Quaternary Fault and Fold Database of the United States

As of January 12, 2017, the USGS maintains a limited number of metadata fields that characterize the Quaternary faults and folds of the United States. For the most up-to-date information, please refer to the interactive fault map.

Toppenish Ridge structures, Mill Creek fault (Class A) No. 566a

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Synopsis	**General:** The east-trending Toppenish Ridge structures include faults with known and inferred Pleistocene and Holocene offsets (Bentley and others, 1980 #4693; Campbell and Bentley, 1981 #3513; Campbell and others, 1995 #5552; Repasky and others, 1998 #5554). The Toppenish Ridge anticline and related folds of the Toppenish Ridge anticlinal uplift, as well as most of the faults associated with the uplift, are only known to fold rocks of the Miocene Columbia River Basalt Group. Quaternary age growth or tightening of the Toppenish Ridge folds and other folds in the Yakima fold belt, however, 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). For the Toppenish Ridge area, Quaternary growth or tightening of folds has been inferred from evidence of Quaternary offset along thrust

	faults and normal faults. The normal faults near the crest of the Toppenish Ridge anticline are interpreted as tensional features related to folding above the underlying Mill Creek thrust fault (Bentley and others, 1980 #4693; Campbell and Bentley, 1981 #3513; Campbell and others, 1995 #5552; Repasky and others, 1998 #5554). 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the strain through active folding and possibly faulting (Pratt, 2012 #7397; Bjornstad and others, 2012 #7394 citing unpublished Zachariasen and others, 2006). As summarized by Bjornstad and others (2012 #7394), global positioning system (GPS) “data indicate relatively low (<1 mm/yr) but non-zero convergence across the Yakima fold belt…. In general, these rates are higher than those calculated on Quaternary faults.” Based on the growing consensus that the Toppenish Ridge 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. Faults and folds associated with the Toppenish Ridge anticlinal uplift are subdivided and discussed as two sections based on the geometry and character of the faults and based on the uncertainty of the continued development of the folds and some of the faults during Quaternary time. The mostly buried Mill Creek fault (thrust) and some normal faults south of it show evidence for Quaternary activity and they are treated as one section of the Toppenish Ridge structures. The Toppenish Ridge anticline and related folds, as well as some of the unnamed faults associated with the uplift, can only be inferred to have been active during Quaternary time. Sections defined here differ in lateral extent from the fault sources prescribed by Coppersmith and others (2014 #7402). Both of their sections are contained within section 566b.
Name comments	**General:** **Section:** The earliest known name for this fault is the Mill Creek fault, as used by Bentley and others (1980 #4693). Campbell and Bentley (1981 #3513) refer to the fault as the Mill Creek thrust fault. Piety (1990 #3733) and Geomatrix Consultants, Inc. (1988 #1311; 1990 #5550) refer to the fault as the Toppenish Ridge fault and note that it is the Mill Creek fault of Bentley and others (1980 #4693). Campbell and others (1995 #5552) and Repasky and others (1998 #5554) refer to the fault as the Mill Creek thrust. The earlier name of Bentley and others (1980 #4693), Mill Creek fault, is used herein. As mapped by Bentley and others (1980 #4693), the fault is about 65 km long, but only about the eastern 24–34 km of the fault is known to show evidence for Quaternary offset (Geomatrix Consultants, Inc., 1990 #5550).
County(s) and	YAKIMA COUNTY, WASHINGTON

State(s)	YAKIMA COUNTY, WASHINGTON
Physiographic province(s)	COLUMBIA PLATEAU
Reliability of location	Good Compiled at 1:250,000 scale. *Comments:* The location of the Mill Creek fault (thrust) and normal faults nearby are from GER_Seismogenic_WGS84 (http://www.dnr.wa.gov/publications/ger_portal_seismogenic_features.zip, downloaded 05/23/2016) attributed to Repasky and others (1998 #5554).
Geologic setting	Toppenish Ridge lies in the south-central 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 45–70°). 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 continued into the Quaternary (Reidel and others, 1989 #5553; 1994 #3539). Named and unnamed, east-striking thrust faults cut the north and south limbs of the Toppenish Ridge uplift. This uplift forms one of the many anticlinal ridges that comprise the Yakima fold belt in south-central Washington. The south-dipping Mill Creek fault is a poorly exposed thrust fault that cuts the north limb of the Toppenish Ridge uplift. Unnamed normal faults, interpreted to be subsidiary faults of the Mill Creek fault, form graben features along the east end of the uplift. The Mill Creek fault and the unnamed normal faults show evidence for Quaternary faulting events, but the folds and other faults of Toppenish Ridge are only known to deform Miocene volcanic and sedimentary rocks, which include the Columbia River Basalt Group. Coppersmith and others (2014 #7402) estimate average structural relief of Toppenish Ridge to be 300–310 m.

Length (km)	This section is 19 km of a total fault length of 82 km.
Average strike	N89°W (for section) versus N80°E (for whole fault)
Sense of movement	Thrust, Normal *Comments:* Exposures and trench studies show that the Mill Creek fault is a south-dipping thrust fault along the north flank of the Toppenish Ridge anticlinal uplift (Bentley and others, 1980 #4693; Campbell and Bentley, 1981 #3513; Woodward-Clyde Consultants, 1981 #5555; Geomatrix Consultants Inc., 1988 #1311; Campbell and others, 1995 #5552; Repasky and others, 1998 #5554).
Dip	9–40° S. *Comments:* Excavations across the northernmost scarp of the Mill Creek fault, north of the Satus Peak segment of the Toppenish Ridge anticline, exposed a thrust dipping 9–15° south (Campbell and others, as cited in Geomatrix Consultants, Inc., 1988 #1311). Campbell and others (1995 #5552) show fault strands of the Mill Creek fault dipping about 20–40° to the south in a diagram of their trench 1. They show normal faults south of the Mill Creek fault dipping steeply north and south (about 60–90°) in diagrams of their trenches 2, 3, and 4.
Paleoseismology studies	Three excavations and six trenches have been cut across scarps related to the Satus Peak part of the Mill Creek fault and normal faults and graben features south of it (Geomatrix Consultants, Inc., 1988 #1311; Campbell and others, 1995 #5552; Repasky and others, 1998 #5554). Geomatrix Consultants, Inc. (1988 #1311) reported that, concurrent with their studies, three closely spaced excavations (NE 1/4, Sec. 1, T9N, R17W) across a north-facing scarp along the Mill Creek fault revealed a gently dipping thrust fault that places Upper Miocene rocks on Pleistocene soils and gravels (site 566-1). No other discussion or documentation of these three excavations is known. Campbell and others (1995 #5552) reported the results from four trenches across the Mill Creek fault and horst and graben features south of the fault; they reported on structural and stratigraphic relations in the trenches and reported radiocarbon and thermoluminescence ages from deformed Holocene sediments exposed in the trenches. Repasky and others (1998 #5554) presented the results from studies of two later trenches located east of the four initial trenches, and these results included a 5,690±390 yr infrared stimulated luminescence (IRSL) date on soil overridden by the Mill Creek fault. Four closely spaced trenches (T-1 to T-4) were excavated and mapped in 1994 by Campbell and others (1995 #5552) across thrust splays and a

	normal fault related to the Mill Creek fault. The trenches, sequentially numbered from west to east in the original study and herein (sites 566-2 through 566-5). Two thrust events were preserved in the stratigraphy of three of the trenches; datable samples were recovered from only one of them. The remaining trench exposed evidence of three earthquakes occurring about (1) 6–10 ka, (2) >40ka to about 165 ka, and (3) about 165 ka. Collectively, the trenches show stratigraphic evidence for at least four Quaternary events occurring approximately: (1) 6–7 ka, (2) 10–11 ka, (3) 40–60 ka, and (4) 145–180 ka (Campbell and others, 1995 #5552; Repasky and others, 1998 #5554). Site 566-6 (trench T-A) was excavated and mapped in 1997 by Repasky and others (1998 #5554) across a thrust splay of the Mill Creek fault 5 km east of T-1. Two thrust events were preserved in the stratigraphy, the younger one dating to 5–7 ka, similar to T-1. The older event was not dated (p. 17–18, Repasky and others, 1998 #5554). Site 566-7 (trench T-B) was excavated and mapped in 1997 by Repasky and others (1998 #5554) across a normal fault related to a graben feature. Trench stratigraphy recorded at least one extensional event that offset Quaternary deposits including a buried soil that contained a mammoth tooth dated to about 7.5 ka (p. 17–18, Repasky and others, 1998 #5554).
Geomorphic expression	Obvious surface expression of the Mill Creek fault is only documented along the north flank of the Satus Peak segment of the Toppenish Ridge anticline (Rigby and Othberg, 1979 #3738; Bentley and others, 1980 #4693; Woodward-Clyde Consultants, 1981 #5555). Along this part of the Mill Creek fault, three east-trending zones of ruptures extend for at least 24 km (Piety and others, 1990 #3733; Geomatrix Consultants, Inc., 1990 #5550; Bjornstadt and others, 2012 #7394). The northern zone of ruptures (basal set) crosses alluvial fans near the projection of the Mill Creek fault; a central zone of ruptures (midslope set) coincides with the northern hinge of the Toppenish Ridge anticline; and, a southern zone of ruptures (crestal set) coincides with the crestal region of the anticline (Bentley and others, 1980 #4693; Campbell and Bentley, 1981 #3513; Woodward-Clyde Consultants, 1981 #5555). The combined zone of rupture includes 100 or more ruptures and is about 0.5–2.2 km wide (Bentley and others, 1980 #4693). Woodward-Clyde (1981 #5555) reported that scarps along these ruptures range from about 90 m to 11 km in length, are typically 1–4 m high, and are both north- and south-facing. Bentley and others (1980 #4693) reported that nearly all of the ruptures in the crestal and midslope sets have straight map patterns and dip steeply, whereas the basal ruptures along the Mill Creek fault have a sinuous pattern and likely a shallow dip. The crestal set of ruptures form a graben, disrupt north-flowing drainages,

	and locally create sag ponds that contain as much as 1.5 m of silt (Bentley and others, 1980 #4693).
Age of faulted surficial deposits	Several studies have documented evidence for deformation of Holocene and Pleistocene sediments along the eastern part (Satus Peak part) of the Mill Creek fault and along normal faults related to horst and graben features directly south of the Mill Creek fault. Bentley and others (1980 #4693) reported that surface ruptures along the Mill Creek fault displace late Pleistocene to Holocene sediments that contain the Mount St. Helens set S tephra with an age of about 13 ka (Mullineaux and others, 1977 #5658; 1978 #5659). Bentley and others (1980 #4693) and Campbell and Bentley (1981 #3513) reported ages of 505±160 14C yr BP and 620±135 14C yr BP for organic matter from sag ponds in a graben associated with ruptures in the crestal region of the Satus Peak part of the Toppenish Ridge anticline. Based on aerial reconnaissance and air photo studies, Geomatrix Consultants, Inc. (1988 #1311) concluded that recent drainages, judged to be Holocene in age, are clearly displaced along normal faults south of the Satus Peak part of the Mill Creek fault. Geomatrix Consultants, Inc. (1988 #1311) also reported that excavations across the Mill Creek fault showed Miocene-Pliocene units thrust on Pleistocene soils and gravel. Trench studies by Campbell and others (1995 #5552) yielded a thermoluminescence (TL) date of 6,690±88 yr from the A-horizon of a soil overridden by the Mill Creek fault. These trench studies also yielded ages of 7,490±70 14C yr BP and 10,200±280 14C yr BP for faulted A and B soil horizons, respectively, in a graben south of the Satus Peak part of the Mill Creek fault. Later trench studies by Repasky and others (1998 #5554) reported an IRSL date of 5,690±390 yr from soil overridden along the Satus Peak part of the Mill Creek fault.
Historic earthquake	
Most recent prehistoric deformation	latest Quaternary (<15 ka) *Comments:* One or more event of latest Quaternary offset along the Satus Peak part of the Mill Creek fault and normal faults south of it appears to be well documented. A post 7,000 yr event along this part of the Mill Creek fault is indicated by a thermoluminescence (TL) date of 6,690±68 yr obtained from trench exposures of a soil overridden by the Mill Creek fault (Campbell and others, 1995 #5552). Later studies of another trench across the Mill Creek fault by Repasky and others (1998 #5554) obtained a 5,690±390 yr IRSL date from a wedge of soil overridden by the Mill Creek fault. Campbell and others (1995 #5552) also reported ages of 7,490±70 14C yr BP and 10,200±280 14C yr BP on faulted A and B soil horizons, respectively, that were obtained from a sag pond along a graben

	south of the Mill Creek fault. Bentley and others (1980 #4693) and Campbell and Bentley (1981 #3513) reported ages of 505±160 14C yr BP and 620±135 14C yr BP for two samples of organic material collected from the lower part of a silt deposit in sag pond south of the Mill Creek fault. Campbell and Bentley (1981 #3513), and numerous other authors, have concluded that normal faults associated with horst and graben features and sag ponds south of the Mill Creek fault probably are tectonic features associated with movement along the underlying Mill Creek fault. Consequently, Campbell and Bentley (1981 #3513) also concluded that the relations and age of the silt deposits in the sag pond (about 400–700 yr) suggest a recent event that postdates about 700 yr ago. Repasky and others (1998 #5554), however, reported that relations along the Mill Creek fault at the site where they obtained the 5,690±390 yr IRSL date indicated that the youngest event along the Mill Creek fault is only slightly younger than the soil they dated. Bjornstadt and others (2012 #7394) conclude there is definite evidence for repeated late Quaternary surface faulting and Toppenish Ridge is obviously an active structure based on surface ruptures as young as 500 years (Appen C cites age of "0.5–0.6 k.y. BP" [sic]). Regardless of the relationship of the Mill Creek fault to normal faults south of it, there appears to be clear evidence for at least one Holocene event along the Satus Peak part of the Mill Creek fault. No evidence for Quaternary events has been reported along other parts of the Mill Creek fault.
Recurrence interval	*Comments:* Published event chronologies suggest recurrence intervals that have varied from a few thousand years to over 100 k.y. Campbell and others (1995 #5552) reported that their trench studies indicate three and possibly four events along the Mill Creek fault in about the last 165 k.y. Repasky and others (1998 #5554) concluded from their trench studies of the Mill Creek fault combined with the earlier studies by Campbell and others (1995 #5552), that there is evidence for at least three and possibly five events along the Mill Creek fault. Repasky and others (1998 #5554) reported the ages of the five events and quality of the evidence for the events as follows: (1) 0.5–1.0 ka, poor; (2) 6–7 ka, very good; (3) 10–11 ka, fair; (4) 40–60 ka, good; and (5) 145–180 ka, fair to good. Bjornstad and others (2012 #7394) reports a slightly different chronology and recurrence interval of 7–120 k.y.
Slip-rate category	Less than 0.2 mm/yr *Comments:* Most data is available on uplift rates of Miocene volcanic rocks across the Toppenish Ridge anticline; rates calculated directly from

	offsets of Quaternary deposits or surfaces are not reported in the original study. Piety and others (1990 #3733) report 1800 m of uplift of 15 Ma volcanic rocks, Geomatrix Consultants, Inc. (1996 #4676) used uplift of 500 m of 10.5–15 Ma volcanic rocks and estimated fault dips of 30°, 45°, and 60° to estimate slip rates of 0.019–0.095 mm/yr along an inferred principle thrust fault underlying the Toppenish Ridge anticline. Based on previous trench studies and dating by Campbell and others (1995 #5552) and their later trench studies and dating, Repasky and others (1998 #5554) reported evidence for three and possibly five significant events since 145–180 ka. Repasky and others (1998 #5554) further reported that there was very good evidence for a 6–7 ka event that produced offset of about 3 m along the Mill Creek fault; they reported good to poor evidence for the other possible four events. Regardless, Bjornstad and others (2012) report a Holocene vertical displacement rate of 0.4 mm/yr based on 3 m of displacement since deposition of the Mount Mazama ash (7,700 calendar years); the short-term rate is substantially larger than the long-term net vertical rate (0.08–0.1 mm/yr). The reported Holocene displacement rate is overestimated because the earliest interevent period is incomplete. Most available evidence points suggest a low slip rate.
Date and Compiler(s)	2016 David J. Lidke, U.S. Geological Survey Kathleen M. Haller, U.S. Geological Survey Robert C. Bucknam, U.S. Geological Survey, Retired
References	#4693 Bentley, R.D., Anderson, J.L., Campbell, N.P., and Swanson, D.A., 1980, Stratigraphy and structure of the Yakima Indian Reservation, with emphasis on the Columbia River basalt group: U.S. Geological Survey Open-File Report 80-200, 73 p., 1. #7394 Bjornstad, B.N., Winsor, K., and Unwin, S.D., 2012, A summary of fault recurrence and strain rates in the vicinity of the Hanford site: Topical report prepared for the U.S. Department of Energy under contract DE-AC05-76RL01830, 90 p. #3513 Campbell, N.P., and Bentley, R.D., 1981, Late Quaternary deformation of the Toppenish Ridge uplift in south-central Washington: Geology, v. 9, p. 519–524. #5552 Campbell, N.P., Ring, T., and Repasky, T., 1995, Final report, 1994 NEHRP grant earthquake hazard study of the vicinity of Toppenish Basin, south-central Washington: Technical report to U.S. Geological Survey, Reston, Virginia, under Contract 1434-94-G-249, December 22, 1995, 9 p. #7402 Coppersmith, R., Hansen, K., Unruh, J., Slack, C., 2014, Structural

analysis and Quaternary investigations in support of the Hanford PSHA, Appendix E *in* Coppersmith, K.J., Bommer, J.J., Hanson, K.L., Unruh, J., Coppersmith, R.T., Wolf, L., Youngs, R., Rodriguez-Marek, A., Al Atik, L., Toro, G. and Montaldo-Falero, V., Hanford sitewide probabilistic seismic hazard analysis: Richland, Washington, Pacific Northwest National Laboratory report PNNL-23361, http://www. hanford. gov/page. cfm/OfficialDocuments/HSPSHA.

#1311 Geomatrix Consultants, Inc., 1988, Seismotectonic evaluation of the northern Cascade Mountains geomorphic province for Bumping Lake, Tieton, Keechelus, Kachess, Cle Elum, and Clear Creek Dams: Technical report to U.S. Department of Interior, Bureau of Reclamation, Denver, Colorado, under Contract 6-CS-81-07310, December 1988, 154 p., 12 pls.

#5550 Geomatrix Consultants, Inc., 1990, Seismotectonic evaluation of the Walla Walla section of the Columbia Plateau geomorphic province for Grand Coulee, North, Dry Falls, Pinto, and O'Sullivan Dams; Soda Lake, north Scooteney, and south Scooteney dikes: Technical report to U.S. Department of the Interior, Bureau of Reclamation, Denver, Colorado, under Contract 6-CS-81-07310, April 1990, 129 p.

#4676 Geomatrix Consultants, Inc., 1996, Probabilistic seismic hazard analysis DOE Hanford site, Washington: Technical report to Westinghouse Hanford Company, Richland, Washington, under Contract WHC-SD-W236A-TI-002, Rev.1, February, 1996, 366 p.

#5658 Mullineaux, D.R., Wilcox, R.E., Ebaugh, W.F., Fryxell, R., and Rubin, M., 1977, Age of the last major scabland flood of eastern Washington, as inferred from associated ash beds of Mount St. Helens set S: Geological Society of America Abstracts with Programs, v. 9, no. 7, p. 1105.

#5659 Mullineaux, D.R., Wilcox, R.E., Ebaugh, W.F., Fryxell, R., and Rubin, M., 1978, Age of the last major scabland flood of the Columbia Plateau in eastern Washington: Quaternary Research, v. 10, p. 171-180.

#3733 Piety, L.A., LaForge, R.C., and Foley, L.L., 1990, Seismic sources and maximum credible earthquakes for Cold Springs and McKay Dams, Umatilla Project, north-central Oregon: U.S. Bureau of Reclamation Seismotectonic Report 90-1, 62 p., 1 pl.

#7397 Pratt, T.L., 2012, Large-scale splay faults on a strike-slip fault system—The Yakima folds, Washington State: Geochemistry, Geophysics, Geosystems, v. 13, Q11004, doi: 10.1029/2012GC004405.

#5545 Reidel, S.P., 1984, The Saddle Mountains—The evolution of an anticline in the Yakima fold belt: American Journal of Science, v. 284, p. 942-978.

#3539 Reidel, S.P., Campbell, N.P., Fecht, K.R., and Lindsey, K.A., 1994, Late Cenozoic structure and stratigraphy of south-central Washington, *in* Lasmanis, R., and Cheney, E.S., eds., Regional geology of Washington State: Washington Division of Geology and Earth Resources, p. 159-180.

#5553 Reidel, S.P., Fecht, K.R., Hagood, M.C., and Tolan, T.L., 1989, The geologic evolution of the central Columbia Plateau, *in* Reidel, S.P., and Hooper, P.R., eds., Volcanism and tectonism in the Columbia River flood-basalt province: Geological Society of America Special Paper 239, p. 247-264.

#5554 Repasky, T.R., Campbell, N.P., and Busacca, A.J., 1998, Earthquake hazard study in the vicinity of Toppenish Basin, south-central Washington: Technical report to U.S. Geological Survey, Reston, Virginia, under Contract 1434-HQ-97-GR-03013, December 1998, 27 p., 7 pls.

#3738 Rigby, J.G., and Othberg, K., 1979, Reconnaissance surficial geologic mapping of the Late Cenozoic sediments of the Columbia Basin, Washington: State of Washington Department of Natural Resources Division of Geology and Earth Resources Open-File Report 79-3, 88 p., 10 pls.

#4654 Schuster, J.E., 1994, Geologic maps of the east half of the Washington portion of the Goldendale 1:100,000 quadrangle and the Washington portion of the Hermiston 1:100,000 quadrangle: Washington Division of Geology and Earth Resources Open-File Report 94-9, 17 p., scale 1:100,000.

#5555 Woodward-Clyde Consultants, 1981, Final report for Task D5, Toppenish Ridge study: Technical report to Washington Public Power Supply System, Nuclear Project WNP-2 and WNP-1/4, Hanford FSAR Geologic Support, San Francisco, California, under Contract C-560, July 15, 1981, 33 p.