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Brockton-Froid fault zone (Class B) No. 707

Last Review Date: 1999-07-27

Compiled in cooperation with the Montana Bureau of Mines and Geology

citation for this record: **Wheeler, R.L., compiler, 1999, Fault number 707, Brockton-Froid fault zone, in Quaternary fault and fold database of the United States: U.S. Geological Survey website, https://earthquakes.usgs.gov/hazards/qfaults, accessed 12/14/2020 02:03 PM.**

Synopsis	Quaternary outwash, alluvium, and colluvium deposits are mapped in a long, narrow, straight zone with glacial tills on both sides. The zone has been mapped as fault bounded, but it is unclear whether the faults penetrate deeply enough to pose a seismic hazard, and whether the hazard remains high now or decreased shortly after the ice sheets melted. Accordingly, the zone is classified as Class B.
Name comments	The fault zone was mapped by Colton (1963 #3653; 1963 #3654) and named by Colton and Bateman (1956 #3655; 1956 #3656). Thomas (1974 #3688) referred to its expression on 1:20,000-scale aerial photographs as the Brockton-Froid lineament. Johns and

	others (1982 #259) combined the fault zone with the Weldon fault, which is parallel to the Brockton-Froid fault zone and on strike several tens of kilometers to the southwest, and named the combination the Weldon-Brockton-Froid fault zone. The most detailed mapping of the fault zone is by Colton (1963 #3653; 1963 #3654), who showed its southwesternmost 24 km. As Colton mapped the zone, it strikes N. 55? E. across the Brockton 15 minute quadrangle and beyond to the northeast, and extends to the southwest 2 km into the Poplar 15 minute quadrangle. Colton (1963 #3653; 1963 #3654) mapped the zone as straight, approximately 0.5 km wide, and composed of two nearly parallel faults that bound a structurally lower block. **Fault ID:** The Brockton-Froid fault zone forms the northeastern part of entry 147 of Johns and others (1982 #259).
County(s) and State(s)	ROOSEVELT COUNTY, MONTANA
Physiographic province(s)	GREAT PLAINS
Reliability of location	Good Compiled at 1:62,500 scale. *Comments:* The Brockton-Froid fault zone was mapped by Colton (1963 #3653; 1963 #3654) at a scale of 1:62,500.
Geologic setting	The Brockton-Froid fault zone strikes northeast in the glaciated plains of northeastern Montana, where the dip angles in bedrock are low. Local relief between streams and uplands is generally 100 ft (30 m) or less, and the ground is covered by glacial deposits (Witkind, 1959 #3702). The nature of the fault zone is uncertain and its origin is enigmatic. No dip directions are indicated for the fault zone, so it is unknown whether the dip-slip components of the faulting are normal or reverse. At several places, one or two smaller faults are also mapped. The downdropped block between the faults contain mainly late Wisconsinan sandy gravel and silt that were deposited as outwash in contact with melting ice, and Quaternary sheetwash alluvium and colluvium (Colton, 1963 #3653, 1963 #3654; D.S. Fullerton, oral commun., 1999). Deposits outside of the fault zone are mainly pre-Illinoian, Illinoian, and late Wisconsinan tills, Quaternary dune sand, and Tertiary and Cretaceous bedrock (Colton, 1963 #3653, 1963 #3654; D.S. Fullerton, oral commun.,

1999). Two sets of auger holes that traverse the fault zone show markedly thicker Quaternary sequences between the faults than outside of them (Colton, 1963 #3653). A third set of auger holes across the zone show the same thing, and a fourth traverse based on outcrop exposures shows that lignite beds are offset 75 ft (23 m) vertically across the fault zone with the southeast side down (D.S. Fullerton, oral commun., 1999, based on R.B. Colton, unpub. data). Faulting is inferred from the auger traverses; nowhere is a fault exposed where outwash in one wall is juxtaposed against till in the other (R.B. Colton, oral commun., 1999).

Earlier, Colton and Bateman (1956 #3656) mapped the fault zone at a scale of 1:125,000, showing it as a pair of parallel faults. They traced the fault zone for 42 km, including 21 km of the length as mapped by Colton (1963 #3653; 1963 #3654) and an additional 21 km to the northeast. Colton and Bateman used petroleum well data to draw structure contours on the Cretaceous Greenhorn limestone, which is approximately 1 km deep below the fault zone. The regional pattern of the structure contours indicate that the fault zone vertically offsets the Greenhorn limestone as much as 300 ft (90 m), with the southeast side down. The fault traces mapped (Colton, 1963 #3653; 1963 #3654) at the surface are 100-300 m northwest than the faults mapped by Colton and Bateman (1956 #3656) on the Greenhorn, and this horizontal difference is consistent with the normal separation indicated by Colton and Bateman. However, only four widely-spaced drill holes control the Greenhorn structure near the fault zone, and these four control points could be honored with contours that show no faulting at the Greenhorn level. Thus, based on the evidence presented by Colton and Bateman (1956 #3656), it is unclear if the fault zone mapped by Colton (1963 #3653; 1963 #3654) extends to significant depths.

In contrast, Gott and others (1959 #3701) mapped a still longer extent of the fault zone as an unfaulted glacial outwash channel. Their 1:62,500-scale map shows four linear, northeast-trending, aligned, discontinuous deposits of outwash and colluvium that, together, span a distance of 41 km. This length includes the northeasternmost 12 km mapped by Colton (1963 #3654) and an additional length of 29 km to the northeast. Of the 41 km, the linear deposits of outwash and colluvium cover 26 km with 15 km of gaps that lack outwash and colluvium. The linear deposits are 100-400 m wide and 4-12 km long. Witkind (1959 #3702, p. 38-

39) named the aligned deposits the "Linear channel". The Linear channel contains elongated, closed depressions that are anomalously large for the area traversed by the Linear channel. The floor of the Linear channel slopes inward and downward from both ends, toward where Big Muddy Creek crosses and interrupts the Linear channel near its middle. "This channel deposit is unusual and difficult to explain" (Witkind, 1959 #3702, p. 39). Witkind speculated about alternative origins, including an ice contact feature, a buried fault-controlled valley, and drainage for a long, straight crevasse in glacial ice.

Finally, Thomas (1974 #3688) used 1:20,000-scale aerial photographs to map a photolineament that coincides with the Brockton-Froid fault zone. The readily visible photolineament begins approximately 2 km northeast of the eastern edge of the map area of Colton (1963 #3653; 1963 #3654) and extends 38 km to the northeast (fig. 3 of Thomas, 1974 #3688). Thus, the Brockton-Froid fault zone was mapped over 24 km by Colton (1963 #3653, 1963 #3654), and it appears to extend another 40 km to the northeast (Colton and Bateman, 1956 #3656; Gott and others, 1959 #3701; Thomas, 1974 #3688).

The Brockton-Froid fault zone is a real feature, but, as mentioned at the start of this section, its nature is unclear and its origin is enigmatic. Its straightness and its path uphill and downhill across streams and interfluves argue against a fluvial origin or deposition by outwash streams. Similarly, the fault zone has no obvious glacial origin, according to D.S. Fullerton (oral commun., 1999), who has examined it in the field. Glaciotectonic structures can involve bedrock, but typically are folds or reverse faults that trend at high angles to the direction of ice movement. In this part of northeastern Montana, Wisconsinan ice advanced from northeast to southwest (Flint and others, 1959 #3663; Colton, 1963 #3653). However, the fault zone trends nearly parallel to this direction, and, as suggested previously, any dip-slip components are more likely to be normal than reverse.

Another puzzling aspect of the fault zone is the absence of till in three of the auger holes in the structurally lower block. Each of the three auger-hole traverses across the fault zone has two holes inside the zone and another two bracketing it (Colton, 1963 #3653; D.S. Fullerton, oral commun., 1999, based on R.B. Colton, unpub. data). On each traverse, one hole inside the fault zone lacks till, having outwash directly overlying bedrock;

whereas, the other three holes of the traverse have till separating outwash from bedrock. Normally one might attribute the absence of till to scouring by flowing meltwater. For example, Colton (1963 #3653) showed several examples of logged holes without till, in a meandering meltwater channel in the northwestern part of the Brockton quadrangle. However, till is widely exposed adjacent to the fault zone (Colton, 1963 #3653; 1963 #3654), so probably any scouring meltwater would have flowed along the fault zone. This is unlikely because the zone rises and falls tens of feet to follow a straight line across present-day topography. Therefore, the local absence of till inside the fault zone remains unexplained.

The simplest explanation of the fault zone is that of a basement fault that was reactivated during glacial or post-glacial time. The northeast-trending Weldon fault is 74 km southwest of, and on trend with, the Brockton-Froid fault zone (Collier and Knechtel, 1939 #3651). It is 13 km long, and its downthrown southeast side has displaced the Cretaceous Fox Hills Sandstone 100-160 ft (30-50 m) in the subsurface (Collier and Knechtel, 1939 #3651). At greater depths, the Mississippian Kibby Limestone is similarly offset, southeast-side-down, 300-400 ft (90-120 m) (Edmisten and Foster, 1985 #3658). At ground level, the Weldon fault is expressed as a concentration of northeast-trending LANDSAT lineaments (Larson, 1985 #3678). Feltis (1981 #3660; 1981 #3661) used drill-hole data to draw structure contours on the Mississippian Madison Group. Feltis interpreted the Weldon fault as extending 84 km farther southwest than Collier and Knechtel (1939 #3651), and 36 km farther northeast, for a total inferred length of 133 km. The vertical separation of the Madison Group is well constrained by pairs of wells and is as great as 600-700 ft (180-210 m), although the separation decreases to the northeast. Thus, Feltis (1981 #3660) extended the Weldon fault to within 38 km of the Brockton-Froid fault zone as mapped by Colton (1963 #3654). Johns and others (1982 #259) used an aeromagnetic data to speculate that the Brockton-Froid and Weldon faults are parts of a single, long basement fault, and Hansen (1966 #3666) and Thomas (1974 #3688) speculated that the Brockton-Froid fault zone is underlain by a basement fault zone. Horner and Hasegawa (1978 #3671) speculated that four historical and early instrumental earthquakes in the region might have occurred on the Brockton-Froid fault and a southwestward extension; however, these early earthquakes are too poorly located to test this speculation.

Unfortunately, the basement-fault explanation poorly fits some of the properties of the fault zone. Three arguments cast doubt on attributing the Brockton-Froid fault zone to tectonic faulting in the basement. (1) Exposed bedrock near the fault zone is Paleocene, lignite-bearing Fort Union Formation (Colton, 1963 #3653; 1963 #3654). Nine subsurface lignites have been correlated and mapped near and beneath the fault zone at depths of approximately 800 ft (240 m) or less (Hardie and Van Gosen, 1986 #3670; Hardie and Arndt, 1989 #3668; 1990 #3669), and structure contour maps of individual lignites, isopachs of the lignites, and a structure contour map of the base of the Fort Union Formation do not show detectable offset across the Brockton-Froid fault zone (Hardie and Arndt, 1988 #3667; Biewick and others, 1990 #3649). At greater depth, Feltis (1981 #3662) extended structure contours of the Madison Group into the vicinity of the fault zone. Well control near the fault zone was sparse, and he could not rule out small offsets, but Feltis did not draw the fault zone on his map.

In North America east of the Rocky Mountains, earthquake depths are typically 5-15 km, with a median depth of approximately 10 km (Wheeler and Johnston, 1992 #2243). If the fault zone does not penetrate into basement and reach hypocentral depths, then it is unlikely to pose a notable seismic hazard. (2) As already mentioned, no exposures of the fault have been observed (Colton, oral commun., 1999). (3) As noted previously in this section, any dip-slip component of the faulting is more likely to be normal than reverse. However, the Brockton-Froid area is part of the North American stable continental region (SCR) (Johnston, 1989 #2039), and SCRs worldwide typically undergo contractional deformation (Zoback and others, 1989 #1923). Extensional faulting occurs in SCRs in thermally uplifted areas and in gravitational-collapse settings like the Gulf coast of the U.S., but neither analogy applies to northeastern Montana.

However, tectonic faulting is not the only alternative to fluvial, glacial, or glaciotectonic formation of the Brockton-Froid linear features. The Brockton-Froid fault zone could have formed by post-glacial faulting, as summarized below. Attributing the Brockton-Froid fault zone to reactivation of a basement fault and to post-glacial faulting are equally speculative; in both cases the phenomenon is real, but in neither case is there evidence that it applies to the Brockton-Froid fault zone. However, the following speculation demonstrates the existence of at least one alternative explanation for the fault zone. Northern Scandinavia and northern North America contain exceptionally large, reverse-faulting, surface ruptures that formed in early post-glacial times, in cratonic areas that are now sparsely seismic (for example, Johnston, 1996 #2205). The scarps along the surface ruptures can be several meters high and tens of kilometers long. Johnston (1989 #3676) and Thorson (1996 #3689) demonstrated that loading of the upper crust by an ice sheet could stabilize faults that would otherwise slip in occasional earthquakes. In such cases, horizontal tectonic stress could continuously accumulate, and when the ice melted, the vertical stress would decrease, and the accumulated excess horizontal stress could be released relatively quickly, producing a cluster of earthquakes that are larger and more frequent than normal for the region. Afterward, the region would return to its normal low level of seismicity. The Brockton-Froid fault zone is approximately parallel to the northeasterly orientation of S Hmax (greatest horizontal compressive stress) in this part of North America (Zoback and Zoback, 1989 #1922). If post-glacial stress release reactivated the fault zone, then the faulting would not be reverse, but normal or normal-oblique, consistent with the mapping by Colton (1963 #3653), to allow northwest-southeast extension in response to SHmax . This speculation, if borne out by testing, would also indicate that the fault zone may pose little or no seismic hazard today because the strain stored during ice loading has probably been released.

In summary, the Brockton-Froid fault zone has evidence of Quaternary deformation, and the deformation probably, but not certainly, occurred by faulting. However, it is not clear whether the faults penetrate deeply enough into the crust to pose a seismic hazard. Even if they do penetrate deeply, it is not clear whether the hazard remains high now, or was only high shortly after the ice melted. For these reasons, the fault zone is placed in class B. What is questionable is primarily the potential for seismic faulting, and only secondarily the presence of faulting. Perhaps the most effective way to answer these questions is with (1) high-resolution seismic-reflection profiles across the fault zone to determine whether faulting penetrates deeply into bedrock, and preferably into basement, and (2) paleoseismological study, including trenching and dating, to test the presence of faulted Quaternary materials and to constrain the time of faulting.

Length (km)	54 km.
Average strike	N51°E
Sense of movement	No data *Comments:* The geologic maps of Colton (1963 #3653; 1963 #3654) do not show evidence of strike slip along the fault zone, nor indications of dip direction for individual faults. The maps show the fault zone as a straight, fault-bounded block a few hundred meters wide and at least 24 km long, with the block structurally lower than the areas on either side of the fault zone. Accordingly, only dip slip is inferred, and present information cannot determine whether it was normal or reverse. The sense of movement on the fault zone is unknown. The straightness of the zone favors strike slip, but Colton (1963 #3653; 1963 #3654) did not report evidence of strike slip along the zone. Any dip-slip components of faulting are more likely normal than reverse. The nearly constant width of the structurally lower block along the zone's mapped length is reminiscent of a graben formed between a single, large normal fault and an adjacent antithetic fault. Such structures are common in extended terranes, for example along young faults of the Basin and Range province. In reverse-faulted terranes, such long, narrow, structurally low blocks of constant width are uncommon except on the crests of anticlines; no such fold is known under the Brockton-Froid fault zone.
Dip	No data *Comments:* It is unknown whether the dip slip, if any, was normal or reverse
Paleoseismology studies	
Geomorphic expression	As mapped by Colton (1963 #3653; 1963 #3654), Gott and others (1959 #3701), and Thomas (1974 #3688), the Brockton-Froid fault zone strikes northeast across ten 1:24,000-scale topographic quadrangles. The zone extends from the Poplar NE and Sprole quadrangles on the southwest to the Capeneys Lake quadrangle on the northeast. In some areas, the zone is expressed as alignments of northeast-trending stream segments and valleys, ridges and elongated hills, and closed depressions that are

	unusually large for the area. The grain is most pronounced in the northeastern quadrangles, in parts of the Medicine Lake, Johnson Lake, and Rocky Point quadrangles, which have a contour interval of five feet (2 m), and in part of the Calais quadrangle, which has a contour interval of 10 ft (3 m). Where the geomorphic expression of the zone is well developed, the zone descends into valleys, crosses streams, and ascends across interfluves, without obvious deflections. Morphologic expression of the zone descends and rises several tens of feet at several places, and in part of the Calais quadrangle, the elevation change along the zone is approximately 200 ft (60 m).
Age of faulted surficial deposits	late Quaternary
Historic earthquake	
Most recent prehistoric deformation	late Quaternary (<130 ka) *Comments:* Colton (1963 #3653) showed the faults in the zone offsetting the younger of two Wisconsinan tills and late Wisconsinan outwash deposits, as well as Quaternary fan alluvium and colluvium and Quaternary dune sands. Depending on the ages of the till and outwash deposits, the faulting could have been either late Pleistocene or early Holocene.
Recurrence interval	 *Comments:* No individual faulting events have been identified.
Slip-rate category	Insufficient data *Comments:* The evidence for one or a few through-going, causal faults is speculative. The causal faults, if any, remain unknown and uncharacterized.
Date and Compiler(s)	1999 Russell L. Wheeler, U.S. Geological Survey, Emeritus
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