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The Chiwaukum Structural Low on the Eastern Flank of the Cascade Range

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ABSTRACT

The eastern flank of the central Cascade Range of Washington State contains the geologic record of Cretaceous to Recent deformation, volcanism, and sedimentation. Previous workers argued that the region underwent either regional extension or transtension during the mid-to-late Eocene. The extension and transtention models derive from the interpretation that clastic Eocene formations were deposited syn-tectonically in local basins. Here, we show that these formations are preserved in structural lows, not in depositional basins.

Our type area is the Chiwaukum graben/Chumstick basin, here renamed the Chiwaukum Structural Low (CSL). The boundaries of the CSL include post-depositional, northwest striking reverse faults with adjacent folds. Reverse faults place the regionally extensive Eocene Swauk Formation over younger Eocene, but also regionally extensive Roslyn Formation. The reverse faults and fold hinges are cut by northerly striking strike-slip faults, likely of Oligocene age. Cataclastic structures in outcrop provide independent evidence for the reverse and strike-slip faulting. The Eocene structures were reactivated by late-to-post Miocene deformation, including folding that largely defines the map pattern around the CSL. Some of this younger deformation is ongoing today. Our reinterpretation of the eastern Cascade Range, therefore, has ramifications both for tectonic reconstructions of the northwest Cordillera and the distribution of neotectonic strain.

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TABLE OF CONTENTS

PREFACE

This field trip on the eastern flank of the Cascade Range near Leavenworth explores two main topics: (1) the stratigraphy and structure of the so-called Chumstick Formation of Eocene arkosic strata in the so-called Chiwaukum graben, and (2) the faults that bound the "graben" on the southwest (Leavenworth fault) and northeast (Entiat fault). We will also examine some of the pre-Cenozoic metamorphic rocks of the Swakane and Mad River terranes northeast of the Entiat fault.

Both of the main topics challenge the common belief that the Chumstick Formation was deposited while the graben was active. This trip advances the alternative hypothesis that the Chiwaukum structural low (CSL) is caused by post-Eocene and post-Miocene regional folding (i.e., episodic crustal shortening), not the crustal extension implied by a graben.

This field guide is from 3 sources that are not seamlessly integrated. Cheney and Hayman (2007) led a precursor of this trip for the Geological Society of America (GSA). The road log and descriptions of stops of that trip that are germane to this trip are included here. Since that field trip, Cheney and Hayman have been writing an article for publication, which deals specifically with the CSL, rather than entire area covered by the GSA trip. A draft of that article is used here for the setting and description of the CSL.

Thirdly, since the GSA field trip, I have become interested in the Entiat fault and the metamorphic rocks immediately northeast of it. Thus, part of this guide is a brief description of the results of my 1:24,000 mapping in 2007 and of stops in those metamorphic rocks.

This field guide pays little attention to Pleistocene deposits. Most of the CSL south of Plain as well as the upland northeast of the Entiat fault are unglaciated (Tabor et al. 1987). In relatively flat areas this permits mapping by float.

The maps of the CSL included here are, necessarily, small of scale (cover big areas), do not show much structural data, and are somewhat outdated by my mapping in 2007. Therefore, I will episodically display laminated copies of my field sheets for several 7.5 minute quadrangles (at 1:24,000) and the 1:100.000 maps of Tabor et al (1982, 1987) for comparison.

Because this trip differs from the GSA trip, the progression of stops will be different. Specifically, the order of stops on the first day probably will be 1-9 to 1-13 and 1-1 to 1-6. Stops 1-7 and 1-8 will be made at the end of Day 2 as we start back to Seattle. Weather permitting, we will have superb overviews of the CSL from Stop 1-6 on the western side of CSL at the end of Day 1 and from Sugarloaf Peak (Stop E-l) northeast of the Entiat fault (on the northeastern side of CSL) early in the morning of Day 2.

INTRODUCTION

The eastern flank of the central Cascade Range of Washington State is a key area in the study of Cordilleran tectonics, arc construction, mid-crustal exhumation, and basin development. The geology of the area is also relevant to volcanic and seismic hazards to a growing population. Reaching a deeper understanding of the processes that operated, and continues to operate, in the Pacific Northwest requires unraveling the Cenozoic geologic history of the region.

The Blushastin-Leavenworth area exposes a suite of volcanic and sedimentary rocks of Eocene age. They are surrounded by fault-bounded areas of pre-Cenozoic basement, such as the Mt. Stuart tonalitic batholith and the Swakane Biotite Gneiss.

Previous studies have led to the interpretation that the Eocene arkosic sediments filled local basins (Gresens, 1981; Gresens et al., 1981; Tabor et al. 1982, 1987; Johnson, 1985; Evans, 1994). One of these basins has interchangeably been called the Chiwaukum graben or Chumstick basin (Willis, 1953; Gresens et al, 1981, Evans, 1994). The Chiwaukum graben is inferred to have formed during either regional extension (Evans, 1994), or as a pull-apart during transtension (Gresens, 1982; Johnson, 1985). Eocene extension is now integral to many recent tectonic models of the region (e.g., Paterson, 2004).

Here, we present the results of 1:24,000 mapping of the southwestern portion of the so-called Chiwaukum graben. We find that rather than a graben, the Chiwaukum "graben" is a post-depositional synclinal low, which we refer

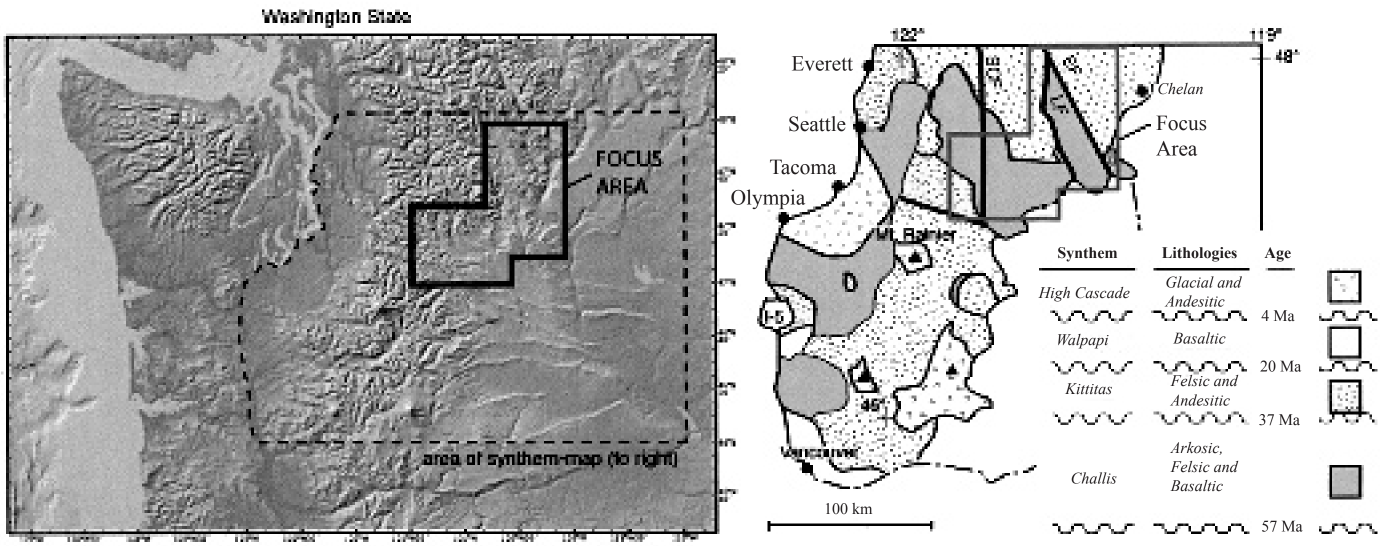


Figure 1 *(Above) Digital elevation model of a portion of Washington State, Generalized map showing the distribution of unconformity bounded lithologic sequences, or synthems. Each synthem has a general lithologic description, such that glacial and andesitic rocks dominate the Cascade mountains in the central part of the range, basaltic rocks dominate the eastern part of the state, felsic and andeditic rocks dominate the western flank of the Cascade range, and various sedimentary rocks fill structural lows throughout the central part of the range. Ages are approximate from the literature cited in the text.*

to as the Chiwaukum Structural Low (CSL). Specifically, our clarification of the stratigraphy of the Eocene formations in the CSL allows us to reevaluate its depositional and structural history. For example, a diamictite mapped along the Leavenworth fault, the major fault on the southwest margin of the reputed graben, was thought to have "flowed" off the fault scarp. We demonstrate that this unit is older than, and cataclastically deformed by, the fault. Furthermore, our mapping indicates that the Leavenworth fault is a high-angle reverse fault that cuts regionally extensive Eocene formations. Northerly striking, strike-slip faults sharply cut the reverse faults and fold hinges. The strike-slip faults are likely of latest Eocene to Oligocene age.

Although we emphasize mid-to-late Eocene stratigraphy and structure, an understanding the younger history of the area is fundamental to understanding the Eocene deformational phases, and vice-versa. After exploring the Eocene development of the region, we show that Neogene regional folds govern the map pattern of the CSL and the surrounding crystalline basement. To clarify this multi-stage history, we present a 6-stage schematic reconstruction of the area. The reconstruction, along with the new maps and cross-sections, should guide future kinematic restorations of the northwest Cordillera. Our results are also useful in understanding the geology of adjacent areas since eroded by young Cascade uplift, covered by Puget Lowland vegetation, and by the Miocene Columbia River Basalt Group. Moreover, because younger intervals of deformation reactivated the older structures, understanding the geology will aid in studies of active deformation throughout the region.

Regional Settings and Previous Interpretations

The regional setting of the CSL (Fig. 1) is largely governed by Miocene and younger anticlinal uplift of the Cascade Range (Cheney, 1997; Cheney and Sherrod, 1999; Reiners et al., 2002; Mitchell and Montgomery, 2006). This regional southerly plunging anticline causes pre-Cenozoic crystalline rocks to dominate the northern part of the range, and Cenozoic sedimentary and volcanic rocks to become progressively younger and more extensive southward. Pleistocene volcanoes, such as Mt. Rainier, discontinuously cap the range. The area around the CSL is midway along the anticline. Thus, the area includes rocks ranging from the Jurassic ophiolitic Ingalls Tectonic Complex, post-accretionary Cretaceous tonalitic plutons, to Cenozoic cover sequences.

One of the key formations in the cover sequences is the arkosic Chumstick Formation, described in the following section. The Chumstick Formation was originally interpreted to fill "the Chiwaukum graben", which is bounded on the west by the northerly striking Leavenworth fault and bounded on the northeast by the northwesterly striking Entiat fault (Willis, 1953; Gresens et al. 1981; Tabor et al. 1892, 1987; Johnson, 1985; Evans, 1994). The Entiat and other major faults in the northern part of the range were known to dextrally offset pre-Cenozoic units by tens to hundreds of kilometers (Umhoefer, 1987). Thus, the Chiwaukum graben was proposed to be a pull-apart basin between these strike-slip faults (Gresens et al., 1981). Although no Eocene dextral displacement on the Entiat fault was known (Gresens et al., 1981) and none has been documented since, this transtensional model has been used to describe the CSL and surrounding area during Eocene time (e.g. Johnson, 1985).

An alternative to the transtensional model is that the area underwent regional extension prior to strike-slip faulting. Geochronology shows that middle crustal rocks were exhumed from late Cretaceous through early Eocene time throughout the region (Haugerud et al., 1991; Wernicke and Getty, 1997; Paterson et al., 2004; Mclean et al.). Many workers consider detachment-style extensional tectonics to be responsible for this exhumation, though some have pointed out that other mechanisms have not been ruled out (e.g. Wernicke and Getty, 1997). The presence of detachment-bound metamorphic core complexes of Eocene age in the northeastern part of Washington State (e.g., Doughty and Price, 1999) also motivates models for regional extension.

Models for regional extension do not specifically address fold hinges within and around the CSL. In a separate hypothesis, the fold hinges were proposed to be transpressive structures near the ends of regional faults superposed on older, extensional basins. Although they differ in detail, both the transtension and the two-stage extension-transpression models describe the CSL as a local basin bounded by a combination of syndepositional normal and/or strike-slip faults. Because elsewhere in the northern part of the Cascade Range these dextral faults are intruded by Oligo-Miocene plutons, the structural history of "the Chiwaukum graben" was thought to be limited to the Eocene.

Significantly, an interval of shortening affected the eastern flank of the central Cascade Range from late Miocene to Recent time. Examples of this younger folding are the anticlinal structure of the Cascade Range and numerous northwesterly trending folds, including the Yakima fold belt, in the Miocene Columbia River Basalt Group. Active seismicity, folds, and faults in the Yakima fold belt (Reidel et al., 2003) and in the Puget Lowland west of the Cascade Range (Blakely et al., 2002; Sherrod et al., 2004; Booth et al., 2004) show that shortening in the region is ongoing. Geodetic monitoring of crustal displacements demonstrates that active block rotation, distributed plate-boundary deformation, and stresses at the base of the lithosphere combine to drive the deformation across the region (Wells et al., 1998; Wang et al., 2003).

Stratigraphy

The Cenozoic sedimentary and volcanic rocks in Washington State consist of four informally named synthems. Synthems are major unconformity-bounded sequences of tectonic origin and of inter-regional extent (Chang, 1975). The four in Washington are (Cheney, 1994; Hanneman et al., 2002): (a) the Challis synthem of Eocene arkosic strata and basaltic and felsic volcanic rocks, (b) the Kittitas synthem of Oligocene to Miocene andesitic and felsic volcanic rocks (these are largely absent from the area of CSL), (c) the Miocene Walpapi synthem of the Columbia River Basalt Group (CRBG) and various felsic volcaniclastic and arkosic interbeds, and (d) the Plio-Pleistocene High Cascade synthem of predominantly andesitic volcanic rocks and surficial sediments. Challis- and Kittitas-aged plutons occur throughout the range.

On the eastern flank of the range, the Challis synthem, which is our major focus, contains five unconformity-bounded formations (Table 1). The Taneum and Naches formations are not known in the vicinity of the CSL. The arkosic Swauk and Roslyn formations are of greatest interest here. Regional structural and stratigraphic relations presented in the following sections indicate that strata originally called the Chumstick Formation in the CSL (Gresens et al, 1981) are equivalent to the previously described Roslyn Formation south of the CSL. Thus, we use the name Roslyn Formation instead of Chumstick Formation.

TABLE 1 UNCONFORMITY-BOUNDED FORMATIONS OF THE EOCENE CHALLIS SYNTHEM ON THE EASTERN FLANK OF THE CASCADE RANGE

Name with precedence	Synonymous names	Composition	Age Ma
Naches		felsic and andesitic volcaniclastic rocks and arkose	39 to 42
Roslyn	Chumstick	predominantly arkosic	43 to 46
Teanaway	Basalt of Frost Mountain	basalt with some felsite, felsic volcaniclastic rocks, and minor arkose	46 to 48
Taneum	Silver Pass, Peoh Point, Mount Catherine	felsite and felsic volcaniclastic rocks	50 to 52
Swauk	Manastash, Guye	predominantly arkosic	53 to 57

Notes: Strigraphically upward is up in the table. Data are from Cheney (1994, 1999). Ages are imprecise because they are K-Ar and fission-track dates.

The arkosic Roslyn and Swauk formations can be difficult to distinguish where they are not separated by the basaltic Teanaway Formation or intruded by dikes related to the basalts of the Teanaway Formation. However, several criteria distinguish these two arkosic formations (Table 2).

The Swauk Formation dominates the Blushastin area and the Roslyn Formation dominates the Leavenworth area. The Blushastin area is astride US 97. Note that the northern end of the Blusshastin area (Fig. 2) joins the southern end of the Leavenworth area (Fig. 3), which is along US 2.

Both areas are forested, have about a kilometer of topographic relief, and are crossed by a system of deteriorating logging roads. Except for the major valleys, the areas are unglaciated; the major valleys are filled with glacial and alluvial sediments, and much of the uplands are mantled with loess. Thus, contacts are rarely seen. Bedding in the formations is moderately to vertically dipping. To be mapped in the above conditions, units must be more than a hundred meters thick. Nonetheless, some areas of superb outcrop exist, and access by logging roads along with topographic maps and GPS technology have improved since the previous phase of geologic mapping (Tabor et al., 1982, 1987).

Internal Stratigraphy of the Swauk Formation

Units of the arkosic Swauk Formation in the Blushastin area have varying amounts of nonmarine conglomerate, sandstone, and black to olive siltstone (Table 3). The stratigraphy of the formation is displayed in a previously unrecognized syncline that underlies Tronsen Ridge (Fig. 2). Major criteria (Table 3) for distinguishing the members of the formation are the amount of conglomerate in the unit, the thickness of the conglomeratic beds, and the size of the clasts in the conglomerates. Other criteria are the style and thickness of bedding, the presence of map-scale unconformities, and stratigraphic position with respect to other members in the syncline. Thicknesses of members are from cross sections (Fig. 4 2); because intraformational faults and folding are impossible to map, the true thicknesses may be less than those shown on the cross sections.

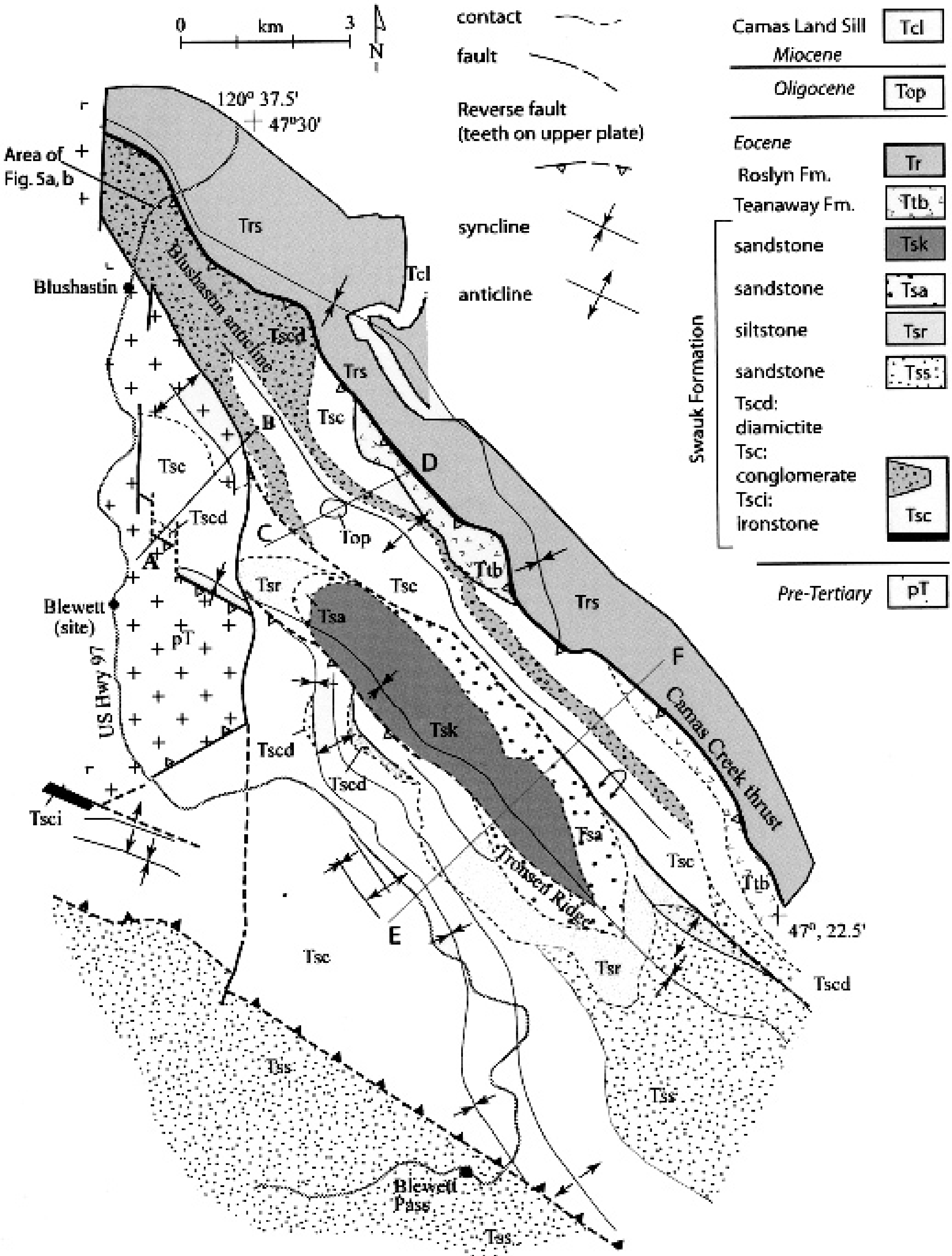
TABLE 2: DISTINGUISHING CHARACTERISTICS OF THE ROSLYN AND SWAUK FORMATIONS

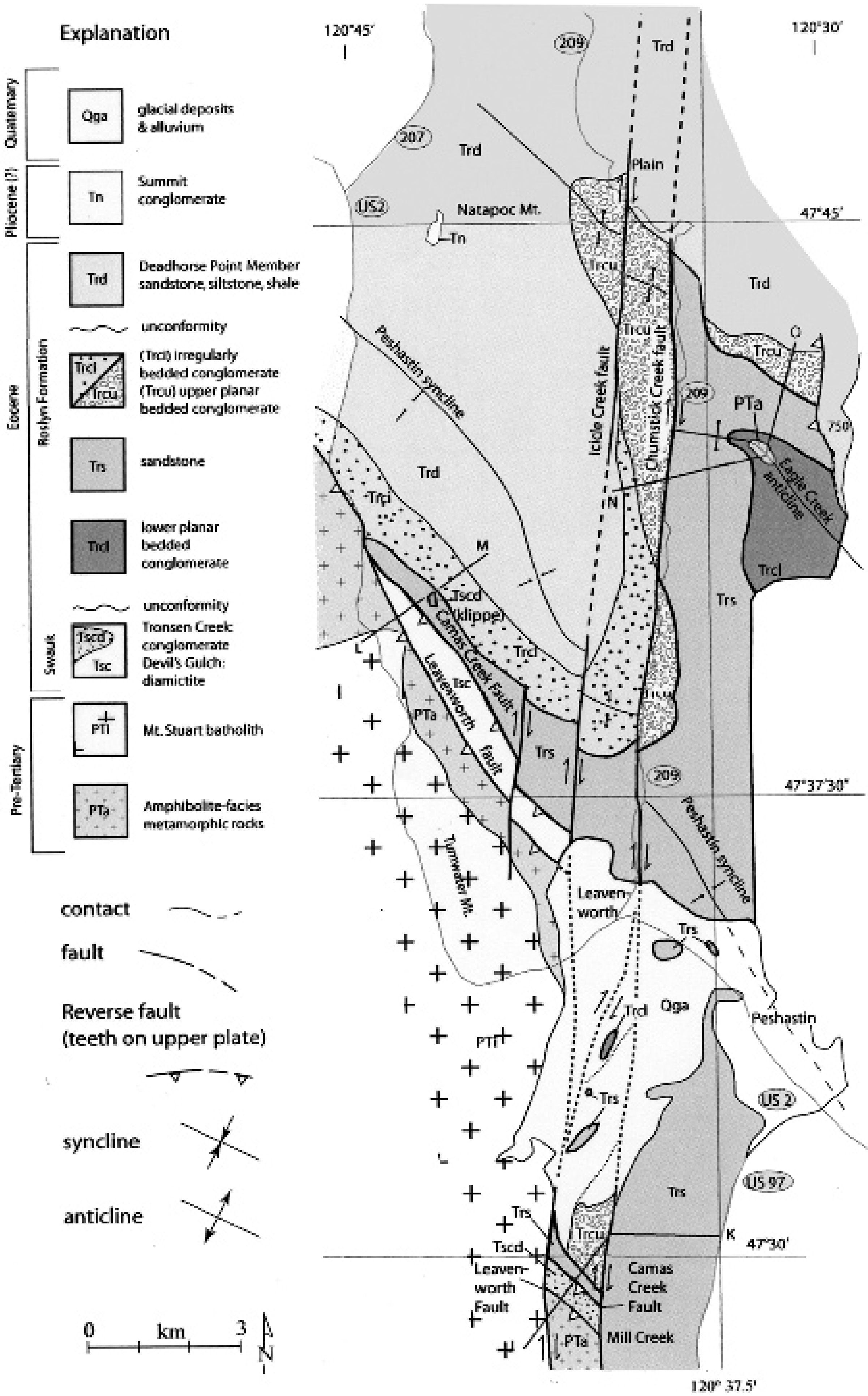
Characteristics	Roslyn Formation	Swauk Formation
Volcaniclastic units	Multiple felsic tuffs, 1-20 m thick FT ages ~45+/-3 Ma (Gresens et al. 1981)	Andesitic, Up to 100's m thick FT ages >49 +/-5 Ma (Cheney, 1994, fig. 8)
Pollen (Newman, 1981)	Late Eocene	Middle Eocene
Felsic volcanic clasts conglomerates	3 to 70% (Fig 13 in Evans, 1994)	>/=10% (Table 3 in Evans, in 1994. Table 1 in Taylor et al. 1988)
Maximum size of clasts in polymict conglomerate	</= 0.4 m	mostly <0.4 m, but in some outcrops 0.4 m to 1.0 m
Teanaway dikes	None	Some, but none in Leavenworth area
Color of outcrops (but not of road cuts)	White	Tan
Monomict diamictite	None	In conglomerate of Tronsen Creek (Table 3)
Lags of pebbles and scattered pebbles < 7 cm in sandstones	Much more comomn than interbedded conglomerate	Much less common than interbedded conglomerate
Thickness of beds, especially sandstones	Many > 8 m	Mostly < 8 m

Note: FT is Fission track age from zircon reported in the cited publications

The most important unit in this area for understanding the structure and geologic history of the CSL is the basal conglomerate of Tronsen Creek (Tsc in Fig. 2). This thickest (~ 2 km) unit of the Swauk Formation contains polymict conglomerate. Lithologies of the clasts are present in basement rocks to the west. The most extensive unit in this conglomeratic unit is the diamictite of Devils Gulch (Tscd in Figs. 2 and 4 and Table 3). The diamictite is unsorted, unstratified, and usually monomict, with rounded clasts mostly < 1 m in diameter of mostly tonalite, ultramafic rocks, or, rarely, phyllite. The granule-sized to microscopic matrix is composed of mineral fragments of the dominant type of clast. The diamictite may be a rock-avalanche deposit. Gresens et al. (1981) and Tabor et al. (1982) believed that the diamictite is part of the Roslyn Formation and that it was deposited along the margin of Chiwaukum graben when the Leavenworth fault was active. However, Figure 2 shows that the diamictite is in the Swauk Formation and is cut by the northwesterly striking Leavenworth fault system.

***Figure 2**. (Right) Geologic map of the Blushastin area. Note that the northern boundary of this figure joins the southern boundary of Figure 3. Cross sections are in Figure 4*


0 km 3
N
contact
fault
Reverse fault
(teeth on upper plate)
syncline
anticline
Camas Land Sill Tcl
Miocene
Oligocene Top
Eocene
Roslyn Fm. Tr
Teanaway Fm. Ttb
Swauk Formation
sandstone Tsk
sandstone Tsa
siltstone Tsr
sandstone Tss
Tscd: diamictite
Tsc: conglomerate
Tsci: Ironstone
Tsc
Pre-Tertiary pT
120° 37.5'
47°30'
Area of Fig. 5a, b
Trs
Tcl
Blushastin
Blushastin anticline
Tscd
Trs
Tsc
B
D
Tsc
Tscd
C
Top
A
Ttb
Blewett (site)
Tsr
Tsc
Tsa
pT
Trs
F
US Hwy 97
Tsk
Camas Creek thrust
Tscd
Tscd
Tsci
Tsa
Tsc
Ttb
Trobsen Ridge
E
47°, 22.5'
Tsc
Tsr
Tscd
Tss
Tss
Blewett Pass
Tss



Explanation
Quaternary
Qga
glacial deposits & alluvium
Pliocene (?)
Tn
Summit conglomerate
Eocene
Roslyn Formation
Trd
Deadhorse Point Member sandstone, siltstone, shale
unconformity
Trcl
Trcu
(Trcl) irregularly bedded conglomerate (Trcu) upper planar bedded conglomerate
Trs
sandstone
Trcl
lower planar bedded conglomerate
unconformity
Swauk
Tscd
Tsc
Tronsen Creek conglomerate Devil's Gulch: diamictite
Pre-Tertiary
PTi
Mt. Stuart batholith
PTa
Amphibolite-facies metamorphic rocks
contact
fault
Reverse fault (teeth on upper plate)
syncline
anticline
0
km
3
N
120°45'
120°30'
47°45'
47°37'30"
47°30'
120° 37.5'
209
207
US2
Trd
Plain
Natapoc Mt.
Tn
Trcu
PTa
Peshastin syncline
Icicle Creek fault
Chumstick Creek fault
Eagle Creek anticline
750'
O
N
M
L
K
Trcl
Trs
Tscd (klippe)
Camas Creek Fault
Leavenworth fault
Tsc
Tumwater Mt.
Leavenworth
Peshastin syncline
Qga
Peshastin
PTi
US 2
US 97
Trcu
Tscd
Leavenworth Fault
Camas Creek Fault
Mill Creek

The overlying members of the Swauk Formation contain three unconformities (Table 3). The presence of these unconformities indicates a “layer cake-like” succession. So, despite having lithologies in common, the members of the Swauk Formation do not interfinger and are not stratigraphic equivalents or facies of each other.

A polymict conglomerate (Ttb in Fig. 2) is similar to the conglomerate of Tronsen Creek, except that it contains angular to sub-rounded clasts of basalt. Some basalt flows (Tabor et al. 1982) and black siltstone also occur in this unit. Although this unit was previously mapped as a member of the Roslyn Formation (Tabor et al., 1982; Evans, 1994), we assign it to the Teanaway formation because of its basaltic clasts, minor basalt flows, and stratigraphic position.

Internal stratigraphy of the Roslyn Formation

Table 4 shows the stratigraphy of the Roslyn Formation in the Leavenworth area. Previous workers in the CSL (Gresens et al, 1981; Evans, 1994; Evans and Johnson, 1989) believed that facies changes dominate the entire vertical section of the Roslyn Formation. However, a previously unrecognized robust marker unit that contains conglomerate-bearing sandstones (Trci and Trcu of Figs. 3 and 4) indicates a laterally extensive stratigraphy (Table 4).

The thickness of the Roslyn Formation in CSL is controversial. Estimates range from a maximum of 12 km based on stratigraphy (Evans, 1994) to a minimum of 2 km based on a gravity survey (Silling, 1979). Table 4 suggests that the composite thickness of the formation in CSL is < 5.5 km. Because intrafdrmational faults and folding are impossible to map, the true thicknesses of some units may be less than shown in the table. Moreover, because the formation is truncated by at least three internal unconformities, the actual thickness at a given place may be significantly less than the composite thickness.

Felsic tuffs are potential markers within the Roslyn Formation in the CSL (Table 2; Gresens et al., 1981). McClincy (1986) recognized 19 tuffs. Cheney and Hayman (2007) reported another six outcrops not previously mapped by Whetten and Laravie (1976) or by Whetten (1980a, b); so, the total number of tuffs may exceed 19. Because most tuffs are <1 to < 5 m thick, they are not useful marker units in this rugged and forested western portion of the CSL. Two tuffs that are > 10 m thick were useful markers for Whetten and Laravie (1976) and Gresens et al. (1981) southeast of Figure 3. The nearest possible source of the tuffs is the Duncan Hill pluton, which is about 20 km northeast of Plain (Fig. 6).

The Deadhorse Point Member of Evans (1994) (Trd in Table 4), is the youngest unit of the Roslyn Formation in CSL. Its stratigraphic position and locally high organic contents (four of eight samples have 1.5 to 4.3 % total carbon;Evans, 1988; table 3.2) suggest that it may be correlative with the coal-bearing upper part of the Roslyn Formation near Cle Elum. However, no coal beds are known in the Roslyn Formation in the CSL (Huntting, 1943).

A common perception is that only the Roslyn Formation is in the Leavenworth area (Gresens et al., 1981; Tabor et al., 1982, 1987; Evans, 1994). However, Figure 3 shows previously unrecognized units of the Swauk Formation. As noted below, the presence of these units has significant structural implications.

Figure 3. *(Left) Geologic map of the Leavenworth area. Note that southern boundary of this figure joins the northern boundary of Figure 2. Cross sections are in Figure 4.*

GEOLOGY OF THE CHIWAUKUM STRUCTURAL LOW

Overview

In the following paragraphs, we discuss the geology of the Blushastin and Leavenworth areas (Figs. 2, 3 and 4) and of individual outcrops (Fig. 5). We then provide a regional synthesis of the two areas in (Fig. 7). For areas where our mapping is limited we rely upon Evans (1994) for much of the northwestern and northern extent of the Roslyn Formation and on Whetten (1980b) for the location of the Peshastin syncline within it.

At the heart of our presentation is a reinterpretation of the Leavenworth fault. The Leavenworth fault is the southwestern bounding fault of the CSL. It was originally thought to be a single, continuous, somewhat sinuous feature (Willis, 1953; Gresens et. al., 1981), but Whetten (1980b) and Tabor et al. (1987) showed that it has northwesterly and northerly striking segments. Our mapping shows that the Leavenworth fault zone consists

TABLE 3: STRATIGRAPHIC UNITS OF THE SWAUK FORMATION NEAR BLUSHASTIN

Informal name and symbol	Original name and reference	Maximum Thickness	Conglom-erate	Volcani-clastics	Other Characteristics	Origin	Stratigraphy
Sandstone of Sand Creek Tsk	This paper	0.7 km x-sec. E-F	None	None	Similar to Tsr except sandstones are cross-bedded and olive siltstone is minor	Fluvial and la-custrine	Unconformable on Tsa and Tsr
Siltstone of Transen Ridge Tsr	Shaly facies of Tronsen Ridge of Tabor et al. (1982), Taylor et al. (1988	0.5 km on southwest side of Tronsen Ridge	None	None	White sandstone, black siltstone, and olive siltstone in planar beds mostly 0.4 to 4 m thick	Lacus-trine	Unconformable on Tss and Tsc
Sandstone of Swauk Pass Tss	Sandstone facies of Swauk Pass of Taylor et al (1987)	0.9 km x-sec. G-H	</=2% clasts</= cobbles, matrix-supported, beds </= 0.9 m	Minor	Sandstone (com-monly cross-bed-ded and tan) and black siltstone, beds mostly <8 m thick, but some >8 and > 16 m thick	Fluvial	Unconformable on Tsg, Tsc and regionally on pre-Tertiary
Green Siltstone Tsg	This paper	0.2 km x-sect G-H	None	Common	Green siltstone and sandstone, minor black siltstone	Volcani-clastic	Conformable on Tsc?

of northwesterly trending reverse faults and younger, northerly strike-slip faults, both of which cut the Swauk and Roslyn formations.

Blushastin Area

The Blushastin area is bound on the west by pre-Tertiary crystalline basement (pT of Fig. 2). This basement consists of the Jurassic greenschist-grade metamorphic and ophiolitic rocks of the Ingalls Tectonic Complex and the 91 to 96 Ma tonalitic Mt. Stuart batholith (Tabor et al., 1982; Harper et al., 2003). The Swauk Formation of the Challis synthem is unconformable on, and locally in fault contact with, the crystalline basement (Fig. 2). Northwesterly trending folds and faults are typical of the Blushastin area (Fig. 2). The northwesterly trending Camas Creek fault is subparallel to the axial trace of the Blushastin anticline, which implies a genetic relationship between the two. Although the fault is not exposed, deflections of its trace up valleys suggest that it dips >70°SW. The fault places topographically higher and older Swauk and Teanaway formations in the Blushastin anticline over a syncline in the younger Roslyn Formation (Figs 2 and 4); thus, it is a reverse fault. Because the fault obliquely truncates more than the 1.5 km-wide limb of the syncline in the Roslyn Formation (Fig. 2), it must have an offset of > 4 km.

TABLE 3: STRATIGRAPHIC UNITS OF THE SWAUK FORMATION NEAR BLUSHASTIN (PART 2)

Informal name and symbol	Original name and reference	Maximum Thickness	Conglomerate	Volcaniclastics	Other Characteristics	Origin	Stratigraphy
Conglomerate of Tronsen Creek Tsc	Conglomeratic facies of Tronsen Creek of Taylor et al (1988)	0.5 km above and 1.3 km below Tscd, x - secs C-D, A-B	~20% clasts </= boulders, clast and matrix-supported, polymict	None	Predominantly sandstone (poorly cross-bedded) and black siltstone, some beds > 20 m thick	Fluvial and mud flow?	Nonconformable on Pre-Tertiary
Diamictite of Devils Gulch Tscd	Breccia of Devils Gulch of Taylor et al. (1988)	0.3 km x - sec. C-D 20 m?	~99% clasts < 3m monomict	None	99% unbedded and unstratified, clasts rounded to angular, mostly tonalitic clasts but locally 0.1 to 100% ultramafic clasts	Mudflow, rock avalanche?	Only mappable unit in Tsc
Ironstone Tsci	Ironstone deposits of Lamey (1950), Tabor et al. (1982)		Clasts </=boulders, matrix-supported	None	Ultramafic and other pre-Tertiary clasts in fine-grained, brown and magnetic matrix, grades downward into laterite	Re-worked laterite	Discontinuous basal unit of Tsc

Notes: Stratigraphically upward is up in the table. Abbreviation: x-sec is cross-section in Figure 5

Independent evidence for shortening in the area comes from a structural analysis of the diamictite of Devil's Gulch exposed along US 97 near milepost 178.7; this locality is in the hanging wall of the Camas Creek fault (Fig. 5a, b). The diamictite has hundreds of small-scale faults with centimeter-scale offsets and slickensides (Fig. 5, b). The slickensides cut across the tonalitic clasts and matrix of the diamictite without deflection. All striae on the slickensides are of the asperity-abrasion or groove type (cf. Means, 1987). We measured 129 striae on multiple surfaces. The trends and plunges of the striae were analyzed with the software FaultKin (e.g., Cladouhos and Allmendinger, 1993) and a focal mechanism solution was determined that is consistent with shortening across the Camas Creek fault (Figure 5b).

Southwest of the Camas Creek fault, another northwesterly trending fault truncates the southwestern limb of the syncline underlying Tronsen Ridge (Fig. 2). The dip of the contact with the conglomerate of Tronsen Ridge is unknown. Farther to the northwest at Windmill Point (at a deeper structural level), this fault cuts the pre-Tertiary basement (cross section C-D of Fig. 4). However, to the southeast the fault dies out in an anticline in the shale of Tronsen Ridge, that is, the fault is a blind thrust (cross section E-F of Fig. 4).

In the vicinity of Tronsen Ridge, the Swauk Formation has folds with sinuous axial traces (Fig. 2).

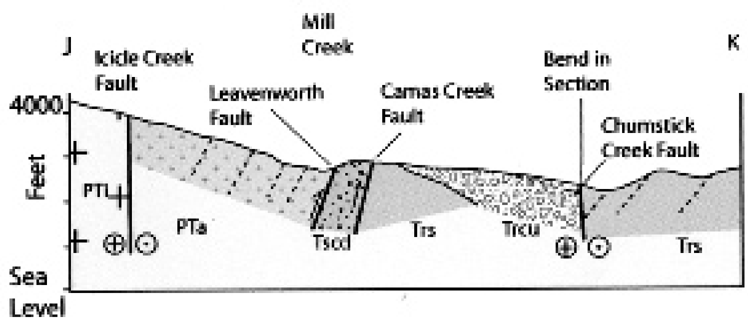
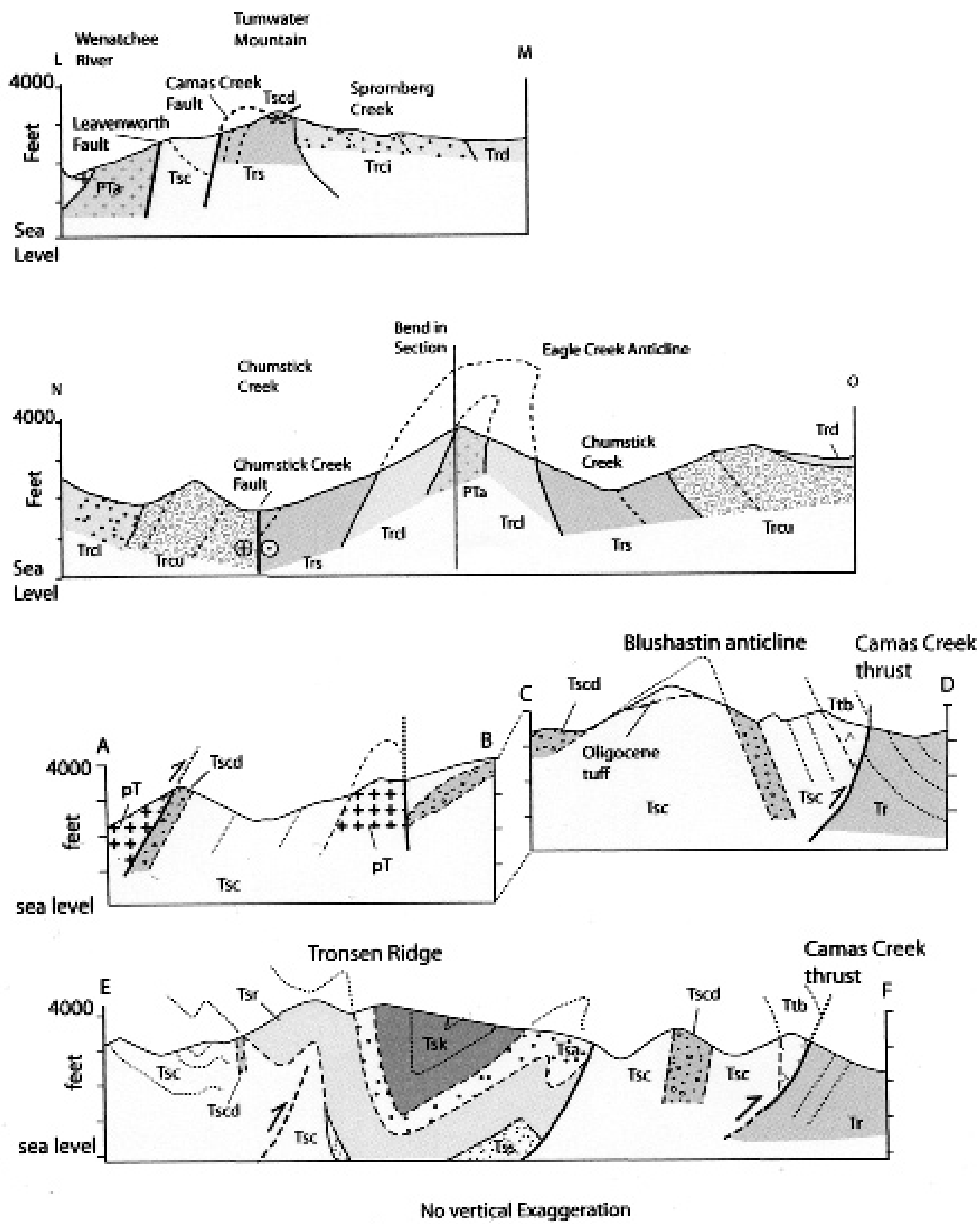


Figure 4. *(Left) Cross sections of the Blushastin and Leavenworth areas arranged from north (top) to south (bottom).. Lines of sections are on Figures 2 and 3. These cross sections have no vertical exaggeration, but they are not the same scale as Figures 2 and 3. See the Explanations to Figures 2 and 3 for map unit definitions.*



Numerous Teanaway dikes are perpendicular to the general trend of these traces. This relationship indicates that the dikes are syn-to-post shortening, i.e., the dikes track stretch along the fold hinges. Thus, the sinuous folds are older than, or the same age as, the Teanaway Formation and are older than the folding that generated the Blushastin anticline and Camas Creek fault and which involve the Roslyn Formation.

Leavenworth Area

The Leavenworth area (Fig.3) is bound on the west by amphibolite-facies rocks of the Nason terrane and by the 91 to 96 Ma tonalitic Mount Stuart batholith (Tabor et al., 1987; Paterson et al., 1994). The most widespread Tertiary formation in this area is the Roslyn Formation. The major structures in the Eocene rocks of CSL are the northwesterly plunging Peshastin syncline on the southwest and the doubly plunging Eagle Creek anticline on the northeast (Page, 1939; Willis, 1953; Whetten, 1980a, Whetten and Laravie, 1976; Tabor et al., 1987). Swakane Biotite Gnesiss crops out in the core of the Eagle Creek anticline and northeast of the Entiat fault.

Whetten (1980a, 1980b) mapped the Leavenworth fault as a northwesterly trending feature on the northeastern side of Tumwater Mountain northwest of Leavenworth and at Mill Creek 9 km south of Leavenworth. At both locations he mapped pre-Tertiary basement rocks on the southwest side of the fault and sedimentary rocks, which he called Chumstick Formation, on the northeastern side. We adopt this as the strict definition of the Leavenworth fault: basement rocks against sedimentary rocks. At Blushastin the fault that places basement rocks against sedimentary rock is the one that also dies out as a blind thrust at Tronsen Ridge.

The dip of the Leavenworth fault is difficult to determine. Along Tumwater Mountain, outcrops are sufficiently sparse, and the dip of the fault is sufficiently steep, that the trace of the fault across valleys cannot be precisely demonstrated. However, at the southeastern end of Tumwater Mt. (Fig. 3) serpentinite adjacent to the mapped location of the fault has an S-C-like fabric that dips 75° to vertical to the southwest; this fabric indicates top-to-the-northeast (Fig. 5c). We interpret this fabric as resulting from high-angle reverse faulting. The fabric must have been imparted after late Cretaceous time because the deformed serpentinite contains a 36 by 50 cm phacoid of tonalite, likely derived from the Mt. Stuart batholith, which intrudes the serpentinite elsewhere.

Another example of fabrics that is consistent with kinematics interpreted from the map pattern is in crystalline rocks near Mill Creek (Fig. 3). There, pre-Tertiary felsic metavolcanic rocks are intensely cleaved and contain centimeter- to meter-scale phacoids of more massive rock with millimeter-scale veinlets in various orientations. The cleavage or incipient foliation in the metavolcanic rock varies from vertical to 70° SW, which also suggests that the fault dips steeply to the southwest. A brecciated Teanaway dike adjacent to the metavolcanic rocks implies that the Leavenworth fault is essentially the same age as the Camas Creek fault.

The Camas Creek fault traces into the Leavenworth area. An outcrop of the diamictite of Devils Gulch is northeast of the Leavenworth fault at Mill Creek (Fig. 3). By analogy to the Blushastin area, the covered trace of the Camas Creek fault is between this diamictite and the Roslyn Formation to the northeast (cross section J-K of Fig. 4).

On the northeastern side of Tumwater Mountain is a thick conglomerate-bearing unit with clasts <_1 m in diameter (Fig. 3). The conglomerate is identical to the conglomerate of Tronsen Creek of the Swauk Formation (Evans, 1994), except that it contains neither the diamictite of Devils Gulch nor Teanaway basaltic dikes. This conglomerate dips northeastward toward non-conglomeratic Roslyn Formation, which dips southwestward. Whetten (1980a, 1980b) mapped these two units as opposite limbs of a syncline in the Roslyn Formation. Because the conglomerate is conglomerate of Tronsen Creek, the contact between the two opposing units is the Camas Creek fault. In the headwaters of Freund Creek (Fig. 3), the fault dips as shallowly as 45°SW, with synclinally folded conglomerate of Tronsen Creek over homoclinally dipping non-conglomeratic Roslyn Formation.

Additionally, a diamictite identical to the one at Blushastin and at Mill Creek caps a hill on the northwestern part of Tumwater Mountain (Fig. 3). Below the diamictite is nonconglomeratic Roslyn Formation (Whetten, 1980a). Therefore, the hill is a klippe of the Camas Creek fault (cross section L-M of Fig. 4). Hills 0.3 km to the west (Whetten, 1980a) and 0.7 km to the southeast have no outcrops of diamictite but have < 0.5 m boulders of tonalite below their summits. We

TABLE 4: STRATIGRAPHIC UNITS OF THE ROSLYN FORMATION IN THE WEST CENTRAL PORTION OF THE CHIWAUKUM STRUCTURAL LOW

Unit Symbol	Previous Name	Lithology	Maximum Thickness	Measured sections of Evans (1988)	Tuffs	Other	Origin	Stratigraphy
Trd	Deadhorse Canyon Member of Evans (1994)	Plannar bedded sandstone and olive and black fine-trained sandstone and silstone; lags of pebbles but almost no conglomerate	~2.0 km Evans (1994)	A.13, 200 m A.14, 790 m A.15, 40 m A.15, 62 m	No	Only sparsely mapped in this study	Lacustrine and fluvial	Unconformable on Trgu, Trci, Trcu, Trgl
Trci		Multiple beds of mostly matrix-supported conglomerate < 2 m thick in sandstone	0.6 km x-sec L-M		Yes	Irregularly bedded; maximum clast >/= 15 cm	Fluvial	Unconformable on Tss; same stratigraphic position as Trcu
Trcu		Multiple beds of mostly clast-supported conglomerate, mostly </= 4 m thick (maximum 12 m) with lesser sandstone	0.8 km x-sec L-M	A.6, 210 m	Yes	Planar bedded, largest clast usually > 15 cm, maximum = 42 cm	Fluvial	Ro>/= 0.70 in underlying units (Evans, 1994, fig 15).
Trs		Mostly sandstone, lags of pebbles and minor conglomerate are more common east of the Chumstick Creek Fault	0.9 km x-sec N-O		Yes		Fluvial	

interpret these tonalitic clasts to indicate that the klippe recently was more extensive.

The other important features of the Leavenworth area are three previously unrecognized N-S faults that dextrally displace the Leavenworth fault (sensu stricto) and other features 0.5 to 9 km (Fig. 3). The Chumstick Creek fault dextrally offsets the Leavenworth fault at Mill Creek and the axial traces of the Peshastin syncline and the Eagle Creek anticline. The fault also offsets the map trace of the upper conglomerate of the Roslyn Formation (Trcu of Fig. 3). North of Mill Creek, the fault juxtaposes southwesterly dipping sandstone of the Roslyn Formation against easterly dipping conglomerate (cross section J-K of Fig. 4). North of US 2, the fault accounts for the anomalous N-S course of the lower portion of Chumstick Creek; farther north the creek follows the eastern limb of the Peshastin syncline. In the upper conglomerate unit (Trci of Fig. 3) along Chumstick Creek are fractured cobbles, white veinlets, and outcrop-scale N-S faults that record cataclastic deformation imposed by the Chumstick Creek fault (Fig. 5d).

TABLE 4: STRATIGRAPHIC UNITS OF THE ROSLYN FORMATION IN THE WEST CENTRAL PORTION OF THE CHIWAUKUM STRUCTURAL LOW (PART 2)

Unit Symbol	Previous Name	Lithology	Maximum Thickness	Measured sections of Evans (1988)	Tuffs	Other	Origin	Stratigraphy
Trcl	Red fanglomerate of Gresens et al (1981)	Beds of mostly clast supported conglomerate < 4 m thick in sandstone; only a few felsite clasts near base	0.4 km x - sec N-O	A.14, 1370 m A.5, 260 m	Yes	Planar bedded., maximum clast . 30 cm	Fluvial	Unconformable on Swakane biotite gneiss
Trge		Sandstone that contains Eagle Creek Tuff; Whetten and Laravie (1976) show Trcl up-section from this tuff	0.3 km Whetten and Laravie (1976)		Yes </= 20 m thick	Not mapped in this study; Tcs of Whetten and Laravie (1976)	Fluvial	
Trf		Redweathering; clast - supported conglomerate with few felsite clasts and minor sandstone	0.2 km Gresens et al (1981)		No	Not mapped in this study; Tcf of Whetten and Laravie (1976)	Fluvial	Unconformable on Swakane biotite gneiss

Notes: Stratigraphically upward is up in the table; x-sec is cross section in fig. 4; Ro is vitranite reflectance

Displacements on the Icicle Creek and Chumstick Creek faults are complex. For example, the Chumstick Creek fault displaces the Camas Creek fault ~1 to 2 km between the Blushastin and Leavenworth areas. However, to the north it displaces the trace of the Eagle Creek anticline 3.2 km. Even more difficult to explain, the Icicle Creek fault, which juxtaposes the Roslyn Formation against crystalline basement, displaces the Leavenworth and Camas Creek faults by nearly 10 km. However, north of Tumwater Mountain, it displaces fold hinges < 1.4 km. No simple explanation exists for these variable displacements. However, some if not most, of this variable displacement is taken up by distributed cataclastic deformation, as indicated by structures in an isolated outcrop of deformed conglomerate (unit Trcl) adjacent to Icicle Creek Fig. 6.

GEOLOGY IN THE VICINITY OF THE ENTIAT FAULT

Introduction

The Entiat fault bounds the CSL on the northeast. It juxtaposes the Eocene Roslyn Formation of the CSL against metamorphic rocks of the pre-Cenozoic Swakane and Mad River terranes to the northeast. The Entiat scarp is a striking feature on the northeastern side of the CSL. However, Laravie (1976) showed that the scarp is not related to the Entiat fault; instead, a mylonitic zone in the metamorphic rocks, which he called the Chumstick fault, is at the base of the scarp. The scarp also coincides with the limb of a major antiform in the metamorphic rocks.

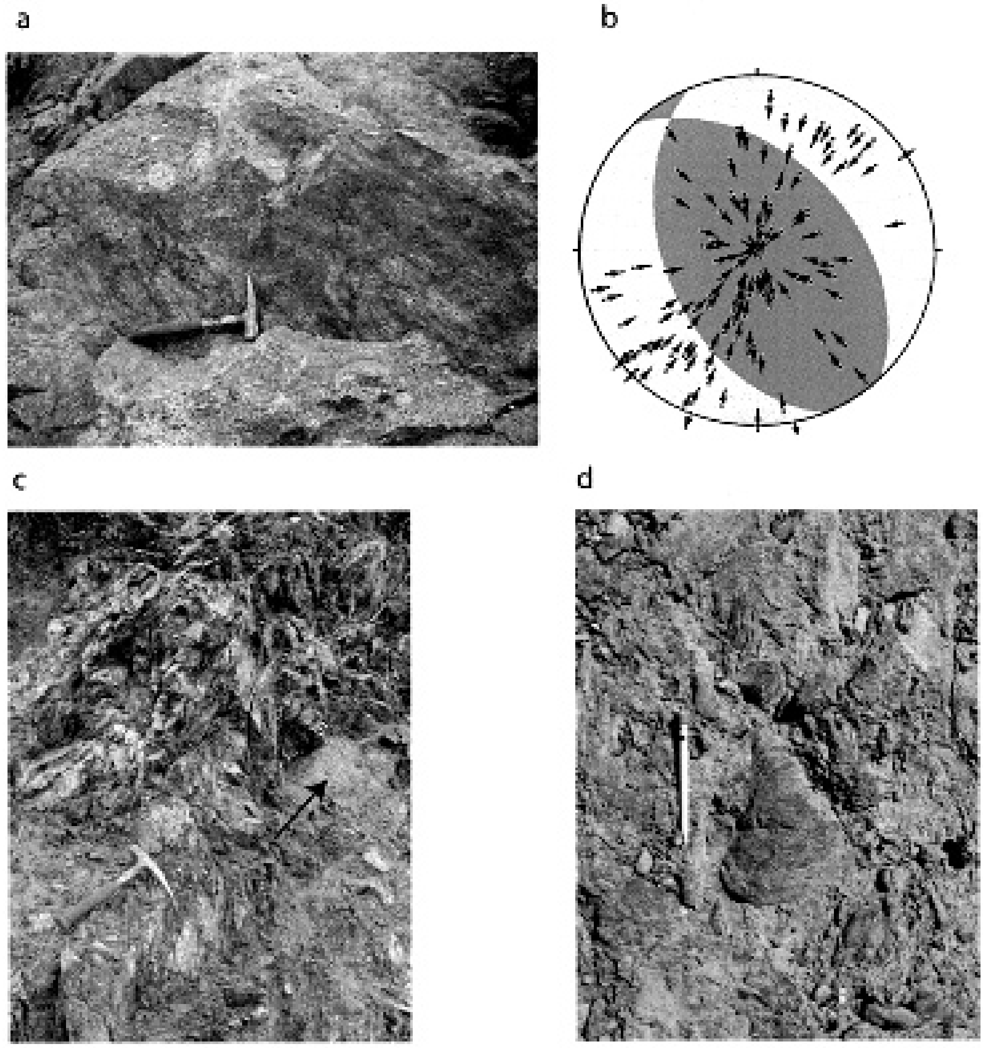


Figure 5. *(Left) (A) One of hundreds of slickensides cutting the diamicite in the hanging wall of the Camas Creek Fault along a 150 m stretch of US Highway 97. (B) Trends and plunges of striae measured on slickensides along US Highway 97, with vector-directions indicating the direction of slip (all reverse sense based upon steps in the abraded surfaces). The shaded region indicates the region of compression, solved by FaultKin (Cladouhos and Allmendinger, 1993) producing a solution compatible with shortening across the nearby Camas Creek thrust. (C) S-C, phacoidal fabric in the serpentine just northwest of the Leavenworth fault (the fault trace can be seen from this locality). The S-C structure is compatible with a high-angle reverse fault, and a lens of tonalite (arrow) shows that the deformational fabric is likely Teriary. (D) Cataclastic features in sandstones adjacent to Icicle Creek indicating distribution strain related to nearby translation faulting along the Icicle Creek and Chumstick Creek faults. Pencil for scale is oriented roughly NS, parallel to the regional strike-slip faults.*

The metamorphic rocks and the Entiat fault have complex histories. Most importantly, as noted by Laravie (1976), closely spaced fracturing related to the Entiat fault affects the metamorphic rocks, the zone of mylonite (Chumstick fault), and the Roslyn Formation.

The second important feature is that although the maps of Tabor et al. (1982, 1987) show that the Entiat fault dextrally displaces the Swakane Biotite Geneiss by at least 50 km, no evidence for dextral displacement of the Roslyn Formation was known by Gresens et al. (1981), and none has been demonstrated since. The sense of movement on the Entiat fault that caused the late and ubiquitous fracturing is still unknown, but it clearly post-dates deposition, and it also obliquely truncates the Chiwawa River syncline , which folds the Roslyn Formation along the northeastern margin of the CSL. .

Metamorphic Rocks

The metamorphic rocks northeast of the Entiat fault are the Swakane Biotite Gneiss and the Mad River terranes. Both teranes contain biotitic gneiss, but the Swakane Biotite gneiss almost exclusively so. Unlike the Swakane Biotite Gneiss, at least within 4 km of the Entiat fault, the Mad River biotitic gneiss contains 1 to 70 % quartz folia (metachert?) <1 cm to > 18 cm thick, and it is intercalated with mappable bodies felsic gneiss (felsic metavolcanic rock), marble, amphibolite and very weakly folated alaskite..

TABLE 5: MAJOR NORTHWESTERLY STRIKING FOLDS ON THE EASTERN FLANK OF THE CASCADE RANGE

Folds	Rocks in core of fold	High-angle reverse fault on steeper NE limb	Maximum altitude of base of CRBG	Folds down plunge to SE in CRBG	Cut by N-S fault
Swakane Anticline	Pre-Tertiary Crystalline	Unnamed fault (Gulick, 1990)	1450 m	Badger Mountain anticline, Moses Stool Anticline (Gulick, 1990)	
Chiwawa River Syncline	Roslyn Formation		1200 m? (Laravie, 1976)	Laurel Hill Monocline	Coulter Creek Fault
Eagle Creek Anticline	Pre-Tertiary crystalline	Eagle Creek fault but low angle to south (Patton and Cheney, 1971)	absent	Hog Ranch Anticline	Chumstick Creek fault, Icicle Creek fault (this study)
Peshastin Syncline	Roslyn Formation		absent		Chumstick Creek fault, Icicle Creek Fault (this study)
Naneum Ridge Anticline	Pre-Tertiary Crystalline	Camas Creek Fault, Leavenworth Fault	2000 m	Naneum Ridge Anticline	Chumstick Creek Fault (this study)
Naneum Creek Syncline	Swauk Formation		1700 m	Naneum Creek Syncline	
Table Mountain Anticline	Swauk Formation		1750 m		
Kitittas Valley Syncline	Roslyn Formation		750 m	Kitittas Valley Syncline	

The Swakane Biotite Gneiss is the youngest and structurally lowest terrane in the eastern Cascade Range (Paterson et al. 2004). The Mad River terrane was emplaced over the Swakane terrane in the Cretaceous along the Dinkleman decollement (Paterson et al., 2004). In the vicinity of Sugarloaf peak, this fault is locally marked by a large body of talc-bearing rock (caused by silicification and hydration of ultramafic rock).

Cenozoic Rocks

The stratigraphy of the Roslyn Formation that Cheney and Hayman (2007) mapped in the southwestern portion of CSL has not yet been mapped in the northeastern part of CSL (in the vicinity of the Entiat fault). The rock types appear to be compositionally and texturally similar (Tabor et al. 1987), but the stratigraphy of the northeastern part could be different.

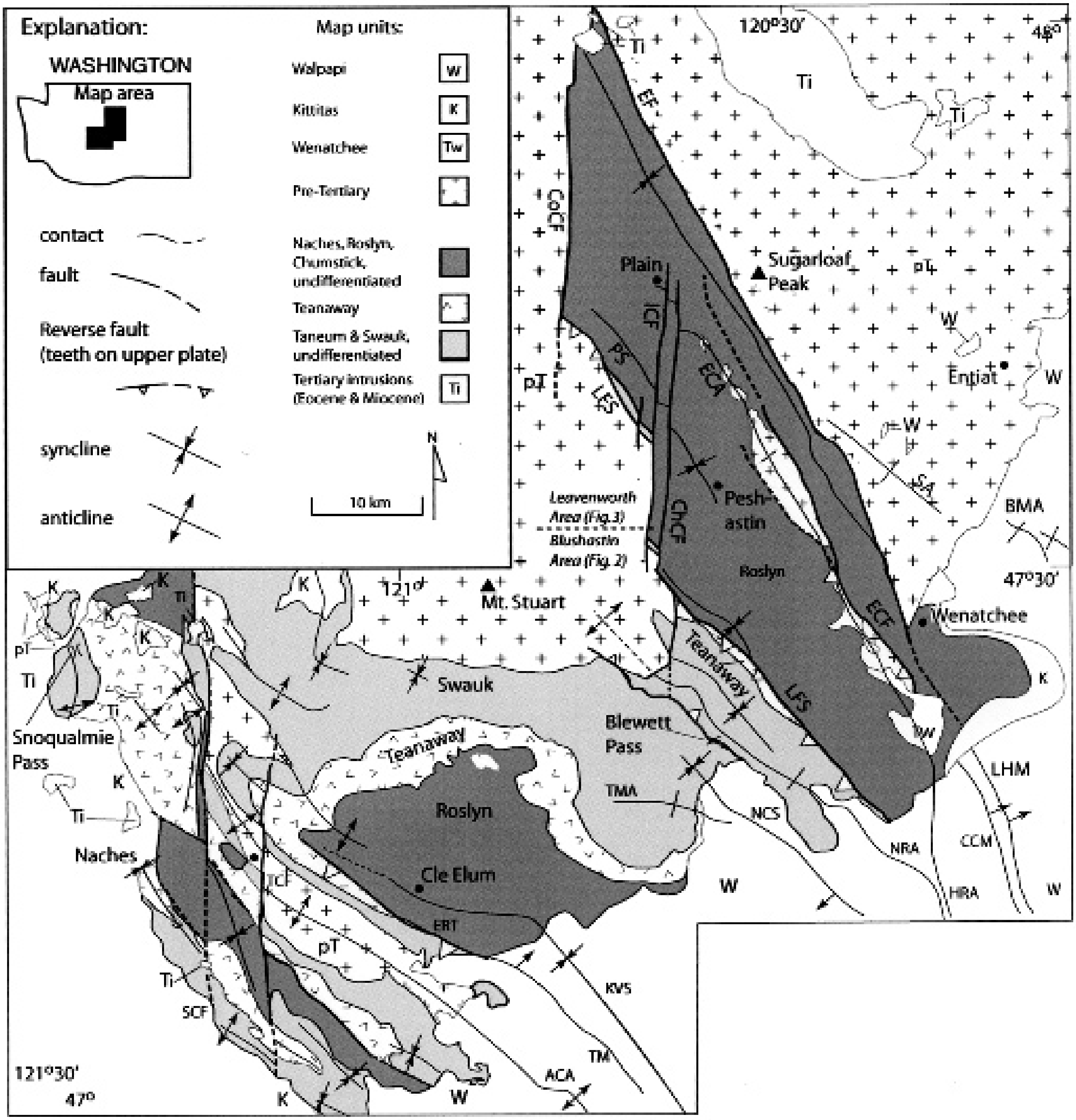


Figure 6. *(Above) Regional geology. For sources of data for the portion of the map south of N 47 30', see Figure 2 of Cheney Hayman (2007); data for the area north of N 47 30' are from Figure 4 and Tabor et al. (1987). Abbreviations are: ACA, Ainsley Canyon anticline; BMA, Badger Mountain anticline; ChCF, Chumstick Creek Fault; CCM, Colockum Creek monocline; CoCF, Coulter Creek fault; EF, Entiat fault; ERF, Easton Ridge thrust; HRA, Hog Ranch anticline; ICF, Icicle Creek fault; KVS, Kittitas Valley syncline; LFS. Leavenworth fault system; LHM, Laurel Hill monocline; NCS, Naneum Creek syncline; NRA, Naneum Range anticline; SA, Swakane anticline; SCF, Straight Creek fault; TCF Tucker Creek fault; TM, Taneum monocline, and TMA, Table Mountain anticline.*

Minor fine-grained diabase cuts the metamorphic rocks northeast of the Entiat fault. Laravie (1974) speculated that this diabase might be equivalent to dikes associated with the Teanaway Formation. If so, the intense fracturing of this basalt indicates that, like the segments of the Leavenworth fault, the age of final movement on the Entiat fault is younger than the Teanaway Formation.

The Sugarloaf Peak andesite of Page (1939) is unconformable on the body of talc-bearing rock in the upland northeast of the Entiat scarp. The pronounced and nearly vertical columnar jointing and a weak planar fabric of the mafic mineral (allegedly hypersthene) in the andesite may indicate that Sugarloaf Peak is the remnant of a welded ashflow (with a composition more felsic than andesite). The preserved thickness of the andesite is about 70 m. The radiometric age of the Sugarloaf Peak andesite is still unknown; clearly, this age is critical to the history of the CSL.

Structural Geology

The Swakane Biotite Gneiss is structurally below the Mad River terrane (Tabor et al, 1987; Paterson et al, 2004). Thus, the Swakane Biotite Gneiss and the body of talc-bearing rock near Sugarloaf Peak outline the core of an antiform, here called the Tillicum Creek antiform. The axial trace of this antiform is sufficiently parallel to the axial trace of the Chiwawa River syncline in Roslyn Formation in the CSL that, perhaps, the antiform, like the syncline, is Tertiary in age.

At least in this area, a zone of mylonite is at the base of the Entiat scarp. By definition, mylonites are caused by a significant reduction in grain size due to ductile deformation. Specifically, mylonitic biotite gneiss of the Mad River terrane is dark gray phyllite. Mylonitic felsic is dark gray and aphanatic. Minor phyllitic folia or phyllitic joint surfaces in more massive rocks mark areas of less pervasive mylonitization. The zone of pervasive mylonitization (phyllite) appears to be about 100 m thick.

In contrast to the northeasterly dip of most nearby metamorphic foliations, mylonitic foliations dip steeply to the southwest. Although the marble-bearing unit is truncated by the mylonite zone, the map pattern in the area southeast of Sugarloaf Peak does not indicate the sense of movement on the mylonitic zone. The discovery of lineations and S-C fabrics in the mylonites could determine the sense movement, as might additional mapping.

The age and origin of the mylonite zone (Chumstick fault) are not well known. Because the mylonite zone is in the hanging wall of (and subparallel to) the Dinkleman decollement, the two might be related.

Ubiquitous and closely spaced fracturing (cataclastic deformation here referred to a "hackly jointing") overprints the ductilely deformed rocks (biotite gneiss, marble, felsic gneiss, rocks in the mylonitic zone, and meter-scale alaskitic bodies near the Entiat fault). This intense fracturing also affects the Roslyn Formation and, therefore is, related to the Entiat fault. The last major movement on the Entiat fault may be post-Teanaway in age.

As Laravie (1976) noted, the Entiat scarp does not coincide with the Entiat fault. In this area, the scarp coincides with the northwestern (southwesterly dipping) limb of the Tillicum Creek antiform, which may be a Tertiary fold.

Conclusions

The Entiat fault cuts the Roslyn Formation. No evidence exists that the Roslyn Formation was deposited while the fault was active. The impressive, northwesterly trending Entiat scarp coincides with the limb of the Tillicum Creek antiform in pre-Cenozoic metamorphic rocks, the antiform may have formed in the Tertiary.

REGIONAL SYNTHESIS AND POST-EOCENE STRUCTURE

Our recognition of the regional style and timing of the CSL stems from two realizations: (1) the unconformity-bounded formations of the Eocene Challis sequence are more extensive than the major faults that cut them, and (2) regional folds in the Miocene Columbia River Basalt Group (CRBG) must be extended into the older rocks. Realization (2) leads us to extend the hinges of major folds in the CRBG (Tabor et al., 1982) into the formations of the Challis sequence and the basement rocks (Fig. 6; Table 54). Some of these folds, like the Ainsley Canyon anticline, trace southward into the Yakima fold belt, demonstrating that some of the shortening throughout the region is late-to-post Miocene in age. The elevations of the base of the CRBG in various folds (Table 5) gives some idea of the structural relief on the post-CRBG folds.

A consequence of extending folds from the CRBG northwestward into older rocks is that lithologically similar formations of the Challis synthem occur in the same stratigraphic order on opposite limbs of regional anticlines (Fig. 6) (Cheney, 1999; Cheney and Sherrod, 1999). Specifically, the basalt-bearing conglomerate of the Blushastin area (Ttb of Fig. 2) and the former Chumstick Formation of CSL occur in the same stratigraphic order on the northeastern limb of the Naneum Ridge anticline as the Teanaway and Roslyn formations, respectively, on the southwestern limb. A similar relationship occurs along the Ainsley Canyon anticline. It is for this reason —as well as their similar ages and lithologies— that the Chumstick Formation of Gresens et al. (1981) is equivalent to the Roslyn Formation.

Another consequence of tracing folds northwestward out of the CRBG into older rocks is that some of the key folds within the Blushastin-Leavenworth areas become regional structures. One example is the Hog Ranch anticline within theCRBG In the Wenatchee area the arkosic Wenatchee Formation unconformably overlies the Roslyn Formation and is unconformably overlain by CRBG (Gresens et al., 1981, Greens, 1983). Outliers of the Wentachee Formation with opposing dips (Gresens, 1983) allow the Hog Ranch anticline to be extended northward to the Eagle Creek anticline, which is cored by the pre-Tertiary Swakane Biotite Gneiss.

Connecting folds within the CRBGs to folds within the CSL region shows that post-CRBG folding led to the map pattern that many workers have interpreted as syn-depositional basins. Whereas many of the faults that bound basement rocks and cut clastic sections throughout the area are due to Eocene deformation, it is late to post-Miocene deformation that controls the map pattern and most of the topography in the region (Cheney and Sherrod, 1999; Cheney and Hayman, 2007 ; Reiners et al., 2002; Mitchell and Montgomery, 2006). The putative Eocene basins are major post-CRBG synclines. The CSL, which was called the Chumstick or Chiwaukum basin/graben, is the synclinal low between the Naneum Ridge and Hog Ranch anticlines. The adjacent Swauk or Roslyn basin is an extension of the Kittitas Valley syncline between the Naneum Ridge and Ainsley Canyon anticlines.

What is particularly confusing about the regional folds is that: though they fold late-to-post Miocene rocks, they initially formed during Eocene time. In other words, these folds were reactivated. Evidence that the post-CRBG folds were reactivated on older fold hinges stems from the differences in shortening across Eocene rocks relative to Miocene rocks. For example, along the Naneum Ridge, Ainsley Canyon, and Eagle Creek anticlines strata of the Challis synthem dip more steeply than the CRBG does down the plunge of the folds.

Reactivation may include faults as well as folds. The Easton Ridge reverse fault in the Ainsey Canyon anticline is remarkably similar to the Camas Creek fault. The Easton Ridge reverse fault is on the steeper northern limb of the anticline and dips 70° to 80° SW in former underground coal mines (Walker, 1980). The fault places Teanaway and Taneum formations over the Roslyn Formation and eliminates the entire 3 km thickness of the Roslyn Formation (Walker, 1980; Tabor et al., 1982). In contrast, the structural relief on CRBGs in the Taneum monocline, on strike and to the southeast of the Easton Ridge fault, is only ~ 300 m (Tabor et al., 1982, fig. 3 therein). Thus, hundreds of meters of structural relief on post-CRBG folds are imposed on kilometers of structural relief in Eocene rocks.

DISCUSSION

Our mapping and our regional structural and stratigraphic analyses effectively rule out many aspects of the previous graben models for the CSL. In short, we see no evidence of significant crustal extension since the northeasterly trending Teanaway dikes were intruded into the northwesterly trending folds in the Swauk Formation. Instead, crustal shortening has occurred episodically since those dikes were emplaced, and it continues today.

The geochronology and structures in basement rocks certainly argue for exhumation of middle crustal units throughout the early-to-mid Eocene (Haugerud, 1991; Wernicke and Getty, 1997; Paterson et al., 2004; .Shea et al. 2007). The mid-Eocene metamorphic core complexes in the northeastern part of Washington certainly developed during an interval of extension (e.g. Doughty and Price, 1999). However, neither of these observations requires that the CSL was an extensional or transtensional graben. Mid-crustal exhumation can occur in regions of shortening. Alternatively, if exhumation occurred via regional extension, the data still allow that upper crustal extension ceased by the mid-to-late Eocene. In other words, no data require that an extensional model applies to the CSL.

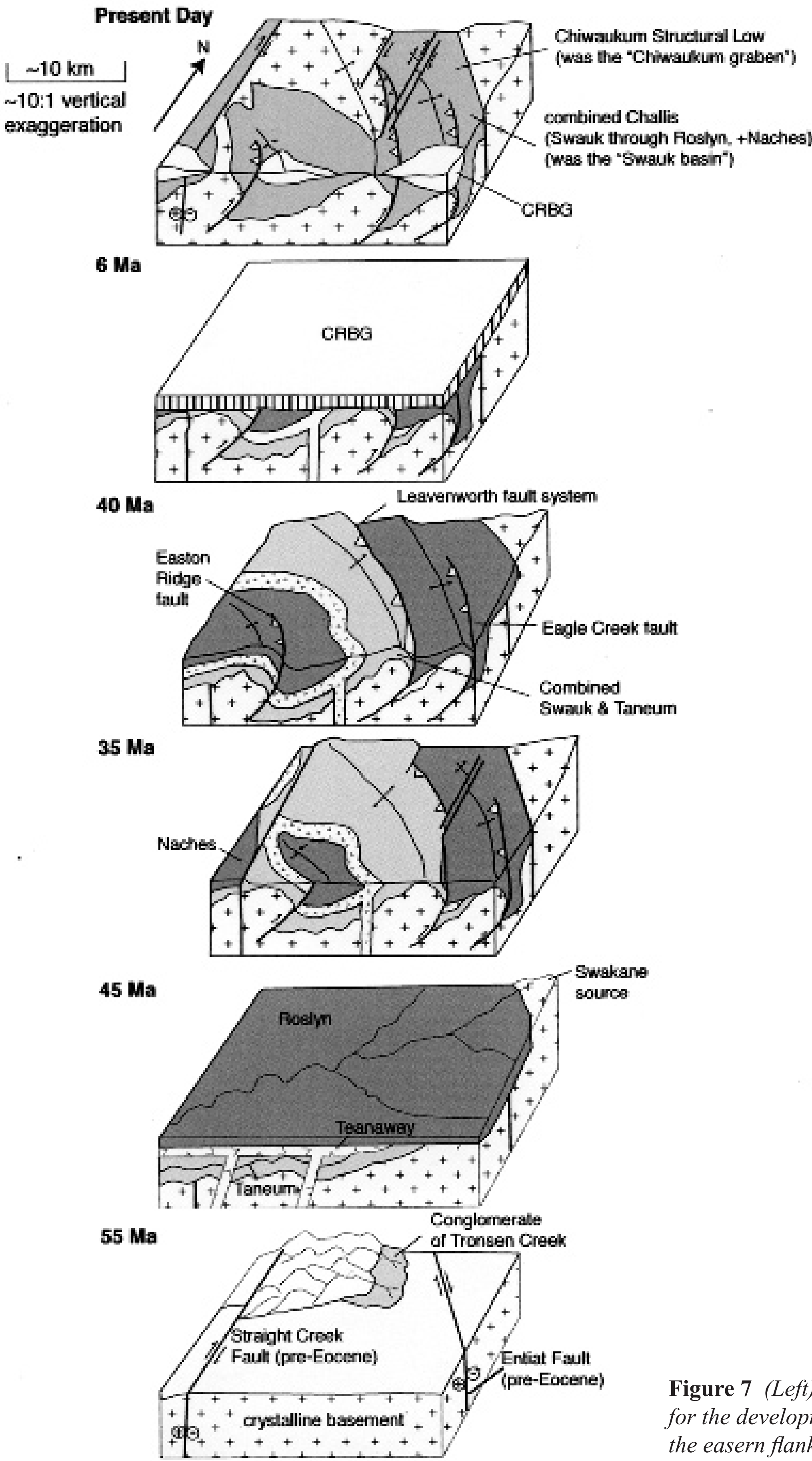


Figure 7 *(Left) Multi-stage tectonic model for the development of the structural lows on the easern flank of the Cascade Range*

To clarify the tectonic history of the CSL, we present a six-stage model (Fig. 7). For contrast with the previous models of grabens see the multi-stage models of Taylor et al. (1988), Johnson and Evans (1989), and Evans (1994):

Stage 1 (ca. 55 Ma): The Straight Creek, Entiat, and other dextral faults of the Cascade Range were active in pre-Challis time but were not active during deposition of the formations of the Challis synthem. Deposition of the Swauk Formation began with the conglomerate of Tronsen Creek being shed off the area that is now Mt. Stuart. If this sedimentation was induced by faulting, the causative fault is still unknown. Sedimentation probably was not due to an early episode of movement on the Leavenworth fault because the conglomerate of Tronsen Creek occurs on both sides of the fault.

Stage 2 (ca. 45 Ma): Prior to this time, the rest of the Swauk Formation and the Taneum Formation were deposited and modestly folded by the earliest stages of regional shortening. Teanaway dikes intruded folds in the Swauk Formation, and the Teanaway Formation was unconformably deposited on the Swauk Formation. Elsewhere the Teanaway Formation was deposited unconformably on the Taneum Formation. By roughly 45 Ma the waning stages of uplift of the basement of Swakane Biotite Gneiss, possibly combined with sources from the metamorphic core complexes to the east, fed the regionally extensive Roslyn Formation.

Stage 3 (ca. 40 Ma): After deposition of the Roslyn Formation and before deposition of Naches Formation (Cheney, 1999), the area underwent shortening that generated well-defined folds and reverse faults, such as the Leavenworth fault system and the Easton Ridge fault.

Stage 4 (ca. 35 Ma): Shortening was followed by an interval of strike slip faulting. Strike-slip faulting offset reverse faults, folds, and units by several kilometers. The emplacement of Kittitas-aged (Oligo-Miocene) plutons along the strike-slip faults in the Cascade Range indicates that this faulting ceased by 35 Ma. A component of dip slip on these faults segmented the formations of the Challis synthem into what appear to be grabens in map pattern, but are actually the synclinal products of a multi-stage history.

Stage 5 (ca. 15 Ma): Any regional topography that was inherited from previous periods of folding and faulting was largely eroded by 16 Ma, producing the regional unconformity upon which the oldest part of Columbia River Basalt Group (CRBG) accumulated.. The Swauk and Roslyn formations already were largely confined to synclines below this unconformity.

Stage 6 (Present Day): Following outpouring of the Miocene CRBG, the region underwent shortening, including generation of the post-Miocene Cascade Range anticlinorium, the northwesterly trending Yakima fold belt, and the other northwesterly trending folds (Figure 6). The northwesterly trending fold hinges are essentially parallel to the Eocene folds of Stage 3. This younger shortening reactivated many Eocene structures. Specifically, the shortening enhanced older synclines that already restricted the map pattern of the Swauk and Roslyn formations. This young folding is mostly responsible for the present regional map pattern. The cover of CRBG (Stage 5) was eroded, producing the present topography of the CSL and the Swauk or Roslyn "basin" in the vicinity of Cle Elum.

It is important to note how extensive and how young the post-CRBG folding is Fig. 6). The northwesterly trending folds occur from the Columbia River, across the Cascade Range to the Puget Lowland (Cheney and Hayman, 2007). In the northwesterly trending Yakima fold belt, the post-CRBG Ringold Formation, which is younger than 6 Ma, is folded (Reidel et al., 1994). Some faults in the fold belt even cut Pleistocene and Holocene sediments (Reidel et al. 1994). Thus, further exploration of the surface and subsurface Eocene structures will shed light not just on the tectonic history of the area, but also of the neotectonics.

CONCLUSIONS

The Eocene Chiwaukum graben and the regional extension that it implies are well established features of the geology of the Cascade Range. However, 1:24,000 mapping of the stratigraphy and structure of the arkosic Eocene Swauk and Roslyn formations show that the southwestern bounding fault of the graben, the Leavenworth fault, is not a normal fault; instead, it is a composite of post-Roslyn Formation reverse faults and younger dextral strike slip faults. Major northwesterly trending folds in the Miocene Columbia River Basalt Group (CRBG) on the eastern flank of the Casacde Range are well known. Extending these folds northwestward into pre-CRBG rocks shows that the Swauk and Roslyn Formations occupy post-CRBG regional synclines, not local, syndepositional Eocene grabens or basins.

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ROAD LOG FOR DAY 1

Introduction to Day 1

In the text, stops are numbered 1-1 to 1-6 for Day 1 and 2-1 to 2-11 for Day 2. Good weather and driving conditions will allow visits to scenic overlooks and outcrops that emphasize structures. Poor conditions will restrict stops mostly to paved roads. Be aware of traffic on all road-side stops. Unlike Day 2, the opportunity for toilet stops is limited.

The locations of stops are keyed to the mileage posts (MP) located every mile along the highways. When instructed to stop at a decimal MP, such as 10.2, look for MP 10, and use the odometer to estimate 0.2 miles. Cumulative mileage can be estimated by the MPs between the stops.

The road log for Day 1 begins at the junction of US-2 (MP 104.7) and US-97 (MP 185.0) about five miles east of Leavenworth.

From the junction proceed westbound on US-2 toward Leavenworth to Stop 1-1. at MP 102.5 of US-2

Stop 1-1. Topical, Massive, White-Weathering Roslyn Sandstone

As noted above, many of the rocks from stops 1-1 to 1-12 previously were thought to be Chumstick Formation and to have been deposited in the Chumstick graben. Most are here assigned to the Roslyn Formation. The sandstones here are white weathering, cross-bedded, have pebble lags, scattered pebbles <7 cm, but almost no conglomerate. The white sandstones are 2-15 m thick and grade upward into thinner, gray to black fine-grained sandstone. The sandstones dip northeasterly and are on the on southwestern limb of the regional Peshastin syncline.
Continue northwesterly on US-2.

MP 100.3 of US-2 At the traffic light near the eastern end of Leavenworth proceed either straight ahead for stop 1-5 or turn northward (right) on the Chumstick Highway (SR-209) toward Plain for stop 1-2.

SR-209 follows the valley of Chumstick Creek, which is the type area of the Chumstick Formation (Gresens et al., 1981). The first few miles of SR-209 are in the southwestern limb of the Peshastin syncline, that is, the drainage cuts across the stratigraphy. This anomaly is caused by the north-south Chumstick Creek fault.

MP 5.4 of SR-209 Turn west (left) on Sunitsch Canyon Road and proceed 0.2 miles to first road cut beyond the railroad tracks.

Stop 1-2. Irregularly Bedded Conglomerate of the Roslyn Formation

This outcrop of multiple, irregularly bedded conglomerates in sandstone is unit Trci of Figure 6 and Table 4.

Return to SR-209 and proceed northward.

MP 8.2 of SR-209 Take the side road to the east (right) to the large parking area adjacent to the railroad tracks. After parking, walk north on SR-209 -300 m past the railroad overpass.

Stop 1-3. Tuffs and Upper Planar Bedded Conglomerate of the Roslyn Formation

This stop examines potential marker units in the Roslyn Formation. This is the upper planar-bedded conglomerate (Trcu of Fig. 6 and Table 4), which is-0.85 km thick. Conglomerate, sandstone and tuff are intercalated on a 1-6 m scale (for a measured section of this locality see Evans, 1988, Fig. A.6 therein). Clasts in the conglomerates are felsic volcanic rocks (which, according to Table 2, are characteristic of Roslyn conglomerates), granitic rocks, felsic to intermediate gneiss, and bull to cherty quartz.
Two felsic tuffs range from aphanitic to barely recognizable lapilli. Rounded grains of quartz are minor and generally <lmm. Compared to tan conglomerate and sandstone, the tuffs weather gray and into angular blocks. These two tuffs continue at least 0.5 km to the north and 1.3 km to the south.

Heretofore, the only known marker units in the Roslyn Formation were such felsic tuffs. The rugged topography, extensive Quaternary cover, and forests make such thin tuffs as these unreliable as marker units (Gresens et al., 1981). However, Gresens et al. (1981) did map two tuffs 7-20 m thick as marker units in the central part of the Chiwaukum structural low. Correlation of tuffs by trace-element geochemistry is not straightforward (McClincy, 1986). The thicker tuff here is geochemically similar to a tuff in Clark Canyon 3.3 km to the southeast, but that tuff is in the lower planar-bedded conglomerate unit (Trcl); whereas, this one is in the upper-planar bedded conglomerate.

The irregularly bedded conglomerate (Trci) and the upper planar-bedded conglomerate (Trcu) occupy the same stratigraphic position in the Peshastin syncline. For 3 km north of stop 1-2, Trci progressively thins, and the underlying Trcu progressively thickens (Fig. 6). Trci and Trcu could be fades equivalents, or Trci could be unconformable on Trcu. In either case, Trcu plus Trci are a robust marker unit in the Roslyn Formation, which is 0.4-1.4 km thick and has a strike length of 28 km (Fig. 6).

Another feature to notice here is minor, irregular white veinlets <1 mm thick in the thickest conglomerate. Northeasterly tending white veinlets are more common in the railroad cut immediately to the east. Such veinlets are proximal to faults (stop 1-4). The Chumstick Creek fault is in the topographic low east of the railroad cut.

Return to the vehicles and continue north on SR-209.

MP 9.8 of SR-209 Highway passes beneath transmission lines.

MP 10.1 of SR-209 Pull out on the western (left) shoulder of the highway.

Stop 1-4. Satellite of the Chumstick Creek Fault

The northeasterly dips of the strata indicate that now we are on the northeastern limb of the Eagle Creek anticline. Multiple beds of conglomerate in the upper planar bedded conglomerate here are thinner and finer grained than at stop I -3. Note that some clasts are fractured. The strata are cut by white veinlets and by a north-south fault with >6 m of dextral displacement. This fault is a satellite or a splay of the north-south Chumstick Creek fault, which is under cover ~0.1 km to the east. From north to south the Chumstick Creek fault dextrally offsets the following steeply southwesterly dipping features: the Leavenworth fault at Mill Creek (stop 1 -8) by 2.0 km, the axis of the regional Peshastin syncline by 1.9 km, and the axis of the Eagle Creek anticline near here by 3.0 km.

Before we turn around, continue northward on SR-209 to the junction with Little Chumstick Creek Road at MP 11.3. At MP 10.7 is the covered contact with the Deadhorse Canyon Member (Trd of Fig. 6 and Table 3) of massive sandstone with intercalated black and olive fine-grained sandstones. The 5-15 m thick, planar beds of massive, white-weathering sandstone of this member are conspicuous on the hills to the northwest and north. At the road junction at MP 11.3 turn around and return southward toward Leavenworth.

MP 5.2 of SR-209 The upper planar-bedded conglomerate is in a road cut on the east side of the valley 0.2 miles south of the junction with the Sunitsch Canyon Road. It is east of the Chumstick Creek fault (Fig. 6); whereas, at stops 1 -3 and 1 -4 upper planar bedded conglomerate is west of the fault. The exact amount of dextral displacement of the conglomerate is unknown.

MP 0.0 of SR-209 and MP 100.3 of US-2 At the junction with US-2 in Leavenworth turn west and proceed 0.8 miles west. At MP 99.5 at the Wells Fargo Bank turn right (northeast) on Ski Hill Drive. Follow Ski Hill Drive 1.2 miles northward and turn left (west) on Maple Street.At the end of Maple Street (0.2 miles) turn right and then stay left to the residence of John Anderson. Walk 0.1 mile west to a quarry.

Stop 1-5. Conglomerate of Tronsen Creek of the Swauk Formation

Cobble and boulder conglomerate is interstratified with sandstone on a l-5m scale. Rounded to subangular clasts in the conglomerate are up to 1 m in diameter. Evans and Johnson (1989, stop 7) examined this conglomerate 1.3 km to the northwest. Their major observations were: (1) The lithologies of the clasts, (53% biotite-quartz schist, 42% granodiorite, 4% quartz or quartzite. I % rhyodacite porphyry clasts; 102 clasts counted) indicate that they were derived from just southwest of the Leaven-worth fault. (2) The conglomerates represent fanhead channels 3-5 m thick and 40-80 wide. (3) Paleocurrent directions from trough cross-beds in the sandstones are to the NNE.

All previous workers (Whetten, 1980b; Evans, 1988, 1994; Evans and Johnson, 1989) included this section in the Roslyn (Chumstick) Formation. However, lithologically and texturally it is similar to the conglomerate of Tronsen Creek of the Swauk Formation (see Table 2) in the Blushastin area (Evans, 1994, Fig. 2 therein; Evans and Johnson, 1989), which we will see at stops I -9 and 1-14. Unfortunately, no Teanaway dikes occur here to confirm that this is the conglomerate of Tronsen Creek.

Return to Ski Hill Drive; then, proceed 0.5 miles southward and turn right (west) on Ranger Road. Proceed 3.4 miles to a pass with a microwave tower. The pavement ends at 0.6 miles (but continue straight). At the first fork in the road stay left; at the second fork stay right.

Stop 1-6. Overview of the Chiwaukum Structural Low and Fabric Related to the Leavenworth Fault

We shall first enjoy the view. We are at an altitude of 920 m; Leavenworth is 3.5 km to the southeast and -360 m below.

(1) The creek below and to the southeast is the trace of the Leavenworth fault. Note that because the conglomerate on the northeast side of the valley (stop 1-5) does not project above the crystalline rocks on the southwest side of valley, a fault (with the southwest side up) is required. The strike of the valley indicates that our viewpoint is adjacent to the fault.

(2) The mountain in the middle distance that just rises above the far horizon at N 170, is Tip Top, 21 km away. The Leavenworth fault passes about 2.5 km south of Tip Top. The total dextral displacement of the fault from south of Tip Top to here is ~ 11 km.

(3) The ridge on the horizon at N 160 (42 km from here) is Mission Ridge. There, at an altitude of 2000 m, the Roslyn (Chumstick) and Swauk formations of the Chiwaukum structural low are unconformably overlain by the Columbia River Basalt Group (CRBG). The northeasterly dip of the CRBG off the Naneum Ridge anticline is well displayed by Mission Ridge, which descends gradually for 20 km northeastward to the Columbia River. Thus, the structural relief is 2000 m in 20 km.

(4) The lateral moraines of the Pleistocene Icicle Creek glaciers are well displayed on the ridge southeast of Leaven-worth. The terminal moraines are in the northern suburbs of Leavenworth.

(5) The north-south valley of Chumstick Creek (along the Chumstick Creek fault) is N 100 and 3 km away.

(6) The ridge at N 090 is underlain by the Roslyn Formation. Because the strata of the Roslyn Formation farther west on this ridge dip toward the older Swauk conglomerate, the two must be separated by a fault. That fault is the offset segment of the southwesterly dipping Camas Creek high-angle, reverse fault.

(7) The highest ridge -16 km to the northeast is the fault-line scarp of the Entiat fault. The Entiat is the northeastern bounding fault of the Chiwaukum structural low; so, we are looking across the entire width of the Chiwaukum structural low. Pre-Cenozoic, amphibolite-facies metamorphic rocks are in the scarp and beyond (Whetten and Laravie, 1976; Tabor etal., 1987).

(8) The highest nubbin (1772 m) 20 km distant at N 045 atop the scaip is Sugarloaf Peak (Fig. 2). Sugarloaf Peak is an erosional remnant of an undated Tertiary welded tuff, with a preserved thickness of-70 m.

(9) The ridge at N 020 (6 km distant) with prominent northwest dipping Chumstick strata is along the axis of the northwest plunging Peshastin syncline.

(10) The peak 14km away at N 000 is Natapoc Mountain (1281 m). The white outcrops below the summit are steeply dipping Chumstick Formation. With binoculars, it is possible to see that the summit of Natapoc Mountain is underlain horizontal beds, the Summit Conglomerate of Page (1939). Because the conglomerate is predominantly composed of clasts of porphyritic andesite and various crystalline rocks (Whetten, 1980a), perhaps, it correlates with the ca. 4 Ma Thorp Gravel (stop 2-4) of the Yakima Valley 80 km to the south. Despite the uncertainties of the ages of the Sugarloaf Peak tuff and the Summit Conglomerate, originally they must have been more extensive across the Chiwaukum structural low. Thus, the important conclusion is that the topography of the Chiwaukum structural low post-dates them and is erosional, not depositional.

(11) The tan ridge in the foreground at N 000 is underlain by Swauk conglomerate; whereas, the higher ground to the left is underlain by pre-Cenozoic ultramafic and metamorphic rocks. Thus, the Leavenworth fault continues to the northwest.

The outcrop at this stop is as important as the scenery. It consists of pre-Cenozoic serpentinite and talc-bearing rock bounded on the south by biotitic (pelitic) metamorphic rocks. The youngest of the pre-Cenozoic rocks in this area is the tonalitic Mount Stuart batholith.

However, here the serpentinite contains a 36 by 50 cm inclusion of tonalite, which suggests that the tonalite was tectonically incorporated into originally older serpentinite in post-Mount Stuart time. The serpentinite also contains phacoids of serpentinite bounded by zones of more foliated serpentinite. The foliations vary from N 295 to N 335 and define one zone that dips vertically and another that dips 75° to 85 ° SW. The two zones impart an s-c-like fabric to the serpentinite with a sense ot top-to-the-northeast. Fabrics in serpentinite can be problematic, and true s-c fabrics occur in rocks with ductile deformation. However, the s-c-like fabrics here may indicate that the adjacent Leavenwoith fault is a reverse fault, dipping steeply to the southwest.

Return downhill to Leavenworth and turn east (left) on US-2.. Drive through Leavenworth to the Wedge Mountain Inn east of Stop 1-1.

ROAD LOG FOR DAY 2

INTRODUCTION TO DAY 2

Weather permitting, our first stop will be a magnificent overview of the CSL and other features from the USFS lookout atop Sugarloaf Peak in the upland northeast of the Entiat fault. Thereafter, we will examine the non-mylonitized metamorphic rocks, the mylonite zone (Chumstick fault), and the Entiat fault. Finally, enroute to Seattle we will examine the Leavenworth fault south Leavenworth

Junction of US-2 and SR-209

From this junction on the eastern side of Leavenworth, proceed northward on SR-209 toward Plain.

MP 1.9 of SR-209

Turn right (east) on Eagle Creek Road

MP 2.4 of Eagle Creek Road

On the north side of the road is the Zeolite Tuff of Gresens et al. (1981) in the Roslyn Formation. This is one the thickest tuffs in the Roslyn Formation and was a useful marker unit for Gresens et al. 1981).

MP 5.9 of Eagle Creek Road

The pavement ends at the junction of USFS-7500 and USFS-7520. Turn left (north) on USFS-7520. Proceed 5.3 miles to the junction of USFS-7520 and USFS-7801 and keep right (southeast) on USFS-7520. Proceed 0.4 miles to the junction of USFS 7520, USFS-5808, USFS-5800, and USFS-5200; turn left (north) on USFS-5200 (and utilize the USFS toilet, if necessary). Proceed north on USFS-5200 for 4.5 miles to the access road to Sugarloaf Peak. Turn right (southeast) on the access road and dive 0.6 miles to the parking lot below the observation tower.

Stop 2-1. Sugarloaf Andesite and panoramic view

At the parking lot observe the columnar jointing and faint fabric in the Sugarloaf andesite. These suggest that the rock may be a welded ashflow and, therefore, more felsic than andesite. The age of the andesite is still unknown but is critical to the history of the CSL.

Ascend the tower for a magnificent view of the following:

1) Glacier Peak to the northwest beyond the Coulter Creek fault and the northwestern end of CSL,

2) The Enitat scarp to the northwest and south,

3) The broad, unglaciated upland from the north to the southeast. This upland is mostly underlain by the Mad River and Swakane terranes, Remnants of CRBG occur on this surface (Tabor et al. 1987) and in the Chiwawa River syncline (Laravie, 1976); so, presumably, the CRB was stripped from this surface (that is, the surface is essentially the unconformity upon which the CRBG accumulated).

4) The Columbia Plateau to the southeast across (east of) the Columbia River. Note the Badger Mountain anticline (covered with dark trees) in the CRBG,

5) Mission Ridge to south is underlain by CRBG in the Naneum Ridge anticline,

6) Leavenworth to the southwest (and about 1.5 km lower than Sugarloaf Peak);

7) The Eagle Creek anticline in CSL (the high ridge in the foreground) from southwest to west,

8) The various escarpments from Leavenworth to NW of Lake Wenatchee. These are caused by the bounding faults of the CSL. Ranger Road (the site of Stop 1-6) is 2 km to the northwest (right) of Leavenworth and ~ 16 km from here on the opposite side of the CSL, and

9) Lake Wenatchee to the NNW. The Coulter Creek fault (the western bounding fault of CSL) is marked by the topographic steps in Nason Ridge (south of the lake) and Dirtyface Mountain (north of the lake).

Return to the vehicles and drive back to USFS-5200. Turn left (south) and proceed 1.6 miles to USFS-210. Turn left (southeastward) on USFS-210 and proceed 0.9 miles and keep right (south) at the road junction where USFS-210 descends the valley of Tillicum Creek Proceed another 0.3 miles.

Stop 2-2. Dinkleman Decollement

Talc-bearing rock (meta-ultramafic rock) is black, white to slightly rusty weathering, easily scratched, and is crudely foliated. It probably also contains magnesite and amphibole. This is near the southern end of the body of talc-bearing rock that continues northward beyond Sugarloaf Peak. The map pattern suggests that this body is nearly horizontal and may be up to 200 m thick. It marks the core of the Tillicum Creek antiform

About 50 m to the southeast is a splendid outcrop of biotitic Mad River gneisss with quartz folia (metachert?) up to 18 cm thick. The easterly dip of the gneiss projects over the talc-bearing rock. Furthermore, the next outcrop down the road from the gneiss is talc-bearing rock

Proceed down USFS-210 for 2.3 miles to its junction with USFS-5808 . Outcrops for the first 1.5 miles are amphibolite and Mad River biotitic gneiss with minor quartz-rich folia < 3 cm thick. At the junction with USFS-5808 turn right (south) and proceed 0.5 miles.

Stop 2-3. Swakane Biotite Gneiss

This underwhelming outcrop is Swakane Biotite Gneiss in the core of the Tillicum Creek antiform, structurally and topographically below the talc-bearing rock of Stop 2-2. Look for fibrolite.

Continue 0.8 miles southeastward to the junction with USFS-5200, US 5800, and USFS-7520. Use the toilet if necessary. Continue almost straight to USFS 7520 and proceed 0.4 miles downhill to USFS-7801. Turn right (northwest) on USFS-7801 and continue 4.0 miles to the junction with USFS-600. Turn right (northeast on FS-600 and proceed 0.4 miles to a curve in the road.

Stop 2-4. Marble.

This white to gray, banded marble varies from aphanitic to coarse-grained. Recrystallization of the marble probably is related to the adjacent mylonite zone (Chumstick fault) of the next few stops. Drag folds in the marble indicate top-to-the-south. Locally the marble is brecciated. It is also cut by closely spaced fractures that can be termed "hackly jointing". Hackly jointing overprints ductile fabrics in virtually all of the metamorphic rocks between the Chumstick and Entiat faults and is spacially related to the Entiat fault.

Walk about 100 m south on FS-600 to note an underwhelming outcrop of hackly conglomerate of the Roslyn Formation. The Entiat fault (covered) juxtaposes the conglomerate against the marble.

Return to the vehicles and continue 0.4 miles northward to the northern end of a quarry. Walk to the northernmost exposures.

Stop 2-5. Mylonitic biotitic gneiss of the Chumstick fault.

This rock is a dark gray phyllite caused by mylonitization of biotitic gneiss of the Mad River terrane. Thus, the rock could be termed a "phyllonite". The rock is mostly aphanitic, but it does contain subtle folia, rare mm-sized feldspar, and mm-thick quartz folia that indicate its protolith. For comparison, the protolith occurs at Stop 2-6.

The phyllitic (mylonitic) foliation in the Chumstick fault consistently dips steeply to the southwest; whereas, the foliation in non-mylonitic rocks adjacent to the fault (but not seen here) usually dips northeastward.
The steep cliffs above the quarry suggest that phyllitic zone is limited to the quarry.

Return to the junction of USFS-600 and USFS-7801. Turn left (southeast) onUSFS-7801. Continue 1.1 miles (past white marble at 0.5 miles) to a curve in the road with a stream.

Stop 2-6. Non-mylonitic Mad River Gneiss.

This is the protolith of the phyllonite of Stop 2-5. Note the abundant mm-thick, quartz-rich folia, the northeasterly dip, and the virtual absence of a phyllitic overprint. Nonetheless, the rock is somewhat hackly.

Walk about 80 m back (northwest) along the road to phyllitic rocks. These rocks are on strike with the phyllonites of Stop 2-5. Perhaps, the mylonitic zone is only about 100 m thick.

Continue 2.5 miles southeastward on FS-780l. Once past Stop 2-6, the rocks are slightly phyllitic (and hackly) for the next ½ mile. At 1.8 miles, white marble is on the left, beyond which are poor outcrops of felsic gneiss.

Stop 2-7. Felsic gneiss.

This rock is almost exclusively composed of 1 to 2 mm quartz and feldspar without mafic minerals. Limonitic specks may have been former pyrite. Some cm-scale concordant quartz veinlets occur in this and many outcrops of the felsic gneiss. The rock originally probably was a submarine felsite (of the sort associated with massive sulfide deposits). The small grain size, weathering, and hackly jointing make the foliation difficult to see. The rock is not phyllitic(mylonitic) but does have hackly joints.

Continue southeastward on USFS-7801 for 0.4 miles to USFS-7520. Turn (or stay) right on USFS-7520 and proceed 1.0 miles downhill (well beyond the power lines).

Stop 2-8. Alaskite

Concordant alaskitic bodies < 2m thick are intercalated with fine grained biotitic schist. The alaskite (an unfoliated [or only weakly foliated] quartz and feldspar rock almost no mafic minerals and with a grain size between 1 and 10 mm) contains some pink feldspar. The alaskite has been ductilely deformed into various shapes and is overprinted by hackly (cataclastic) jointing. The hackly jointing is due to proximity to the Entiat fault. Perhaps the ductile deformation is due to a fault like the Chumstick fault.

Continue 0.3 miles down USFS-7520.

Stop 2-9. Rosetta Stone

Intense hackly jointing gives this rock a very deformed appearance. Is this a fragmental rock (conglomerate), fragmental rock (breccia), or both?

Poor outcrops for the next 0.5 miles down USFS-7520 are very hackly, southwesterly dipping conglomerate.

Thus, Stop 2-9 is conglomerate in the Roslyn Formation and is immediately southeast of the Entiat fault. Clearly, the fault cuts the Roslyn Formation.

The dip of the Entiat fault in this area is unknown. The fault crosses the topography without deflection (suggesting that the dip is steep), but it crosses no major valleys (where "V-ing" of the contact would provide information on the direction of the dip). Likewise, the relationship of the prominent easterly dipping jointing here to the dip of the fault is unknown.

Return to Leavenworth via USFS-7520, Eagle Creek Road, and SR-209.

At the junction of SR-209 with US-2 in Leavenworth, turn left (east) and cross the bridge over the Wenatchee River. Just east of the eastern abutment of the bridge, turn right (south) on East Leavenworth Road. This intersection is at MP 100.5 of US-2 . Continue 0.1 miles on East Leavenworth Road and turn east (left) on Mountain Home Road. Follow Mountain Home Road (which becomes unpaved) 4.8 miles past second homes and large erratics of Mount Stuart tonalite to the lip of a hanging valley.

Stop 2-10. Overview of Icicle Creek

We are at 735 m at with a magnificent view to the north of Leavenworth and the glaciated valley of Icicle Creek. Features to note (other than the numerous erratics and the narrow-gauge railroad tracks) are:

(1) Several lateral moraines of Pleistocene glaciers (or still-stands of thereof) that issued from the valley of Icicle Creek, the upper part of which is at N 270. The highest and most weathered (i.e., oldest) moraine is ~125m above to the southeast. That is, the Icicle Creek glaciers moved up what is now the hanging valley.

(2) At N 015 in the far distance is the Entiat fault-line scarp. In the middle distance is the mouth of Chumstick Creek in the north-south Chumstick Creek fault, which passes to the east of us.

(3) The ridge of conglomerate of the Swauk Formation adjacent to Ranger Road (stops I -5 and 1 -6) is N 000 and 8 km distant. From here the conglomerate appears to have a nearly horizontal dip. Note the abrupt eastern termination of the ridge.

(4) The mountainous topography from the northwest to the southwest has bold outcrops, most of which are rocks of the Mount Stuart batholith. The outcrop across the valley at N 250 (0.4 km distant) also is Mount Stuart tonalite. Outcrops at the end of the hanging valley (to the south) and below it (to the north) indicate that bedrock at this stop is Roslyn Formation (Fig. 6). Thus, a fault occurs between us and the outcrop of Mount Stuart tonalite at N 250. The apparent displacement of the Leavenworth fault by this north-south Icicle Creek fault(from Tumwater Mountain, stop 1-5) to Mill Creek (stop 1-8) is -10 km; this large displacement requires some sort of concealed transfer fault in the valley below between the Chum-stick Creek and Icicle Creek faults.

Continue southward 1.7 miles on Mountain Home Road. At 1.2 miles is a road junction and a pass, beyond and below which the road becomes Mill Creek Road. Stop 0.5 miles south of the pass at an abandoned (and bermed) logging road on the uphill (west) side of road.

Stop 2-11. Mill Creek Segment of the Leavenworth Fault

This is the approximate trace of the Leavenworth fault east of the Icicle Creek fault. Walk about 0.25 mile along the abandoned and brushy logging road to view rocks adjacent to the fault.

The eastern outcrops along the road are intensely cleaved felsic metavolcanic rock. Centimeter- to meter-scale phacoids of more massive felsic volcanic rock have mm-scale veinlets in various orientations. Cleavage or incipient foliation in the metavolcanic rocks varies from vertical to 70° SW.

The western outcrop is a dike of basalt -40 m thick, which is megascopically and geochemically similar to Teanaway dikes (Peters, 2006). Along its margins the dike is intensely jointed and brecciated. The northeastern sheared contact of the dike with felsic metavolcanic rock dips 75° SW. The southwestern contact of the dike is not exposed. From these outcrops we infer that the Leavenworth fault dips steeply to the southwest (is a reverse fault), is either syn- or post-Teanaway in age and was active after the dike was emplaced.

Return to the vehicles and continue down Mill Creek Road 2.9 miles toward US-97.

At 0.3 to 0.7 miles from Stop 2-11, the road crosses a landslide on the intersection of the Leavenworth and Chumstick Creek faults.

At 1.0 to1.7 miles from Stop 2-11 are views (through trees) to the north of the valley that contains the north-south Chum-stick Creek fault. Strata on the eastern side are typical white-weathering Roslyn sandstones and dip to the southwest. Strata on the skyline to the northwest are the upper planar-bedded conglomerate, which dips easterly.

At 2.9 miles the road enters US-97 at MP 181.1. Turn southbound (right) on US-97 for Ellensburg and Seattle.

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