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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 - Reply

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Reply

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Introduction

Johnson's lengthy comment [this issue] is ironic, for two reasons. First, the age of the base of the Chumstick Formation is far better understood that the age of the base of the nearby Swauk and Chuckanut Formations, upon which Johnson bases so many of his interpretations. Second, the Chumstick Formation provides the best unambiguous evidence for the influence of strike-slip tectonics on the deposition of Paleogene sedimentary rocks in the Pacific Northwest, a hypothesis long championed by Johnson, but he finds it necessary to discredit this study because of the evidence presented for an earlier episode dominated by extension, and a later episode dominated by strike slip.

The words "unambiguous" and "dominated", as used above, are important toward resolving this disagreement. In addressing Johnson's comments I wish to reiterate how I am applying a different (and in my view, more correct) set of criteria for recognition of a strike-slip basin than Johnson and his coworkers [*Johnson*, 1985; *Taylor et al.*, 1988]. The criteria that I am using allow recognition of the more complex two-stage model, while Johnson's criteria fail to discern it.

I should also note at the onset that Johnson continues (through several versions of his comment) to misread this paper. The phrase "pure extension" used repeatedly by Johnson and attributed to me is, in fact, nowhere to be found in my paper. The central point of *Evans* [1994] was the evidence for an earlier episode dominated by extension, and a later episode dominated by strike slip. Does this mean that the Chumstick Formation was deposited in an "oblique-slip basin?" Well, that depends upon one's definition of the term. Technically "oblique slip" implies any component of both dip slip and strike slip [e.g., *Biddle and Christie-Blick*, 1985]. In practice, such definition is too broad to be meaningful. *Evans* [1994] uses the term "oblique slip" only when there is clear evidence for the development of structural features whose origin required significant components of both dip slip (probably hundreds of meters) and strike slip (probably kilometer scale). Thus I cannot preclude the possibility that the earlier phase of basin formation, dominated by dip slip, also included some minor component of strike slip. The key word here is "minor."

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This argument is not merely semantic. I initiated approximately 10 years of research on these sedimentary basins fully expecting them to conform to models of classical strike-slip basins, such as the Mio-Pliocene Ridge basin of California [*Crowell*, 1982]. I have come to the conclusion that there is no such thing as a "classical" strike-slip basin, a view reinforced by recent literature. Some geologists might be surprised to learn that many "strike-slip" basins are bounded by listric normal faults, these include the Dead Sea Rift [*Reches*, 1987; *ten Brink and Ben-Avraham*, 1989] and the Ridge basin itself, where newly available deep seismic data show that the San Gabriel fault is listric and flattens at about 4 km depth [*May et al.*, 1993]. Other recent studies have supported the concept of *Evans* [1994], that there may be an evolutionary sequence of structural domains in the history of a "strike-slip" basin. For example, the Cenozoic As Pontes basin of northwest Spain evolved through a restraining overstep generation stage (dominated by normal and thrust faults) to a restraining bend generation and activity stage (the generation of strike-slip faults by linking of existing fault segments) [*Cabrera et al.*, 1995]. In the case of the Ridge basin, the modified model for "conveyor-belt sedimentation" provided by *May et al.* [1993] requires a significant amount of extension to accommodate block rotation, prior to the onset of translation of the "coal cars."

It's a different way of looking at things. Johnson and I reference the exact same papers, but while he attributes all evidence of regional extension as "transtension," what I read is the careful documentation of detachment faults [e.g., *Tempelman-Kluit and Parkinson*, 1986] and listric normal faults [e.g., *Harms and Price*, 1992]. To me, it's not a question of whether the Pacific Northwest was a region of oblique convergence during the Paleogene, but how that stress field was manifested, and if as a result there was an evolution of structures in any particular sedimentary basin.

Age of the Base of the Chumstick Formation

In attempting to discredit the radiometric dates for intrusives in the base of the Chumstick Formation, Johnson is apparently unaware of the proprietary data recently made available from the underground gold mines near Wenatchee that strongly support the interpretations presented by *Evans* [1994]. The gold mining district is located between strands of the Eagle Creek fault zone. There is a coherent stratigraphy that has been broken into a series of folded and faulted blocks. The lowest unit exposed in the underground mine works is a gneissic- and plutonic-clast cobble-boulder conglomerate with minor interbedded sandstone greater than 50 m thick [*Cameron*, 1994]. This unit is probably the base of the Chumstick Formation [e.g., *Gresens*, 1983], representing a coarse-grained rift-fill deposit. The basal conglomerate is overlain by about 500 m of sandstone and conglomerate with several interstratified amygdaloidal olivine basalt flows. Locally silicified and argillized portions of this sandstone serve as the ore body. Overlying this sandstone is a series of porphyritic hornblende-plagioclase andesite flows with tuffs and flow breccias, about 35 m thick. This is the unit from which the K-Ar whole rock age of 50.9 $\pm$ 3.5 Ma was obtained [*Ott*, 1988]. The andesite is overlain by a thick carbonaceous mudstone that is deformed and accommodated local thrusting (the "footwall shear" unit). To the north, this stack is intruded by a gabbro sill with a K-Ar whole rock age of 48.3 $\pm$ 2.8 Ma [*Gresens*, 1983]. To the south, this stack is overlain by the Norco Volcanic complex of *Margolis* [1987], which has a K-Ar biotite age of 47.3 $\pm$ 1.8 Ma for the basal flow unit and which includes a rhyolitic ashflow tuff with a K-Ar whole rock age of 46.2 $\pm$ 1.8 Ma that acted as an impermeable seal above the hydrothermal system [*Margolis*, 1994]. The intrusion of the Wenatchee Dome, a series of porphyritic rhyodacite plugs and dikes, was responsible for mineralization. Asamera Minerals (U.S), Inc., reports five K-Ar ages that cluster at 44 Ma for the age of mineralization [*Cameron*, 1994], only one has been published, a K-Ar age for vein andularia of 44.2 $\pm$ 1.9 Ma [*Ott*, 1988]. Other published ages are from younger, unmineralized portions of the Wenatchee Dome, such as the 41-43 Ma K-Ar ages reported by *Gresens* [1983] and *Tabor et al.* [1982]. Zircon fission-track ages from the Wenatchee Dome typically cluster at 47-52 Ma, including the 51.4 $\pm$ 2.8 Ma reported by *Tabor et al.* [1982] that Johnson seeks to discredit. Possibly these zircons do represent incorporated detrital zircons, as implied by observations of *Coombs* [1952]. It is nevertheless true that there is a coherent stratigraphy, with a 51 Ma andesite flow unit overlying >550 m of Chumstick strata, and so clearly the base of the Chumstick Formation is significantly older than Johnson is prepared to accept.

I might add at this point that strike-slip offset on the Eagle Creek fault zone truncates folds, minor faults, ore veins, and mineralized zones, indicating that the onset of significant strike slip on this system was younger than about 44 Ma [*Cameron*, 1994]. The detailed work by mine geologists in this region is an independent confirmation for the *Evans* [1994] model of a two-phase basin evolution, with an earlier (>44 Ma) phase dominated by extension, volcanic activity, and premineralization brecciation and jointing, followed by a later (<44 Ma) stage dominated by strike slip. According to *Cameron* [1994, p. 49], "the dates indicate the deformation and mineralization telescoped into a narrow time interval after the deposition of ...[the lower part of]... the Chumstick Formation" (addition is mine).

Taylor et al. [1988] (Johnson was a coauthor) and *Johnson* [this issue] have stated that unexposed basal or intraformational unconformities prove that the Chumstick basin was uplifted and partially to completely eroded prior to about 50 Ma. This argument involves negative evidence and is somewhat disingenuous. There is no question that the base of the Eocene Chumstick Formation rests unconformably on Precambrian and Mesozoic basement, but the presence of such unconformity (whether exposed or not) proves nothing regarding the validity of Johnson's arguments. As for an intraformational unconformity that is not exposed... this is simply wishful thinking on the part of Johnson and his coworkers. The evidence against this unconformity is as follows: (1) no field evidence at the surface, (2) not recognized or mapped in the subsurface mine workings, (3) does not cause a break in slope of the plot of vitrinite reflectance versus depth from the NORCO-1 well [*Evans*, 1994, Figure 16], and (4) does not cause a break in slope on the sediment accumulation rate curve (J.E. Evans, unpublished data, 1993). There is, in fact, no positive evidence in support of Johnson's claim.

Criteria for Recognizing a Strike-slip Basin

Johnson and his coworkers [*Johnson*, 1985; *Taylor et al.*, 1988] use a list of criteria for recognizing a strike-slip fault basin: (1) location between strike-slip faults, (2) great stratigraphic thickness and high sediment accumulation rates, (3) abrupt lateral and vertical facies changes, (4) disruption and reversals of drainage patterns, (5) intermittent internal drainage systems, (6) interbeds and intrusions of extension-related volcanic rocks, (7) deformation consistent with transpression, and (8) alternating pulses of subsidence and deformation.

Although useful, such a list is not diagnostic. In the Pacific Northwest, the regional faults have a long and complex history involving Mesozoic contraction and strike slip and Paleogene extension and strike slip. Under the circumstances, criterion 1 is certainly circular reasoning. Criterion 6 can hardly apply to differentiate extensional and strike-slip faulting. Criterion 7 cannot be used in this case, because all of these basins were deformed by postdepositional transpression (which does not prove anything regarding the origin and syntectonic fill of the basin). The "alternating pulses of subsidence and deformation" (criterion 8) are not seen in the deposition of the Swauk Formation and lower Chumstick Formation. Such alternating phases are seen in younger portions of the Swauk basin (deformation of the Swauk Formation and subsequent deposition of the Teanaway and Roslyn Formations) and in younger portions of the Chumstick basin (deposition of the Clark Canyon Member followed by transpressive uplifts in the Leavenworth fault zone followed by deposition of the Tumwater Mountain Member), but this is precisely the point of *Evans* [1994]: the diagnostic evidence for strike-slip tectonics comes later (post-48 Ma) in the history of these basins.

Finally, the other evidence Johnson uses (facies changes, drainage disruption, internal drainage) is simply not diagnostic. These are also found in the Newark Supergroup [e.g., *Turner-Peterson and Smoot*, 1985] and East African Rift System [e.g., *Frostick and Reid*, 1989]. As a relevant example, Johnson states that only one of the eight basin phases described for the Swauk Formation [*Taylor et al.*, 1988] match the half graben model of *Alexander and Leeder* (1987), therefore he argues the Swauk Formation was deposited in a strike-slip basin. The literature does not support his contention [e.g., *Blair and Bilodeau*, 1988; *Heller and Paola*, 1992]. Changes in subsidence rates in an half graben could account for (1) trapping of coarse-grained deposits near the fault zone ("breccia facies of Devil's Gulch") and proximal onlap of fine-grained deposits ("shale facies of Scotty Creek" and "shale facies of Tronsen Ridge") due to increased subsidence rates of the master fault; and (2) proximal offlap and progradation of coarse-grained deposits across the basin ("conglomerate facies of Cougar Gulch", "conglomerate facies of Tronsen Creek") from hanging-wall sources, due to decreased subsidence rates of the master fault. If anything, the facies relationships in the Swauk Formation are more consistent with an extensional half graben than with a pull-apart or rhombochasm basin, this coupled with the absence of structural features diagnostic of syndepositional strike-slip faulting led to the observation made by *Evans* [1994].

In the Chumstick basin, the following structural features can be unambiguously attributed to strike slip and can be shown to be syndepositional in the time interval of about 44-40 Ma: (1) uplifts at left-stepping bends on the dextral Leavenworth fault, interpreted as transpressive pop-up structures, controlled deposition of the Tumwater Mountain Member, of late middle Eocene age (approximately 44-40 Ma); (2) formation of a subbasin in the overlap zone between the dextral Entiat and Eagle Creek fault zones, interpreted as a transtensional step-over basin, controlled deposition of the Nahahum Canyon Member of late middle Eocene age (approximately 44-40 Ma); and (3) thrust faults and overturned bedding near the Eagle Creek fault zone are interpreted as flower structures and can be observed at the surface near the town of Cashmere [*Evans*, 1994] and in underground mine workings near the town of Wenatchee [*Cameron*, 1994], these faults cut mineralized portions of the Clark Canyon Member near the Eagle Creek fault zone, hence are younger than about 44 Ma in age. In addition, other structural data such as the orientation of fold axes and postdepositional secondary faults, and the unconformity between the Chumstick and 33-34 Ma Wenatchee Formation indicate an episode of post-depositional (37-34 Ma) dextral transpression.

Finally, Johnson discusses at length the possibility of "conveyor-belt" sedimentation in the Chumstick Formation: isn't this evidence for strike slip on the Entiat fault system during the deposition of the Clark Canyon Member? As the person who developed the database and discovered the discrepancy between stratigraphic thickness and basin burial depth (determined by thermal maturity indicators), I of course considered this possibility. There is one irreconcilable problem: the depocenters in the Clark Canyon Member young to the northwest, whereas if the Entiat fault system was dextral (and all evidence suggests it was), these depocenters should young to the southeast. I believe that the best explanation is a combination of extension and tilting (scissor like motion) on the fault, producing a migrating depocenter to the northwest. This explanation is consistent with facies relationships, paleocurrent data, and thermal maturity data.

Regional Depositional Systems

For the Pacific Northwest, the recognition of a episode of extension prior to 48 Ma, followed by the onset of strike-slip faulting commencing sometime after 48 Ma, has implications for the evolution of depositional systems. It has been proposed that there was an interval of early Eocene "regional" drainages, characterized by numerous fluvial systems draining source areas to the northeast [*Evans*, 1991; *Evans and Ristow*, 1994]. Johnson disagrees with this, and appears in this critique to be commenting on the paper by *Evans and Ristow* [1994]. For the benefit of those readers that have not read *Evans and Ristow* [1994], the argument is based on the evidence that the oldest sedimentary units in each basin have the following similarities: (1) they were avulsion-dominated, mixed-load fluvial depositional systems; (2) they had relatively high sediment accumulation rates; (3) each basin was characterized as "open" drainages, with west-southwest directed paleoflow crossing each basin (including the linking of the Chumstick and Swauk depositional systems); and (4) these units had broad similarities in sandstone petrofacies [*Frizzell*, 1979; *Hartman*, 1973], for example Chumstick Formation petrofacies overlap the other three units at one standard deviation (J.E. Evans, unpublished data, 1993).

Johnson appears to confuse the concept of an alluvial plain with a peneplain, and his criticisms are thus unduly restrictive. An ancient alluvial plain is a paleogeographic feature that could incorporate numerous individual drainage basins (thus accounting for minor differences in source material, such as lithic content) and does not preclude the presence of topography, such as the Mount Stuart block, in the form of drainage divides. Johnson himself has advocated similar views. In an earlier paper [*Johnson*, 1984, p. 102] he notes that "the sedimentology of the Slide and Bellingham Bay members in the main outcrop belt and of the Chuckanut Formation in neighboring areas suggests sedimentation on a regionally extensive alluvial plain," and then he goes on to suggest the probable source terrane for these units was eastern Washington or adjacent parts of British Columbia. The presence of such large Eocene regional drainage systems has also been advocated by *Heller et al.* [1992a, b] for the Chuckanut Formation, Puget Group, Paleogene units in the Olympic Mountains and other regions on the basis of similar sandstone isotopic compositions. The similar trace element content of the Chumstick Formation, Naches Formation, and Puget Group [*Byrnes*, 1985] also suggests mixing and homogenization of sediment through regional drainages.

Finally, it should be observed that there are stratigraphic trends in sandstone compositions, as seen in the Clark Canyon, Tumwater Mountain, and Nahahum Canyon members of the Chumstick Formation [*Evans*, 1994], in "type 1, 2, and 3" petrofacies from the northwestern outcrop belt of the Chuckanut Formation [*Johnson*, 1984], and in the Coal Mountain, Sperry Peak, and Higgins Mountain units from the southeastern outcrop belt of the Chuckanut Formation [*Evans and Ristow*, 1994]. Compositional changes in each basin form a stratigraphic trend toward the recycled-orogen petrofacies field. Possibly this is due to a shift toward more restricted drainages and local source areas as a result of tectonic partitioning of drainage due to the onset of strike-slip faulting. These trends are not observed in the Swauk Formation [*Taylor et al.*, 1988], where the petrofacies for all units in the stratigraphy cluster together.

Possibly this anomaly can be explained because the Swauk Formation was deposited prior to the tectonic partitioning of regional drainages due to the onset of strike-slip tectonics in the region.

Fault Kinematics and Timing

Johnson questions the applicability of the *Wernicke and Axen* [1988] model as a alternative explanation for the truncation of the Chumstick - Swauk depositional system at 51-49 Ma due to uplift in the Leavenworth fault zone. He points out differences between the model (specifically the width of the zone of uplift) and this example. It should be noted that *Evans* [1994] never stated that the width of this zone was "about 1 km," as attributed by Johnson. The alternative model was proposed because, while the second interval of tectonic partitioning (at about 44-42 Ma) produced transpressive pop-up structures, transtensional stepover basins, and flower structures, the first interval of tectonic partitioning (at about 51-49 Ma) did not. The relatively narrow width of this proposed zone of uplift may have been due to basement structures, specifically the fact that this portion of the Leavenworth fault zone (between the Swauk and Chumstick Formations) lies approximately above the basement suture zone between the Jurassic Ingalls Complex, an obducted ophiolite [*Miller*, 1985] and the Precambrian Swakane Biotite Gneiss.

Johnson argues that microstructure data from the Entiat fault zone does not support the interpretation of extension. I do not agree with his interpretation of *Laravie* [1976] and *Hurlow* [1992]. The Entiat fault zone is a zone of deformation including, in places, parallel and subparallel fault strands, fault step overs, fault terminations, and folds. The late middle Eocene episode of oblique slip was probably accommodated by the growth and linking of preexisting fault strands, some of these recording evidence of Mesozoic contractional faulting and oblique slip [*Hurlow*, 1992], and some recording evidence for "early Tertiary extension" (D1 of *Laravie*, [1976]). The point is, we don't know exactly where the fault responsible for the first episode (dominated by extension) was located relative to the existing Entiat fault zone, which took its present form in the subsequent episode (dominated by strike slip). As clearly discussed in *Evans* [1994], the fault-proximal sedimentary facies are missing from the Clark Canyon Member, because these deposits were eroded and recycled as a result of formation of the eastern subbasin (filled by the Nahahum Canyon Member). This earlier fault or set of faults was probably located relatively close to the existing Entiat fault zone but could easily have been somewhat east of it.

Finally, a number of other workers in the Pacific Northwest have noted that Eocene extension could be explained in the context of transtension [e.g., *Ewing*, 1980; *Harms and Price*, 1992]; however it is important to note that the link is not yet conclusive. A careful reading of *Harms and Price* [1992] for example, would show that they documented 52-45 Ma crustal-scale extension by a listric normal fault system (that had only minor oblique slip), and that they evoked the *Wernicke and Axen* [1988] model to explain the observed footwall rotation and isostatic adjustment in the adjacent basin. It is true that *Harms and Price* [1992] explained the origin of this listric normal fault as a consequence of a regional stress regime affected by "Eocene" dextral slip, but their study did not closely examine the relationship between the timing of extension on this particular fault and the timing of the onset of dextral slip on this or adjacent faults. Other workers have found evidence that the onset of regional strike-slip faulting was between 48 Ma [*Frizzell*, 1979; *Tabor et al.*, 1984] and 46.5 Ma [*Coleman and Parrish*, 1991]. In the Chumstick Formation, the cutting of 44 Ma mineralized veins suggests that the onset of strike-slip faulting was even younger.

Summary

In summary, it remains my contention that the Chumstick basin formed as an extensional basin prior to 51 Ma, which was affected by syndepositional oblique-slip faulting that commenced at about 44 Ma on the Entiat-Eagle Creek fault system and possibly as early as 48 Ma (but the best evidence in the Chumstick basin would indicate at about 44 Ma) on the Leavenworth fault. The implication here is that it may be necessary to reconsider pigeon holing these basins as "strike-slip basins" when in fact their origin is less clear. The Chumstick Formation was deposited in what is best described as an extensional basin that was modified by syndepositional oblique slip and deformed by post-depositional oblique slip. In contrast, the best evidence would suggest that the Swauk Formation was deposited in an extensional (not a strike slip) basin, which was subsequently deformed by postdepositional oblique-slip.

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