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Saddle Mountains structures, Saddle Mountains fault (Class A) No. 562a

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Synopsis	**General:** The east-trending Saddle Mountains uplift are part of the Yakima fold and thrust belt, defined by asymmetric, anticlinal folds in the hanging wall of generally blind reverse faults that extend across a region that covers more than 15,000 square kilometers. Thrust faults bound the north side of the Saddle Mountains. Also included in this group are related normal faults that show evidence of Quaternary offset (Reidel, 1984 #5545; Reidel and others, 1994 #3539; West and others, 1996 #3514; West, 1997 #5548). The Saddle Mountains anticline and related folds and some faults of the Saddle and Boylston Mountains, however, are only known to deform Miocene and Pliocene rocks. Quaternary age growth or tightening of the Saddle Mountains folds and other folds in the Yakima fold belt, has been suggested and inferred from several local and regional geologic relations in the Yakima fold belt (Campbell and Bentley, 1981 #3513; Reidel, 1984 #5545; Reidel and others, 1994 #3539). Contemporaneous contraction across the region suggests that the Yakima

	folds are favorably oriented in the current strain field and accommodate the strain through active folding and possibly faulting (Pratt, 2012 #7397; Bjornstad and others, 2012 #7394 citing unpublished Zachariasen and others, 2006). Site investigation that address the recency of faulting, and thus folding, have been located on subsidiary faults and age control remains ambiguous. Although the trenches exposed compelling evidence for repeated Quaternary surface faulting. West and others (1996 #3514) and West (1997 #5548) reported on Quaternary normal faults and a graben, which are present in the Smyrna Bench area of the Saddle Mountains, and they interpreted these normal faults as hanging-wall tensional features related to Quaternary movement along the underlying Saddle Mountains fault. They noted that the Saddle Mountains anticline probably cannot accommodate much additional strain by folding and that additional strain would likely instead induce fault slip. Based on the growing consensus that the Saddle Mountains folds are cored by buried Quaternary fault, the faults are reassigned to Class A as opposed to the prior Class B classification. **Sections:** This fault has 2 sections. Section, as defined here, differs in lateral extent from the fault sources prescribed by Coppersmith and others (2014 #7402) and includes Saddle Mountains-East and part of the Saddle Mountains-West.
Name comments	**General:** **Section:** The Saddle Mountains fault was mapped as an unnamed vertical fault by Grolier and Bingham (1971 #5542) and is referred to as the Saddle Mountains fault by Grolier and Bingham (1978 #5543), Reidel (1984 #5545), Reidel (1988 #5546), Reidel and Fecht (1994 #5565), and Reidel and others (1994 #3539). Detailed studies, which are discussed in West and others (1996 #3514) and West (1997 #5548) identified a graben and normal faults that displace Quaternary deposits in the Symrna Bench area of the Saddle Mountains. These normal faults offset late Pleistocene-Holocene sediments, are interpreted as tensional features related to movement along the Saddle Mountains fault (West and others, 1996 #3514; West, 1997 #5548), and are discussed herein with the Saddle Mountains fault. The Saddle Mountains fault is mapped as a thrust fault that coincides with north flank of the Saddle Mountains and at a minimum the fault extends from the Columbia River eastward to directly west of Eagle Lakes (Reidel and Fecht, 1994 #5565; Schuster and others, 1997 #3760). An apparent continuation of the Saddle Mountains fault is mapped west of the Columbia River in Miocene volcanic rocks along the northern flank of the Saddle and Boylston Mountains (Reidel, 1984 #5545; Schuster and others, 1997 #3760). No evidence for Quaternary deformation related to faults and folds of the Saddle and Boylston

	Mountains has been documented west of the Columbia River.
County(s) and State(s)	GRANT COUNTY, WASHINGTON ADAMS COUNTY, WASHINGTON FRANKLIN COUNTY, WASHINGTON KITTITAS COUNTY, WASHINGTON
Physiographic province(s)	COLUMBIA PLATEAU
Reliability of location	Good Compiled at 1:24,000 scale. *Comments:* Location of fault from GER_Seismogenic_WGS84 (http://www.dnr.wa.gov/publications/ger_portal_seismogenic_features.zip, downloaded 05/23/2016) attributed to West (1997 #5548) and Reidel and Fecht (1994 #5565). However, Casale and Pratt (2015 #7396) point out that the possible location of the tip of the thrust fault is highly uncertain and their thick-skinned listric-fault model suggests the tip of the fault is located several hundred meters north of the topographic expression of the Saddle Mountains anticline.
Geologic setting	The Saddle and Boylston Mountains lie in the northeastern part of the Yakima fold belt, a structural-tectonic sub province of the western Columbia Plateaus Province (Reidel and others, 1989 #5553; 1994 #3539). The Yakima fold belt consists of a series of generally east-trending narrow asymmetrical anticlinal ridges and broad synclinal valleys formed by folding of Miocene Columbia River basalt flows and sediments. In most parts of the belt the folds have a north vergence with the steep limb typically faulted by imbricate thrust faults. According to Reidel and others (1989 #5553) these frontal faults are typically associated with the areas of greatest structural relief. In the few places where erosion exposes the frontal faults deeper in the cores of the anticlinal ridges the faults are seen to become steeper with depth (as steep as 45° to 70°). Along their lengths the anticlines are commonly broken into segments ranging between 5 and 35 km long with boundaries defined by abrupt changes in fold geometry. Anticlinal ridges of the Yakima fold belt began to grow in Miocene time (about 16–17 Ma), concurrent with eruptions of Columbia River basalt flows, and continued during Pliocene time and may have continued to the present (Reidel and others, 1989 #5553; 1994 #3539). The south-dipping Saddle Mountains fault is a thrust fault that cuts the north limb of the north-vergent Saddle Mountains anticline, one of the many anticlinal ridges that comprise the Yakima fold belt in south-central Washington. The Saddle Mountains anticline and related folds deform

	rocks of the Columbia River Basalt Group (Miocene) and overlying sedimentary rock (Pliocene). Quaternary deformation is generally associated with the most tightly folded and structurally complex interval of the anticline (West, 1997 #5548). Quaternary faulting also includes development of grabens and beheading of modern streams in the hanging wall south of the Saddle Mountains thrust fault. This is analogous to surface rupture accompanying the Oct. 10, 1980, El Asnam, Algeria, M 7.3 earthquake (Philip and Meghraoui, 1983 #5544; Meghraoui and others, 1988 #803; Avouac and others, 1992 #5540). Contemporary seismicity in and near the Saddle Mountains also suggests late Quaternary tectonism (Ludwin and Qamar, 1995 #1350). Campbell and Bentley (1981 #3513) and Mann and Meyer (1993 #3535) reported and suggested late Quaternary deformation on other structures in the Yakima fold and thrust belt. Using seismic reflection data, borehole logs, and surface geologic data, Casale and Pratt (2015 #7396) tested two proposed kinematic end-member thick- and thin-skinned fault models beneath the Saddle Mountains anticline. Observed subsurface geometry can be produced by 600–800 m of heave along a single listric-reverse fault or about 3–5 km of slip along two superposed low-angle thrust faults. Both models require decollement slip between 7 and 9 km depth. In addition, the seismic reflection profiles show that rocks below the Columbia River Basalt Group are more deformed that the overlying units suggesting deformation preceded the emplacement of the basalts. Coppersmith and others (2014 #7402) estimate average structural relief of Saddle Mountains West to be 320–335 m.
Length (km)	This section is 60 km of a total fault length of 104 km.
Average strike	N71°W (for section) versus N71°W (for whole fault)
Sense of movement	Thrust *Comments:* The Saddle Mountains fault is shown as a mostly buried thrust fault on geologic maps by Reidel (1988 #5546), Reidel and Fecht (1994 #5565), Schuster and others (1997 #3760) and Mège and Reidel (2001 #7407). Trench exposures confirmed the fault as a thrust (West, 1994 #5547, 1997 #5548). Detailed studies by West (1994 #5547; 1997 #5548) also identified a graben and numerous normal faults in the region directly south of the Saddle Mountains fault in the Smyrna Bench area. The graben and normal faults deform Quaternary sediments and these features are interpreted as tensional structures related to late Pleistocene to Holocene movement along the Saddle Mountains fault (West and others, 1996 #3514; West, 1997 #5548).

Dip	18–33° S *Comments:* The Saddle Mountains fault is poorly exposed. Detailed studies of trenches showed the basal shear zone of the Saddle Mountains fault dipping 9–18° S, and showed smaller subsidiary thrusts dipping 30–40° S (West and others, 1996 #3514; West, 1997 #5548). Reidel (1984 #5545) notes that near the surface the fault is imbricate with the dip controlled by the dip of basalt flows north of the uplift. Reidel and others (1989 #5553) reported that in the few places where erosion exposes the frontal faults deeper in the cores of the anticlinal ridges, the faults are seen to become steeper with depth (as steep as 45–70°). Mège and Reidel (2001 #7407) report a mean fault dip of 19–33° for the Saddle Mountains thrust fault based on a combination of field measurements and accessible seismic profiles. Based on comparative borehole stratigraphy, Tincher (2009 #7398) concludes the Saddle Mountains thrust dips 30° to the south at depth. The kinematic models of Casale and Pratt (2015 #7396) place specific limits upon the faults constrained by the geometry of the upper basalt layers and topography. A variety of dips have been assigned for modeling fault sources in seismic hazard assessments. For an idealized model of the Saddle Mountains fault, Reidel (1984 #5545), citing Grolier and Bingham (1978 #5543), assumed a dip of about 45° at depth based on the dip of the Frenchman Hills fault exposed 20 km to the north along the Columbia River. Geomatrix Consultants Inc. (1996 #4676) used fault dips of 30°, 45°, and 60° in their calculations of slip rates for the Saddle Mountains fault. West and others (1996 #3514) modeled the fault using dips of 20–40°. West and others (1996 #3514) and West (1997 #5548) show moderate to steep dips for normal faults exposed in trenches south of the Saddle Mountains fault in the Smyrna Bench area.
Paleoseismology studies	West and Shaffer (1988 #5549) and West (1994 #5547; 1997 #5548) collectively excavated and mapped four trenches (Sites 575-1 to 574-4) across the Saddle Mountains fault, across apparent late Quaternary faults on the northern flank of a 13-km-long graben, and across a 5-m-high scarp north of the graben. For the westernmost trench, which crossed the Saddle Mountains fault, West (1997 #5548) reported that relations of shear zones, colluvial wedges, and soil development suggest a late Pleistocene to Holocene event with about 1.3 m of surface offset as well as two or more older Pleistocene events. West and others (1996 #3514) and West (1997 #5548) concluded, from a trench across the northern fault of the graben, that the graben is tectonic in origin and probably related to movement on the underlying Saddle Mountains fault. Bjornstad and others (2012 #7394)

	reemphasize that two of the trenches expose compelling evidence for repeated Quaternary surface faulting on multiple faults. Dating of deformed Quaternary sediments and paleosols in this trench across the graben also indicated that graben development began about 100 ka and continued into the Holocene (West and others, 1996 #3514; West, 1997 #5548). The two eastern trenches cross a 5-m-high scarp but these trenches did not reveal the Saddle Mountains fault as was initially expected. These trenches instead exposed medial and distal parts of stacked colluvial wedges that were interpreted by West (1997 #5548) as deposits that formed from loess "avalanching" triggered by surface fault ruptures upslope. Trench 562-1 was excavated in 1987 (Trench #1 in West and Shaffer, 1988 #5549) across a 5-m-high scarp and is also shown and discussed in West (fig. 3, 1997 #5548). West (1997 #5548) shows paleosols thrusted over a repeated section of soils, which in turn is buried by an undeformed loess; no datable material was recovered from the trench. The stratigraphy was not convincingly diagnostic and no no samples for dating were collected. Trench 562-2 was excavated in 1994 (Trench #2 in West, 1994 #5547 and Trench #3 in West, 1997 #5548) near Trench 562-1 across the same 5-m-high scarp and is also shown and discussed in West (fig. 3, 1997 #5548). Trench 562-3 also was excavated in 1994 (Trench #1 in West, 1994 #5547 and Trench #2 in West, 1997 #5548) across the northern fault of the Syrna Bench graben and is shown and discussed in West (fig. 3, 1997 #5548). The exposed fault places bedrock against Quaternary fault-derived colluvium with intercalated Mazama ash; West (1997 #5548) concludes that the relations in the exposure do not reflect primary surface rupture. Trench 562-4 was excavated in 1997 (Trench #4 in West, 1997 #5548) across the trace of the Saddle Mountains fault. This trench crossed the inferred trace of the Saddle Mountains thrust fault where sheared basalt is emplaced against Quaternary fault-related colluvium.
Geomorphic expression	The Saddle Mountains fault is poorly exposed and is mapped as a buried fault along most of its trace. A thick mantle of highly mobile Holocene loess and colluvium, as well as talus and landslide deposits, obscure and bury most of the northern flank of the Saddle Mountains (Grolier and Bingham, 1971 #5542; Reidel, 1988 #5546; Reidel and Fecht, 1994 #5565; Schuster and others, 1997 #3760). Primary geomorphic evidence of Quaternary faulting along the trace of the Saddle Mountains fault is sparse. West and Shaffer (1988 #5549), Geomatrix (1990 #5550), and West (1997 #5548) reported the presence of some lineaments along and

	near the trace of the fault in the area north of Smyrna Bench and east of the Bench. They also reported that an erosional origin was possible for some or all of these lineaments. West (1997 #5548) identified a graben immediately inboard (south) of the buried thrust trace(s) in the Smyrna Bench area and noted that the primary geomorphic expression of the graben was disruption of streams by offsets along normal faults that beheaded some streams and created local depressions (sag ponds). A 5-m-high scarp north of the graben, originally interpreted to be the thrust trace, exposed in trenches what is now believed to be the medial and distal parts of colluvial wedges that formed in response to faulting and surface rupture upslope, to the south (West, 1997 #5548). North of Smyrna Bench and the Smyrna Bench graben, the location of the Saddle Mountains fault may be marked by a topographic bulge (West, 1997 #5548).
Age of faulted surficial deposits	The most detailed information concerning deformed Quaternary deposits is from trench studies across a graben that is located directly south of the Saddle Mountains fault in the Smyrna Bench area of the Saddle Mountains (West and others, 1996 #3514; West, 1997 #5548). The graben and associated normal faults are interpreted by West and others (1996 #3514) and West (1997 #5548) to be related to late Pleistocene to Holocene movement along the underlying Saddle Mountains fault. West and others (1997 #5548) identified scarp-derived colluvium in the graben that contains the 6850 14C yr old Mazama climactic tephra (Crandell and others, 1981 #5541). They also identified a faulted 20–40 ka paleosol in the graben that contains the Mt. St. Helens, set M tephra (>18,560±180, and <20,350±350 14C yr) as described by (Crandell and others, 1981 #5541; Busacca, 1991 #3598).
Historic earthquake	
Most recent prehistoric deformation	late Quaternary (<130 ka) *Comments:* West (1997 #5548) inferred that the latest event probably occurred about 6,850 14C yrs based on the inclusion of Mazama tephra (Crandell and others, 1981 #5541) in scarp-derived, colluvial-wedge deposits in the graben south of the Saddle Mountains fault in the Smyrna Bench area. Based on relations exposed in a trench across the Saddle Mountains fault in Smyrna Bench area, West (1997 #5548) concluded that relations of shear zones, colluvial wedges, and soil development suggest a late Pleistocene to Holocene age for the most recent event. Because relations of the Smyrna Bench graben relative to the Saddle Mountains fault are not tightly constrained, a late Quaternary (<130 ka) age for the most recent event is assigned to the part of the fault near Smyrna Bench. A more speculative Quaternary age is assigned to the remaining parts of

	the fault that are locally associated with lineaments suggestive of Quaternary fault activity (Geomatrix Consultants Inc., 1990 #5550).
Recurrence interval	*Comments:* Piety and others (1990 #3733) used uplift rates calculated from 13.5 Ma volcanic rocks to estimate recurrence intervals of 490–24,500 years based on displacement per events of 0.02–1.0 m. Based on relations in a trench that crossed the Saddle Mountains fault, West (1997 #5548) reported that relations of shear zones, colluvial wedges, and soil development suggest a late Pleistocene to Holocene event with about 1.3 m of surface offset as well as two or more Pleistocene events. A minimum of 6.5 m of displacement of a 20–40 ka paleosol along the fault zone bounding the north flank of the Smyrna Bench graben and poorly-developed colluvial wedge stratigraphy, mainly in loess, may indicate multiple events in the last 20–40 ka (West and others, 1996 #3514; West, 1997 #5548). These relations may indicate a recurrence interval that is measured in thousands to tens-of-thousands of years.
Slip-rate category	Between 0.2 and 1.0 mm/yr *Comments:* Reported rates of deformation are vary from study to study and remain highly uncertain. Assigned slip-rate category is based on the largest uplift rates of Miocene volcanic rocks reported (Reidel, 1984 #5545; Piety and others, 1990 #3733; Geomatrix Consultants Inc., 1996 #4676). Reidel (1984 #5545) compared relative amounts of uplift of volcanic units in the core of the Saddle Mountains and determined that post-Miocene uplift of the Saddle Mountains was relatively constant and about 0.04 mm/yr. Piety and others (1990 #3733) report 550 m of uplift of 13.5 Ma volcanic rocks, which yields an uplift rate of 0.04 mm/yr. Coppersmith and others (2014 #7402) report the average relief of the Saddle Mountains anticline is 300–415 m with a maximums of 175–725 m. Geomatrix Consultants Inc. (1996 #4676) used various uplift amounts and ages for Miocece volcanic rocks and used estimated fault dips of 30°, 45°, and 60° to estimate long-term slip rates of 0.007_0.175 mm/yr for an inferred principle fault underlying the Saddle Mountains. Bjornstad and others (2012 #7394) state that vertical displacement rates of the Saddle Mountains anticline (>0.16 to 0.65 mm/yr, reported as 160 to 650 m/m.y.) compare well with the normal long-term average net slip rate for the Yakima fold and thrust belt. However, table 2.1 (Bjornstad and others, 2012 #7394) reports long-term vertical growth rates for the Saddle Mountains anticline of 6–48 m/m.y. (0.006–0.48 mm/yr). Casale and Pratt (2015 #7396) estimate long-term rates of slip for each of their end-member fault models. The thick-skinned model requires about 600–800 m

	of total heave since the middle and late Miocene. In contrast, 350–450 m of post-Columbia River Basalt Group heave is required of their thin-skinned model resulting in average slip rates of about 0.07–0.09 mm/yr for the deep listric fault and lower slip rates (0.04–0.05 mm/yr) on the upper the shallowly dipping faults. Pleistocene-Holocene displacement rates on the subsidiary Smyrna Bench structure were estimated (West and others, 1996 #3514; West, 1997 #5548) based on normal offsets of Quaternary units in the graben,. West and others (1996 #3514) and West (1997 #5548) concluded that the graben is tectonic and related to movement along the underlying Saddle Mountains fault. West and others (1996 #3514) and West (1997 #5548) also concluded, based largely on similar relations documented for the El Asnam fold and thrust Belt (Philip and Meghraoui, 1983 #5544; Meghraoui and others, 1988 #803; Avouac and others, 1992 #5540), that vertical and horizontal components of slip in the graben should approximate (less than or equal to) vertical and horizontal components of slip along the primary, causative thrust fault. For normal faults in the graben, West and others (1996 #3514) and West (1997 #5548) calculated a minimum, vertical displacement rate of 0.16–0.33 mm/yr, based on displacement of at least 6.5 m of a 20–40 ka paleosol (Busacca, 1991 #3598). According to West and others (1996 #3514) and West (1997 #5548), resolution of at least 6.5 m of vertical displacement on a 30° dipping thrust fault yields a minimum slip of 13 m in the fault plane in 20–40 ka and minimum slip rates of 0.33–0.65 mm/yr, also reported by Bjornstad and others (2012 #7394).
Date and Compiler(s)	2016 David J. Lidke, U.S. Geological Survey Kathleen M. Haller, U.S. Geological Survey
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