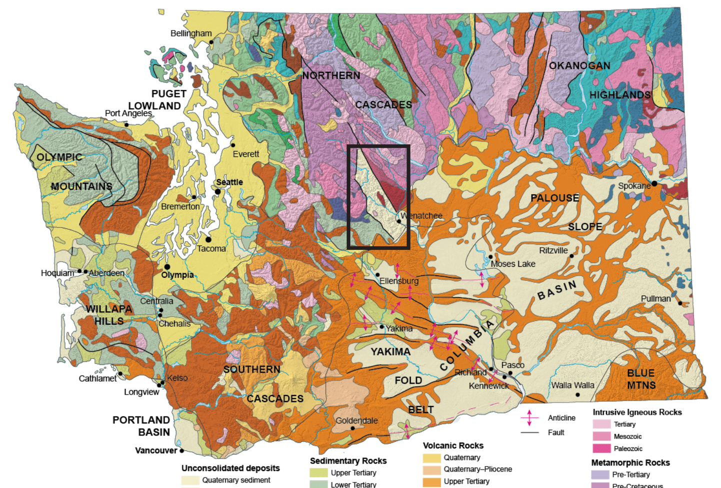
In contrast, mapping by Cheney and Hayman (2009) led them to propose that the Leavenworth fault is a SW-dipping post-Chumstick reverse fault, segmented by their N-striking Icicle Creek and Chumstick Creek faults.

Eddy and others (2016) presented high-precision ages for the Swauk (60–51 Ma) and Chumstick (49–44.5 Ma) formations and placed Eocene deposition and transcurrent faulting in the context of accretion of Siletzia and interaction with the Kula-Farallon-North America triple junction.

SYNOPSIS

The Leavenworth fault forms the western boundary of middle Eocene fluvial strata of the Chiwaukum structural low in central Washington State. It has been interpreted as a steep normal fault, a dextral oblique-slip fault, and a reverse fault segmented by cross faulting.

This study suggests the "Leavenworth fault" is in places a depositional contact and elsewhere is a significant thrust that places crystalline basement over middle Eocene strata.



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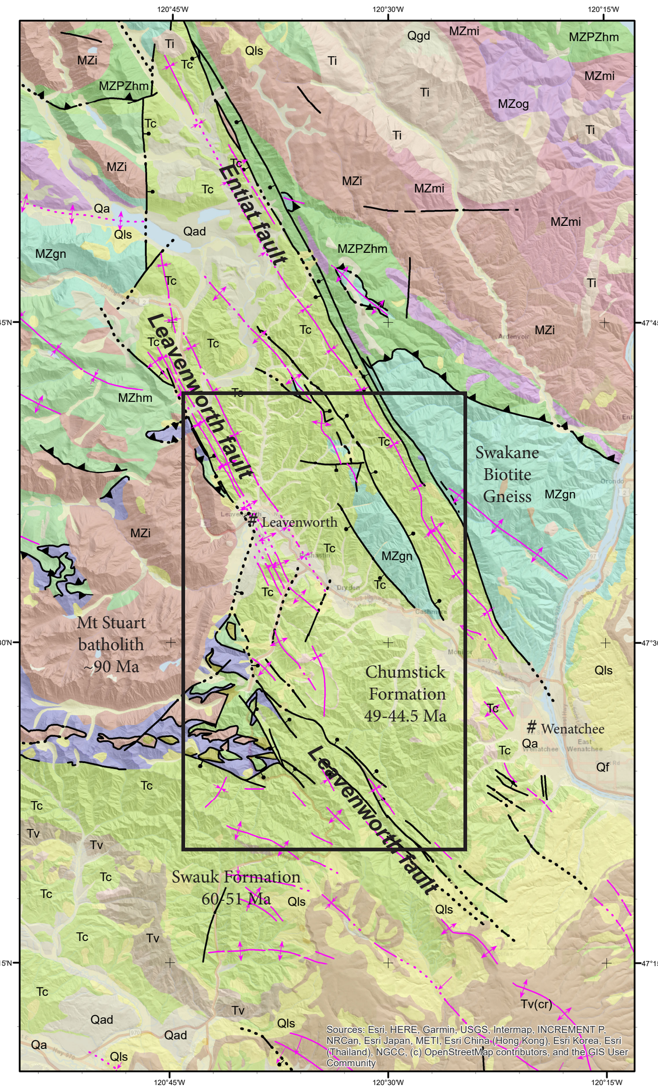

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THIS STUDY

Much of the Chumstick Formation lies in a west-dipping homocline with an astounding apparent stratigraphic thickness of more than 9 km. Is this the depositional thickness? How were the strata tilted? What was the genesis of folds that are locally evident? I seek a map with a restorable structural interpretation as a necessary step towards better understanding of the history of central Washington and a guide to the internal geometry of the seismogenic middle crust beneath the Yakima fold belt.

In late 2018 I began work on a geologic map of the Tiptop 7.5' quadrangle. I learned that, despite steep hillsides and 2,000 ft of local relief, outcrop of modestly-indurated Chumstick Formation in this unglaciated terrain is not good. Where outcrop is present, paleo-horizontal is commonly hard to identify in these massive to thickly crossbedded channel sandstones.

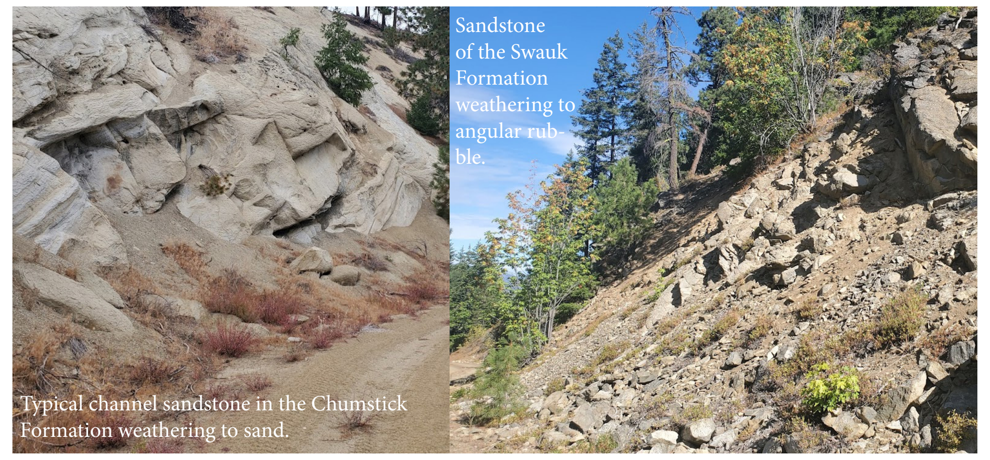
Yet bedding traces are widely evident in lidar topography of this area. I developed code to extract strike and dip from ensembles of digitized bedding traces and the lidar DEM. Code to export bedding attitudes for analysis in Stereonet (Rick Allmendinger, *https://www.rickallmendinger.net/stereonet*). And code for down-plunge projection with apparent-dip corrections. These codes, packaged as an ArcMap toolbox, are available at *https://github.com/rhaugerud/PlanarOrientationsTools*.

My working database currently contains 1266 bedding attitudes extracted from lidar topography, 964 attitudes from Whetten and others (1976-1980, via WGS 1:24K digital compilation), 408 attitudes from Gresens (1983, via WGS 1:24K digital compilation), 905 attitudes digitized from Cheney and Hayman (2009), and 118 (and growing) attitudes from my field work.

A) **Distinguishing Chumstick from Swauk can be challenging.** Both units are predominantly fluvial, sandy, and quartzofeldspathic.

Chumstick Formation is characterized by thick beds of feldspar-quartz-mica channel sandstone. Outcrops of overbank deposits are rare. Conglomerate clasts are largely felsic volcanic rocks, granitic rocks, gneiss, and vein quartz. Outcrops generally weather to loose sand. Fold wavelengths are 10^3–10^4 m.

Swauk Formation is more lithic, more variable in grain size and bed thickness, and has more overbank deposits. Some sandstones are dark. Conglomerate clasts include mafic volcanic rocks, low-grade metamorphic rocks, granitic rocks, chert, and local ultramafic rocks. Outcrops weather to angular rubble. Fold wavelengths are 10^2–10^3 m.



Typical channel sandstone in the Chumstick Formation weathering to sand.

Sandstone of the Swauk Formation weathering to angular rubble.

B) **Monolithologic fanglomerates are Swauk Formation.** Distinctive sub-angular to sub-rounded cobble to boulder conglomerates, commonly with a single clast lithology, were considered by earlier workers to occur in both Swauk and Chumstick. Perhaps the best-known of these outcrops is at the entrance to the Mission Ridge Ski Area parking lot.

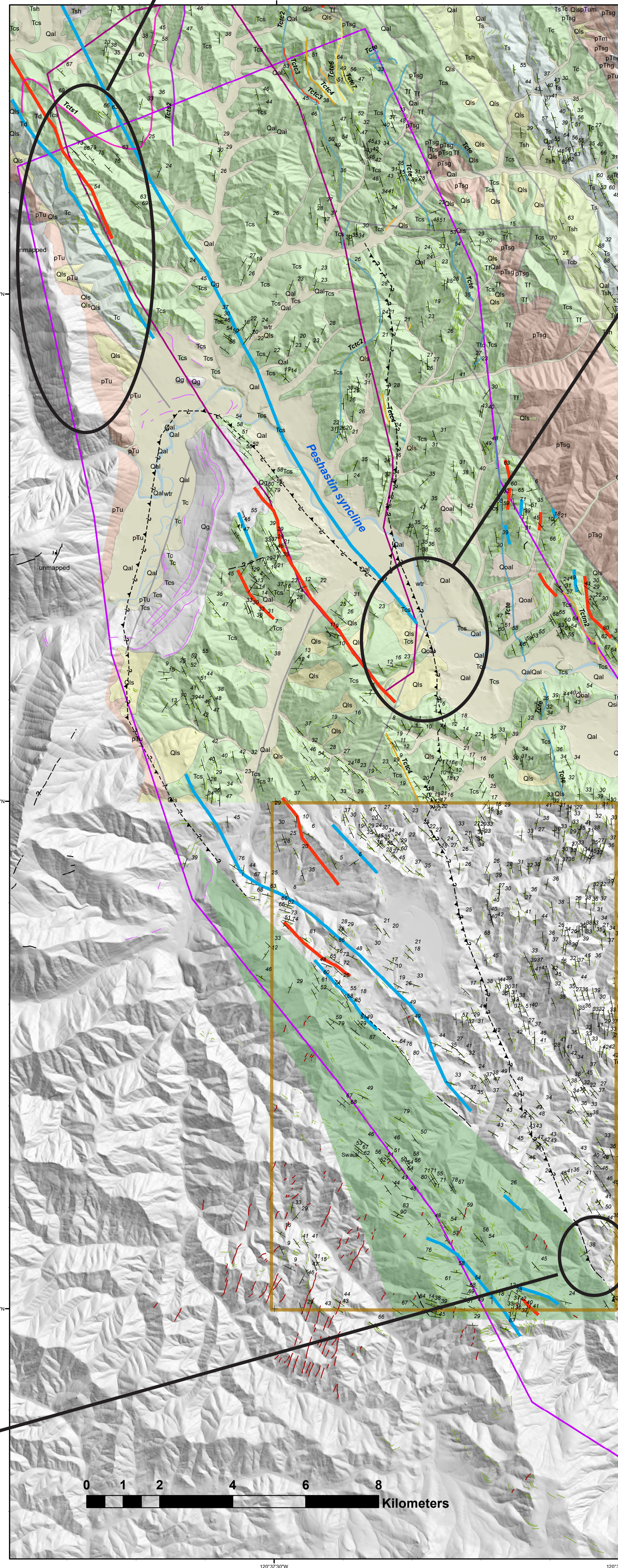
I find that it makes more lithologic and structural sense to place these fanglomerates entirely in the Swauk. This has the effect of moving the Swauk-Chumstick contact to the northeast. This also removes the evidence for syn-Chumstick deformation on the Leavenworth fault.

C) **The fault between Swauk and Chumstick formations dips SW** in the southeast corner of the Tiptop quad. Farther northwest the dip is less well constrained and may be vertical.

D) **On Tumwater Mountain the Chumstick-basement contact appears to be depositional** as bedding traces evident in lidar topography are sub-parallel to the contact. Note that this was Ben Page's interpretation in 1939.

With one exception, observed bedding attitudes in this stretch of the Leavenworth "fault" are sub-parallel to the contact. The Tumwater Mountain member, which here is well-rounded polymict conglomerate, is a plausible basal conglomerate.

The overhang evident in the down-plunge projection is likely a consequence of non-cylindrical structure, bad mapping, and(or) an unrecognized cross-fault.



E) **The Peshastin syncline is rootless.** It extends from Winton at 47° 44'N SSE through Leavenworth to 47° 32'N, about a km west of Dryden, and plunges to the NW. At Dryden, the west limb of the syncline disappears and strata beneath the fold are homoclinal.

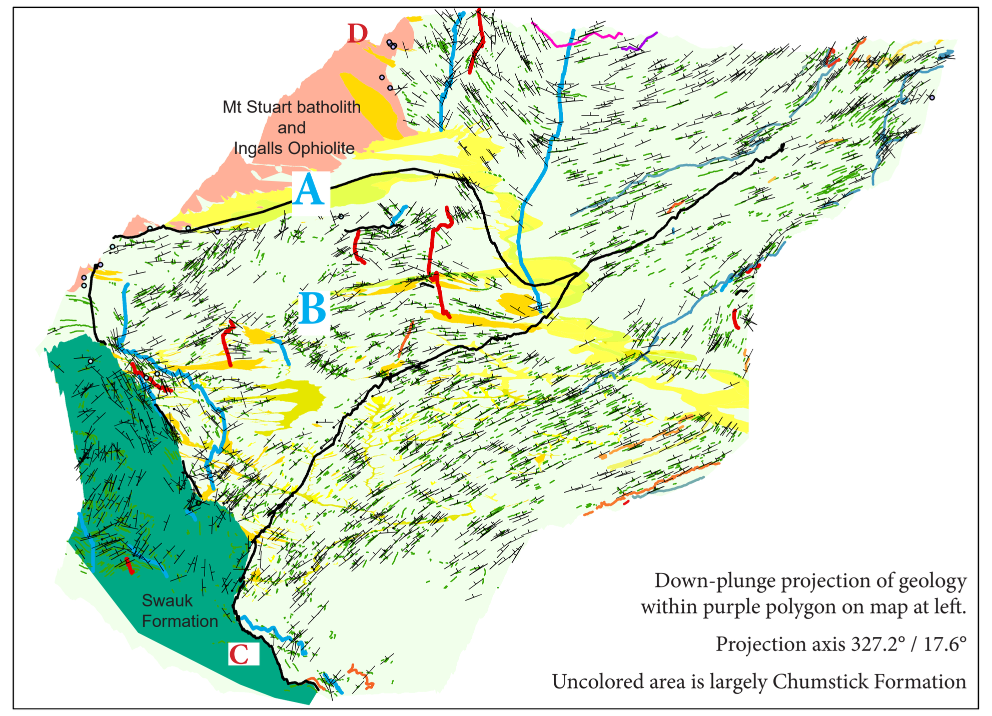
This geometry requires the presence of a significant decollement at the base of the fold.

F) **Down-plunge projection indicates basement rocks overlie Chumstick Formation at A south of the town of Leavenworth.** Modest uncertainty in the choice of projection axis does not affect this conclusion. The mapped trace of the axial plane of the Peshastin syncline trends about 330°. Bedding planes in the Peshastin syncline define an axis 327°/18°. Bedding planes throughout the domain that includes the Peshastin syncline and much of the Tiptop quad define an axis 320°/14°. Projection along any of these axes gives similar results.

Cheney and Hayman (2009) explained this map geometry by dextral separation on hypothesized north-striking. However, lack of offset of the Peshastin syncline make such faults unlikely.

The cross section also suggests aduplex within the Chumstick in the area B between Leavenworth and the center of the Tiptop quadrangle.

Several incongruities (e.g., east dip of the Leavenworth fault at depth C, overhang on the basement-Chumstick contact at the north end of Tumwater Mountain D, irregular fault traces, zig-zags in tuff beds and fold axes) likely reflect a combination of structure that is not entirely cylindrical and inaccurate mapping.



Down-plunge projection of geology within purple polygon on map at left.
Projection axis 327.2° / 17.6°
Uncolored area is largely Chumstick Formation

EXPLANATION OF SYMBOLS

- Outline of the Tiptop 7.5-minute quadrangle
- Bedding traces evident in lidar topography
- Basalt dikes of the Teanaway swarm
- Moraine crests

Bedding attitudes shown were extracted from lidar topography.

Within and west of the Tiptop quadrangle, dark green denotes Swauk Formation. Uncolored area is largely Chumstick Formation

- Anticline axis
- Syncline axis
- Tuff beds as reported by McClincy (1986) *various pastel colors*

Colored geology north and east of the Tiptop quadrangle is from Whetten and others (1976-1980) and Gresens (1983)
- Faults from these sources.

- Outline of area of down-plunge projection
- Outline of area from which bedding attitudes were used to calculate axis of Peshastin syncline

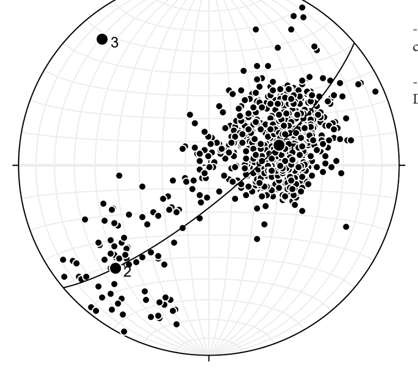
DISCUSSION

Age of deformation SW-NE shortening of the Chumstick Formation pre-dates and post-dates deposition of the early Oligocene Wenatchee Formation. As noted by Gresens (1983), the Wenatchee sits on a profound angular unconformity above the Chumstick Fm and is itself involved in NE verging thrusts.

Strain partitioning Fold axes are not oblique to Entiat fault as predicted by simple models of transpressive deformation, indicating either alternating episodes of NW-trending strike-slip faulting and NE-SW shortening or, more likely, effective partitioning of transpressive strain into domains of NE-SW shortening (Leavenworth fault, Chumstick Fm) and domains of pure strike slip (Entiat fault).

Tectonic setting of Chumstick deposition is undefined This work does not address the setting of the Chumstick basin, beyond noting that evidence for strike-slip deposition in later Chumstick time (coarse fanglomerates of the southern Tumwater Mountain member of Evans, 1994) has been misinterpreted.

More work is needed Mapping should be extended to the north end of the Chiwaukum structural low and around the Eagle Creek horst. McClincy's (1986) correlations of Chumstick tuffs on the basis of their chemistry should be reexamined in the light of possible effects of analytical errors. The structural analysis presented here could be improved by a clearer understanding of the along-strike changes in fold plunge and better delineation of zones within which structure is truly cylindrical.

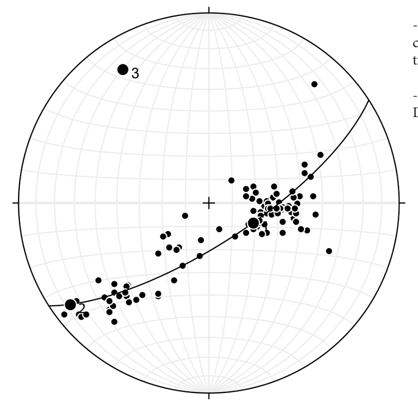


---------- Poles from Planes | 9/21/2021 at 9:16 PM ----------
calculated from 855 planes from Data set: '1bAll.txt'

----- Bingham Analysis | 9/21/2021 at 9:16 PM-----
Data set: poles to 1bAll.txt

Axis	Eigenvalue	Trend Plunge	a95 min	a95 max
1.	0.8280	074.1, 58.4	1.0	1.5
2.	0.1338	222.3, 27.6		
3.	0.0382	319.9, 14.1	1.0	4.0

Stereonet 10.0, R.W. Allmendinger



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calculated from 103 planes from Data set: 'PeshastinSyncline.txt'

----- Bingham Analysis | 9/22/2021 at 6:23 PM-----
Data set: poles to PeshastinSyncline.txt

Axis	Eigenvalue	Trend Plunge	a95 min	a95 max
1.	0.7091	114.6, 69.3	2.0	9.0
2.	0.2751	233.9, 10.5		
3.	0.0158	327.2, 17.6	2.1	3.2

Stereonet 10.0, R.W. Allmendinger

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