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Depositional History of the Eocene Chumstick formation - Implications of Tectonic Partitioning for the History of the Leavenworth and Entiat-Eagle Creek Fault Systems, Washington

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Depositional history of the Eocene Chumstick Formation: Implications of tectonic partitioning for the history of the Leavenworth and Entiat-Eagle Creek fault systems, Washington

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Abstract. The Chumstick basin opened as an extensional half-graben prior to 51 Ma, and was subsequently modified by two episodes of tectonic partitioning of drainage prior to basin deformation. Initially, westward flowing fluvial systems formed a unified depositional system with the Swauk basin. Tectonic partitioning of drainage at 51-49 Ma and at 44-42 Ma was controlled by localized uplift on the Leavenworth (LFZ), Eagle Creek (ECFZ), and Entiat (EFZ) fault zones and led in each instance to the truncation of regional depositional systems, modification and reversal of paleoflow, and internal drainage. Relief on the LFZ at 51-49 Ma may be the result of isostatic uplift of the extensional footwall, producing the Swauk and Chumstick basins as a pair of west facing half grabens. The earliest convincing evidence for the onset of oblique slip in the region is at about 48 Ma (folding in the Swauk basin) or about 44-42 Ma (probable transpressive uplift at left-stepping bends of the LFZ, development of a transtensional step-over basin between the ECFZ and EFZ, horsetail splays in the ECFZ, and possible flower structures in the LFZ and ECFZ in the Chumstick basin). Each episode of tectonic partitioning was followed by proximal onlap and overtopping of fault zones, to reestablish regional flow systems. The Chumstick Formation was deformed by dextral transpression between 37-34 Ma, and is unconformably overlain by the Oligocene Wenatchee Formation. The Chumstick basin is an example of an extensional basin modified by subsequent strike-slip tectonics, thus caution should be used in applying idealized basin models.

Introduction

Recent studies have advanced our understanding of the response of nonmarine depositional systems to syntectonic extension. For example, tectonosedimentary facies models have been proposed for continental rift basins with either closed (interior) drainages or open (throughgoing axial) drainages [e.g., Leeder and Gawthorpe, 1987; Fedo and Miller, 1992; DiGuiseppi and Bartley, 1991; Cavazza, 1989]. Interior drainages typically lead to the development of small alluvial fans from the steep, tectonically active footwall block and broad fans fed by the lower-gradient hanging wall block [Leeder and Gawthorpe, 1987]. Axial-fluvial systems are typically restricted to a narrow belt representing the locus of active basin subsidence [Mack and Seager, 1990]. Intervals of rapid subsidence can result in migration of axial-fluvial and lacustrine depositional systems toward the fault-controlled basin-margin depression, whereas intervals of decreased basin subsidence can result in progradation of alluvial fans from the master fault and resultant basinward displacement of the axial-fluvial systems [Blair, 1987].

In the Pacific Northwest a major controversy exists regarding the significance of Eocene nonmarine sedimentary basins (Figure 1). Interpretation of the structural setting for these basins ranges from wrench fault basins [e.g., Gresens, 1982; Johnson, 1985] to fault bounded, erosion remanents of what was once a broadly subsiding coastal plain [e.g., Cheney and Stewart, 1992]. The region is characterized by a series of northwest trending faults that were compressional during the Mesozoic and were re-activated as extensional or oblique-slip faults during the Paleogene [Davis et al., 1978]. These northwest trending faults were displaced by the Fraser River-Straight Creek fault system, a transcurrent fault [Jones et al., 1992] with dextral offset of approximately 105 km [Vance and Miller, 1992]. Although many of the sedimentary basins show the effects of syndepositional faulting, there is disagreement regarding the age of onset of strike-slip faulting on this system and whether the formation of some of these sedimentary basins preceded dextral offset [e.g., Johnson, 1985; Coleman and Parrish, 1991; Vance and Miller, 1992; Brandon et al., manuscript in preparation, 1994].

Complicating the story further is mixed provenance evidence. Many basins contain locally derived conglomerates, suggesting evolution as distinctive, fault-bounded basins [Johnson, 1984a,b; Evans, 1988]. In contrast, most of the basins demonstrate similar sandstone petrofacies [Hartman, 1973; Frizzell, 1979], accessory mineral assemblages [O'Connor, 1992], trace element composition [Byrnes, 1985] and isotopic compositions [Heller et al., 1992a, b], suggesting evolution as regional drainages. Paleocurrent data have been used to support both arguments.

The purpose of this paper is to apply depositional systems analysis to one basin in the Pacific Northwest, the Chum-

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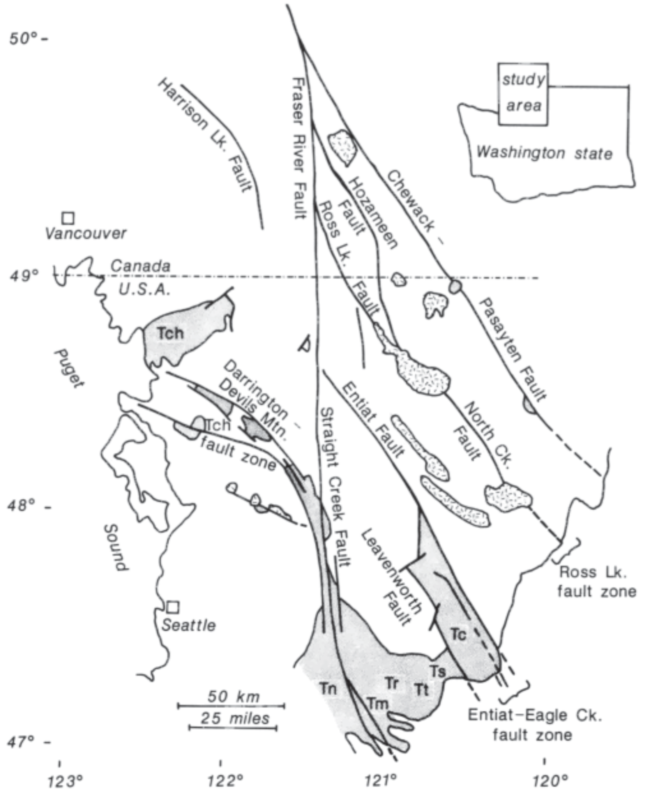


Figure 1. Generalized geologic map of northwestern Washington state and southwestern British Columbia showing major faults of known Mesozoic and Paleogene displacement, Tertiary batholiths, and Paleogene sedimentary basins (stipled areas). Abbreviations used on map are Tc, Chumstick Formation; Tch, Chuckanut Formation; Tm, Manastash Formation; Tn, Naches Formation; Tr, Roslyn Formation; Ts, Swauk Formation; and Tt, Teanaway Formation.

stick basin (filled by the Eocene Chumstick Formation). The specific goals of this study are (1) to document the depositional history of the Chumstick Formation using structural, stratigraphic, paleocurrent, provenance, and thermal maturity data (a stratigraphic revision is necessary to fully develop this history); (2) to show how the Chumstick basin is an example of an extensional basin that was modified by later syndepositional oblique-slip faulting; and (3) to discuss the implications of this study regarding regional fault histories and the application of idealized basin models.

Methods

This study is based upon mapping, measurement of 4225 m of section from 27 localities (Figure 2), 1514 paleocurrent measurements, 41 thin section point counts, 4625 conglomerate clast counts from 35 localities, new zircon fission track ages from a tuff and a sandstone, and vitrinite reflectance values were obtained from 78 coal samples. The results of facies analysis and depositional interpretations have been reported earlier [Evans, 1991a]. The identification of 34 plant macrofossil taxa and 19 plant microfossil taxa, interpretation of paleosols, and trace fossils made possible the paleoclimatic interpretations reported earlier [Evans, 1991b].

Results

Structural Setting

The Chumstick Formation comprises over 12 km of fluvial and lacustrine strata, mostly deposited in the region between the Entiat and Leavenworth fault zones (Figure 2). The Entiat, Leavenworth, and Eagle Creek fault zones divide the Chumstick basin into two subbasins, which are called the "eastern subbasin" (between the Entiat and Eagle Creek fault zones) and the "western subbasin" (between the Eagle Creek and Leavenworth fault zones). These subbasins had separate depositional histories, based upon age, facies patterns, paleocurrents, provenance, and thermal maturity data.

The Entiat fault zone is a linear zone >40 km long and 0.3-0.8 km wide (Figure 3), recording at least three episodes of movement, a pre-Chumstick Formation phase of dip-slip movement that resulted in extensive mylonite formation in the western part of the fault zone; a phase of oblique slip that at least partly coincided with the deposition of the Chumstick Formation, and a post-Chumstick Formation phase of dip-slip movement that occurred in the eastern part of the fault zone [Laravie, 1976]. Gresens [1982] argued the Entiat fault was a significant strike-slip fault for part of its history, given the linearity of the fault and mismatches across the structure in pre-Tertiary rocks and in the orientation of Tertiary dike swarms.

The Leavenworth fault zone contains major bends and en echelon faults (Fig. 3) with kinematic indicators for both strike-slip and dip-slip movement [Cashman, 1974]. Sedimentary evidence suggests that the Leavenworth fault zone shows a reversal of dip-slip movement sense, being west side down during deposition of the Swauk Formation and east side down during deposition of the Chumstick Formation [Taylor et al., 1988; Evans and Johnson, 1989; S.Y Johnson, personal communication, 1984]. The offset of granodiorite fanglomerate deposits 34 km from their nearest known source area (Mount Stuart batholith) has been cited as evidence both for and against dextral offset [Frizzell and Tabor, 1977; Brandon et al., manuscript in preparation, 1994].

The Eagle Creek fault is a throughgoing, northwest trending fault that parallels and partly overlaps the Entiat fault zone (Figure 3). In the north the Eagle Creek fault zone terminates in a set of WNW trending fault splays. It continues southeast along the eastern side of a series of uplifted blocks of Swakane biotite gneiss, through the trend of a series of Eocene felsic intrusives near the town of Wenatchee, and along the eastern side of Wenatchee Heights. Hydrothermal mineralization associated with these syndepositional intrusives suggests that the Eagle Creek fault zone acted as a conduit for the emplacement of the intrusives and the movement of hydrothermal fluids [Margolis, 1987]. Isopachs based on drill core evidence in the mineralized

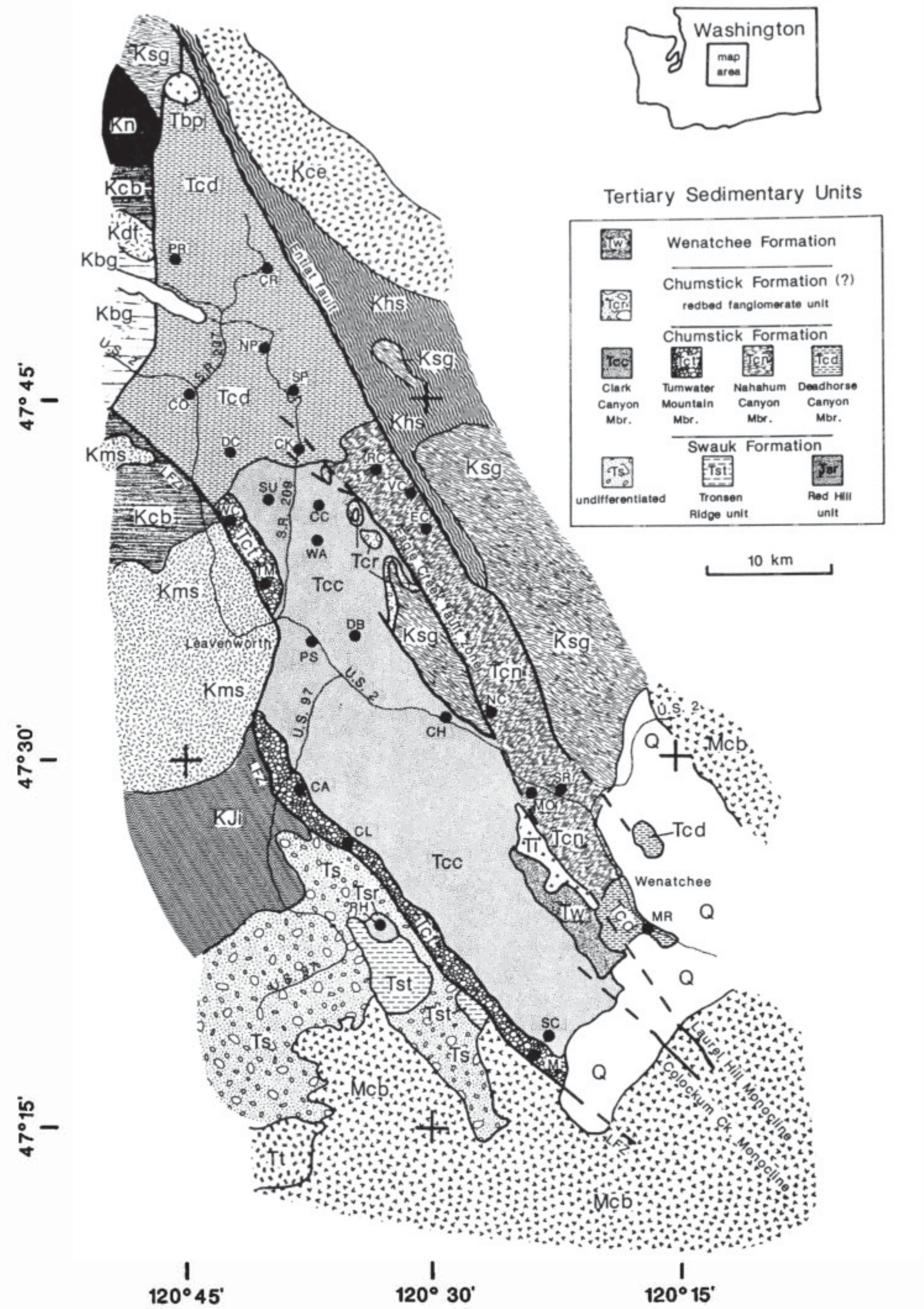


Figure 2. Geologic map of the Chumstick basin and related rocks showing locations of measured sections (based upon mapping by Tabor et al. [1982, 1987] and Evans [1988]). Geologic units are Kbg, banded gneiss; Kcb, Chiwaukum Schist; Kce, Entiat pluton; Kch, banded hornblende and biotite gneiss; Kdf, Dirty Face pluton; Khs, heterogeneous schist; Kms, Mt. Stuart batholith; Kn, rocks of the Napeequa River area; Ksg, Swakane Biotite Gneiss; KJi, Ingalls Tectonic Complex; Mcb, Columbia River Basalt; Q, alluvium; Tbp, Basalt Peak pluton; Tc, Chumstick Formation (Tcc, Clark Canyon Member; Tcd, Deadhorse Canyon Member; Tcn, Nahahum Canyon Member; Tcr, red bed fanglomerate unit; Tct, Tumwater Mountain Member); Ti, Wenatchee dome; Ts, Swauk Formation (Tsr, Red Hill unit; Tst, Tronsen Ridge unit); Tt, Teanaway Formation; and Tw, Wenatchee Formation. Locations are: CA, Camas Creek; CC, Clark Canyon; CH, Cashmere; CK, Chumstick Creek; CL, Camasland; CO, Cole's Corner; CR, Chiwawa River; DB, Derby Canyon; DC, Deadhorse Canyon; EC, Eagle Creek; MA, Malaga Road; MO, Monitor; MR, Mission Ridge; NC, Nahahum Canyon; NP, North Plain; PR, Pole Ridge; PS, Peshastin; RC, Railroad Canyon; RH, Red Hill; SC, Squilchuck Canyon; SP, South Plain; SR, Sunnyslope Road; SU, Sunitsch Canyon; TM, Tumwater Mountain; VC, Van Canyon; WA, Walker Canyon; and WC, Wright Canyon.

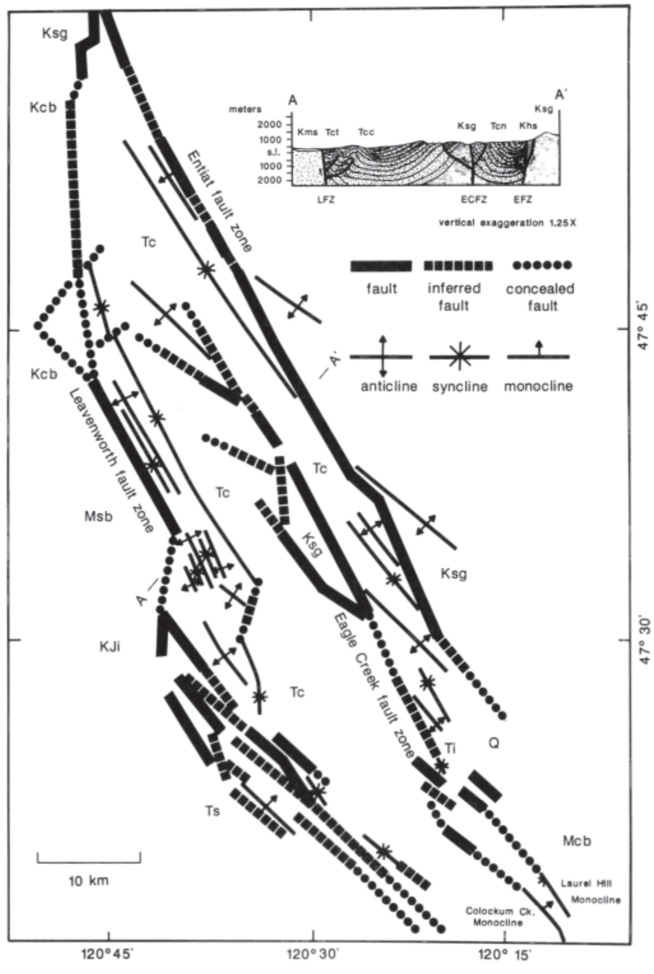


Figure 3. Map showing the structural features of the Leavenworth, Eagle Creek, and Entiat fault zones and related folds and intrabasinal faults. Insert cross section shows proposed structural relationships on a transect across the middle of the basin.

zone also suggests that one or more small grabens formed along the trace of the structure [Margolis, 1987]. Farther south, the trace of the Eagle Creek fault zone coincides with the Colockum Creek and Laurel Hill monoclines in the Miocene Columbia River Basalt (Figure 2). These monoclines have been interpreted as fault propagation folds generated by subbasalt structures [Plescia and Golombek, 1986; Reidel, 1984].

Previous workers described the Eagle Creek fault zone as a fold ("Eagle Creek anticline" of Willis [1953]) and as a horst block [Whetten, 1976; Buza, 1979; Gresens et al., 1981]. It is proposed here that the Eagle Creek fault is a major oblique-slip fault, based upon the following evidence: (1) the linearity of the structure, its position parallel to and partly overlapping the Entiat fault, and its continuity into sub-Columbia River Basalt structures; (2) the orientations of faults and fold axes in the northern part of the Chumstick basin are consistent with horse-tail splays and other structures observed at the terminus of an oblique-slip fault [e.g., Aydin and Page, 1984]; (3) some of the uplifted basement blocks are bordered on the west by contractional faults and by fold axes that diverge NW 15° to 30° from the fault zone, and also by overturned bedding in the Chumstick Formation (such features have an orientation that is consistent with transpression in a system of dextral shear [e.g., Harding, 1974]); (4) sedimentary evidence suggests that the region between the Entiat and Eagle Creek fault zones subsided to form a transtensional step-over basin (i.e., the eastern subbasin); and (5) sedimentary evidence indicates the existence of small pop-ups and grabens in the fault zone (rather than as one continuous uplift or scarp) an observation that is more consistent for an oblique-slip fault than for pure extension.

Stratigraphic Revision

"Chiwaukum graben." The region between the Entiat and Leavenworth faults has been referred to as the "Chiwaukum graben" [Willis, 1953]. Strata in this area were originally referred to as the Swauk Formation (Figure 4), until Gresens et al. [1981] defined the Chumstick Formation and determined its age. Gresens et al. [1981] believed that three stratigraphic units were found in the Chiwaukum graben, the "Swauk(?)", Chumstick, and Wenatchee formations (Figure 4); however, subsequent studies have shown that their Swauk(?) Formation exposures are actually hydrothermally altered Chumstick Formation that surround the felsic intrusives of the Wenatchee dome [Margolis, 1987]. The Wenatchee Formation is a lower Oligocene fluvial and lacustrine unit that unconformably overlies the Chumstick Formation, overlaps the basin, and postdates basin-margin faulting [Gresens, 1982, 1983; Hauptman, 1983]. The simpler term "Chumstick basin" is preferred, because the syntectonic fill of the "Chiwaukum graben" is the Chumstick Formation.

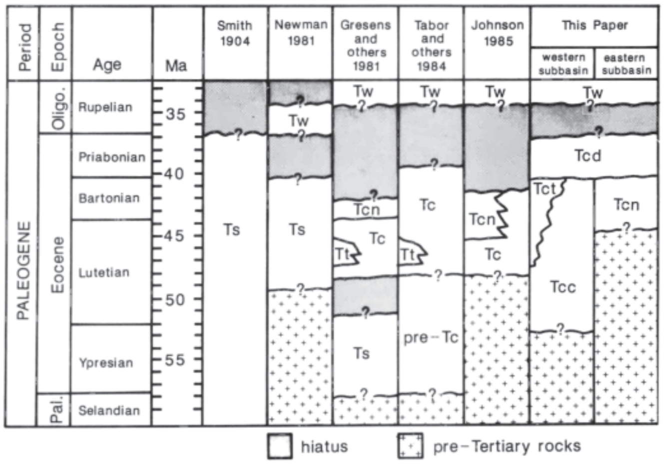


Figure 4. Stratigraphic nomenclature for the Chumstick Formation. Abbreviations used are Tc, Chumstick Formation; Tcc, Clark Canyon Member; Tcd, Deadhorse Canyon Member; Tcn, Nahahum Canyon Member; Tct, Tumwater Mountain Member; Ts, Swauk Formation; Tt, Teanaway Formation; and Tw, Wenatchee Formation.

Previous stratigraphic subdivisions. Gresens et al. [1981] split the Chumstick Formation into an undifferentiated lower part, and an upper unit of mostly lacustrine strata called the Nahahum Canyon Member (Figure 4). This study restricts the Nahahum Canyon Member to lacustrine and fluvial strata in the eastern subbasin. Fine-grained deposits in the northern part of the basin, mapped by Tabor et al. [1987] as Nahahum Canyon Member, are actually younger fluvial deposits (Deadhorse Canyon Member), which overlie the Nahahum Canyon Member. This study also proposes to subdivide the undifferentiated Chumstick Formation into three additional members: the Clark Canyon, Tumwater Mountain, and Deadhorse Canyon Members (Figure 4). These new units are defined below, and their stratigraphic relationships are shown in a fence diagram (Figure 5).

Clark Canyon Member. The Clark Canyon Member is approximately 10.6 km thick and is found entirely in the western subbasin, (Figure 2). To the west, the unit extends across the Leavenworth fault zone to include a distinctive unit others mapped as part of the Swauk Formation (the "sandstone facies of Red Hill" of Taylor et al. [1988]). The Clark Canyon Member is named for a continuously exposed, 1400 m section that contains nine interstratified tuffs in Clark Canyon (U.S. Legal Land Coordinates T.25N., R.18E., Section 10 NW1/4 to Section 8 NW1/4).

The unit consists of fluvial conglomerate, sandstone, and mudrocks, with 18 interstratified airfall and ash-flow tuffs and numerous paleosols (Figure 6). The tuffs are between 30 cm and 20 m thick, have distinctive trace element compositions [McClincy, 1986], and form mappable units that can be been traced up to 41 km, providing stratigraphic control throughout the western subbasin.

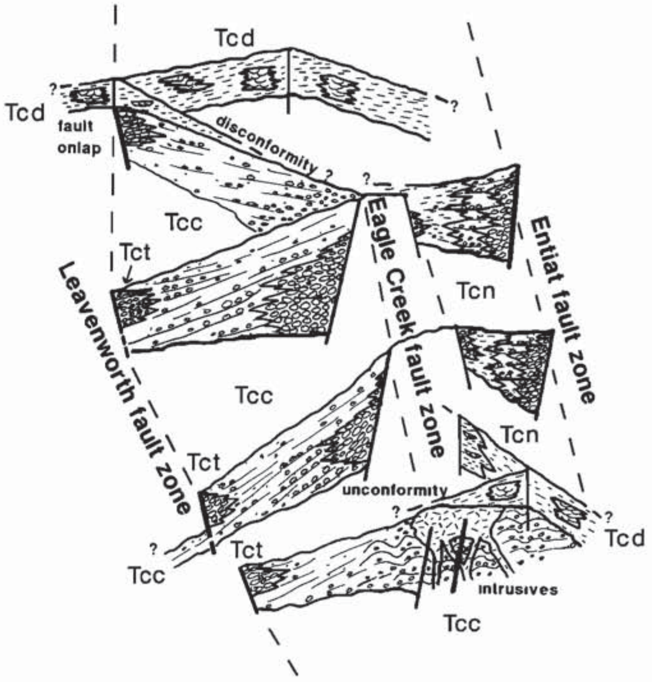


Figure 5. Schematic fence diagram showing stratigraphic relationships of the four members of the Chumstick Formation. Abbreviations used are Tcc, Clark Canyon Member; Tcd, Deadhorse Canyon Member; Tcn, Nahahum Canyon Member; and Tct, Tumwater Mountain Member.

The Clark Canyon Member is the oldest part in the Chumstick Formation. The basal contact is not exposed, but the lowest part of the section is intruded by igneous dikes having maximum K-Ar and zircon fission track ages $\geq$51 Ma (Table 1a). Detrital zircon suites from sandstone in the lower part of the section yield depositional ages of about 48 Ma (Table 1b). Zircon fission-track ages of tuffs in the middle to upper part of the unit range from approximately 46 Ma to 42 Ma (Table 1a). The upper part of the Clark Canyon Member is intruded by a dike with a K-Ar age of about 41 Ma (Table 1a). The upper part of the Clark Canyon Member intertongues with the Tumwater Mountain Member. The upper contact with the Deadhorse Canyon Member changes in part from gradational to disconformable. Paleobotanical collections indicate that the Clark Canyon Member is early middle Eocene in age (presence of Calkinsia franklinensis, Dryophyllum pugetensis, and Pterocarya pugetensis [Evans, 1991b].

The Clark Canyon Member consists of gravel and sand bedload stream deposits, overbank deposits, paleosols, and interbedded tuffs and volcaniclastic debris flow deposits. The unit is interpreted as a humid-fan system (i.e., dominated by fluvial processes), based upon sedimentology and paleobotanical analysis [Evans, 1991a,b]. In the Clark Canyon Member, "proximal fan deposits" (fanhead channels filled by stratified cobble-boulder conglomerate) are relatively rare. Most of the unit consists of "distal fan deposits" (sheetlike deposits representing gravel bars, channel fill sandstones, and overbank deposits) and "axial basin-fill sequences" (essentially a sandy braidplain divided into active channel belts with extensive regions of proximal overbank deposits). Interbedded with these are tuffs and rare volcaniclastic debris flow deposits [Evans, 1991a].

Tumwater Mountain Member. The Tumwater Mountain Member is a tabular body of narrow outcrop belt width east of the Leavenworth fault zone (Figure 2). The unit ranges in thickness from zero to about 1000 m, with greatest thickness along the two northwest trending strands of the Leavenworth fault zone. The unit is named for a 150 m continuous section through excellent exposures of fanhead channels on Tumwater Mountain (T.25N., R.17E., Section 35 NW1/4).

The Tumwater Mountain Member consists of fluvial conglomerate, sandstone, and mudrock with interstratified paleosols (Figure 7). This unit can be differentiated from the Clark Canyon Member in the field based upon three aspects (1) there are no interstratified tuffs; (2) paleoflow was directed eastward (Figure 8); and (3) distinctive clast types were derived from western source areas. These include: peridotite, metavolcanic, and metasedimentary clasts from the Ingalls tectonic complex; graphite-biotite-quartz schist clasts from the Chiwaukum Schist; granodiorite clasts from the Mt. Stuart batholith; and basalt clasts that were probably derived from the Teanaway Formation.

The age of the Tumwater Mountain Member is approximately late middle Eocene. The unit is intertongued with the upper part of the Clark Canyon Member, and partly overlies tuffs that have zircon fission track ages of about 42

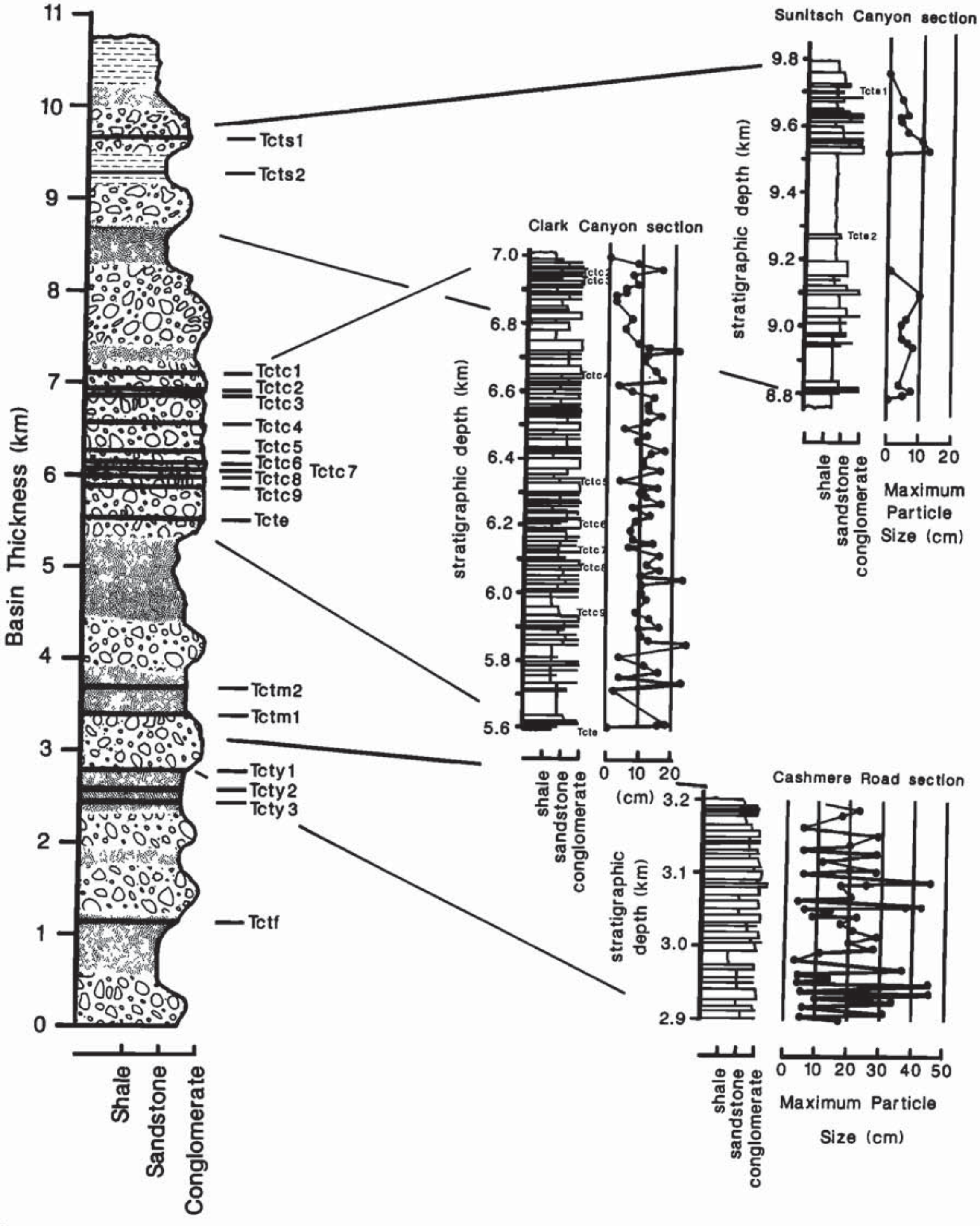


Figure 6. Stratigraphy of the Clark Canyon Member, showing (left) the composite column and (right) some individual sections.

Ma. The unit also contains detrital basalt clasts derived from the Teanaway Formation (K-Ar ages range from 47 Ma to 46 Ma), and detrital granodiorite clasts from the Mt. Stuart Batholith (K-Ar age of about 46 Ma). The Tumwater Mountain Member contains late middle Eocene paleoflora (Pterocarya pugetensis and Cladrastis pugetensis [Evans, 1991b]. The upper contact of the unit with the Deadhorse Canyon Member is disconformable.

The Tumwater Mountain Member mostly consists of gravel and sand bedload stream deposits, with associated overbank deposits and paleosols (Figure 7), similar to the humid region fans discussed for the Clark Canyon Member, with two important differences. First, "proximal facies" are more evident in the Tumwater Mountain Member, and show evidence for upward coarsening and thickening megasequences that are interpreted to represent the basinward

Table 1a. Radiometric Ages of Intrusives In Clark Canyon Member

Radiometric Age, Ma	Method	Lithology	Reference
Wenatchee Dome and Dike Complex			
51.4 ± 2.8	zircon FT	rhyodacite	Tabor et al. [1982]
50.9 ± 3.5	WR K-Ar	andesite	Ott [1988]
48.3 ± 2.8	WR K-Ar	gabbro	Gresens [1983]
45.0 ± 1.8	biotite K-Ar	rhyodacite	Ott [1988]
44.2 ± 1.9	andularia K-Ar	ore vein	Ott [1988]
43.2 ± 0.4	biotite K-Ar	rhyodacite	Tabor et al. [1982]
42.9 ± 1.9	WR K-Ar	basalt	Ott [1988]
42.5 ± 1.6	biotite K-Ar	rhyodacite	Tabor et al. [1982]
42.2 ± 0.4	biotite K-Ar	rhyodacite	Ott [1988]
41.4 ± 1.6	biotite K-Ar	glass margin	Gresens [1983]
40.1 ± 2.5	plagioclase K-Ar	andesite	Ott [1988]
Walker Canyon Dike			
41.5 ± 2.6	hornblende K-Ar	gabbro	Gresens [1983]

Abbreviations are FT, fission track; K-Ar, potassium-argon; and WR, whole rock.

Table 1b. Radiometric Ages of Detrital Clasts and Interbedded Tuffs

Radiometric Age, Ma	Method	Lithology	Reference
Clark Canyon Member			
56.6 ± 5.2	zircon FT	sandstone	Tabor et al. [1987]
51.0 ± 9.6	zircon FT	sandstone	Evans [1988]
50.2 ± 2.4	zircon FT	sandstone	Tabor et al. [1987]
47.7 ± 7.7	zircon FT	sandstone	Tabor et al. [1987]
44.4 ± 2.6	zircon FT	tuff Tctm1	Gresens et al. [1981]
46.2 ± 1.8	zircon FT	tuff Tcte	Gresens et al. [1981]
46.1 ± 1.9	zircon FT	tuff Tcte	Gresens et al. [1981]
42.9 ± 5.0	zircon FT	tuff Tcte	Evans [1988]
42.7 ± 1.5	zircon FT	tuff Tcte	Gresens et al. [1981]
46.4 ± 1.9	zircon FT	tuff Tctc6	Gresens et al. [1981]
42.7 ± 3.7	zircon FT	tuff Tctc6	Gresens et al. [1981]
48.8 ± 7.2	zircon FT	tuff Tctc2	Gresens et al. [1981]
42.7 ± 5.1	zircon FT	tuff Tctc2	Gresens et al. [1981]
41.9 ± 6.8	zircon FT	tuff Tctc2	Gresens et al. [1981]
Tumwater Mountain Member			
46.3 ± 0.3	biotite K-Ar	sandstone	Tabor et al. [1982]
Nahahum Canyon Member			
50.6 ± 2.2	zircon FT	sandstone	Tabor et al. [1987]
46.6 ± 2.4	zircon FT	sandstone	Tabor et al. [1987]
45.4 ± 2.0	zircon FT	sandstone	Tabor et al. [1987]
Deadhorse Canyon Member			
66.4 ± 3.9	zircon FT	sandstone	Tabor et al. [1987]
47.5 ± 2.3	zircon FT	sandstone	Tabor et al. [1987]

Abbreviations are the same as in Table 1a. Tuffs are Mission Creek tuff #1 (Tctm1), Eagle Creek tuffs (Tcte), and Clark Canyon tuffs #2 (Tctc2) and #6 (Tctc6), using the nomenclature of McClincy [1986].

progradation of fanhead regions. Second, there is a greater abundance of soft-sediment deformation structures in the Tumwater Mountain Member, including syndepositional slumps, small growth faults, and clastic dikes, probably representing paleo-earthquake activity [e.g., Plint, 1985].

Nahahum Canyon Member. The Nahahum Canyon Member is about 1900 m thick and, as redefined here, is entirely restricted to the eastern subbasin (Figure 2). The redefinition maintains its original sense as a mostly lacustrine sequence which interfingers with basin-margin fan deposits [Gresens et al., 1981]. The type section defined by Gresens et al. [1981], at Sunnyslope Road (T.23N., R.20E., Sect. 19 NE1/4), is part of the lacustrine sequence.

The Nahahum Canyon Member consists of conglomerate, sandstone, and mudrock of both fluvial and lacustrine origin (Figure 9). The lithology is generally similar to the Clark Canyon Member, with several exceptions (1) there are no interstratified tuffs; (2) conglomerate clasts immediately east of the Eagle Creek fault zone are entirely biotite gneiss and quartz clasts; (3) there are few paleosols; and (4) there are lacustrine sequences.

The base of the Nahahum Canyon Member is not exposed and is presumed to be an unconformity with pre-Tertiary rocks. The unit is considered to be late middle Eocene in age, based upon: (1) a depositional age of 45 Ma or less from zircon fission track ages of detrital clasts (Table 1b); (2) the unit being younger than the Clark Canyon Member (<42 Ma) because development of the eastern subbasin truncated the west-directed drainage system responsible for the deposition of the Clark Canyon Member in the western subbasin; and (3) the lack of interstratified tuffs in the Nahahum Canyon Member, contrasted to their presence in the Clark Canyon Member.

The minimum age for the Nahahum Canyon Member is constrained by the coeval hydrothermal activity in the Eagle Creek fault zone. The Eagle Creek fault zone not only influenced deposition of the Nahahum Canyon Member, but also served as a conduit for the emplacement of felsic

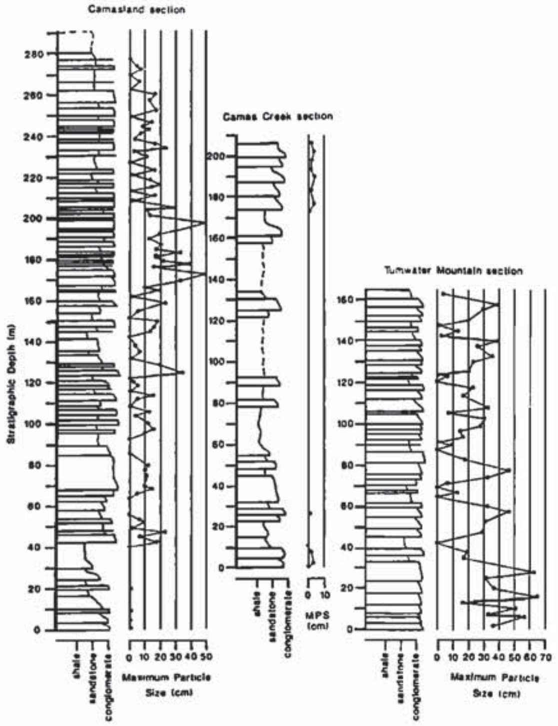


Figure 7. Stratigraphy of the Tumwater Mountain Member showing three individual sections.

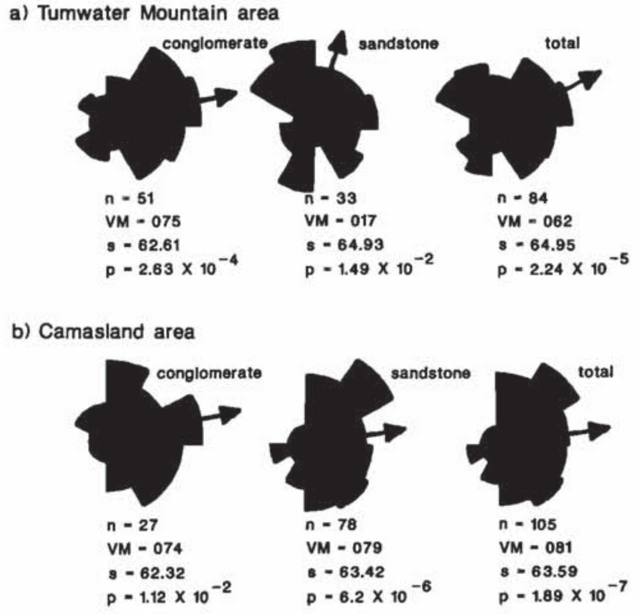


Figure 8. Paleocurrent roses for conglomerates and interbedded sandstone of the Tumwater Mountain Member from two localities adjacent to the Leavenworth fault zone, (a) near Tumwater Mountain, and (b) near Camas-land. Rose diagrams are plotted on a nonlinear scale [Nemec, 1988], showing number of samples (n), vector mean (VM), circular standard deviation (s) [Krause and Geijer, 1987], and a Rayleigh test of significance (p) [Curray, 1956]. All of the paleocurrent data are statistically significant ($p < 0.05$). The composite paleocurrent rose for the entire Tumwater Mountain Member (Figure 14) is different because it includes these measurements with about 120 paleocurrents from basin-fill sandstones located farther east. These sandstones were axial-fluvial systems, with paleoflow SW toward the fault zone and SE parallel to the fault zone.

intrusives in the Wenatchee dome, with K-Ar ages for emplacement of the main dome complex between 44 Ma to 42 Ma; and late stage hydrothermal activity to about 40 Ma (Table 1a). Because the Nahahum Canyon Member contains interbedded eruption breccias, [Margolis, 1987], its minimum age may be about 40 Ma.

The Nahahum Canyon Member consists of marginal coarse-grained facies, axial-fluvial facies, and lacustrine-deltaic facies. Gravel bedload stream deposits with westerly or easterly paleocurrents represent short, steep marginal fans draining into the subbasin from the Entiat and Eagle Creek fault zones, respectively. These coarse-grained deposits are vertically stacked, tabular bodies with a narrow outcrop width, adjacent to the fault zones (Figure 10a). Multistory sandstones and related proximal overbank sequences with southeasterly paleocurrents represent axial-fluvial systems that supplied the major deltaic system in the southeast part of the subbasin. The vertical stacking of delta-front facies northwest of the town of Wenatchee, without evidence of progradation, suggest tectonic control of the lake margin. The Nahahum Canyon Member contains an unusual diversity of soft-sediment deformation structures near the fault zones, including clastic dikes, large flame structures, mud diapirs, convoluted bedding, load structures, and deformed cross-bedding (Fig. 10b), suggesting the effects of paleo-earthquake activity [e.g., Plint, 1985].

Deadhorse Canyon Member. The Deadhorse Canyon Member is approximately 2.2 km thick and is found in both the northern and southeastern parts of the basin (Figure 2). The unit overlies the rest of the Chumstick Formation with contacts that range from a possible disconformity in the northern part of the basin, to an angular unconformity in the southern part of the basin [Gresens, 1983; Evans, 1988]. Unlike the previous units, the Deadhorse Canyon Member shows no evidence for proximal-to-distal facies relationships with respect to fault zones. Paleoflow indicates proximal onlap and eventual overtopping of fault zones. Deadhorse Canyon Member was deposited east of the Entiat fault zone and (based on paleocurrent data) probably was deposited west of the Leavenworth fault zone. The Deadhorse Canyon Member is named for a 760 m sequence in Deadhorse Canyon (T.26N., R.17E., Section 34 SE1/4 to NW1/4).

The Deadhorse Canyon Member consists of fluvial sandstone and mudstone, with minor conglomerate, numerous paleosols, and one interstratified diabase sill (Figure 11). The unit is lithologically similar to underlying units with several exceptions (1) fluvial deposits are distinctly finer grained; (2) there are no tuffs; (3) paleosols are extensive and well developed; and (4) there is a higher proportion of felsic volcanic clasts.

The Deadhorse Canyon Member is probably late Eocene in age, based upon: (1) paleobotanical collections of late

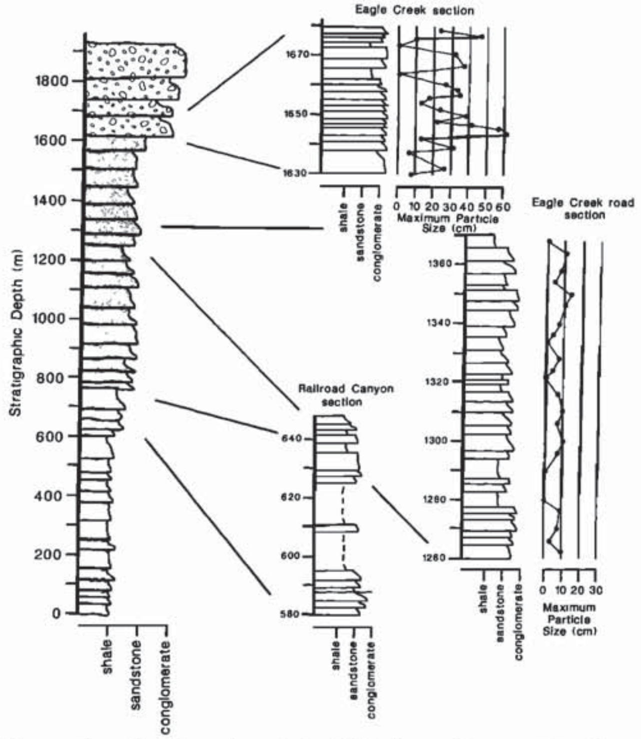


Figure 9. Stratigraphy of the Nahahum Canyon Member showing (left) the composite column and (right) some individual sections.

Figure 10a. Photograph of vertically stacked cobble conglomerates and sandstone representing proximal gravel bedload streams, Van Canyon region, in the Nahahum Canyon Member.

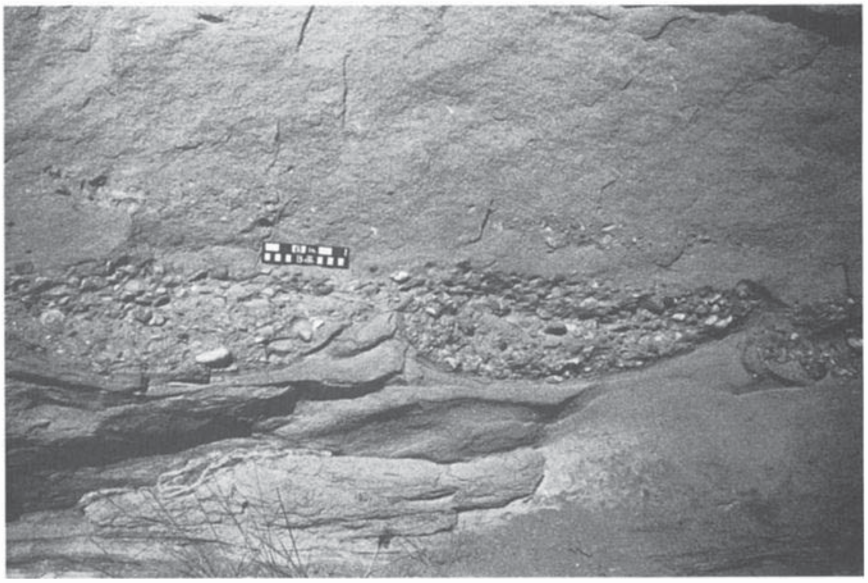


Figure 10b. Photograph of large flame structures in conglomerate and sandstone, Eagle Creek locality, in the Nahahum Canyon Member (scale = 15 cm).

Eocene age (Viburnum pugetensis, Fothergilla durham-ensis, and Macclintockia pugetensis [Evans, 1991b]); (2) zircon fission track ages from detrital sandstones of less than 47 Ma (Table 1b); and (3) unconformable relationships with the older units of the Chumstick Formation. The minimum age estimate of approximately 37 Ma is based upon increased conifer pollen in upper parts of the section, which is considered to represent Eocene-Oligocene paleoclimate modifications in this region (E. Leopold, personal communication, 1986).

The Deadhorse Canyon Member consists of sand bedload and mixed-load fluvial deposits. The unit is organized into multistory channel sandstones, proximal- and distal-overbank sequences. Lateral accretion surfaces and point-bar sequences indicate that the fluvial systems were meandering [Evans, 1991a]. The main channel belts were oriented to the WSW, and the unit may have formed a continuous depositional system with the Roslyn Formation.

Provenance and Paleocurrents

Sandstone petrography. Sandstones in the Chumstick Formation are feldspathic arenites (Table 2). Petrofacies diagrams [e.g., Dickinson and Suczek, 1979] indicate

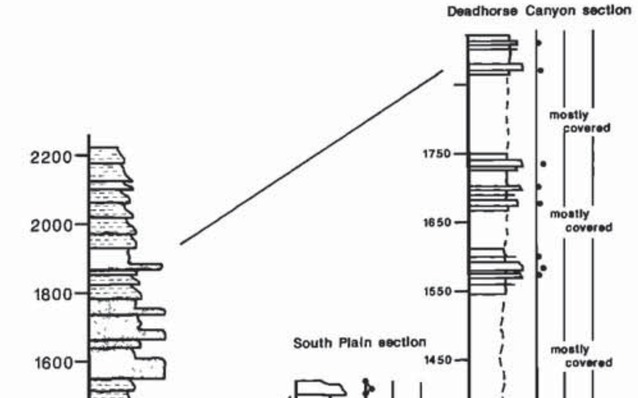


Figure 11. Stratigraphy of the Deadhorse Canyon Member showing (left) the composite column and (right) some individual sections.

potential source areas were dissected arc and uplifted basement terranes. Each of the four members is compositionally similar, and distributions overlap at one standard deviation about the mean (Figure 12). Minor compositional differences can be explained by local sediment sources. For example, the Tumwater Mountain Member has greater amounts of metamorphic lithics, polycrystalline quartz, and chert, with a higher plagioclase-to-total feldspar ratio, in accord with local metamorphic and pelitic source terranes west of the basin. The increase in resistant mineralogies (monocrystalline quartz, chert, and accessories), higher amounts of sedimentary rock fragments, and lower plagioclase-to-total feldspar ratio in the Nahahum Canyon Member may be explained by the erosion and reworking of older Chumstick deposits due to formation of the eastern subbasin (i.e., uplift and erosion of part of the older Clark Canyon Member).

Conglomerate clast lithology. Conglomerate clast counts also show the effects of local source areas. The Clark Canyon and Nahahum Canyon Members are higher in felsic-volcanic and gneiss clasts; while the Tumwater Mountain Member is higher in intermediate-volcanic, mafic-volcanic, and schist clasts (Table 3).

In the Clark Canyon Member there is a notable stratigraphic trend in the upward increase of felsic-volcanic (rhyodacite porphyry), flow-banded rhyolite, and vitric tuff clasts (Figure 13). Ages of interstratified tuffs suggest that the two major increases in percent rhyodacite porphyry clasts occurred at about 45-44 Ma and 42 Ma and that the significant increases in percent flow-banded rhyolite clasts occurred at some later time (approximately 41-40 Ma). Sources for these clasts include a number of plutons northeast of the Chumstick basin, including the 47-40 Ma Duncan Hill Pluton [Cater and Crowder, 1967; Engels et al., 1976; Tabor et al., 1987]; the 48 Ma Cooper Mountain Pluton [Tabor et al., 1987]; and the 54-43 Ma Railroad Creek Pluton [Engels et al., 1976]. Within the Chumstick basin a major intrusive complex, the Wenatchee dome, was emplaced within the Eagle Creek fault zone. This complex includes a felsic dome and associated dikes, flows, ash flows, and eruption breccias representing episodic magmatic activity from about 51-40 Ma [Gresens, 1983; Tabor et al., 1982; Ott et al., 1986; Margolis, 1987]. The trend in flow-banded rhyolite clasts is particularly interesting, because this lithology is prevalent along the margins of the Wenatchee dome. Assuming an emplacement age of about 44-42 Ma for the Wenatchee dome [Gresens et al., 1981], the increase in flow-banded rhyolite clasts in Chumstick strata at about 41-40 Ma suggests rapid unroofing of these intrusives.

Paleocurrents. Vector means were calculated and plotted for each location where paleocurrent data were obtained and composite rose diagrams were created for each unit. All paleocurrent data are statistically significant (Rayleigh test for significance, $p < 0.05$). The average maximum particle size (average intermediate diameter of the 10 largest clasts in a bed) was also plotted to show areal trends in grain size (Figure 14).

Paleoflow in the Clark Canyon Member was directed to the west, based upon paleocurrent data, proximal-to-distal grain size trends, provenance data, and facies relationships (Figure 14a). The deposits closest to the Eagle Creek fault zone represent mostly distal facies from a humid-region fan [Evans, 1991a], suggesting that most of the proximal facies were later eroded. It is likely that formation of the eastern subbasin led to cannibalization of part of the proximal sequence, explaining the higher proportion of sedimentary rock fragments in the Nahahum Canyon Member.

Paleoflow in the Tumwater Mountain Member was somewhat more complex. In the region adjacent to the Leavenworth fault zone, paleocurrents (Figures 8 and 14b), proximal-to-distal grain size trends, provenance data, and facies relationships indicate eastward directed paleoflow, suggesting uplift in the Leavenworth fault zone. East of the Leavenworth fault zone, basin-fill sandstones have SE to SW directed paleocurrents. These are interpreted to represent a basin-axial drainage system that flowed toward and parallel to the Leavenworth fault zone.

The Nahahum Canyon Member shows paleoflow, grain-size, and facies distributions indicating westerly flow off the

Table 2. Sandstone Petrography of the Chumstick Formation

	Clark Canyon Member	Tumwater Mountain Member	Nahahum Canyon Member	Deadhorse Canyon Member
Monocrystalline Quartz	27.6 ± 5.5	24.0 ± 4.2	32.3 ± 11.3	25.0 ± 7.8
Polycrystalline Quartz	7.8 ± 5.2	10.3 ± 10.3	9.6 ± 7.2	7.9 ± 5.8
Chert	0.6 ± 1.1	1.3 ± 2.1	1.3 ± 1.1	1.0 ± 2.6
Plagioclase	39.5 ± 9.4	36.6 ± 7.9	24.4 ± 7.6	38.0 ± 8.2
Potassium feldspar	3.3 ± 2.4	1.6 ± 1.1	3.0 ± 2.2	4.1 ± 3.5
Volcanic lithics	3.6 ± 4.6	2.0 ± 2.1	2.7 ± 2.9	4.2 ± 3.5
Metamorphic lithics	3.6 ± 1.9	8.4 ± 4.2	5.3 ± 3.4	3.4 ± 1.2
Sedimentary lithics	0.0	0.5 ± 0.6	1.0 ± 1.3	0.4 ± 0.6
Micas	6.5 ± 3.6	7.0 ± 4.1	7.8 ± 2.5	8.7 ± 6.5
Accessory minerals	3.6 ± 1.0	2.2 ± 1.9	3.5 ± 4.0	3.2 ± 1.9
Matrix	2.2 ± 1.4	3.7 ± 4.1	2.8 ± 2.1	2.7 ± 2.3
Cement	1.6 ± 3.1	1.0 ± 1.5	5.9 ± 8.7	1.0 ± 2.5
Unknown/altered	0.1 ± 0.2	1.7 ± 1.8	0.4 ± 0.4	0.4 ± 0.3
No. of Samples	17	8	7	9
P/F ratio	.92 ± .04	.96 ± .03	.88 ± .07	.91 ± .06
QFL ratio	42,49,09	43,44,13	54,35,11	40,50,10
QmFLt ratio	32,50,18	28,46,26	40,35,25	30,50,20

Each sample had between 400 and 500 grains counted, using the Gazzi-Dickinson method. Abbreviations are P, plagioclase; F, total feldspar; Q, total quartz; L, lithics; Qm, monocrystalline quartz; Qp, polycrystalline quartz; Lt, total lithics (Qp + L).

Entiat fault zone, easterly flow off a portion of the Eagle Creek fault zone, and the development of a basin-axial fluvial and lacustrine-deltaic system that flowed southeast (Figure 14b). The formation of the eastern subbasin, filled by the Nahahum Canyon Member, truncated the older Clark Canyon Member depositional system.

The Deadhorse Canyon Member does not show textural or facies distributions indicative of tectonic control of drainage. Paleoflow and facies distributions indicate flow across all three of the major fault zones (Figure 14c). Overall paleoflow is westerly, but there is a higher dispersion about the mean, which is in accord with the higher sinuosity of these depositional systems.

Thermal Maturity Data

Vitrinite reflectance data. Vitrinite reflectance values (Figure 15) indicate differences in thermal maturity between the eastern and western subbasins. In the eastern subbasin, vitrinite values are lower overall (the maximum reflectance (R_o) is 0.58%), and the pattern can be interpreted to show that maximum burial occurred in the delta-front deposits northwest of the town of Wenatchee. In the western subbasin, values are higher overall (the maximum R_o is 2.08%). Using the tephrostratigraphy as a control, it can be shown that vitrinite values in the Clark Canyon Member vary along strike, to produce a half bull's-eye pattern in the central part of the basin. Inliers of lower values in the north and on the west side of the basin can be interpreted as the lower thermal maturity of the strata of the Tumwater Mountain Member and Deadhorse Canyon Member, both of which overlie the Clark Canyon Member.

The highest vitrinite values (1.5 to 2.1% R_o) are located in the southwest part of the western subbasin. These values coincide with the location of a positive magnetic anomaly as discussed by Brandon et al. (manuscript in preparation, 1994). The combination of a positive magnetic anomaly and high vitrinite reflectance values in this area clearly indicates a buried intrusive of post-Chumstick age, and not buried Ingalls tectonic complex.

Basin burial temperatures. By using a time-dependent temperature model for vitrinite reflectance data [Hood et al., 1975], with a maximum 2.1% R_o, and an effective heating time of 10 to 40 m.y., the maximum burial temperature can be calculated as between 180°C and 210°C [Evans, 1988]. Discordant apatite and zircon fission track ages [Gresens et al., 1981; Tabor et al., 1987], indicate that the basin was heated to above the blocking temperature for apatite (105 ± 10°C according to Parrish [1983]) and below the blocking temperature for zircon (225 ± 10°C according to Naeser [1979]). Zeolite minerals in the Chumstick Formation (laumontite and clinoptilolite in sandstones and tuffs and lizardite overgrowths on peridotite clasts) indicate maximum burial temperatures of about 100°C to 130°C [Castano and Sparks, 1974; Cashman, 1974; Cashman and Whetten, 1976].

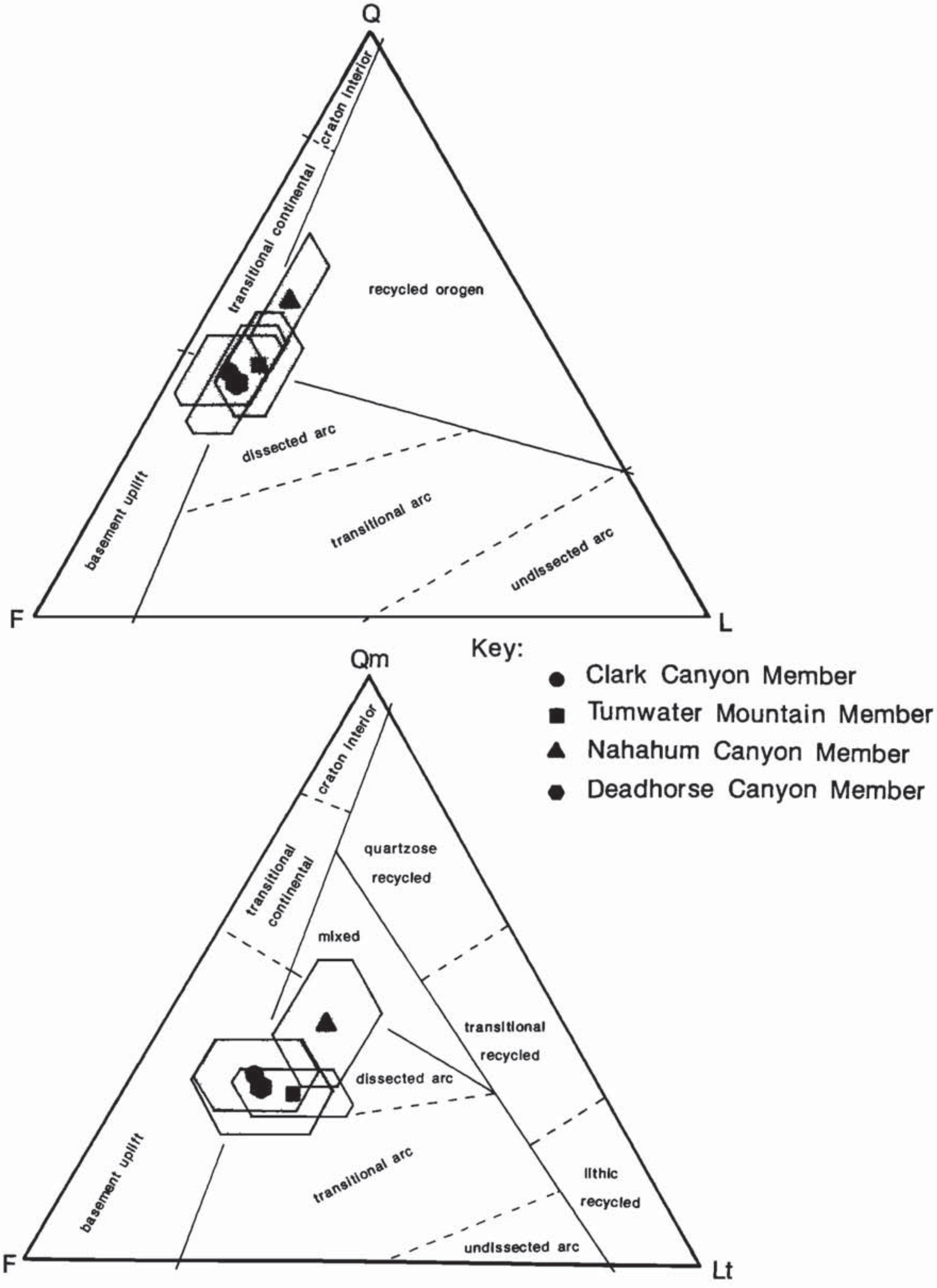


Figure 12. Ternary diagrams showing sandstone petrofacies for the Chumstick Formation (provenance fields from Dickinson and Suczek [1979]). Top diagram shows quartz (Q), feldspar (F) and lithics (L) fields, lower diagram shows monocrystalline quartz (Qm), feldspar (F) and total lithics (Lt) fields.

Table 3. Clast Lithology of Conglomerates

	Clark Canyon Member	Tumwater Mountain Member	Nahahum Canyon Member	Deadhorse Canyon Member
Vein quartz	15.4 ± 12.4	22.9 ± 16.0	25.8 ± 30.9	12.4 ± 4.5
Plutonics	22.0 ± 13.5	24.1 ± 12.0	24.1 ± 21.1	20.4 ± 18.0
Rhyodacite porphyry	30.0 ± 23.5	7.3 ± 9.8	21.6 ± 31.3	49.8 ± 28.9
Felsic tuff	2.4 ± 3.3	1.4 ± 3.8	1.4 ± 2.1	2.4 ± 1.5
Flow-banded rhyolite	2.8 ± 6.4	0.3 ± 0.8	0.9 ± 1.6	2.8 ± 2.7
Intermediate volcanic	3.0 ± 5.9	6.1 ± 9.0	1.3 ± 2.3	1.0 ± 2.2
Mafic volcanic	0.5 ± 1.8	11.6 ± 27.2	0.4 ± 1.1	0.0
Gneiss	22.9 ± 18.9	4.0 ± 7.5	20.9 ± 24.3	5.6 ± 6.6
Schist	0.4 ± 0.6	22.6 ± 24.0	1.8 ± 3.9	3.2 ± 5.2
Low-grade meta.	0.2 ± 0.6	0.0	1.6 ± 2.3	0.0
Sedimentary	0.5 ± 1.2	0.1 ± 0.4	0.0	0.0
Unknown	0.3 ± 0.7	0.0	0.3 ± 0.7	2.8 ± 3.6
Number of clasts	2344	952	694	635
Number of localities	15	7	8	5

Clast counts were made by identifying all clasts within an area approximately 0.5 m X 0.5 m within an individual bed.

Paleogeothermal gradient. Vitrinite samples were recovered from the NORCO-1 well (Figure 16), located just southeast of the town of Wenatchee, and vitrinite reflectance values were calculated (T. Walsh, personal communication, 1986). Sedimentary and vitrinite data indicate that the section in the well is repeated by a fault with about 400 m offset [Evans, 1988]. A simple adjustment for offset (Figure 16) has been used to reconstruct a paleogeothermal gradient curve (approximately 60°C/km to 70°C/km), and to calculate a surface intercept ($R_o = 0.13\%$). The low value for the surface intercept indicates that Chumstick strata were not buried deeply by overlying units, which is in accord with estimates for the maximum thickness of the overlying Wenatchee Formation [Gresens et al., 1981; Gresens, 1983]. The relatively high paleogeothermal gradient can be attributed to rapid subsidence and high heat flow due to the proximity of syndepositional intrusives.

Calculation of basin fill thickness. Basin burial temperature from discordant zircon and apatite fission track dates, zeolite mineral assemblages, and vitrinite reflectance are reasonably consistent with maximum basin burial temperatures in the range of 170°C to 225°C. Considering the maximum and minimum values, the thermal maturity indicators suggest maximum burial depth of about 3.5 km in the western subbasin and 2.2 km in the eastern subbasin. A gravity survey used estimates of rock densities to predict present day thicknesses of strata as about 2 km in the western subbasin and about 1 km in the eastern subbasin [Silling, 1979].

In summary, the thermal maturity and stratigraphic data agree that the eastern subbasin had a maximum thickness of about 2 km, but the data sets strongly disagree for the maximum thickness of the western subbasin. The great contrast between stratigraphic thickness (≥12 km) and actual basin-fill thickness (≥3.5 km) in the western subbasin suggests either repeat of the section by faulting (which can be discounted, owing to the stratigraphic control given by tephrostratigraphy) or that deposition was dominated by rapid lateral shifting of depocenters.

Discussion

Basin Evolution

Initial extension (prior to 51 Ma). The Clark Canyon Member represents the oldest deposits in the Chumstick basin, with basal intrusives having K-Ar and zircon fission track ages of >51 Ma (Figure 17). Paleoflow was oriented to the west throughout the deposition of the Clark Canyon Member. In the Swauk basin, the "sandstone facies of Swauk Pass" represents equivalent age fluvial strata with similar paleocurrent and provenance characteristics. There is no evidence for tectonic relief in the Leavenworth fault zone while these two units were deposited. It is therefore proposed that the Swauk and Chumstick formed an integrated fluvial depositional system at this time (Figure 18a) [Evans, 1988, 1991c; Evans and Johnson, 1989; Taylor et al., 1988]. There is no convincing evidence that controlling faults (the Entiat-Eagle Creek system) were oblique slip. The half bull's-eye pattern shown by vitrininte samples in the Clark Canyon Member suggest that this was a half-graben open to the west. The timing for extension in this basin is consistent with regional studies [e.g., Harms and Price, 1992].

Tectonic partitioning (51 Ma to 49 Ma). Taylor et al. [1988] have documented two episodes of drainage disruption and modification in the Swauk Formation during this

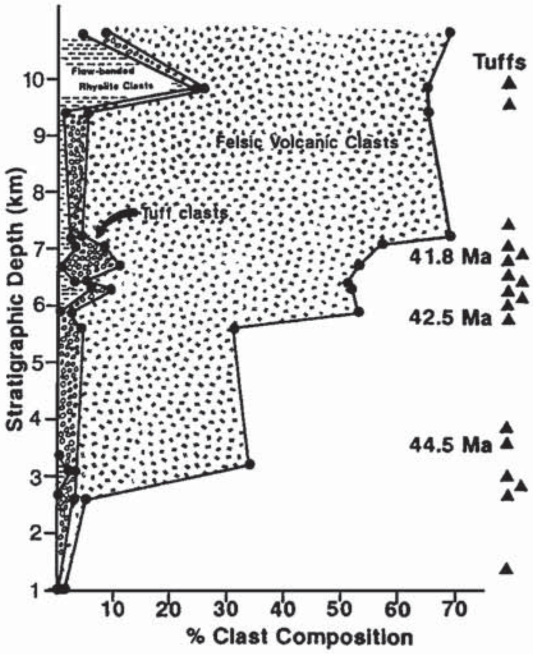


Figure 13. Volcanic clast composition of the Clark Canyon Member. The stratigraphic column shows the upward increase in three lithologies, flow-banded rhyolite, tuff, and porphyritic rhyodacite. At each stratigraphic level the set of data points represent a sample of 300 to 500 clasts. The stratigraphic positions and radiometric ages of tuffs are shown on the right.

approximate time interval (Figure 18b). The first episode consisted of east flowing rivers ("conglomerate facies of Cougar Gulch") that entered a lacustrine-deltaic system (the "shale facies of Scotty Creek") near the Leavenworth fault zone (Figure 17). The second episode consisted of southeast flowing rivers ("conglomerate facies of Tronsen Creek") that entered a second lacustrine-deltaic system near the Leavenworth fault zone ("shale facies of Tronsen Ridge"). All of these units are interbedded with a coarse-grained mass-flow deposit found near the Leavenworth fault, called the "breccia facies of Devil's Gulch" [Taylor et al., 1988].

It has been argued that the Swauk Formation was deposited in a strike-slip basin [Johnson, 1985; Taylor et al., 1988], but in contrast to evidence discussed below, there is no convincing evidence for oblique slip on the Leavenworth or Entiat-Eagle Creek fault systems at this time. Facies relationships and other data are entirely consistent with the formation of the Swauk basin as an extensional half-graben, with short, steep fans west of the Leavenworth fault zone, a belt of fine-grained deposits in the zone of maximum subsidence west of the fault, and broad fans on gentler slopes entering from west [e.g., Alexander and Leeder, 1987].

The nature of faulting on the Leavenworth fault zone at this time is problematical. Taylor et al. [1988] suggest it was a high-angle fault, and that some or all of the older Chumstick deposits to the east were eroded, but there are two problems with this hypothesis. The first is the lack of evidence for a basinwide unconformity in the Clark Canyon Member (the angular unconformity in the Eagle Creek fault zone noted by Gresens [1983] is local in scale, is between Clark Canyon Member and Deadhorse Canyon Member, and is probably related to the emplacement of the Wenatchee Dome at about 44-42 Ma). Second, when average sedimentation accumulation rates are calculated for different intervals of the Clark Canyon Member, they show relatively consistent values. One would expect obvious variations in average sediment accumulation rate if portions of the section were missing due to erosion. An alternative explanation to the above is that relief in the Leavenworth fault zone at this time represents isostatic uplift of the extensional footwall [e.g., Wernicke and Axen, 1988], resulting in the Chumstick and Swauk basins forming a pair of west facing half-grabens.

Overtopping of fault zone (49 Ma to 48 Ma). West of the Leavenworth fault zone, the "sandstone facies of Red Hill" (Figure 17) represents sand bedload and suspension load fluvial deposits which interfinger with the upper part of the lacustrine deposits of the "shale facies of Tronsen Ridge", and overlie the rest of the Swauk Formation [Taylor

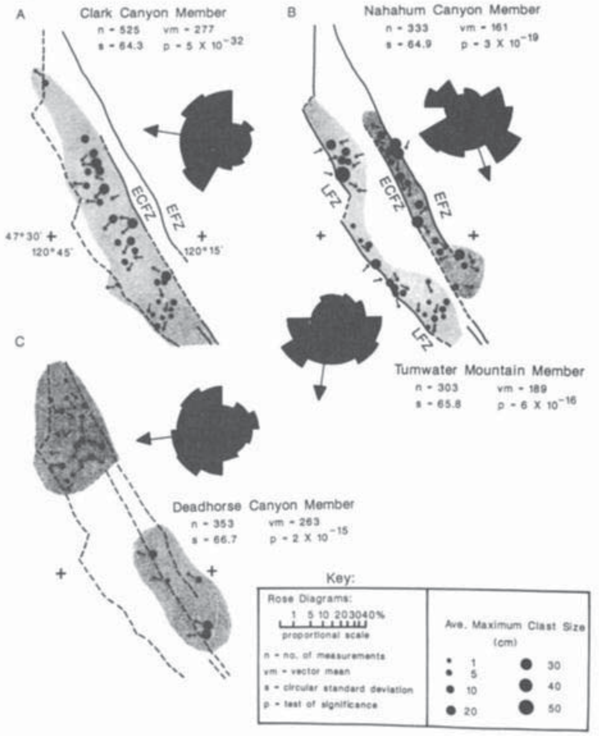


Figure 14. Map showing paleocurrent data from the Chumstick Formation, for the (a) Clark Canyon Member, (b) Tumwater Mountain and Nahahum Canyon Members, and (c) Deadhorse Canyon Member. Paleocurrent data are from cross-bedding, clast imbrication, flute casts, ripple marks, clast long-axis orientations, primary current lineations, groove casts, and log-cast orientations. Vector means were calculated and plotted for each location, and composite rose diagrams were created for each unit using a non-linear scale [Nemec, 1988], showing vector mean, circular standard deviation [Krause and Geijer, 1987] and Rayleigh test of significance [Curray, 1956]. All of the paleocurrent data are statistically significant ($p < 0.05$). The average maximum particle size was based upon the average intermediate diameter of the 10 largest clasts in a bed.

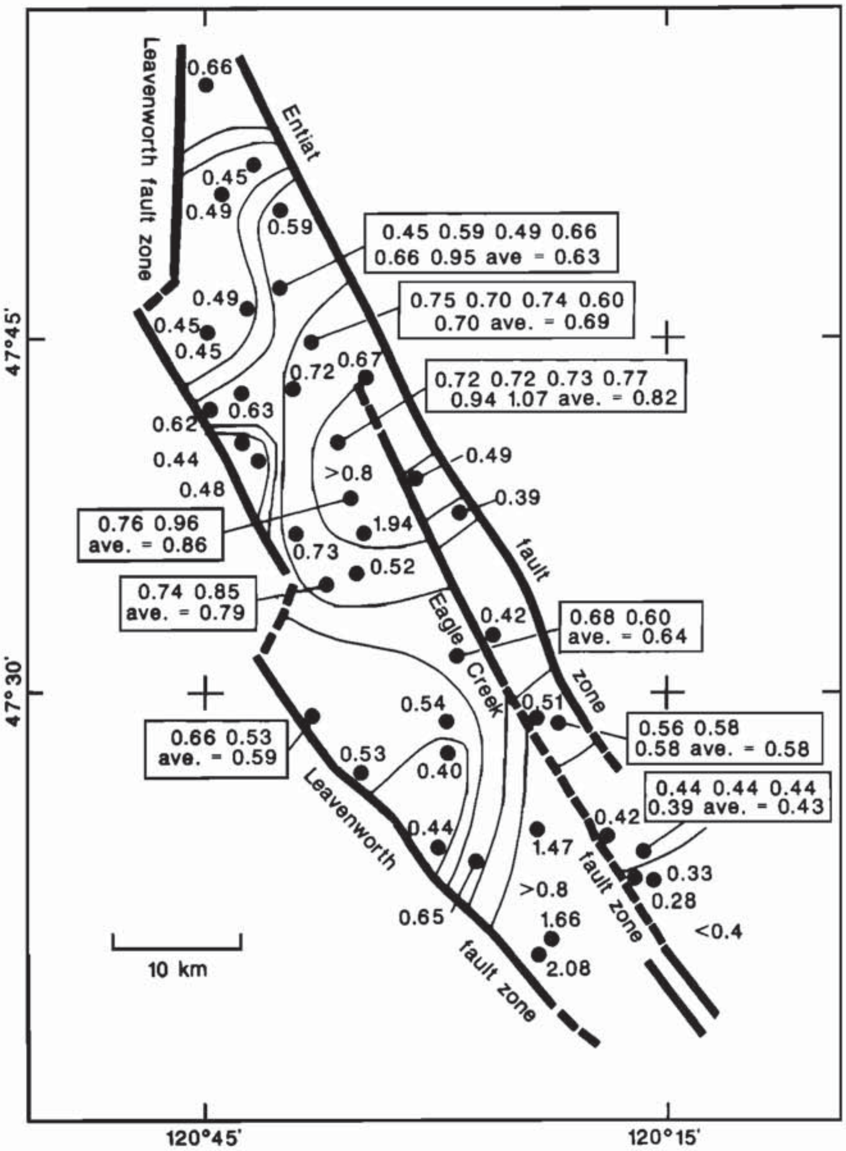


Figure 15. Vitrinite reflectance values from surface outcrops in the Chumstick Formation showing the different distribution patterns in the eastern and western subbasins.

et al., 1988; Tabor et al., 1982]. On the basis of lithology, fluvial facies, depositional style, and paleoflow indicators, the "sandstone facies of Red Hill" can be correlated to the upper part of the Clark Canyon Member of the Chumstick Formation [Taylor et al., 1988; Evans, 1988; Evans and Johnson, 1989]. These deposits west of the Leavenworth fault zone indicate the reestablishment of a regional west-southwest drainage.

The reestablishment of regional drainages (Figure 18C) implies that tectonic relief in the Leavenworth fault zone was reduced by some combination of tectonic quiescence, scarp erosion, and aggradation rates greater than subsidence rates. Proximal onlaps of basin-fill sediments in the Chumstick basin led eventually to overtopping of the Leavenworth fault zone, and thus represent a change from closed (internally drained) basins to open (through-going drainage) basins.

Tectonic partitioning (48 Ma to 41 Ma). The Swauk Formation was folded at about 48 Ma, and is unconformably overlain by the volcanic rocks of the middle Eocene Teanaway Formation, with K-Ar ages clustering around 47 to 46 Ma [Tabor et al., 1982, 1984]. In the Swauk Formation, folding and faulting were more pronounced adjacent to the Straight Creek and Leavenworth fault zones, with fold axes orientations consistent with north-south dextral shear, suggesting the onset of strike-slip motion on the Straight Creek fault system about 48 Ma [Frizzell, 1979; Tabor et al., 1984].

In the Chumstick Formation, uplifts that served as sediment sources feeding eastward directed alluvial fan systems of the Tumwater Mountain Member were located at left-stepping (northwest trending) segments on the Leavenworth fault zone, suggesting that these were transpressive

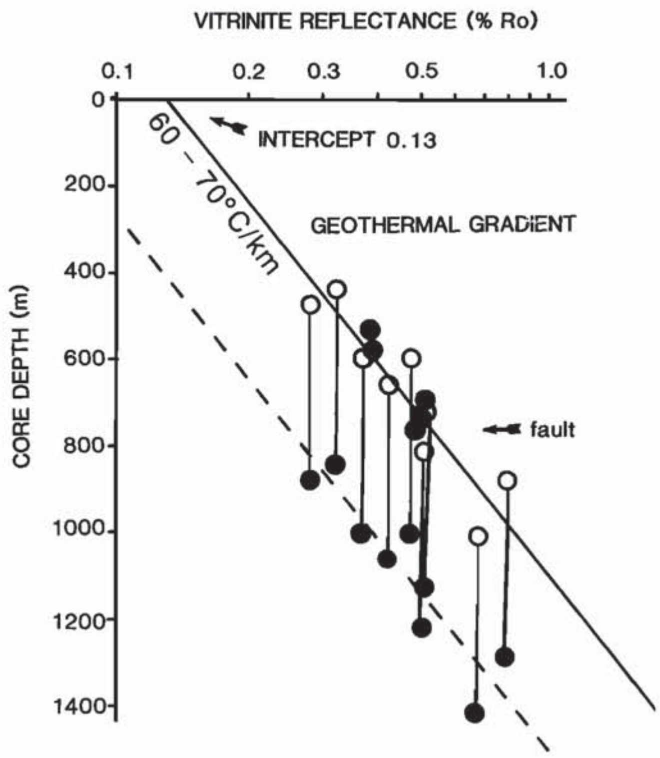


Figure 16. Vitrinite reflectance values from the NORCO-1 well near Wenatchee showing that the section is repeated by a fault, and that the offset can be removed to reconstruct a consistent data set. The paleogeothermal gradient is calculated based upon a time-temperature model (see text for discussion).

uplift blocks (Figure 18d). Although the Tumwater Mountain Member might be as old as earliest Swauk deformation (about 48 Ma), most of these deposits are probably younger because the Tumwater Mountain Member overlies 42 Ma tuffs in the Clark Canyon Member in the northern part of the basin.

On the basis of age relationships the eastern subbasin formed at about 42 Ma, beheading west flowing drainages and effectively ending deposition of the Clark Canyon Member (Figure 18d). The parallel orientation and partial overlap of the Entiat and Eagle Creek fault zones and orientation of subsidiary faults and fold axes, suggest that both fault zones accommodated dextral shear. Both the structural and sedimentary data suggest that the eastern subbasin formed as a transtensional step-over basin between these two overlapping dextral faults. The eastern subbasin then filled by deposition of the Nahahum Canyon Member (Figure 17), with marginal fans feeding an axial-fluvial drainage and extensive lacustrine-deltaic system in the southeast part of the basin.

Overtopping of fault zone (40 Ma to 37 Ma). The Deadhorse Canyon Member overlies the rest of the Chumstick Formation, with contacts that change from a possible disconformity in the northern part of the basin to an angular unconformity in the southern part of the basin, where these strata overlie the hydrothermally altered and deformed strata of the Clark Canyon Member near Wenatchee and contain mineralized clasts eroded from this unit.

The Deadhorse Canyon Member does not show any relationship, in terms of texture, facies, paleocurrents, or provenance, to the major fault zones (Figure 17). The average maximum clast size of conglomerates in the Deadhorse Canyon Member is significantly less than from older conglomerates in the Chumstick Formation, and there are no obvious proximal-to-distal trends in grain size. Paleocurrent data indicate a generally west-southwest paleoflow, and the unit may have formed a continuous depositional system with the late Eocene Roslyn Formation (Figure 18e).

The Deadhorse Canyon Member represents a second phase of proximal onlap and overtopping of faults. In the northern part of the basin, paleoflow was directed toward the Leavenworth fault zone and may indicate that the fault zone was overtopped by these deposits. In the southern part of the basin, Deadhorse Canyon Member is found both east and west of the Entiat fault zone and had paleoflow directed across the Entiat and Eagle Creek fault zones.

Basin deformation (about 37 Ma to 34 Ma). Chumstick strata were folded prior to the deposition of the early Oligocene Wenatchee Formation, which unconformably overlies the Chumstick Formation and contains tuffs with zircon fission track ages of 34 Ma to 33 Ma [Gresens et al., 1981; Gresens, 1983]. Along the Leavenworth fault zone, forced-parallel folds are observed in the region of two left-stepping, transpressive bends; while elsewhere fold axes are en echelon and diverge northwesterly from the trend of the Leavenworth fault by 15° to 40°. The orientation of these fold axes is consistent with a system of dextral shear (Figure 18f).

Along the Eagle Creek and Entiat fault zones, folds are en echelon and diverge northwesterly from the trend of the faults by 15° to 30°. Folds with similar orientation are also present in the pre-Tertiary Swakane Biotite Gneiss [Tabor et al., 1987]. The orientation of these structures are in accord with dextral shear. In the Eagle Creek fault zone, uplifted basement blocks are bounded on the west by probable contractional faults with locally overturned bedding in the Chumstick Formation. The orientations of these contractional faults and related folds resemble positive flower structures [e.g., Harding et al., 1983].

Post-Chumstick sedimentation. Conglomerates composed of biotite gneiss clasts are found adjacent to uplifted blocks of Swakane biotite gneiss on the west side of the Eagle Creek fault zone (Figure 2). Gresens et al. [1981] thought these "redbed fanglomerates" were the basal unit of the Chumstick Formation, but the deposits are lithologically different from the oldest conglomerates in the Clark Canyon Member and show bedding relationships that crosscut bedding in the Clark Canyon Member. Instead, it is proposed that this is a paleocolluvium deposit that surrounded basement blocks which were uplifted and exposed during Chumstick basin deformation. The fanglomerates postdate the Chumstick Formation, but their age relationship to the Wenatchee Formation remains unclear.

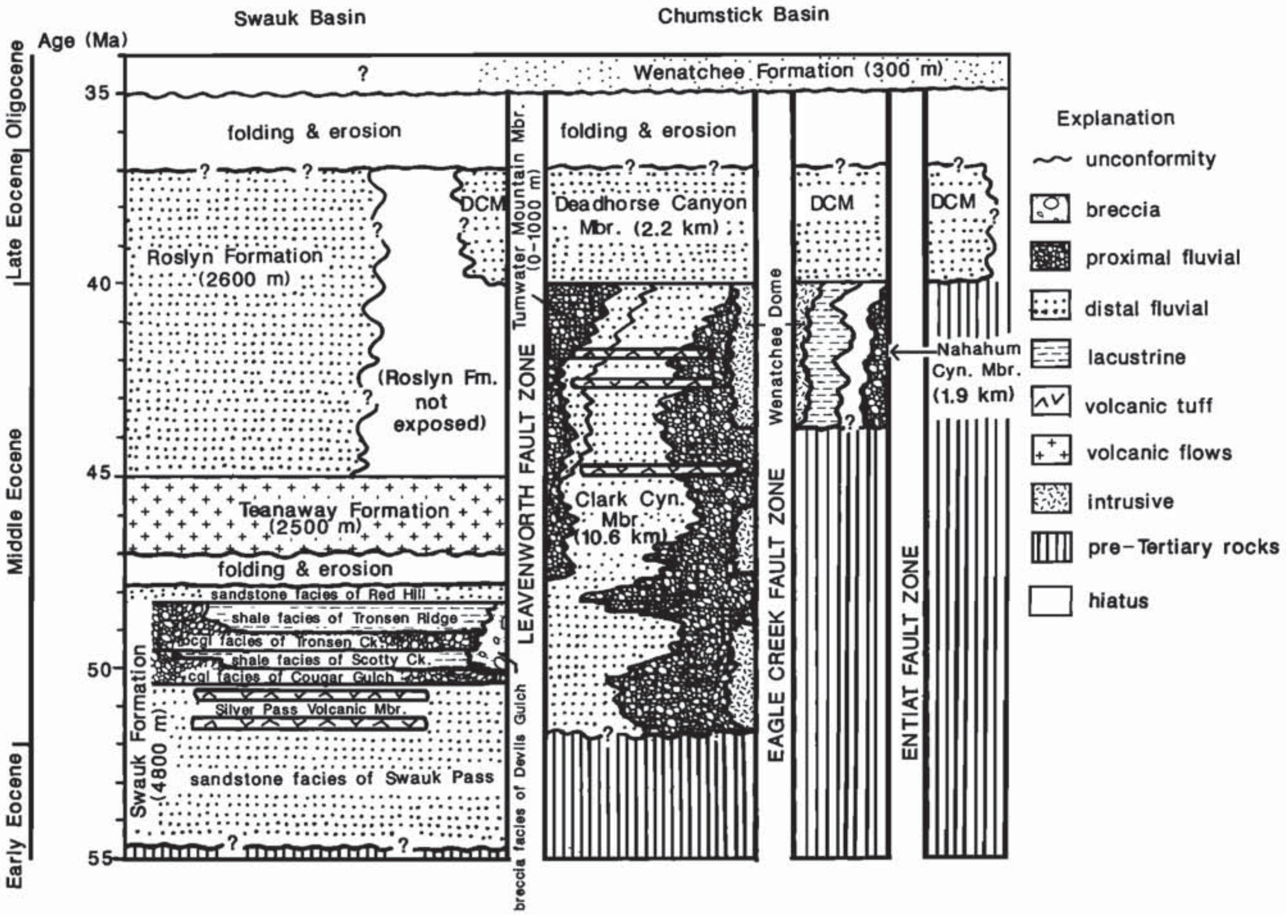


Figure 17. Lithostratigraphic relationships between the Swauk basin (Swauk, Teanaway, and Roslyn Formations) and the Chumstick basin (Chumstick and Wenatchee Formations) modified from Evans and Johnson [1989]. DCM is the Deadhorse Canyon Member (Chumstick Formation).

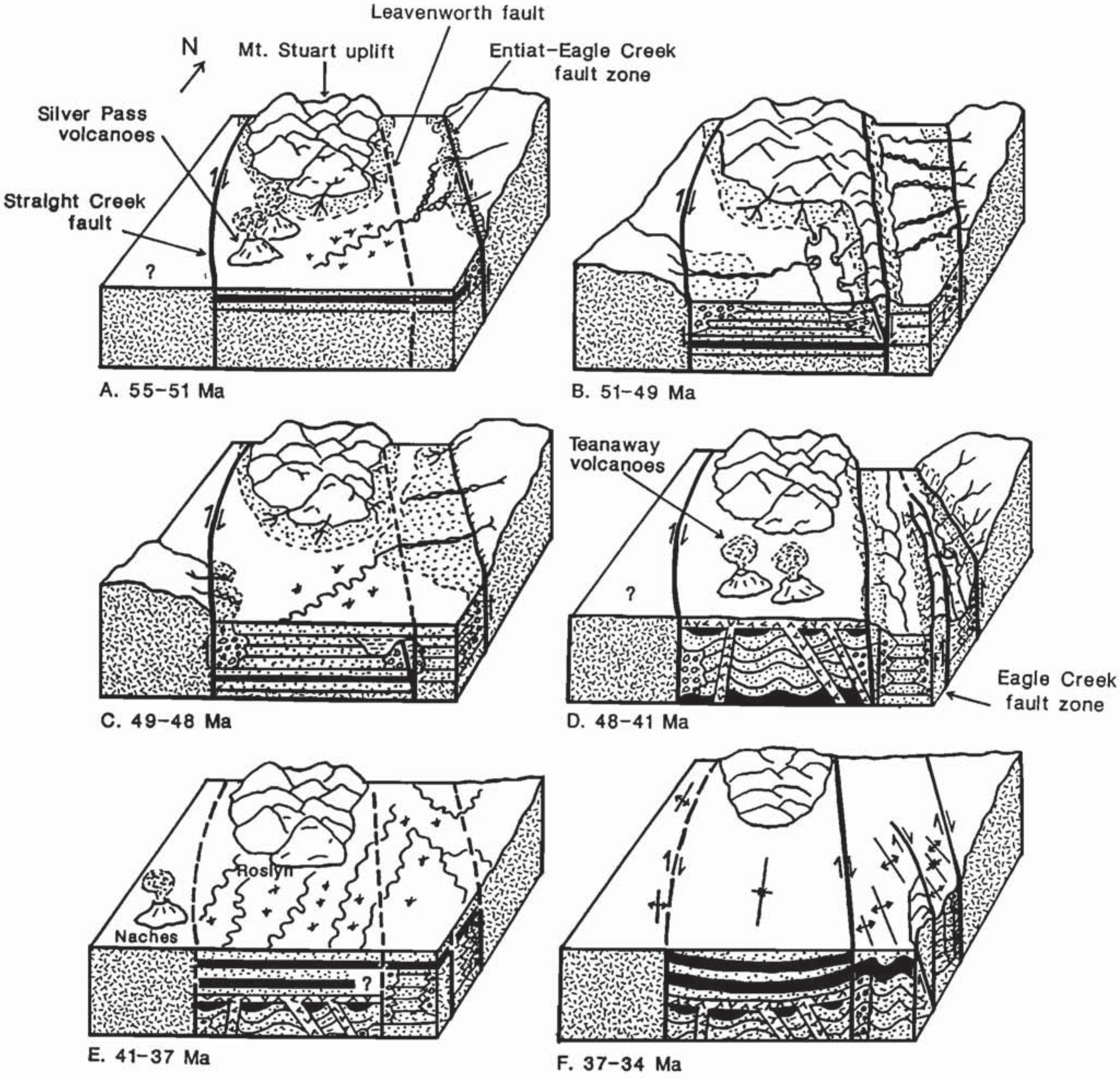
Regional Fault Histories

Entiat-Eagle Creek fault system. The Entiat-Eagle Creek fault system clearly has a long and complex history. For part of its history it accommodated contraction between late Mesozoic terranes [Tabor et al., 1989]. Hurlow and Nelson [1991] argued that structures in the Mesozoic crystalline rocks to the northeast are consistent with dextral shear between the Entiat and Ross Lake fault systems during the interval of about 70-67 Ma. There is no compelling evidence that the Entiat-Eagle Creek fault system had a strike-slip component during deposition of the Clark Canyon Member (pre-51 Ma to about 42 Ma). The fact that blocking temperature ages [Tabor et al., 1987] in the Swakane Biotite Gneiss are virtually the same as depositional ages of biotite gneiss clasts in the Chumstick Formation suggests rapid uplift east of the Entiat fault.

Evidence for oblique slip at about 44-42 Ma on the Entiat-Eagle Creek fault system includes the formation of the eastern subbasin as a transtensional step-over basin; this was accompanied by hydrothermal activity, emplacement of intrusives, and formation of small grabens and pop-ups in the Eagle Creek fault zone. This interpretation is consistent with Laravie's [1976] study on micro-structures on the Entiat fault, as restated to account for this stratigraphic revision: (1) pre-Nahahum Canyon Member extension and mylonite formation, (2) syn-Nahahum Canyon Member oblique slip, and (3) post-Chumstick Formation uplift east of the fault zone.

There is no evidence for tectonic relief on the Entiat or Eagle Creek fault zones during the deposition of the Deadhorse Canyon Member (about 40-37 Ma), which is found draped across all three fault zones. Basin deformation at 37-34 Ma may represent a second episode of dextral strike slip, given the orientation of fold axes and subsidiary faults.

Leavenworth fault zone. The Leavenworth fault zone also has a complex history, but its origins are more obscure. Rapid uplift in the region is indicated by zircon fission track and K-Ar blocking temperatures ages in the Mt. Stuart batholith [Tabor et al., 1987] that are virtually the same as depositional ages of granodiorite clasts in the Swauk and Chumstick Formations. The "breccia facies of Devil's Gulch" of the Swauk Formation indicates relief on the Leavenworth fault zone, with the west side down, at about 51-49 Ma. There is no compelling evidence that the Swauk



A. 55-51 Ma

B. 51-49 Ma

C. 49-48 Ma

D. 48-41 Ma

E. 41-37 Ma

F. 37-34 Ma

Figure 18. Block diagrams showing the basin evolution of the Chumstick Formation. (a) Deposition of the Clark Canyon Member of the Chumstick Formation and related strata of the Swauk Formation as part of a unified depositional system in an extensional basin setting. (b) First episode of tectonic partitioning, caused by uplift in the Leavenworth fault zone, segmenting the regional drainage system shown in Figure 18a. (c) Proximal onlap and overtopping of the Leavenworth fault zone, and reestablishment of regional depositional systems. (d) Second episode of tectonic partitioning, deformation, uplift, and volcanism in the Swauk Basin was coupled with drainage reorganization in the Chumstick basin, deposition of the Tumwater Mountain and Nahahum Canyon Members. (e) Second episode of proximal onlap, overtopping of fault zones, and deposition of the Deadhorse Canyon Member of the Chumstick Formation and the Roslyn Formation. (f) Basin deformation in latest Eocene.

Formation formed in a strike-slip basin, in fact, it could be argued that facies distributions in the Swauk Formation are more consistent with an extensional half-graben.

The oldest evidence for the onset of strike slip in this region is folding in the Swauk Formation along the Straight Creek fault at about 48 Ma, and the reversal of movement sense (from west side down, to east side down) of the Leavenworth fault at about 44-42 Ma. Source areas for the Tumwater Mountain Member were located at left-stepping segments of the Leavenworth fault zone, which is consistent with the likely positions of transpressive uplifts and pop-ups along a dextral fault. The Deadhorse Canyon Member overtopped the Leavenworth fault zone during the interval 40-37 Ma. Again, basin deformation at 37-34 Ma may represent a second episode of dextral strike slip, given the orientation of folds and subsidiary faults.

Summary and Conclusions

The implications of the data set are that this region of the Pacific Northwest underwent regional extension in the interval from about 55 Ma to about 48 Ma. If oblique slip was first manifested on the Straight Creek fault at about 48 Ma, this motion may not have been transferred to the northwest trending fault systems until somewhat later (about 44-42 Ma). The sedimentary evidence that constrains this history was the formation of local sediment sinks (transtensional basins) and sediment sources (transpressional uplifts). Evidently there was a period of tectonic quiescence at about 40-37 Ma, followed by an interval of basin deformation at about 37-34 Ma that manifests structures suggestive of dextral transpression.

The Chumstick basin is an example of a sedimentary basin of mixed origin, with an early history probably dominated by extension, and a later history strongly influenced by strike slip. It serves to suggest caution about applying idealized basin models for extensional basins or strike-slip basins to any study area.

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