The Monroe Fault, Anticline, and Synclinal Basin—A Potentially Active Fault and Fold System in the Skykomish River Valley, Snohomish County, Washington

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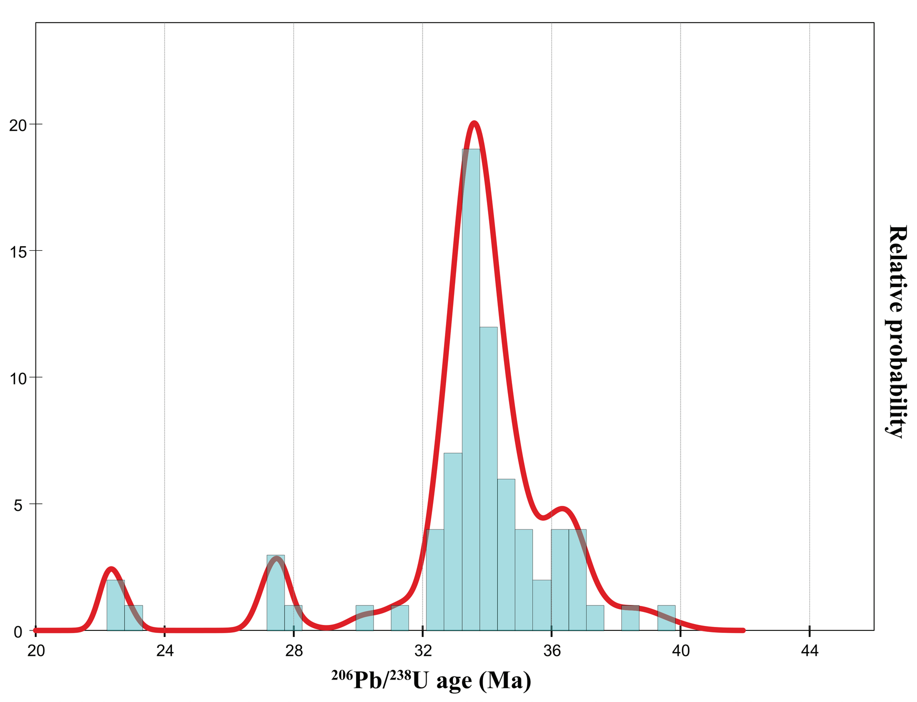
Sand U-Pb Detrital Zircon Geochronology

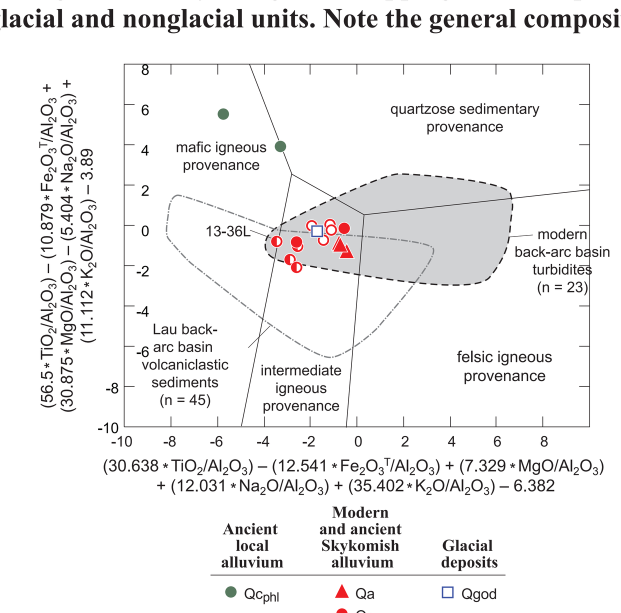
Detrital zircon age spectra show a Cascade signal with distinct Tertiary to Cretaceous peaks (Index Batholith ~32Ma).



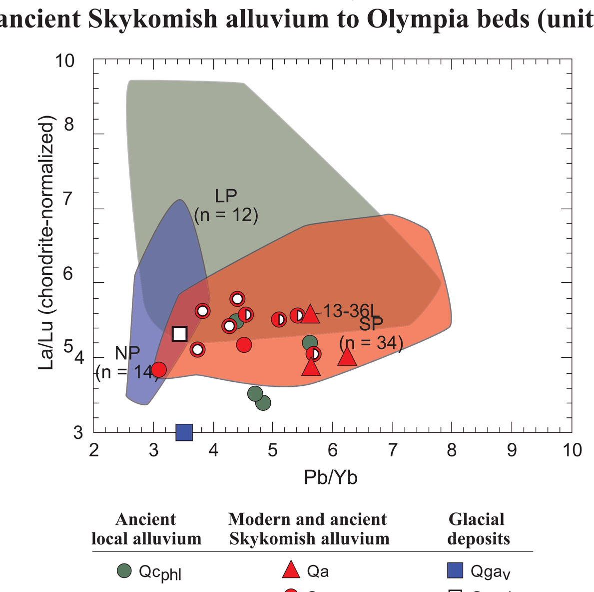
We obtained detrital zircon U-Pb age data from nonglacial sand from the southwestern part of the Lake Chaplain map area at age site 37A (unit Qco)(see Regional Diagram). The agreement between (1) the detrital zircon age distribution of the sands of this sample, (2) Cascade or SP provenance of this sample, (3) other age information in and around the Monroe syncline, and (4) geochemistry of this sample and other SP sediments is striking. See OSL/IRSL table for the 40.5 and 48.3 ka ages for sample 37A. Note the age peaks at ~34 and 90 Ma. The detrital zircons were transported to the sample site by ancient fluvial transport during the Olympia nonglacial interval (20–60 ka) and deposited 40.5 to 48.3 ka as indicated by the IRSL and OSL samples from site 37A.

Sand Geochemistry

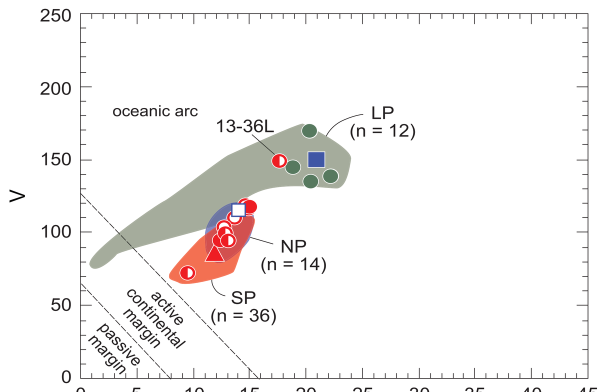
Sand geochemistry along with mapping and sand petrography supports our correlation of Quaternary sediments with various glacial and nonglacial units. Note the general composition ranges from ancient Skykomish alluvium to Olympia beds (unit Qco)



Roser and Korsch discriminant function diagram for Quaternary samples (Roser and Korsch, 1988). Note that the SP samples plot primarily in the intermediate igneous provenance field, consistent with their petrography (Sand Provenance Table).



Chondrite-normalized Lanthanum/Lutetium (La/Lu) vs. Lead/Ytterbium (Pb/Yb) diagram for Quaternary sand samples. Chondrite normalization values are from McDonough and Sun (1995). LP, local provenance from the Tolt River and Youngs–Elwell Creek; NP, northern provenance deposited during continental glaciations; SP, modern and ancient Skykomish and Snoqualmie River basin provenance. Colored fields for NP, SP, and LP derived from previous studies (n, number of samples).



Ancient local alluvium: Qc_{phl}. Modern and ancient Skykomish alluvium: Qa, Qc_o, Qc_{ph}, Qc_{ws}. Glacial deposits: Qga_v, Qgod.

Vanadium (V) vs. Scandium (Sc) provenance diagram of Bhatia and Crook (1986) for Quaternary sand samples. LP, local provenance from Tolt River and Youngs–Elwell Creek; NP, northern provenance deposited during continental glaciations; SP, Skykomish and Snoqualmie River basin provenance. Colored fields for NP, SP, and LP derived from previous studies (n, number of samples).

Sand Provenance

Sand petrography and geochemistry show a Cascade provenance or ancient Skykomish River provenance for most mapped nonglacial Pleistocene sediments.

Sedimentary provenances for quaternary deposits in the Lake Chaplain, Sultan, Lake Joy, Monroe, Carnation, North Bend, Fall City, and Snoqualmie quadrangles. Provenances are defined by compositional data derived from sand point-count data, petrographic observations, sand geochemistry, and field data. Nonglacial Pleistocene geologic units were deposited in fluvial depositional environments similar to modern (Holocene) river deposits of the same provenance.

Group	Geologic unit(s)	Sedimentary provenance and facies notes
SP (Snoqualmie or Skykomish River basin provenance)	Qa (Snoqualmie and Skykomish Rivers), Qc_o, Qc_{ws}, Qc_h, Qc_{pf}, Qc_{ph}	Snoqualmie and Skykomish River basin or central Cascade (nonglacial) provenance from easterly erosional sources carried by rivers generally flowing west. The major bedrock erosional sources for SP sediments are Tertiary intrusive rock bodies such as the expansive Snoqualmie, Index, and Grotto batholiths. Ancient (Pleistocene) and modern Skykomish River alluvial facies are similar to ancient and modern Snoqualmie River alluvial facies. These units contain abundant monocrystalline quartz, K-spar, and plagioclase, and lesser but distinct granitic lithic grains, biotite, pyroxene, and hornblende. Dragovich and others (2009a,b,c, 2010a,b, 2011a,b, 2012, 2013, this study) postulate structural control of parts of these major river valleys by faults such as the RMFZ–SWIF or Monroe fault systems, resulting in locally thick sedimentary basins. The Monroe synclinal basin hosts a substantial thickness of SP deposits.
LP (local provenance)	Qa (Tolt River, Youngs–Elwell Creek, and Sultan River), Qc_{ol}, Qc_{hmp}, Qc_{phl}	Nonglacial small-basin provenance from local sources carried by low-order rivers flowing generally west, away from the Cascade foothills. Sources include both the modern and ancient basins of the Tolt River, Sultan River, and Youngs–Elwell Creek (40–100 mi²; 104–259 km²). Sediments are distinctly locally sourced and contain significant volcanic lithic grains, meta-argillite, and metasandstone, primarily derived from the volcanic rocks of Mount Persis and Western mélange belt (WMB).
PG (Puget Group)	Qc_{wp}	Puget Group nonglacial provenance from local erosional sources to the south and southwest and delivered via fluvial mechanisms. Sands are lithic rich and contain significant andesite detritus, as well as some arkosic (feldspathic) sandstone and siltstone from the Tukwila, Renton, and Tiger Mountain Formations. Fluvial PG sediments likely interfinger with ancient SP fluvial sediments, near Carnation.
NP (northern provenance)	Qgl_r, Qgos, Qgod, Qgof, Qgic, Qgik, Qgog, Qgt_v, Qga_v, Qgl_v, Qgt_p, Qgo_p, Qgl_p, Qgd_d, Qgd_{pd}	Northern provenance sediments were deposited during continental glaciations. These sediments are locally mixed with some sediments of eastern and northeastern Cascade provenance (particularly for some Vashon Stade recessional deposits transported by ice-marginal meltwater). Glacial units contain various lithic clast types, including high-grade metamorphic clasts, and have a high polycrystalline/monocrystalline quartz ratio and less K-spar when compared to local Cascade sources.

Radiocarbon and OSL/IRSL

New Pleistocene ages support our correlation with nonglacial intervals including Olympia nongacial intervals. This ancient alluvium is folded and liquified by the Monroe anticline and syncline.

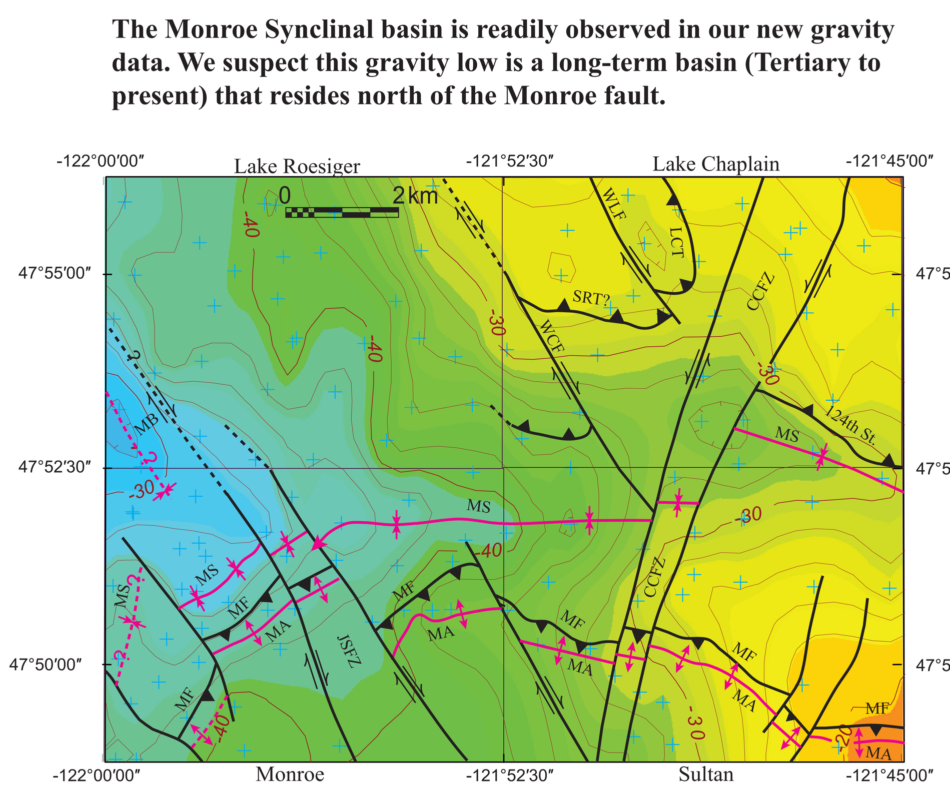
Sample ID/ information	Age (ka)e	Unit
Sultan Quadrangle		
43B	112 ±7.60	Qa
43D	39.8 ±1.94	Qc_{ol}
44A	22.9 ±2.00 23.8 ±1.83	Qc_o
44B	73.3 ±2.67	Qc_o
44D	36.8 ±1.47	Qc_o
44E	24.5 ±1.31	Qc_o
44G	1.46 ±0.09	Qa
45A	29.0 ±1.88 >215	Qc_o
45B	>300	Qc_{pf}
Lake Chaplain Quadrangle		
37A	40.5 ± 3.1 48.3 ± 3.9	Qc_o
37B	32.3 ± 2.4 29.7 ± 2.5	Qc_o
37C	14.1 ± 0.59 16.3 ± 0.64	Qga_v
37D	>125 >550	Qc_{ph}
37E	21.5 ± 1.3 71.9 ± 6.1	Qc_{ph}
38A	75.4 ± 2.2 80.4 ± 7.0	Qc_{ws}
Monroe Quadrangle		
10-24A	50.5 ± 3.53	Qc_o
10-24B	233 ± 10.9	Qc_h
10-24C	>155	Qc_h
10-24D	51.1 ± 3.84	Qc_o
10-24E	123 ± 8.24	Qc_{ws}
10-25A	101 ± 4.47	Qc_{ws}
10-25B	107 ± 9.87	Qc_{ws}

Samples highlighted in yellow are located on the Monroe anticline and syncline system.

Age Site	Analyzed organic material (geologic unit)	$^{13}C/^{12}C$ (o/oo)	Conventional radiocarbon age (yr BP)
Sultan Quadrangle			
40D	wood (unit Qa of Youngs Creek)	-27.8	9,440 ±40
102A	wood (unit Qc_o)	-24.7	18,020 ±70
31AE	sticks/twigs (unit Qc_{ol})	-26.2	21,890 ±80
31AB	sticks/twigs (unit Qc_{ol})	-27.2	22,020 ±100
44A	sticks (unit Qc_o)	-28.1	23,760 ±100
10-49E	plant material (unit Qc_o)	-27.1	24,790 ±170
10-24D	charred organics (unit Qc_o)	-24.9	>43,500
31E	wood (unit Qgl_v)	-27.4	>43,500
41P	wood (unit Qc_{pf})	-23.9	>43,500
Monroe Quadrangle			
10-56A #2	Peat (unit Qc_o)	-31.3	17,500 ± 80
10-50H	Plant material (unit Qc_o)	-29.6	18,7300 ± 110
10-56A #1	Wood from peat (unit Qc_o)	-25.1	19,920 ± 130
OW-8	Organic sediment (unit Qc_o)	-25.6	23,090 ± 110
10-49E	Plant material (unit Qc_o)	-27.1	24,790 ± 170
OW-5	Plant material (unit Qc_o)	-27.5	38,660 ± 390
10-22A	Peat (unit Qc_{ws})	-25.1	40,000 ± 350
10-24D	Charred organics (unit Qc_o)	-24.9	>43,500
10-25A	Charred organics and charcoal (unit Qc_{ws})	-25.0	>43,500
10-28D	Charred organics (unit Qc_{pf})	-24.0	>43,500
Lake Chaplain Quadrangle			
13-34P	Plant material (unit Qga_v)	-26.1	14,900 ± 50

Geophysics

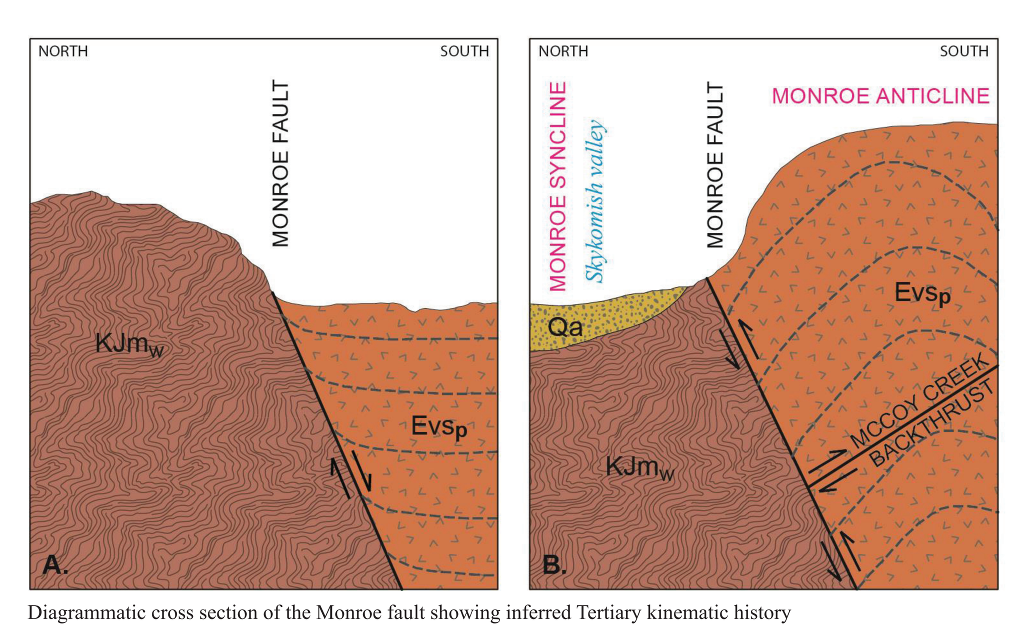
The Monroe Synclinal basin is readily observed in our new gravity data. We suspect this gravity low is a long-term basin (Tertiary to present) that resides north of the Monroe fault.



Isostatic gravity map of the northern halves of the Monroe and Sultan 7.5-minute quadrangles and the southern halves of the Lake Roesiger and Lake Chaplain quadrangles. The blue plus signs indicate where gravity measurements were taken. Cooler colors indicate lower gravity values, and warmer colors, higher values. Gravity contour interval is 2 mGal; small hachures indicate closed lows. Approximately 135 gravity measurements constrain the contours. Gravity data in the Lake Roesiger quadrangle is preliminary. Superimposed fault and fold structures are simplified from Dragovich and others (2011a,b, 2013, this study). To simplify the illustration, we show some reverse faults as thrusts. MF, Monroe fault; MS, Monroe syncline; MA, Monroe anticline; MB, Monroe basin; CCFZ, Cherry Creek fault zone; JSFZ, Johnson's Swamp fault zone; 124th St, 124th Street reverse fault; WCF, Woods Creek fault; WLF, Woods Lake fault. Note the regional gravity low formed by the Monroe synclinal basin as well as offset of the syncline by the CCFZ. Continued study of the extension of the JSFZ in the southern corner of the Lake Roesiger quadrangle are warranted, especially near the more northerly gravity low on the west side of the fault zone that we informally here term the Monroe basin (MB).

Tertiary Structure of the Monroe Fault

Monroe Fault suspected to have a complex history with Tertiary extension and later rejuvenation as a potentially active reverse fault.



Diagrammatic cross section of the Monroe fault showing inferred Tertiary kinematic history

A. Eocene north-south extension across the Monroe fault produced the Mount Persis volcanic basin. Some Mount Persis beds have a partial western mélange belt provenance consistent with basin-marginal deposition.

B. Post-Eocene kinematic reversal of the Monroe fault and rejuvenation as a compressional reverse fault; McCoy Creek backthrust and the Monroe anticline also help accommodate compression. The rejuvenation initiated in the Oligocene to Miocene and likely accompanied the onset of north-south compression in the Puget Lowland and may be currently ongoing. Rejuvenation explains the younger Mount Persis unit over the older western mélange belt fault arrangement and it probably resulted in the formation of the Monroe synclinal basin. The reversal of the Monroe fault from an extensional Eocene basin-bounding fault structure to a later compressional structure is similar to the east-west trending active Boulder Creek fault in Whatcom County northeast of Bellingham. In that area the Eocene Chuckanut Formation basin was likely structurally controlled by the Boulder Creek fault. This fault was later rejuvenated as a compressional structure and is currently active.

Percentage area of major geologic units in the Skykomish River basin east, or 'up-basin', of the Lake Chaplain quadrangle; the western part of our basin analysis area terminates at (single U-Pb zircon) sample site 13-37A. We obtained the major geologic units from the 1:250,000-scale geologic map of Washington (northwest quadrant) of Dragovich and others (2002). Sample 13-37A from the Lake Chaplain Quadrangle is ancient Skykomish River alluvium as indicated by the SP composition of the sand. This provenance is supported by the detrital zircon ages, which show a strong correlation with the presently exposed Skykomish basin geology. This table documents the strong correlation between the major geologic units of the basin, such as Oligocene and mid-Cretaceous intrusive rock bodies, and the age spectrum of the sand zircon grains in the sample.

Major geologic units	Notes	Total area geologic units in Skykomish basin (%)	Combined total area of geologic units (%)	General distribution of zircon age data (sample 37A)
	Geologic unit information			
Eocene volcanic and sedimentary rocks	Mostly sedimentary rocks such as the Sauk Formation and the volcanic rocks of Mount Persis. Significant contribution of zircons from nearby volcanic rocks of Mount Persis seems likely.	14.5	14.5	11.4% of zircons by age are Late Eocene
Cretaceous–Triassic metamorphic basement rocks	Mostly eastern and Western mélange belts as well the Tonga Formation schist and Chiwaukum Schist.	17.0	35.8	51.9% of zircons by age are Cretaceous to Triassic
Cretaceous intrusive rocks including orthogneiss	Plutons in the crystalline core of the North Cascades. Distinct peak at ~90 Ma is correlated with the abundant mid-Cretaceous plutonic rocks of the southern part of the crystalline core (for example, ~90 Ma Tenpeak pluton).	18.8		
Miocene–Oligocene intrusive rocks	General 1:250,000-scale unit MØig of Dragovich and others (2002) such as parts of the Snoqualmie batholith.	19.6	29.8	35.5% of zircons by age are Miocene to Oligocene
Oligocene intrusive rocks	General unit Øigd of Dragovich and others (2002).	10.1		
Pliocene–Miocene intrusive dacite	Biotite-hornblende-hypersthene dacite plugs and dikes. This unit can include altered breccia and flows.	0.1		
Quaternary deposits	Mostly alpine drift but some continental deposits as well. Much of the Quaternary sediment in the Skykomish basin is alpine drift that reworked intrabasinal deposits. However, continental glacial deposits mapped in the geographically lower part of the Skykomish basin east of Sultan likely contributed some detrital zircons from the north, including zircons from the Mesozoic Coast plutonic complex.	18.8	18.8	0% of zircons by age are Quaternary
Ice and water		1.2	1.2	Not applicable
Total		**100.1**	**100.0**	

Discussion

Folding of the Olympia beds and the older nonglacial deposits in the map area indicates that the Monroe syncline and anticline are potentially active flexural slip folds associated with the Monroe fault. The Monroe fault is not observed to displace Quaternary strata directly. The vertical distribution of the SP Olympia beds across the Monroe fault, anticline, and syncline supports Quaternary uplift and subsidence.

The thickness and distribution of ancient Skykomish River SP deposits suggests protracted control of the valley by these structures. The Monroe synclinal basin contains a composite sequence of ancient SP alluvium that is at least 300 ka and preserves several nonglacial formations with most of these sequences thickening towards the synclinal axis. This fold is actively shortening over the river basin and is generally been confined to the valley. The most compelling evidence is the general dip orientation of various SP nonglacial stratigraphic sequences that correlate with the Olympia Beds, Whidbey Formation, Hamm Creek formation or pre-Hamm creek units relative to the fold axes.

Pleistocene deposits are SP, supported by the geochemical, petrographic, and stratigraphic similarity of the modern Skykomish alluvium with older nonglacial deposits. All SP units have meandering river stratigraphic architecture dominated by sand, silt, and peat overbank deposits with lensoidal interbeds of gravel channel deposits. Both modern and ancient sands contain abundant monocrystalline quartz, plagioclase and K-spar with lesser but significant hornblende, pyroxene and mica derived mostly from granite and granodiorite of the Cascade Range. New detrital zircon ages confirm that the Olympia bed sands contain significant detritus from Oligocene to Cretaceous intrusive bodies, particularly the voluminous ~33 Ma Index Batholith located directly east of the study area.

The dominance of the SP nonglacial strata in the Monroe synclinal basin is not only observed at the surface but also inferred from the mild magnetic susceptibility of the basin sediments.

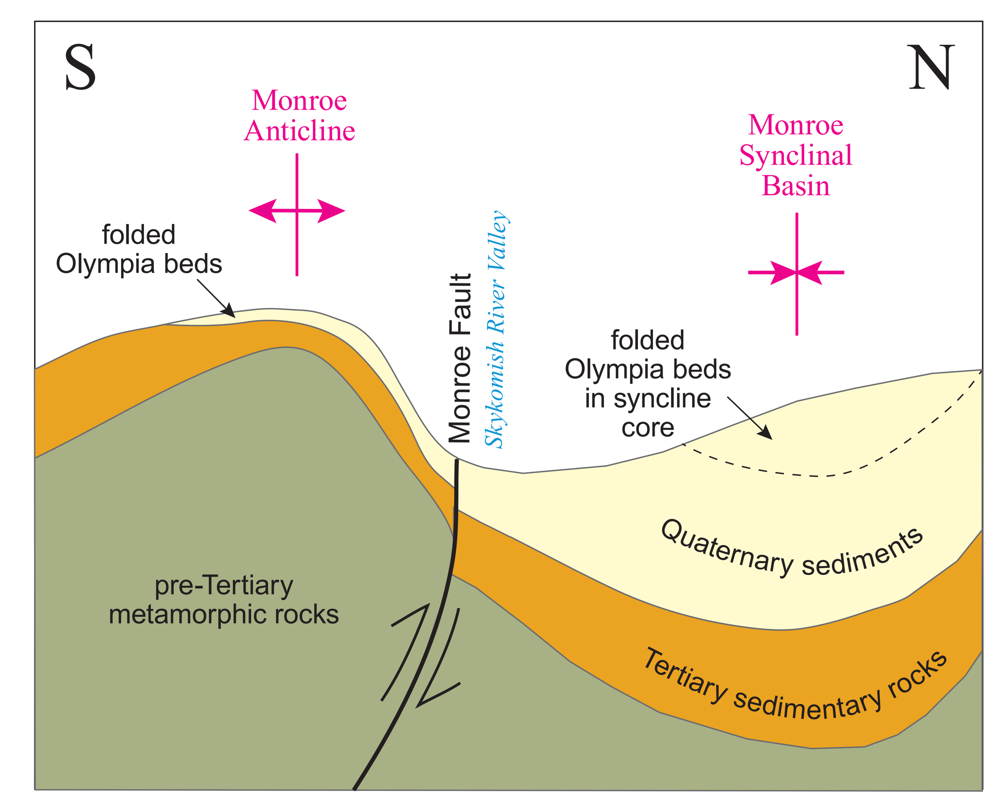
Folding and tilting of the Olympia beds across the Monroe anticline (particularly in the Sultan quadrangle) is well-constrained by both field mapping and geochronology with the Olympia bed SP sediments dated and mapped at various elevations from Skykomish River south across the fold axis where they interfinger with Olympia bed local detritus.

The Monroe syncline is cored with Olympia beds from near Monroe to northeast of Sultan, based on mapping and geochronology. Gravity data and mapping suggest that the synclinal axis is offset by the active CCFZ, with offset of this fold probably beginning in the Eocene.

Striking similarities exist between the Monroe fault with the Seattle fault; both are east-west trending, north-verging structures responding to regional north-south compression with southerly hanging wall uplifts bounded by major basins to the north; Possible origin in the Oligocene with the Monroe synclinal basin being generally comparable to the Seattle basin.

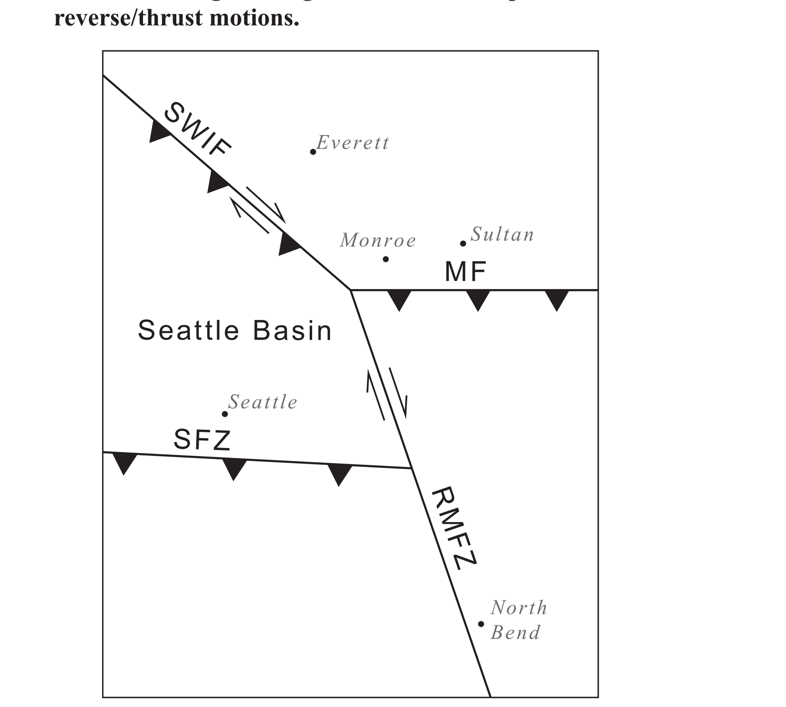
Previous mapping in the North Bend, Fall City, Snoqualmie, Carnation and Lake Joy quadrangles show that the RMFZ is a right-lateral, strike-slip fault zone that structurally controls the Snoqualmie River valley. The RMFZ merges with the SWIF NW of Carnation in the Maltby area where Sherrod and others (2008) show that the SWIF is an active fault zone. Our more recent mapping presented here shows that the MF is a potentially active reverse fault with northerly vergence.

Conclusion



Pleistocene SP alluvium in the SRV is correlated with the "Olympia beds", Whidbey Fm, Hamm Creek Fm, and older nonglacial sequences on the basis of their distribution, geochemical and modal composition, stratigraphy, geophysics, and geochronology. New detrital zircon U-Pb ages from Olympia beds confirm the Cascade provenance of this ancient alluvium. The Monroe anticline overlies the MF as an upper plate flexural slip fold. The anticline folds SP Olympia beds as young as ~22ka according to multiple radiocarbon and OSL/IRSL ages. North of the MNF, the Monroe synclinal basin is cored by SP Olympia beds over a long axial area and locally preserves a ~300-m thick composite sequence of folded SP alluvium spanning several non-glacial episodes. Buried Tertiary strata in the syncline suggest growth folding since the Oligo-Eocene.

The Southern Whidbey Island fault zone, Rattlesnake fault zone, and the Monroe fault might be kinematically related potentially active to active fault zones with possible strain partitioning between each fault zone. SWIF may be accommodating both right lateral strike slip and reverse/thrust motions.



The NW-trending southern Whidbey Island fault zone (SWIF) extends into the NNW-trending Rattlesnake Mountain fault zone (RMFZ). The MF intersects the SWIF–RMFZ at an inflection in this composite structure. We suspect the MF, RMFZ, and SWIF are primarily reverse, strike-slip, and oblique-slip faults, respectively, with the MF an eastward Cascade foothills partition of the SWIF accommodating only north-south contraction.

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